Numerical and Experimental Investigation on Pool Boiling Heat Transfer Performance using Nanofluids

Dissertation submitted to Budapest University of Technology and Economics/ Géza Pattantyús-Ábrahám Doctoral School of Mechanical Engineering for the degree of Doctor of Philosophy (Ph.D.) in Mechanical Engineering

Prepared by
Mohammed Saad Kamel

Supervisor
Ferenc Lezsovits, Ph.D.

Budapest, 2020
1. CHAPTER 1: INTRODUCTION AND LITERATURE REVIEW
   1.1 Introduction ........................................................................................................ 1
   1.2 The motivation for this research ........................................................................ 2
   1.3 Objectives .......................................................................................................... 3
   1.4 Thesis outline and organization ....................................................................... 4
   1.5 Literature review ............................................................................................. 5
       1.5.1 Pool boiling heat transfer (general concept) ............................................. 5
       1.5.2 Nanofluids thermophysical properties .................................................. 7
           1.5.2.1 Density specific heat of NFs ......................................................... 7
           1.5.2.2 Thermal conductivity of NFs ....................................................... 9
           1.5.2.3 Viscosity of NFs ......................................................................... 13
           1.5.2.4 Surface tension and contact angle of NFs ................................. 16
       1.5.3 Pool boiling heat transfer of nanofluids ............................................... 18
           1.5.3.1 Experimental studies ................................................................. 18
           1.5.3.2 Computational fluid dynamic (CFD) studies ............................. 29

2. CHAPTER 2: NUMERICAL INVESTIGATION ................................................................ 32
   2.1 Introduction ...................................................................................................... 32
   2.2 Model description ............................................................................................ 32
       2.2.1 Geometry structure .............................................................................. 32
       2.2.2 Eulerian-Eulerian multiphase model formulation ............................... 33
           2.2.2.1 Governing equations .................................................................. 35
           2.2.2.2 Phase interaction mechanism .................................................... 36
           2.2.2.3 Heat flux partitioning model HFP .............................................. 38
           2.2.2.4 Nucleate boiling parameters .................................................... 39
   2.3 Numerical method and assumptions .................................................................. 41
   2.4 Boundary conditions ....................................................................................... 42
   2.5 Thermo-physical properties of nanofluids .................................................. 42
   2.6 Results and discussion .................................................................................... 43
       2.6.1 Results of simulation No.1 .................................................................... 43
           2.6.1.1 Grid sensitivity test ........................................................................ 43
           2.6.1.2 Results validation ......................................................................... 44
           2.6.1.3 Contours of vapor volume fraction ............................................. 46
           2.6.1.4 Vectors of vapor velocity ........................................................... 47
       2.6.2 Results of simulation No.2 ....................................................................... 49
           2.6.2.1 Grid independence test .................................................................. 50
           2.6.2.2 Results validation ......................................................................... 50
           2.6.2.3 Void fraction and PBHTC results .................................................. 52
2.6.3 Results of simulation No.3 .................................................. 54
  2.6.3.1 Mesh sensitivity test ................................................. 54
  2.6.3.2 Validation of the present model with experimental data ... 55
  2.6.3.3 The portion of RPI model components ....................... 56
  2.6.3.4 Further discussion ................................................ 57

3. CHAPTER 3: EXPERIMENTAL INVESTIGATION 59
  3.1 Introduction ..................................................................... 59
  3.2 Experimental methodology ............................................ 59
    3.2.1 Pool boiling chamber setup ...................................... 59
    3.2.2 Experimental procedure ......................................... 61
    3.2.3 Nanofluids preparation method ................................. 62
      3.3.3.1 Nanopowder types and the supplier ....................... 64
      3.3.3.2 Dispersion process and stability checking ............... 65
    3.2.4 Thermal conductivity measurements .......................... 66
  3.3 Data reduction and uncertainty analysis ............................... 66
  3.4 Results and discussion .................................................. 68
    3.4.1 Results of thermal conductivity for nanofluids ............... 68
    3.4.2 Results of pool boiling heat transfer performance for nanofluids .. 73
      3.4.2.1 Test No. 1 (CeO$_2$ based DI-W nanofluid) ............... 74
      3.4.2.2 Test No. 2 (WO$_3$ based DI-W nanofluid ) .............. 79
      3.4.2.3 Test No. 3 (MgO based DI-W nanofluid ) ................. 82
      3.4.2.4 Test No. 4 (AlN based DI-W nanofluid ) ................. 83
      3.4.2.5 Test No. 5 (Al$_2$O$_3$ based DI-W nanofluid ) .......... 85
      3.4.2.6 Test No. 6 (Hybrid Al$_2$O$_3$+CeO$_2$ based DI-W nanofluid) .. 87
      3.4.2.7 Test No. 7 (Hybrid Al$_2$O$_3$+MgO based DI-W nanofluid) .. 90

4. CHAPTER 4: CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH 92
  4.1 Conclusion ...................................................................... 92
  4.2 Recommendations for future research ................................. 93

5. CHAPTER 5: THE THESES .......................................................... 95

List of Publications ....................................................... 99
References ........................................................................ 101
Appendix A The calculations of nanopowder quantities ...................... 111
Appendix B Scanning electron microscope images for nanomaterials ........ 113
Appendix C Stability checking of the prepared nanofluids .................... 118
Appendix D Thermal conductivity measurements for nanofluids ............. 125
**Abstract**

In many heat exchange systems, boiling heat transfer play a significant role in transferring heat from one medium to another. Boiling heat transfer is an efficient heat transfer mode among others, and this is due to the latent heat of vaporization during the boiling phase change phenomenon. The nucleate boiling regime involved in many industrial applications to remove high heat flux in relatively small superheat temperature, which, in turn, makes these systems more durable and efficient. Adequate cooling fluids are needed to pass high heat flux from a heating surface to the fluid by applying the smallest temperature difference per unit time and area in the solid surface during boiling phase change. Nanofluids are engineered colloids or suspensions, which are produced by dispersing nanoscale solid materials such as metallic, non-metallic, and carbon into conventional liquids such as water, oil, ethylene, tri-ethylene-glycols, polymeric solutions, and refrigerants to enhance thermal transport properties. In the present research, the pool boiling heat transfer performance of deionized water and different types of nanofluids from a horizontal heated copper typical tube at atmospheric pressure condition was investigated. Firstly, the boiling model under the Eulerian-Eulerian multiphase model was corrected and extended to mimic the pool boiling heat transfer from different heating element geometries. The commercial computational fluid dynamics CFD code using build-in functions and additional user-defined functions UDFs related to nucleate boiling parameters of silica nanofluids was used to investigate pool boiling behavior from flat plate heating element. Afterward, the corrected model by modifying the bubble waiting time coefficient in quenching heat flux partition was used to validate and predict the pool boiling heat transfer of ceria nanofluids from a horizontal heated tube at atmospheric pressure. Next, an experimental setup was designed, fabricated and collected for validation of the numerical results of ceria nanofluids and also to investigate the pool boiling heat transfer performance of other types of nanofluid from a typical horizontal heated copper tube with an outer diameter (22 mm). Before the test of nanofluids for pool boiling performance, the thermal conductivity of deionized water and various nanofluids was measured by the transient plate source sensor at different volume concentrations and temperatures. The two-step method was utilized to prepare our mono and hybrid nanofluids and the stability of the nanofluids was checked to confirm the applicability of using those nanofluids in the current tests. The results demonstrated that the thermal conductivity of prepared nanofluids was enhanced compared to deionized water as a baseline case, and this enhancement was increased with increasing the volume concentrations and temperatures. The obtained results regarding the pool boiling tests showed that using nanofluids as working fluids in the pool boiling heat transfer process might reduce or enhance the pool boiling heat transfer coefficient. The pool boiling heat transfer coefficient enhancement ratio of nanofluids relative to deionized water was improved or deteriorated depends on the nanomaterials type, size, concentrations and the heating surface characteristics. Moreover, a new kind of nanofluids so-called hybrid nanofluids which are produced by adding complex nanopowders (hybrid ones) or by mixing two different nanofluids were prepared to investigate the pool boiling behavior in the current research. Results have shown that the pool boiling heat transfer performance was enhanced for both types of hybrid nanofluids that are used for pool boiling tests when using dilute volume concentrations.
I, the undersigned, Mohammed Saad Kamel declare, that the present Ph.D. dissertation is my own work, and only the sources referred have been used in the document. Each part used literally, or taken over paraphrased from other sources have been obviously indicated by the identification of its source.

Budapest, January 6, 2020

....................................
Mohammed Saad Kamel
Firstly and foremost, I would like to express my sincere gratitude to my supervisor, 
**Associate Professor Dr. Ferenc Lezsovits** for his continuous support during my Ph.D. journey and related work, for his patience, motivation, encouragement, and immense knowledge. His guidance helped me in all the time of research and writing of this dissertation. I feel that the words alone are not enough to show the great gratitude and compliment that I owe for him.

I owe my deepest gratitude to **Dr. Gyula Gróf**, and **Dr. Imre Miklos Szilagyi** for their careful and comprehensive reading of my dissertation and for the thoughtful comments and constructive suggestions, which help me to improve the quality of my thesis book. I would also like to thanks **Dr. Omid Mahian, Dr. Tarek Maiyaleh, Dr. Attila Imre, Dr. Edit Cséfalvay, Dr. Tamás Fülöp, Dr. Viktor Józsa, and Krisztián Péter Kovács** and all other Ph.D. students and colleagues at Department of Energy Engineering for their continuous support and consultation during my study period.

I want to thank **Dr. István Csontos, Dr. Benjámin Gyarmati, Dr. Czampa Miklós, Dr. Ezddin Hutli, István Rudy, and Sherwan M. Najm** for their support throughout my experimental side.

I am also thankful to the Hungarian government for their financial support represented in the Stipendium Hungaricium Scholarship. Besides, I would also like to thank the **Tempus Public Foundation (TPF)** in Hungary for their continuous administrative support since the application stage until graduation. **Thank you very much.**

The special gratitude should go for my lovely and beautiful family, my wife, my son (**Ali**), and my twin daughters (**Fatimah** and **Baneen**), without them, life would not be easy in Budapest. I acknowledge the immense love and support that they have given to me all the time. I am also grateful for my **father** and my **mother**, who have never stopped wishing me the best in my study and life through their continuous support and prayers. This accomplishment would not have been possible without them.
List of Figures

Fig. (1.1) Documents by keyword of (“pool boiling”) since 1996 to present; “Science Direct” on 19/Oct/2019.
Fig. (1.2) Typical pool boiling curve and transition regimes [3].
Fig. (1.3) Parameters influence the thermal conductivity of nanofluids.
Fig. (1.4) Publications by keywords of (“pool boiling” AND “nanofluid”) since 2003 to present; “Scopus database” on 19/Oct/2019.
Fig. (1.5) Factors affect the pool boiling heat transfer performance.
Fig. (2.1) Physical geometry for present simulations.
Fig. (2.2) Flowchart for multiphase flow types and some examples.
Fig. (2.3) Total heat flux mechanisms during the RPI wall boiling model [132].
Fig. (2.4) Pool boiling curve of water for present simulation against experimental work [78].
Fig. (2.5) Pool boiling heat transfer coefficient of water against heat flux for present simulation and experimental work [78].
Fig. (2.6) Bubbles waiting time coefficient vs. superheat temperature proposed in the simulation No.1 to modify the quenching heat flux part for pool boiling of water.
Fig. (2.7) Contours of vapor volume fraction with different time and superheat temperature (7.5 K); A (200 ms), B (400 ms), C (500 ms), and D (600 ms).
Fig. (2.8) Contours of vapor volume fraction at time (600 ms) with different superheat temperatures; A (7.5 K), B (8.5 K), and C (10 K).
Fig. (2.9) Velocity vectors of vapor phase with different time steps and superheat temperature (7.5 K); A (200 ms), B (400 ms), C (600 ms), D (800 ms), and E (1000 ms).
Fig. (2.10) Velocity vectors of vapor phase at time (500 ms) with different superheat temperatures; A (7.5 K), B (8.5 K), and C (10 K).
Fig. (2.11) The boiling curve of pure water for the present model compared to experimental data of Akbari et al. [117], and Rohesnow correlation [19].
Fig. (2.12) Bubbles waiting time coefficient vs. superheat temperature proposed in the simulation No.2 to modify the quenching heat flux part for pool boiling of water.
Fig. (2.13) Pool boiling heat transfer coefficient of nanofluids against heat flux for present extended RPI model and experimental work [162].
Fig. (2.14) Vectors of a vapor velocity of silica-based water nanofluid at different superheat temperatures. (i) $\Delta T_{\text{sup}} = 10$ K, time = 1000 ms;
(ii) $\Delta T_{\text{sup}} = 20$ K, time = 1000 ms.
Fig. (2.15) The void fraction of the vapor phase for pure water and (0.01% Vol.) silica-based water nanofluid along the vertical distance with various superheat temperatures.
Fig. (2.16) Pool boiling heat transfer coefficient against heat flux for pure water and (0.01% Vol.) silica nanofluid predicted by the present model.
Fig. (2.17) Grid independence test for present model for pool boiling of deionized water.
Fig. (2.18) The boiling curve of pure water for the present model compared to present experimental data for deionized water and ceria nanofluids.

Fig. (2.19) The pool boiling heat transfer coefficient against the heat flux for deionized water and ceria nanofluids for present model.

Fig. (2.20) Bubbles waiting time coefficient vs. superheat temperature proposed in the simulation No.3 to modify the quenching heat flux part for pool boiling of deionized water and ceria nanofluids.

Fig. (2.21) The Portion of heat flux components of the classical RPI model and extended RPI model against the total heat flux for (0.007% Vol.) ceria nanofluid.

Fig. (2.22) Contours of vapor volume fraction with different time and superheat temperature for water and (0.007% Vol.) ceria nanofluids.

Fig. (3.1) (A) schema of pool boiling apparatus, (B) Real photo of pool boiling facility.

Fig. (3.2) Heating element assembly and sleeve configuration used in this experiment.

Fig. (3.3) Roughness profiles for two polished copper tubes in the present work.

Fig. (3.4) The steps of prepared nanofluids in the present research.

Fig. (3.5) Thermal conductivity tester used in the present work.

Fig. (3.6) The validation of thermal conductivity results for deionized water with NIST data [159].

Fig. (3.7) Thermal conductivity ratio results of ceria nanofluids against temperatures at different volume concentrations.

Fig. (3.8) The comparison between measured thermal conductivity ratio results of ceria nanofluid and theoretical H-C model [35].

Fig. (3.9) Thermal conductivity of alumina nanofluid compared to other theoretical models [35, 36].

Fig. (3.10) Thermal conductivity ratio results of alumina nanofluids with temperatures at different volume concentrations.

Fig. (3.11) The comparison between measured data of alumina nanofluid and Esfe et al. [46] at volume concentration (0.5% Vol.).

Fig. (3.12) Thermal conductivity ratio results of hybrid nanofluids with temperatures at different volume concentrations.

Fig. (3.13) The variations of thermal conductivity ratio for all types of nanofluids at a temperature (50 °C) and different volume fractions.

Fig. (3.14) (3-D) analysis of thermal conductivity ratio for hybrid nanofluid at various volume fractions and temperatures.

Fig. (3.15) The margin of deviation for the proposed correlation and measured data.

Fig. (3.16) Thermal conductivity ratio of WO3 nanofluids relative to deionized water at different volume concentrations and temperatures.

Fig. (3.17) The comparison between the pool boiling curve for present experimental work and literature work for deionized water as a working fluid.

Fig. (3.18) The comparison between the pool boiling heat transfer coefficient PBHTC for present experimental work and literature works for deionized water.

Fig. (3.19) Pool boiling curves of deionized water and cerium oxide nanofluids at different volume concentrations.
Fig. (3.20) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and cerium oxide nanofluids at different volume concentrations.

Fig. (3.21) Pool boiling heat transfer coefficient ratio of cerium oxide nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.

Fig. (3.22) Surface roughness against different volume fraction of cerium oxide nanofluids at various tube locations.

Fig. (3.23) Contact angles of the deionized water droplet on the bottom side of the tube before and after (0.01% Vol.) nanoparticles deposition layer.

Fig. (3.24) Visualization of pool boiling of DI-W and cerium oxide nanofluids with the volume fraction of (0.001% Vol.) at various heat fluxes.

Fig. (3.25) Pool boiling curves of deionized water and tungsten oxide nanofluids at different volume concentrations.

Fig. (3.26) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and tungsten oxide nanofluids at different volume concentrations.

Fig. (3.27) Pool boiling heat transfer coefficient ratio of tungsten oxide nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.

Fig. (3.28) (A) Schema of nanoflakes deposition on the heating surface, (B) Deposition nanolayer of WO$_3$ nanoflakes on different radial and axial locations at (0.05% Vol.) nanofluid concentration.

Fig. (3.29) Pool boiling curves of deionized water and Magnesium oxide MgO nanofluids at different volume concentrations.

Fig. (3.30) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and Magnesium oxide MgO nanofluids at different volume concentrations.

Fig. (3.31) Pool boiling heat transfer coefficient ratio of Magnesium oxide MgO nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.

Fig. (3.32) Pool boiling curves of deionized water and Aluminum nitride AlN nanofluids at different volume concentrations.

Fig. (3.33) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and Aluminum nitride AlN nanofluids at different volume concentrations.

Fig. (3.34) Pool boiling heat transfer coefficient ratio of Aluminum nitride AlN nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.

Fig. (3.35) Pool boiling curves of deionized water and Aluminum oxide Al$_2$O$_3$ nanofluids at different volume concentrations.

Fig. (3.36) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and Aluminum oxide Al$_2$O$_3$ nanofluids at different volume concentrations.
Fig. (3.37) Pool boiling heat transfer coefficient ratio of Aluminum oxide $Al_2O_3$ nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.

Fig. (3.38) Pool boiling curves of deionized water and $(Al_2O_3+CeO_2)$ hybrid nanofluids at different volume concentrations.

Fig. (3.39) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and $(Al_2O_3+CeO_2)$ hybrid nanofluids at different volume concentrations.

Fig. (3.40) Pool boiling heat transfer coefficient ratio of $(Al_2O_3+CeO_2)$ hybrid nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.

Fig. (3.41) Pool boiling curves of deionized water, Alumina, Ceria, and their hybrid nanofluids at volume concentrations (0.01% Vol.).

Fig. (3.42) Pool boiling heat transfer coefficient PBHTC against applied heat fluxes for deionized water, Alumina, Ceria, and their hybrid nanofluids at volume concentrations (0.01% Vol.).

Fig. (3.43) Pool boiling heat transfer coefficient ratio of deionized water, Alumina, Ceria, and their hybrid nanofluids at volume concentrations (0.01% Vol.).

Fig. (3.44) Pool boiling curves of deionized water and $(Al_2O_3+MgO)$ hybrid nanofluids at different volume concentrations.

Fig. (3.45) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and $(Al_2O_3+MgO)$ hybrid nanofluids at different volume concentrations.

Fig. (3.46) Pool boiling heat transfer coefficient ratio of $(Al_2O_3+MgO)$ hybrid nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.
List of Tables

Table (1.1) Thermal conductivities of different materials at room temperature [6, 8]. 2
Table (1.2) Summarized experimental studies on pool boiling of nanofluids. 25
Table (1.3) Summary of CFD studies of pool boiling using nanofluids. 31
Table (2.1) Dimensions of the computational domains for pool boiling chamber in present simulations. 32
Table (2.2) Number of simulations for various cases changing in geometry structures, working fluids, boundary conditions, and investigated parameters. 34
Table (2.3) Models used in these simulations for the interfacial exchange of heat and mass transfer (phase interactions). 36
Table (2.4) Closure correlations for nucleate pool boiling parameters used in present simulations. 39
Table (2.5) Thermo-physical properties of working fluids used in present simulations at saturation temperature condition (100 ºC). 43
Table (2.6) Grid independence test for average vapor volume fraction at superheat temperature ($\Delta T_{sup} = 6$ K). 44
Table (3.1) Types of working fluids used to investigate pool boiling heat transfer in this research. 63
Table (3.2) Specification of the nanopowders from the supplier (US Research Nanomaterials, Inc.). 64
Table (3.3) The details of nanofluids formation methods and stability checking. 65
## Nomenclatures

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBHTC</td>
<td>Pool boiling heat transfer coefficient</td>
<td>[kW.m⁻².K⁻¹]</td>
</tr>
<tr>
<td>ΔT&lt;sub&gt;sup&lt;/sub&gt;</td>
<td>Superheat temperature</td>
<td>[K]</td>
</tr>
<tr>
<td>T&lt;sub&gt;w&lt;/sub&gt;</td>
<td>Wall temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>T&lt;sub&gt;sat&lt;/sub&gt;</td>
<td>Saturation temperature</td>
<td>[°C]</td>
</tr>
<tr>
<td>m</td>
<td>Mass</td>
<td>[Kg]</td>
</tr>
<tr>
<td>V</td>
<td>Volume</td>
<td>[m³]</td>
</tr>
<tr>
<td>c&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Specific heat</td>
<td>[J.kg⁻¹.K⁻¹]</td>
</tr>
<tr>
<td>d&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Nanoparticles diameter</td>
<td>[nm]</td>
</tr>
<tr>
<td>K</td>
<td>Thermal conductivity</td>
<td>[W.m⁻¹.K⁻¹]</td>
</tr>
<tr>
<td>K&lt;sub&gt;B&lt;/sub&gt;</td>
<td>Boltzmann constant</td>
<td>[J.K⁻¹]</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>[kPa]</td>
</tr>
<tr>
<td>A, B, a, b, c</td>
<td>Constants appeared in viscosity models</td>
<td>[—]</td>
</tr>
<tr>
<td>T&lt;sub&gt;0&lt;/sub&gt;</td>
<td>Reference temperature (room temperature)</td>
<td>[°C]</td>
</tr>
<tr>
<td>q</td>
<td>Heat flux</td>
<td>[kW.m⁻²]</td>
</tr>
<tr>
<td>R&lt;sub&gt;a&lt;/sub&gt;</td>
<td>Arithmetical mean height</td>
<td>[µm]</td>
</tr>
<tr>
<td>C&lt;sub&gt;μ&lt;/sub&gt;, σ&lt;sub&gt;K&lt;/sub&gt;, σ&lt;sub&gt;e&lt;/sub&gt;, C&lt;sub&gt;e1&lt;/sub&gt;, C&lt;sub&gt;e2&lt;/sub&gt;</td>
<td>Constants in turbulence model</td>
<td>[—]</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number</td>
<td>[—]</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
<td>[—]</td>
</tr>
<tr>
<td>Pr</td>
<td>Prandtl number</td>
<td>[—]</td>
</tr>
<tr>
<td>Eo</td>
<td>Eötvös number</td>
<td>[—]</td>
</tr>
<tr>
<td>C&lt;sub&gt;VM&lt;/sub&gt;, C&lt;sub&gt;D&lt;/sub&gt;, C&lt;sub&gt;L&lt;/sub&gt;, C&lt;sub&gt;TD&lt;/sub&gt;</td>
<td>Coefficients appeared in phase interactions</td>
<td>[—]</td>
</tr>
<tr>
<td>d&lt;sub&gt;bubble&lt;/sub&gt;</td>
<td>Bubble diameter</td>
<td>[mm]</td>
</tr>
<tr>
<td>C&lt;sub&gt;w&lt;/sub&gt;</td>
<td>Bubble waiting time coefficient</td>
<td>[—]</td>
</tr>
<tr>
<td>A</td>
<td>Area</td>
<td>[m²]</td>
</tr>
<tr>
<td>N&lt;sub&gt;a&lt;/sub&gt;</td>
<td>Nucleation site density</td>
<td>[Sites.cm⁻²]</td>
</tr>
<tr>
<td>f</td>
<td>Bubble frequency</td>
<td>[Hz]</td>
</tr>
<tr>
<td>h&lt;sub&gt;lg&lt;/sub&gt;</td>
<td>Latent heat of vaporization</td>
<td>[kJ.kg⁻¹]</td>
</tr>
<tr>
<td>g</td>
<td>Gravitational acceleration</td>
<td>[m.s⁻²]</td>
</tr>
<tr>
<td>j&lt;sub&gt;a&lt;/sub&gt;</td>
<td>Jacob number</td>
<td>[—]</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
<td>[s]</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
<td>[m]</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
<td>[m]</td>
</tr>
<tr>
<td>E</td>
<td>Electrical power</td>
<td>[W]</td>
</tr>
<tr>
<td>C&lt;sub&gt;sf&lt;/sub&gt;</td>
<td>Constant that depends on surface characteristics</td>
<td>[—]</td>
</tr>
<tr>
<td>pr</td>
<td>Reduced pressure ratio</td>
<td>[—]</td>
</tr>
<tr>
<td>F&lt;sub&gt;p&lt;/sub&gt;, F&lt;sub&gt;q&lt;/sub&gt;, F&lt;sub&gt;SR&lt;/sub&gt;</td>
<td>Constants appeared in Gorenflo Correlation</td>
<td>[—]</td>
</tr>
</tbody>
</table>
### Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>PBHTC</td>
<td>Pool boiling heat transfer coefficient</td>
</tr>
<tr>
<td>DI-W</td>
<td>Deionized water</td>
</tr>
<tr>
<td>HTC</td>
<td>Heat transfer coefficient</td>
</tr>
<tr>
<td>RPI</td>
<td>Rensselaer polytechnic institute</td>
</tr>
<tr>
<td>HFP</td>
<td>Heat flux partitioning</td>
</tr>
<tr>
<td>CHF</td>
<td>Critical heat flux</td>
</tr>
<tr>
<td>ONB</td>
<td>Onset of nucleate boiling</td>
</tr>
<tr>
<td>NFs</td>
<td>Nanofluids</td>
</tr>
<tr>
<td>H-C</td>
<td>Hamilton and Crosser</td>
</tr>
<tr>
<td>EG</td>
<td>Ethylene glycol</td>
</tr>
<tr>
<td>BN</td>
<td>Boron nitride</td>
</tr>
<tr>
<td>MWCNTs</td>
<td>Multi-walled carbon nanotubes</td>
</tr>
<tr>
<td>CNTs</td>
<td>Carbon nanotubes</td>
</tr>
<tr>
<td>SDS</td>
<td>Sodium dodecyl sulfate</td>
</tr>
<tr>
<td>CFD</td>
<td>Computational fluid dynamics</td>
</tr>
<tr>
<td>FVM</td>
<td>Finite volume method</td>
</tr>
<tr>
<td>UDFs</td>
<td>User defined functions</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning electron microscope</td>
</tr>
<tr>
<td>NIST</td>
<td>National institute for standard and technology</td>
</tr>
</tbody>
</table>

### Greek symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \phi )</td>
<td>Volume fraction</td>
<td>[%]</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Viscosity</td>
<td>[Pa.s]</td>
</tr>
<tr>
<td>( \beta )</td>
<td>Ratio of the nanolayer thickness to the diameter of the nanoparticles</td>
<td>[-]</td>
</tr>
<tr>
<td>( \rho )</td>
<td>Density</td>
<td>[Kg.m(^{-3})]</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>Surface tension</td>
<td>[N.m(^{-1})]</td>
</tr>
<tr>
<td>( \theta )</td>
<td>Contact angle</td>
<td>[°]</td>
</tr>
<tr>
<td>( \varepsilon )</td>
<td>Turbulence dissipation rate</td>
<td>[m(^2).s(^{-3})]</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>Wall-liquid interaction parameter</td>
<td>[-]</td>
</tr>
<tr>
<td>( \vartheta )</td>
<td>Hydrodynamic interaction</td>
<td>[-]</td>
</tr>
</tbody>
</table>

### Subscripts

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
<th>Symbol</th>
<th>Meaning</th>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>( nf )</td>
<td>nanofluid</td>
<td>( tot )</td>
<td>total</td>
<td>( m )</td>
<td>mass</td>
</tr>
<tr>
<td>( p )</td>
<td>nanoparticles</td>
<td>( quen )</td>
<td>quenching</td>
<td>( out )</td>
<td>outer</td>
</tr>
<tr>
<td>( f )</td>
<td>fluid</td>
<td>( conv )</td>
<td>convection</td>
<td>( corr )</td>
<td>correlation</td>
</tr>
<tr>
<td>( s )</td>
<td>surface</td>
<td>( evap )</td>
<td>evaporation</td>
<td>( exp )</td>
<td>experimental</td>
</tr>
<tr>
<td>( sup )</td>
<td>superheat</td>
<td>( sub )</td>
<td>subcooled</td>
<td>( VM )</td>
<td>virtual mass</td>
</tr>
<tr>
<td>( l )</td>
<td>liquid</td>
<td>( atm )</td>
<td>atmospheric</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
1.1 Introduction

In many heat exchange systems, boiling heat transfer and two-phase flow plays a significant role in transporting heat from one medium to another. Boiling heat transfer is an efficient mode among other heat transfer modes, and this is due to the latent heat of vaporization during the boiling phase change phenomenon. However, the nucleate boiling regime involves many industrial applications to remove high heat flux in relatively small superheat temperatures, which, in turn, makes these systems more durable and efficient. Nowadays, there is an increasing demand to develop new products with high heat flux and compact space. For these products with high thermal loads, the liquid-cooling systems with boiling phase change are more efficient compared to air-cooling systems [1, 2]. Adequate cooling liquids are needed to pass high energy from a heating surface to fluid by applying the smallest temperature difference per unit time and area in the solid surface. On the other hand, the active heat transfer modes, for example, nucleate boiling, will offer a lot of heat removal per unit area. Therefore, new and functional cooling fluids should be used to overcome the inherently limited thermal properties of conventional liquids such as water, ethylene glycol, and engine oil. During the last decades, considerable research effort devoted to finding new efficient thermal fluids with thermal properties that adequately satisfy the cooling requirements of these high heat dissipation products, as mentioned earlier. One of the essential passive heat transfer enhancement techniques is the use of ultrafine solid particles, which provide efficient thermal-transport properties compared to conventional fluids [3, 4].

Nanofluids are engineered colloids of nanoscale solid materials (e.g., metallic, non-metallic, carbon, etc.) with base fluids (e.g., water, oil, ethylene, tri-ethylene-glycols, polymeric solutions, and refrigerants) [5-8]. Materials widely utilized as nanopowders include metals (e.g., gold, copper, silver), metal oxides (e.g., alumina, ceria, silica, zirconia, titania etc.), metal carbides (e.g., silicon carbide, zirconium carbide, and tungsten carbide), metal nitrides (e.g., aluminum nitride, silicon nitride), carbon in different forms (e.g., diamond, graphite, carbon nanotubes, fullerene) and functionalized nanoparticles. It was widely reported that the solid materials have thermal conductivities that are larger than those of conventional cooling liquids, as shown in Table (1.1). When dispersing those materials into base liquids to enhance thermal properties of the suspension (e.g., thermal conductivity property), the heat transport performance can be notably intensifying as reported in studies [9, 10]. Numerous studies in the literature indicated that the nanofluids thermo-physical properties especially, the thermal conductivity was enhanced when adding those solid materials into conventional fluids, and this is due to the higher thermal conductivity of solid particles which, in turn, increase the conductive between the solid particles and liquid molecules [11-13]. However, there were some critical issues regarding the other thermo-physical transport properties such as the viscosity, heat capacity, and density for those new thermal fluids which, need more extensive investigations to show the overall merits for using those liquids in the real industrial applications that involve heat transfer of single and two-phase flow regimes.

[1]
Table 1.1 Thermal conductivities for different materials at room temperature [6, 8].

<table>
<thead>
<tr>
<th>Materials</th>
<th>Type</th>
<th>Thermal conductivity [W/m. K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallic solids</td>
<td>Gold</td>
<td>318</td>
</tr>
<tr>
<td></td>
<td>Silver</td>
<td>429</td>
</tr>
<tr>
<td></td>
<td>Cooper</td>
<td>401</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td>237</td>
</tr>
<tr>
<td>Non-metallic solids</td>
<td>Silicon</td>
<td>148</td>
</tr>
<tr>
<td></td>
<td>Alumina (Al₂O₃)</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>Diamond</td>
<td>3300</td>
</tr>
<tr>
<td></td>
<td>Carbon nanotubes</td>
<td>3000</td>
</tr>
<tr>
<td></td>
<td>Graphite</td>
<td>110-190</td>
</tr>
<tr>
<td></td>
<td>Fullerene film</td>
<td>0.4</td>
</tr>
<tr>
<td>Metallic liquids</td>
<td>Sodium at 371 °C</td>
<td>72.3</td>
</tr>
<tr>
<td>Nonmetallic liquids</td>
<td>Water</td>
<td>0.613</td>
</tr>
<tr>
<td></td>
<td>Ethylene glycol</td>
<td>0.253</td>
</tr>
<tr>
<td></td>
<td>Engine oil</td>
<td>0.145</td>
</tr>
<tr>
<td></td>
<td>R134a</td>
<td>0.0833</td>
</tr>
</tbody>
</table>

1.2 The motivation for this research

Nowadays, the demand for miniaturization of heat exchange systems with efficient operation resulted in increasing heat dissipation from such systems hence, reduce the efficiency of the systems. Such growing in heat fluxes not a problem just in miniaturization systems such as microelectronic devices, but also for systems involved in those things like thermal equipment, manufacturing Industries, thermal power plants, nuclear reactors, etc. Therefore, to enhance the efficiency as well as the life-time of these systems, we must overcome such high heat fluxes. For efficient heat removal adequate cooling system is required for heat transfer.

Boiling heat transfer is encountered in many industrial heat exchange systems due to the phase change represented by the latent heat of vaporization that could happen during this process. Two-phase flow heat transfer is an efficient process to remove high thermal energy from the surface. Systems that include boiling are extensively investigated during the last decades by many scientists and researchers. However, the nucleate boiling regime is a vital region among all boiling transition regimes, and this due to the high heat dissipation that can be removing in relatively small superheat temperatures. In other words, the boiling heat transfer mode leads to significant heat transfer coefficients compared to single-phase convection processes. Because of the considerable heat transfer coefficients that appeared during the boiling mode, it is considered as a desirable heat transfer process to thermal power engineers. For example, boiling is crucial for thermodynamic systems. In a power plant cycle, the working fluid (e.g., water) is usually heated inside the boiler, until phase change takes place, and the required vapor is used to drive the turbine.

Nanofluids are a new class of working fluids, which are made by dispersing ultrafine solid materials under range 100 nm. As discussed before, and according to existing literature, the use of nanofluids could enhance the heat transfer performance in the application of single-phase systems, but the question is those fluids applicable in two-phase flow systems? Applying nanofluids in the frontier research in two-phase flow, boiling heat transfer, and critical heat flux (CHF) in some heat exchange systems is another exciting topic, but there are also
extraordinary challenges in this aspect. As indicated by many investigations and during the stage of collecting data to understand the gap of this topic, several issues in the related subject are reported and listed as follows:

- The absence of understanding related to the experimental results of the boiling heat transfer coefficient from different investigators.
- The absence of the theoretical background associated with the mechanism of boiling two-phase flow using nanofluids.
- There was no comprehensive understanding of the influence of nanomaterial type, size, and loading, as well as the heating element geometry on boiling heat transfer performance when using nanofluids.
- Up to date, there is no model to predict the boiling heat transfer of nanofluids employing both pool and flow boiling due to the contradictory experimental results in the literature regarding this subject.
- The absence of real applications of heat exchange systems related to nanofluids as a new thermal fluid, although this topic has been investigated for several years ago.
- What should we do to understanding the performance of boiling heat transfer and complex two-phase flow phenomenon when using nanofluids as working fluid.

The issues mentioned above were huge enough to motivate me to investigate the boiling heat transfer by using nanofluids with new types, size, dilute concentrations, and typical horizontal heated tube as the heating element to well understanding this mechanism.

### 1.3 Objectives

The objectives of this research are listed as follows:

- To build up a pool boiling apparatus for carrying out the pool boiling heat transfer performance test represented by pool boiling heat transfer coefficient PBHTC from a horizontal copper heated tube with a typical diameter (22 mm).
- To examine the effect of applied heat flux on the pool boiling heat transfer coefficient for deionized water and various types of nanofluids.
- To investigate different types of fairly stable nanofluids with various dilute volumetric concentrations, and compared the results to deionized water as a baseline case.
- To measure the thermal conductivity of different types of nanofluids with various volume concentrations and temperatures experimentally.
- To prepare new mono and hybrid nanofluids to examine the pool boiling heat transfer performance, and compared the results to the baseline case (deionized water).
- To visualize the bubble dynamics during the nucleate pool boiling regime for dilute nanofluids and comparing to deionized water.
➢ To compare the experimental results of deionized water with well-known correlations and empirical studies in the literature to see the reliability of the pool boiling chamber.
➢ To extend and correct the boiling model under the Eulerian-Eulerian multiphase approach by modifying the bubble waiting time coefficient, which involved in quenching heat flux partition of heat flux partitioning model (RPI).
➢ To validate the extended numerical model with experimental results of cerium oxide nanofluid under the atmospheric condition.

The necessity for measuring surface temperatures along with the heating element with a proper and accurate way was because the measuring of those surface temperatures could play a significant role in obtaining precise pool boiling heat transfer coefficient. Furthermore, efforts have been made during the fabrication of the heating element stage to fix the thermocouples on the tube surface to measuring surface temperatures from different axial and radial directions and ensure acceptable accuracy through measurement. Besides, to investigate the pool boiling process for various working fluids, Pool boiling apparatus was built at the Department of Energy Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics BME, (Hungary). All the experimental details will be discussed later on in chapter 3.

1.4 Thesis outline and organization

In this research work, the dissertation organized to be as following:

Chapter 1 gives an introduction to the research topic and shows the motivation for this research. Also, the objectives of this work are stated and listed. Moreover, a literature review regarding pool boiling heat transfer using nanofluids, and the most important thermo-physical properties such as thermal conductivity, specific heat, density, viscosity, surface tension, and the wettability are introduced to cover the importance of theoretical and empirical models proposed in the literature related to nanofluids. Finally, the experimental and numerical works reported in recent years regarding pool boiling heat transfer of nanofluids are presented and discussed.

Chapter 2 Theoretical formulation of the Eulerian-Eulerian multiphase model involving boiling model with heat flux partitioning model introduced in detail with the essential boiling closure correlations related to heat and mass transfer and bubble dynamics parameters. Then, the description of the geometries used in this work is presented. Assumptions for this simulation with the thermo-physical properties of nanofluids used in this work are presented. Finally, numerical methods and boundary conditions utilized in these simulations, as well as the results of the simulations, are stated in detail.

Chapter 3 deals with the experimental setup and measurement facility for pool boiling chamber and thermal conductivity of nanofluids and materials that were used to prepare and characterize the nanofluid systems. Also, data reduction and uncertainty analysis are discussed in this chapter. Finally, the obtained results of the thermal conductivity, as well as the pool boiling performance for all types of nanofluids, are introduced and discussed.
Chapter 4 A summary of all the experimental and numerical results is presented and some recommendations for future research are listed in this chapter.

Chapter 5 The main contributions of the present research were listed in the form of theses in this chapter.

The dissertation also includes four appendices (A, B, C, and D) which explain the calculations of nanopowder quantities to prepare the nanofluids, the scanning electron microscope images for nanomaterials used in the current work, the stability checking images for our nanofluids via sediment-time method, and the measurements of thermal conductivity enhancement ratio for our nanofluids.

1.5 Literature review

1.5.1 Pool boiling heat transfer (general concept)

Boiling heat transfer happens when the temperature of the heating surface, $T_w$, is sufficiently above the saturation temperature, $T_{sat}$, of the liquid that contacts the heating surface. It is a phase change from a liquid state to a vapor state in which the vapor bubbles grow and collapse to the bulk fluid. Boiling heat transfer is one of the most efficient heat transfer modes, and it has been used in a variety of technological and industrial applications related to heat-exchange systems, energy conversion, and the cooling of high-power electronics and nuclear reactors [14-16]. Nukiyama introduced the first attempt at establishing a criterion for boiling heat transfer [17, 18]; he was the pioneer who conducted the first experimental investigation of boiling heat transfer in 1934 in Japan. He used a platinum heating wire as a heating element inside a water test chamber at 100 °C, and the electrical wire resistance measured the temperature of the surface heater during the run. His results demonstrated that the heat of the boiling water increased rapidly as the wire was heated above 100 °C; this increase continued until the temperature of the heating element reached about 149 °C, which is the point of CHF. Since that experiment, investigators of boiling heat transfer have carried out intensive efforts to understand this phenomenon well [19-21]. Bulk-fluid motion boiling is classified into two main categories: pool boiling and flow boiling (forced convective boiling). In the next portion, we will concisely explain them. As reported above, when the liquid is in contact with the heating surface, boiling will happen at the solid-fluid interface if the temperature of the solid surface is significantly above the saturation temperature of the fluid. Boiling can be divided into two main types: Pool boiling is a boiling heat transfer in which the heating surface is submerged in a pool of stationary liquid. The buoyancy effect of the produced vapor plays a vital role in circulating the fluid near the heating surface; thus, bubbles grow and collapse into the bulk liquid. The other form of the boiling process is the forced convective flow boiling, and it refers to the boiling of a moving stream of fluid within the heating surface that carries it. Fig. (1.1). Depicts the most recent records related to the number of annual research publications on the topic of pool boiling heat transfer. Browsing through the Science Direct, 1658 documents with all article types related to pool boiling have been found since 1996 to present. The highest percentage of publications is (11%), representing 185 matches in 2019.
Fig. (1.2) illustrates a typical pool boiling curve. This curve demonstrates the various pool boiling heat transfer transition regimes at different superheat temperature ($\Delta T_{sup} = T_w - T_{sat}$). At first, the process of heat transfer at small temperature differences is natural convection. At point A, small bubbles seem to appear on the surface of the heater. The point A is known as the onset of nucleate boiling ONB. The phase from A-B is the partial nucleate boiling region when there a few active nucleation sites. Next, B-C is the fully developed nucleate boiling regime where bubbles tend to coalesce and come out as vapors column from the surface of the heater. The fully developed regime is until a point which called the critical heat flux CHF after that point there is a sudden decrease in heat flux with further increase in superheat temperature, and the curve bypasses C-D, passes rapidly from D-E and stabilizes at point E, after which burn out of the heating surface happens [3].
As reported from literature, pool boiling heat transfer studies are interested in improving the nucleate pool boiling regime by increasing the heat transfer performance in that region and raise the point of critical heat flux. Among the various heat transfer enhancement techniques that have been utilized from the scientists of heat transfer related to passive methods is to add solid particles that have higher thermal conductivity to the base fluid to intensify the thermal properties of the fluid. These colloidal suspensions are termed as nanofluids. Nano-scale solid particles are chosen because it is believed that they would stay suspended in liquid compared to a millimeter and micrometer-sized solid particle.

1.5.2 Nanofluids thermophysical properties

Nanofluids (NFs) are a new class of working thermal liquids, which are obtained by dispersing nano solid materials within base fluids such as water, oil, ethylene glycol etc. To study the effect of these new working fluids on heat transfer applications, it is crucial to understand the conventional fluids that are enhanced by adding those ultrafine particles. In the heat transfer applications, various thermal transport properties of nanofluids such as density, specific heat, thermal conductivity, viscosity, surface tension were considered as a significant role to enhance the heat transfer. In the next sections, the thermal properties of nanofluids will be discussing in more detail.

1.5.2.1 Density and Specific heat of NFs

The density of a substance is a property that can be defined as the mass of a substance per unit volume. The density of nanofluids can be determined according to the mixing theory as follows:

$$\rho_{nf} = \frac{m_{nf}}{V_{nf}} = \varphi \rho_{np} + (1 - \varphi)\varsigma_f$$  (1.1)
Where: \( m_{nf}, V_{nf} \) are the mass and volume of nanofluids. \( \rho_n, \rho_f \) are the nanoparticles and basefluid densities. While the \( \phi \) is the concentration of nanoparticles. There are two specific heat models widely used in the nanofluids literature.

- **The first model** is similar to the mixing theory for ideal gas mixtures as mentioned in studies [22-24]. It is calculated the nanofluid specific heat as follows:

\[
C_{p, nf} = C_{p, np} + (1 - \phi)C_{p, f}
\]  
(1.2)

Where: \( C_{p, nf} \) is directly related to nanofluid specific heat, \( C_{p, f} \) is the basefluid specific heat, \( C_{p, n} \) nanoparticle specific heat and \( \phi \) is the volume fraction. While it was considered a simple model and thus commonly utilized for calculation of nanofluid specific heat, but also Model I has little theoretical justification in the context of nanofluid [22].

- **The second model** is based on the assumption of thermal equilibrium between the solid particles and the base fluid [22-24].

\[
C_{p, nf} = \frac{\phi(\rho C_p)_n + (1-\phi)(\rho C_p)_f}{\phi \rho_n + (1-\phi) \rho_f}
\]  
(1.3)

A notable change was seen in specific heat and density of nanofluids by the vast majority of researchers. By increasing the concentration of the nanoparticles, a notable decrease in particular heat was observed by some studies in the literature [22-24]. O’Hanley et al. [22] studied the specific heat capacities of water-based SiO\(_2\), Al\(_2\)O\(_3\), and CuO nanofluids. Their results reported that the specific heat of nanofluids was decreased when increasing the concentration of nanoparticles. Nanoparticle concentrations were varied between (5-50% wt.). Test results were found to be in excellent agreement with the second model, while the predictions of the first model deviated very significantly from the data. Therefore, the second model is recommended for nanofluids. Zhou et al. [23, 24] studied the effect of specific heat property by adding Al\(_2\)O\(_3\) and CuO nanoparticles into the water as nanofluids. They used a differential scanning calorimeter to measure the specific heat of the prepared nanofluids. Their result demonstrated that the specific heat \( C_{p, nf} \) of both nanofluids decreases gradually as the nanoparticle volume fraction \( \phi \) increases. Pantzali et al. [25] conducted a systematic measurement for all thermophysical properties to their nanofluids. They determine nanofluids density and specific heat for the prepared nanofluids. It was observed that the specific heat and density decrease and increase respectively, by increasing the concentration of nanoparticles.

Żyła et al. [26] presented experimentally the isobaric heat capacity of ethylene glycol (EG) based nanofluids by dispersing three types of nitride nanoparticles: aluminum nitride (AlN), silicon nitride (Si\(_3\)N\(_4\)) and titanium nitride (TiN) with different particles size and concentration. Each type of nanomaterial was used within two different sizes of nanoparticles and different specific surface areas. Their results demonstrated that the fraction of nanoparticles strongly influences isobaric heat capacity and density of nanofluids, while the size of the particles does not significantly impact these properties. Kedzierski [27] experimentally investigated the density of CuO nano lubricant with various nano-particle mass concentrations (2.9%, 5.6% and 39.2% by weight) for a temperature variation of (15-45 °C) with 30 nm nanoparticle diameter. Results showed that the density of the CuO nano-lubricant decreases with
temperature increase at atmospheric pressure. The author as well assumed that the density of nanofluid increases with an increase in the CuO mass fraction. Sekhar and Sharma [28] carried out an experimental study by utilizing the alumina-based water nanofluids with 47 nm Al₂O₃ nanoparticle diameter and working temperature variation from (25- 45 °C). A correlation was developed and introduced for water-based nanofluids, and this equation determines the specific heat mentioned as follows:

\[ C_{p,nf} = \left[ 0.8429 \left( 1 + \frac{T_{nf}}{50} \right)^{-0.3037} \left( 1 + \frac{d_p}{50} \right)^{0.4167} \left( 1 + \frac{\varphi}{100} \right)^{2.272} \right] \]  

(1.4)

Where: \( \varphi \), \( T_{nf} \), \( d_p \) are the nanoparticles volume fraction, temperature, and diameter, respectively. Mahian et al. [29] carried out an experimental study to investigate the ZnO nanoparticles having a size of (20 nm) suspended in water and ethylene glycol mixed with a ratio of 60:40 by weight. The temperature ranges were 25 to 40 °C for the most extreme concentration of about 4%. Deviation of around 7% was observed in the density values when compared with the model of Eq. (1.1) density values. Up to date still, there was a lack of experimental investigations, which tell about the effect of specific heat and density towards boiling heat transfer performance. Profound studies on the influence of these parameters required in the future to understand thoroughly the impact these properties on heat transfer application when using nanofluids.

1.5.2.2 Thermal conductivity of NFs

Thermal conductivity is a valuable property when we are talking about heat transfer applications. Notably, using metallic or non-metallic materials with conventional liquids could enhance the thermal conductivity of these fluids. The majority of studies in literature reported that the thermal conductivity for nanofluids has a higher value compared to basefluids [30-32]. A literature review on thermal conductivity of solid-liquid mixture shows that there are numerous models available for determining the thermal conductivity of nanofluids. From the reported literature, the existing models can be classified into two groups: First, the static models that assume the static nanoparticles inside the conventional fluid in which the thermal conductivity is predicted by the conduction-based model using the conductivity of matrix phase (e.g., liquids) and solid volume fractions. Second, the dynamic models that based on random motion and collision of the nanoparticles in fluid (e.g., Brownian motion, and transferring energy through the collision between nanoparticles, mixing that enhances the transport of thermal energy) [32, 33]. In 1881, Maxwell [34] proposed a theoretical model of effective thermal conductivity for two-phase solid-liquid mixtures given in Eq. (1.5). This model introduced to predicts the spherical shaped particles and low solid volume fractions at ambient conditions.

\[ \frac{K_{nf}}{K_f} = \left[ \frac{K_p + 2K_f + 2\varphi(K_p - K_f)}{K_p + 2K_f - 2\varphi(K_p - K_f)} \right] \]  

(1.5)

Where: \( K_{nf} \), \( K_f \), and \( K_p \) are the thermal conductivities of nanofluids, basefluid, and nanoparticles, respectively. \( \varphi \) is the solid volume fraction. Later in 1969, Hamilton and Crosser [35] modified the Maxwell model to determine the effective thermal conductivity of non-spherical particles by applying a shape factor (n). These extensions are taken into account
of different factors related to the thermal conductivity, such as particle shape, high volume fraction, particle shell structure, and interface contact resistance. The equation for calculating the nanofluids thermal conductivity is given in Eq. (1.6).

$$\frac{K_{nf}}{K_f} = \left[ \frac{K_p+(n-1)K_f-(n-1)(K_f-K_p)\phi}{K_p+(n-1)K_f+\phi(K_f-K_p)} \right]$$

(1.6)

Where: \((n)\) is the shape factor, \(n = 3/\psi\), \(\psi\) is defined as the sphericity ratio. \(\psi = 1\) for spherical shape, and \(\psi = 0.5\) for cylindrical shape. This model found to be reduced to the Maxwell model when \(\psi = 1\) and is found to agree with experimental data for solid volume fraction \(\phi < 0.3\). The effects of particle size and the temperature are not taken into account in this model. Besides, this model was found to be valid as long as the conductivity of the solid particles is more significant by a factor of 100 compared to the conductivity of the basefluid. **Yu and Choi** [36] reformulated the Maxwell model for nanofluid thermal conductivity, where all volume fractions can be taken into account. They studied the effect of interfacial nanolayers on the thermal conductivity of nanofluids and found significance for particle diameter < 10 nm. They have also mentioned that the thermal conductivity is improved up to eight-times with the including of nanolayers in the model. They have considered the thermal conductivities of nanoparticles and the nanolayers to give net thermal conductivity of nanofluid as shown in Eq. (1.7).

$$\frac{K_{nf}}{K_f} = \left[ \frac{K_p+2K_f+2\phi(K_p-K_f)(1+\beta)^3}{K_p+2K_f-\phi(K_p-K_f)(1+\beta)^3} \right]$$

(1.7)

Where: \(\beta\) is the ratio of the nanolayer thickness to the diameter of the nanoparticles. **Wasp et al.** [37] introduced an expression given in Eq. (1.8) for calculation of the effective thermal conductivity of solid-liquid mixtures. This equation is a particular case of Hamilton and Crosser model with \(\psi = 1\).

$$\frac{K_{nf}}{K_f} = \left[ \frac{K_p+2K_f-2(K_f-K_p)\phi}{K_p+2K_f+\phi(K_f-K_p)} \right]$$

(1.8)

**Koo and Kleinstreuer** [38] proposed a useful thermal conductivity model for nanofluids as mixtures by considering kinetic energy of the nanoparticles due to the Brownian movement along with the influence of particle size, particle volume fraction, and temperature dependence, as well as properties of the basefluid. They combined the thermal conductivity due to the static dilute suspension and Brownian motion \(k_{nf} = k_{static} + k_{Brownian}\). The final equation for this model is given by Eq. (1.9).

$$\frac{K_{nf}}{K_f} = \left[ \frac{K_p+2K_f-2(K_f-K_p)\phi}{K_p+2K_f+\phi(K_f-K_p)} \right] + \frac{5\times10^4}{K_f} \theta \rho_f C_{p,f} f(T,\phi) \phi \sqrt{\frac{K_B T}{\rho_p d_p}}$$

(1.9)

Where: \(\rho_f\), \(C_{p,f}\) and \(T\) are the density, specific heat temperature of basefluid, respectively. \(K_B\) is the Boltzmann constant. \(\theta\) is the hydrodynamic interaction between particles affected fluid and \(f\) considers the augmented temperature dependence due to particle interactions. They established an empirical equation for \(f(T,\phi)\) using the experimental data of **Das et al.** [39].
for CuO nanofluids given in Eq. (1.10), and this correlation is valid for range of volume fraction \(0.01 < \varphi < 0.04\) and temperature \(300 < T_{nf} < 325 \, K\).

\[
f(T, \varphi) = (-6.04\varphi + 0.4705)T_{nf} + (1722.3\varphi - 134.63)
\]

(1.10)

Where: \(\varphi, T_{nf}\) are the volume concentration and temperature of nanofluids respectively. Different techniques were introduced to measure the thermal conductivity of liquids; the transient hot-wire method was common among other techniques used in literature. Earlier experimental measurements reported in 1999, Lee et al. [40] shown in their study that the thermal conductivities of prepared oxide nanoparticles contain \(\text{Al}_2\text{O}_3\) and CuO nanoparticles have higher thermal conductivities than those of pure fluids. By compared their experimental results and the model of Hamilton and Crosser, they suggested that the enhancement in thermal conductivity not only particle shape but the size was considered to be dominant in improving the thermal conductivity of produced nanofluids. Maiga et al. [41] proposed a semi-empirical model for alumina-based water nanofluids using the model of Hamilton and Crosser [35], and the correlation is shown in Eq. (1.11).

\[
\frac{K_{nf}}{K_f} = 4.97\varphi^2 + 2.72\varphi + 1
\]

(1.11)

Where: \(\varphi\) is the volume concentration of nanofluids. Azmi et al. [42] introduced a correlation for the thermal conductivity of nanofluids. Their model considered the effect of material on nanofluid thermal conductivity data was affected through the thermal diffusivity ratio of particle to water \((\alpha_p/\alpha_f)\). They considered the effect of material, volume concentration, temperature, and particle size to propose their model, as shown in Eq. (1.12).

\[
\frac{K_{nf}}{K_f} = \left[0.8938 \left(1 + \frac{\varphi}{100}\right)^{1.37} \left(1 + \frac{T_{nf}}{70}\right)^{0.2777} \left(1 + \frac{d_p}{150}\right)^{-0.0336} \left(\frac{\alpha_p}{\alpha_f}\right)^{0.01737}\right]
\]

(1.12)

Where: \(\varphi, T_{nf}\) are the volume concentration, temperature of nanofluids, \(d_p\) is the diameter of the particle. Keyvani et al. [43] conducted an experimental study to measure the thermal conductivity of cerium oxide base ethylene glycol nanofluids. They used a transient hot-wire method for measuring the thermal conductivity of the prepared nanofluids. They proposed a correlation for the thermal conductivity ratio of \(\text{CeO}_2/\text{EG}\) using curve-fitting. This correlation, a two-variable function of temperature and volume fraction, showed a linear relationship between thermal conductivity ratio and these variables, and it was valid for volume fraction \(0.0025 < \varphi < 0.025\) and temperature \(25 < T < 50^\circ\text{C}\). The correlation in Eq. (1.13).

\[
\frac{K_{nf}}{K_f} = 0.9320 + 0.0673\varphi + 0.0021T_{nf}
\]

(1.13)

Where: \(\varphi, T_{nf}\) are the volume concentration, the temperature of nanofluids. Michael et al. [44] measured the thermal conductivity of boron nitride BN nanoparticles based ethylene glycol EG and EG+W (40:60) nanofluids by hot transient wire method. The reported that the thermal conductivity ratio for all nanofluid enhanced compared to basefluid. Furthermore, they proposed a correlation for thermal conductivity ratio of the nanofluids within range of volume
fraction $0.005 < \varphi < 0.02$ and temperature $30 < T < 60 \, ^\circ C$. The correlations for NB based EG and BN based EG+W (40:60) shown in Eq. (1.14) and Eq. (1.15) respectively.

\[
\frac{K_{nf}}{K_f} = 0.2485 + (0.00714T_{nf}^{0.2686}) + (\varphi^{0.74905}) \quad (1.14)
\]

\[
\frac{K_{nf}}{K_f} = 0.35271 + (0.0438T_{nf}^{0.1871}) + (\varphi^{0.2230}) \quad (1.15)
\]

Where: $\varphi$, $T_{nf}$ are the volume concentration, the temperature of nanofluids. Buongiorno [45] proposed empirical correlations of thermal conductivity for Al$_2$O$_3$ and TiO$_2$ based water nanofluids depends on volume concentrations of solid nanoparticles as shown in Eqs. (1.16) and (1.17), respectively.

\[
\frac{K_{nf}}{K_f} = 1 + 7.47\varphi \quad (1.16)
\]

\[
\frac{K_{nf}}{K_f} = 1 + 2.92\varphi - 11.99\varphi^2 \quad (1.17)
\]

Where: $\varphi$ is the volume concentration of nanofluids. Esfe et al. [46] carried out an experimental study to measure the thermal conductivity of Al$_2$O$_3$ based water nanofluid. They used ultrafine nanoparticles (5 nm) suspend in water as a nanofluid. A correlation was proposed and validate with their experimental data for this type of nanofluid. This correlation was valid within range of volume fraction $0.0025 < \varphi < 0.05$ and temperature $26 < T < 55 \, ^\circ C$. Eq. (1.18) shown their empirical model.

\[
\frac{K_{nf}}{K_f} = 0.911 \times T_{nf}^{(-0.0415 - 0.4044/ln\varphi)} \quad (1.18)
\]

Where: $\varphi$, $T_{nf}$ are the volume concentration, the temperature of nanofluids. Mintsa et al. [47] introduced an empirical model for effective thermal conductivity for oxide metals nanoparticles of Al$_2$O$_3$ and CuO based water nanofluids, as shown in Eqs. (1.19) and (1.20) respectively.

\[
\frac{K_{nf}}{K_f} = 1 + 1.72\varphi \quad (1.19)
\]

\[
\frac{K_{nf}}{K_f} = 0.99 + 1.74\varphi \quad (1.20)
\]

Where: $\varphi$ is the volume concentration of nanofluids. From all the above-reported literature, we can conclude that the thermal conductivity property of nanofluids is an essential transport property for heat transfer applications. Numerous experimental and theoretical works have been conducted by various researchers to predict the effective thermal conductivity of nanofluids [30- 47]. Although many investigators have reported the enhancement of thermal conductivity using nanofluids, there are still no theoretical formulas that are currently available to predict the thermal conductivity of nanofluids satisfactorily. Moreover, different parameters
that could affect the thermal conductivity of nanofluids were reported from the literature, as shown in Fig. (1.3).

**Figure (1.3) Parameters influence the thermal conductivity of nanofluids.**

### 1.5.2.3 Viscosity of NFs

Viscosity is another important thermo-physical property from an economic point of view in many heat transfer industrial applications. It measures the resistance of fluid flow to deformation at a given rate. During the last years, many mechanisms and models were proposed by various researches for the viscosity of nanofluids. In 1906, *Einstein* [48], theoretically introduced a model which can predict the effective viscosity of mixture with a dilute volume fraction of suspended particles. This equation is valid for the volume concentration of $\varphi < 1\% \ Vol.$ this model is shown as Eq. (1.21).

$$ \frac{\mu_{nf}}{\mu_f} = 1 + 2.5\varphi $$

(1.21)

Where: $\mu_{nf}, \mu_f, \varphi$ are the viscosity of nanofluids, the viscosity of the basefluid and volume concentration of nanofluids, respectively. After some decades in 1952, *Brinkman* [49] renovated Einstein’s model to make this correlation valid up to particle volume concentration of $\varphi < 4\% \ Vol.$, as shown in Eq.(1.22).

$$ \frac{\mu_{nf}}{\mu_f} = \frac{1}{(1-\varphi)^{2.5}} $$

(1.22)

Where: $\mu_{nf}, \mu_f, \varphi$ are the viscosity of nanofluids, the viscosity of the basefluid and the volume concentration of nanofluids, respectively. Later a model adopted by *Batchelor* [50] in
1977 to study the effect of the hydrodynamic interactions or the Brownian motion on the viscosity of various suspensions and developed a correlation valid for $\phi < 10\% Vol.$ as shown in Eq.(1.23).

$$\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\phi + 6.25\phi^2$$ (1.23)

Where: $\mu_{nf}, \mu_f, \phi$ are the viscosity of nanofluids, the viscosity of the basefluid and volume concentration of nanofluids, respectively. Namburu et al. [51] conducted an experimental study to measure the rheological properties of CuO nanoparticles based ethylene glycol and water (60:40) by weight. The nanofluids volume fraction used in their study range from (0-6.12% Vol.), and the temperatures from (-35 to 50 °C). They proposed an empirical correlation based on the above mentioned experimental conditions, as shown in Eq. (1.24).

$$\log(\mu_{nf}) = Ae^{-BT}$$ (1.24)

Where: $\mu_{nf}$, is the nanofluid viscosity in centipoise (cP), $T$ is the temperature in K. $A, B$ are functions of nanoparticle volume fraction $\phi$. And these coefficients represented as follows:

$$A = 1.8375(\phi)^2 - 29.643(\phi) + 165.56 \text{ with } R^2 = 0.9873$$ (1.25)

$$B = 4 \times 10^{-6}(\phi)^2 - 0.001(\phi) + 0.0186 \text{ with } R^2 = 0.988$$ (1.26)

In another study, Nguyen et al. [52] experimentally investigated the effect of temperature, nanoparticles size, and nanoparticle volume concentrations on the dynamic viscosity for the water/ Al$_2$O$_3$ nanofluid. The viscosity data were measured using a piston-type commercial viscometer for temperatures ranging from room conditions up to 75 °C. Results found that the nanofluid dynamic viscosity increases considerably with particle volume concentration but significantly decreases with a temperature increase. The viscosity values obtained for 36 and 47 nm particle diameter are relatively close ones except for high particle volume fractions. Results demonstrated that Einstein’s model and some other ones formulated from the classical linear fluid theory seem to be limited to nanofluids with dilute particle volume fractions. Duangthongsuk and Wongwises [53] carried out an experimental study to measure the viscosity of TiO$_2$ nanoparticles based water nanofluids. Nanoparticles were dispersed in water with a volume fractions ranging from (0.2 – 2% Vol.) and the data collected at a temperature ranging (15 – 35 °C). They used Bohlin rotational rheometer (Malvern Instrument) to measure the viscosity of nanofluids. Their results demonstrated that the measured viscosity of nanofluids increased as the particle concentrations increased compared to the base liquids. Furthermore, the viscosity of nanofluids decreased with the increasing temperature of nanofluids. Besides, a new correlation was proposed for predicting the viscosity of nanofluids, as shown in Eq. (1.27).

$$\frac{\mu_{nf}}{\mu_f} = (a + b\phi + c\phi^2)$$ (1.27)

Where: $a, b$ and $c$ are constant values for different temperatures as follows:
For temperature 15°C
\[
\frac{\mu_{nf}}{\mu_f} = (1.0226 + 0.0477\varphi - 0.0112\varphi^2) \text{ with } R^2 = 0.9885
\] (1.28)

For temperature 25°C
\[
\frac{\mu_{nf}}{\mu_f} = (1.013 + 0.092\varphi - 0.015\varphi^2) \text{ with } R^2 = 0.9767
\] (1.29)

For temperature 35°C
\[
\frac{\mu_{nf}}{\mu_f} = (1.018 + 0.112\varphi - 0.0177\varphi^2) \text{ with } R^2 = 0.9937
\] (1.30)

Where: \(\mu_{nf}, \mu_f, \varphi\) are the viscosity of nanofluids, the viscosity of the basefluid and volume concentration of nanofluids, respectively. Moldoveanu et al. [54] studied the viscosity of stabilized Al\(_2\)O\(_3\), TiO\(_2\) nanoparticles based water nanofluids, and their hybrid nanofluids. Viscosity measurements were achieved at room temperature 25°C and 0.5% Vol. The proposed new correlations for mono nanofluids and their hybrid by applying a regression analysis were also done to connect the relative viscosity with volume fractions of both nanofluids and hybrid nanofluid.

For Al\(_2\)O\(_3\) nanofluid
\[
\frac{\mu_{nf}}{\mu_f} = 0.6152\varphi^2 - 1.5449\varphi + 2.3792 \text{ with } R^2 = 1
\] (1.31)

For TiO\(_2\) nanofluid
\[
\frac{\mu_{nf}}{\mu_f} = 0.2302\varphi^2 - 0.3202\varphi + 1.5056 \text{ with } R^2 = 1
\] (1.32)

For hybrid nanofluid
\[
\frac{\mu_{nf}}{\mu_f} = 0.3371\varphi^2 - 0.1011\varphi + 1.2921 \text{ with } R^2 = 1
\] (1.33)

Further on, they proposed a more general correlation that described the behavior of all studied nanofluids, including the hybrid nanofluid.

\[
\frac{\mu_{nf}}{\mu_f} = 2.06 - 1.32\varphi_{Al_2O_3} - 0.96\varphi_{TiO_2} + 1.2921\varphi_{Al_2O_3}^2 + 0.39\varphi_{TiO_2}^2 + 1.89\varphi_{Al_2O_3}\varphi_{TiO_2} \text{ with } R^2 = 0.9992
\] (1.34)

Eq. (1.34) describe very well their experimental results and can be applied for both mono nanofluids and hybrid nanofluid. Saeedi et al. [55] measured the dynamic viscosity of CeO\(_2\) nanoparticles based ethylene glycol nanofluid within temperatures range of 25–50°C with 5°C intervals and volume fractions (0.05 – 1.2% Vol.) experimentally. The viscosity of nanofluid increases with an increase in the volume fraction of the nanoparticles. Besides, at a given volume fraction, nanofluid viscosity decreases when the temperature is increased. They proposed a new correlation that depends on volume fraction and temperature, as shown in Eq. (1.35) below.

\[
\frac{\mu_{nf}}{\mu_f} = 781.4 \times T_{nf}^{-2.117} \times \varphi^{0.2722} + \frac{0.05776}{T_{nf}^{-0.7819} \times \varphi^{-0.04009}} + 0.511 \times \varphi^2 - 0.1779 \varphi^3
\] (1.35)
Where: $\mu_{nf}, \mu_f, \varphi$ are the viscosity of nanofluids, the viscosity of the basefluid and volume concentration of nanofluids respectively, while $T_{nf}$ the temperature of the nanofluid. From all reported theoretical and experimental works regarding the viscosity of nanofluids, it can be noted that the concentration and the temperature were considered to be the most influential factors that could alter the viscosity of the nanofluids. However, good review studies related to the viscosity of nanofluids were comprehensively discussed and outlined this property for nanofluids and this can be seen in reported studies [56-60].

1.5.2.4 Surface tension and contact angle of NFs

The surface tension and wettability represented by contact angle for working fluids are significant in understanding the performance of thermal systems involving the boiling process and two-phase flow. However, surface tension property affects the contact angle and bubble dynamics. Therefore, surface tension is, together with the wettability, latent heat of vaporization and the density difference between liquid and vapor phases, the essential parameters to understand the mechanism of boiling heat transfer [61, 62]. Different methods applied for the measurement of surface tension of nanofluids. Hence, the reader can refer to a vital review work done by [62] in 2018 for more details regarding the measurements of surface tension and wettability properties of nanofluids used in two-phase applications. The first attempt considering surface tension was studied in 2003 by Das et al. [63]. It was motivated by the possible surface tension property effect on the pool boiling heat transfer process. Aluminum oxide nanoparticles with volume fraction in the range 0–4% Vol, and particle size of 38 nm was dispersed in water without using a surfactant. The surface tension of Al2O3 based water nanofluids, which was measured from the conventional ring method at ambient temperature, results showed that the surface tension is quite to be constant with nanoparticle concentration and very close to surface tension of basefluid.

An experimental study to measure the surface tension of different nanomaterials based on various fuels was conducted by Tanvir and Qiao [64]. They used the pendant drop method by solving the Young-Laplace equation to measure the surface tension of nanofluids with different concentrations, sizes, and surfactants. Their results revealed that the surface tension of the prepared nanofluids increased with increasing particle concentration and particle size as compared to that of the base fluids. This was due to the increasing Van der Waals force between the aggregated particles at the liquid-gas interface, which increases the surface free energy and causes the surface tension to be improved. However, at low particle concentrations, the addition of particles has little effect on surface tension because of the considerable distance between dispersing particles. An exception was discussed in their study, that when surfactant was added or when Multi-walled carbon nanotube (MWCNTs) was involved. For such cases, the surface tension decreases compared to the base fluid. This is due to the increasing the electrostatic repulsive force between particles due to the presence of a surfactant layer and the polymer attached to MWCNTs, which reduce the surface free energy and then reduced the surface tension for nanofluids. Xue et al. [65] measured surface tension for carbon nanotube-based water nanofluid by using the maximum bubble pressure technique. With the addition of CNTs into the water, the surface tension increases by about 13.5% compared to pure water at temperature 25 °C. Murshed et al. [66] experimentally investigated the influence of adding TiO2 based water nanofluids with nanoparticle diameter of 15 nm on surface interfacial tensions compared to basefluid. Their results demonstrated that these surface and interfacial tensions of using nanofluid were found to decrease almost linearly with increasing temperature.
The Brownian motion of nanoparticles dispersing in deionized water was considered as a possible mechanism for reduced surface and interfacial tensions of the nanofluid. Chinnam et al. [67] performed surface tension measurements for different types of oxide nanoparticles (ZnO, Al₂O₃, SiO₂, and TiO₂) based (60:40) propylene glycol and water by mass nanofluids. Data were collected for water and nanofluids within a temperature range of 30 to 70 °C for volumetric particle concentrations ranging from 0 to 6 % Vol., and particle sizes in the range of 15 to 50 nm. Results have shown that the surface tension of all nanofluids decreased with an increase in temperature. Besides, at a constant temperature, an increase in the particle volume fraction of a nanofluid gives a decrease in the surface tension. Moreover, for nanofluids at constant volume fraction and temperature, the surface tension was found to be lower for smaller particle sizes except for the ZnO nanofluid. Finally, the authors proposed an interesting correlation for nanofluid surface tension depend on all the above-mentioned parameters, and it was valid for all types of nanofluids used in their study. The proposed correlation predicts results successfully with an average deviation of 2.6% from the measured data. Eq. (1.36) shows the proposed correlation with $R^2 = 0.988$

$$\frac{\sigma_{nf}}{\sigma_f} = -1.02219\varphi - 0.27706\left(\frac{T_0}{T}\right) + 0.0006358\left(\frac{d_p}{d_f}\right) + 1.17344 \tag{1.36}$$

Where: $\sigma_{nf}, \sigma_f$ are the surface tensions of nanofluids and water respectively. $T_0, T$ are the reference temperature room temperature 299 K, and the absolute temperature, respectively. $d_p, d_f$ are the average particle size and base fluid molecule size respectively. While $\varphi$ is the volume concentration. The Eq. (1.36) has the range of validity: 303 $K < T < 343 K$, 0.005 $< \varphi < 0.06$, and 15 nm $< d_p < 50$ nm. The contact angle between the liquid and the surface is another essential parameter for understanding the mechanism behind the boiling two-phase flow. Some studies measured the contact angle of nanofluids which may be changed after the boiling processes due to the nanoparticle depositions on the surface during the boiling heat transfer. Recently, we detected new works in this trend [68-70]. Kim et al. [68] measured the contact angle of Al₂O₃, ZrO₂, and SiO₂ based water nanofluids for clean surface (before boiling of nanofluids) and after boiled nanofluids. Their results showed that the contact angle does not depend on the nanoparticle volume fraction and is the same for ZnO₂ nanofluid as for water and it is equal to $\theta_{nf} \approx 79^\circ$, while there was a reduction in contact angles for other nanofluids compared to water.

Ciesiński and Krygier [69] presented a measurement for the contact angle by sessile droplets methods for three types of nanofluids (e.g., Al₂O₃/ water, TiO₂/ water, and Cu/ water). They used three types of substrates, glass, anodized aluminum and stainless steel with different roughness. Nanoparticles were tested at the concentration within the range of (0.01 – 1%) by weight. Their measurements revealed that the droplet contact angle of all prepared nanofluids depends on surface roughness, type of substrate, the material of nanoparticles, and the concentration of nanoparticles. Hernaiz et al. [70] conducted a contact angle measurement for graphene oxide, alumina, and gold nanoparticles suspended in deionized water as a nanofluid within the framework of joint research cooperation of nine European teams. They revealed apparent differences in the contact angle of nanofluids compared to the pure deionized water with focusing on obtaining some correlations for the contact angle in dependency of droplet sessile temperature and volume. They extrapolated these functions to zero droplet volume to deliver the searched limiting contact angle depending only on the temperature. Furthermore,
the latent heat of vaporization for nanofluids is crucial in studying and understanding boiling heat transfer and two-phase flow phenomenon. However, the related works are rare in the literature.

During the last years, some investigators studied the latent heat of evaporation of nanofluids [71-73]. Results have shown that the latent heat of vaporization of nanofluids could be enhanced and degraded using nanofluids compared to basefluid. Hence, more investigations are needed to fully understand the mechanism of such behavior for this parameter with the presence of nanoparticles inside basefluid. To date, studies on these parameters are rare in literature; efforts should be put on experimental studies to investigate these essential properties during two-phase thermal exchange systems. Therefore, more measured surface tension, contact angle and latent heat of vaporization are needed to build a database for these parameters using nanofluids. Besides, relevant physical mechanisms should be understood entirely to develop prediction methods and models.

1.5.3 Pool boiling heat transfer of nanofluids

1.5.3.1 Experimental studies

Enhancement of pool boiling heat transfer performance by adding nanomaterials into conventional fluids is a hot recent research topic. Pool boiling using nanofluids has been extensively investigated over the last years. In many industrial heat exchange systems nucleate boiling heat transfer regime plays an essential role due to its ability to remove high heat flux in relatively small superheat temperatures. Pool boiling heat transfer from tubes has received significant attention from heat transfer experts due to its applications in various industrial sectors such as boilers tubes, evaporators, cooling of nuclear reactors, cooling of high heat flux electronic devices and so on [1-5]. Using nanofluids as a new class of cooling liquids in pool boiling heat transfer have shown contradictory results in the literature regarding the pool boiling heat transfer coefficient (PBHTC). Numerous investigators have been studied the pool boiling of nanofluids with different operating conditions to understand the mechanism thoroughly. Fig. (1.4) illustrates the number of publications deals with pool boiling heat transfer using nanofluid since 2003 to present.

![Figure (1.4) Publications by keywords of (“pool boiling” AND “nanofluid”) since 2003 to present; “Scopus database” on 19/Oct/2019.](image)

Yang and Maa [74] conducted early in 1986 a careful experimental study to clarify the behavior of pool boiling heat transfer using dispersed alumina particles with a dilute
concentration between 0.1 – 0.5 wt.%. Their results showed an enhancement in pool boiling heat transfer using alumina particles. Das et al. [63] studied the effect of adding alumina nanoparticles on the behavior of the pool-boiling curve and heat transfer coefficient from narrow horizontal heated tubes. Their results have shown that the mechanism of pool boiling is different from small tubes to those of typical industrial pipes due to the sliding of bubbles from the bottom part to the upper region. They also demonstrated that the pool boiling performance decreased while adding those nanoparticles. Kathiravan et al. [75] conducted an experimental study to examine the copper-based water nanofluid. Their results demonstrated that the pool boiling heat transfer coefficient was decreased with increasing particle concentrations while increase when adding surfactant for nanofluids. Trisaksri and Wongwises [76] carried out an experimental study to investigate the pool boiling performance of TiO₂ based R141b nano-refrigerant. They used a cylindrical copper heated tube as a heating element. Their results showed that the heat transfer coefficient was degraded with increasing particle concentration especially for high heat flux.

In another work, Suriyawong and Wongwises [77] studied the pool boiling performance of TiO₂ nanoparticles based water nanofluid at various volume fractions. They used two types of heated surfaces (copper and aluminum tubes) in their study with different surface roughness. Their results demonstrated that the pool boiling heat transfer coefficient was enhanced for a copper tube with a concentration of (0.0001% Vol.), while there was a degradation with aluminum tube. Cieśliński and Kaczmarczyk [78] studied the heat transfer performance experimentally during pool boiling of two nanofluids (Al₂O₃, and Cu nanoparticles based water nanofluids). They used a horizontal smooth copper and stainless steel tubes as a heating element. Nanoparticles were tested at the concentration of 0.01 – 1 wt.%. Their results have shown that the concentration of nanofluids had almost no influence on the heat transfer coefficient, while the higher heat transfer coefficient was recorded for stainless steel tube compared to copper tube for the same applied heat flux. Again Cieśliński and Kaczmarczyk [79] examined the influence of operating pressure 200, 100, and 10 Kpa on two types of nanofluids during the pool boiling process. Their results revealed that independent of nanoparticle materials (Al₂O₃ and Cu) and their concentration, while an increase in operating pressure enhanced the heat transfer performance.

Kole and Dey [80] presented an experimental study on pool boiling heat transfer performance of ZnO-ethylene glycol (EG) nanofluid from a horizontal copper tube. The nucleate pool boiling heat transfer performance of ZnO-EG nanofluids with different volumetric fractions of ZnO nanoparticles tested at atmospheric pressure from a cylindrical polished copper heating surface. The pool boiling heat transfer coefficient PBHTC enhanced with ZnO nanofluid about 22% compared to that of EG for 1.6% Vol. concentration. Ahmed and Hamed [81] conducted an experiment to study the pool boiling from a horizontal flat copper surface for Al₂O₃ within a range of 40 to 50 nm water-based nanofluids within a range of concentrations of 0.01 to 0.5 Vol. Nanofluids boiling tests have been followed by pure water boiling tests on the same nanoparticle-deposited surfaces. Their results showed that the boiling of pure water on the nanoparticle-deposited surface formed using the highest concentration nanofluid resulted in the highest heat transfer coefficient. Sarafraz et al. [82] studied experimentally the pool boiling heat transfer coefficient of Al₂O₃ based water-glycerol mixture nanofluid under atmospheric pressure. Results demonstrated that the pool boiling heat transfer coefficient increased with the presence of alumina nanofluid compared to base fluids and this improvement considerably improved with a higher volume fraction of nanoparticles.
Duangthongsuk et al. [83] conducted an experimental study on pool boiling heat transfer performance of alumina nanofluid at 1 and 2 atm pressure. The boiling heating element was a horizontal copper tube with a diameter of 28.5 mm and length 90 mm. Their results indicated that the heat transfer coefficient of nanofluid was lower than pure water and this degradation was increased with higher volume fraction. Kim et al. [84] carried out an experimental study on pool boiling heat transfer from a copper flat plate surface. They used very light volume concentration to see the effect of the alumina nanofluid during the boiling process. Results showed that the heat transfer coefficient was decreased as volume fraction increased.

Raveshi et al. [85] experimentally investigated the pool boiling heat transfer behavior of alumina-based water-EG nanofluid at atmospheric conditions. Their results indicated that there is an optimum value of volume concentration of nanoparticles, in which the heat transfer coefficient has its maximum enhancement. The optimum volume concentration of nanoparticle and the maximum increment of boiling heat transfer coefficient in their study were 0.75% Vol. and 64 % respectively. Shahmoradi et al. [86] conducted an experimental investigation on nucleate pool boiling heat transfer performance of alumina nanofluid. Their results showed that the heat transfer coefficient during the pool boiling process was reduced with an increasing volume concentration of nanoparticles and this due to the deposition of nanoparticles on the surface which make the surface modified by reducing nucleation sites cavities. Shoghl and Bahrami [87] performed an experimental study on pool boiling heat transfer using two types of nanofluids at different heat fluxes, concentrations and surfactants. Obtained results demonstrated that the addition of sodium dodecyl sulfate SDS increases the boiling performance considerably.

Sarafraz and Hormozi [88] experimentally examined the pool boiling heat transfer coefficient of dilute stabilized aluminum oxide-based ethylene glycol nanofluids. They studied the effects of various parameters such as heat flux, the concentration of nanofluids, heating surface nano-roughness and fouling resistance on the pool boiling heat transfer coefficient. Their results showed that with increasing the heat flux, the PBHTC of nanofluids significantly increases. Besides, with increasing the concentration of nanofluid, due to the deposition of nanoparticles on the surface, the average roughness of the surface and the heat transfer coefficient dramatically decrease, while a significant increase in fouling resistance was reported. Hegde et al. [89] conducted experimental work on pool boiling heat transfer from a vertical heated tube using dilute CuO based distilled water nanofluids at and above atmospheric pressure. They studied the pool boiling characteristics of nanofluids at different heat fluxes, concentrations and pressure. Results showed that the pool boiling heat transfer coefficient was reduced due to the deposition of nanoparticle on the surface, which resulted in a reduction in nucleation sites density during the filling up the microcavities of the surface. Based on their experimental results, it was concluded that there is an optimum thickness of nanoparticle coating at which heat flux is maximum and beyond this coating boiling heat transfer coefficient reduction. Besides, at higher pressures, the boiling heat transfer coefficient and specific excess temperature remained nearly the same without any change compared to the water case. Cieśliński and Kaczmarczyk [90] studied pool boiling of Al2O3 and Cu based water nanofluids on rough and porous-coated horizontal tubes. Their experimental study conducted under different absolute operating pressures and nanoparticle mass concentrations. Their results observed that there was an enhancement for boiling performance using nanofluids on rough stainless steel tube and this enhancement increase with increasing pressure. While for a porous-coated tube, there was a reduction in boiling performance with a growing concentration
of nanofluid. They concluded that the pressure system, surface modification and concentrations of nanoparticles could affect the pool boiling performance. A correlation was proposed for prediction of the average heat transfer coefficient during the boiling of nanofluids on smooth, rough and porous-coated surfaces. The correlation includes all tested variables in dimensionless form and is valid for low heat flux (< 100 kW/m²).

**Sarafraz and Hormozi** [91] performed a set of experiments to investigate the pool boiling heat transfer coefficient of dilute copper oxide-based water nanofluids at mass concentrations ranging (0.1 – 0.4%). They studied the influence of surfactant as a surface-active agent additive on the pool boiling heat transfer coefficient of nanofluids. Also, other operating parameters were studied, such as heat flux and concentrations of nanofluids. Results have shown a significant reduction in the heat transfer coefficient of nanofluids comparing with the base fluid without using surfactants; however, in the presence of surfactant led higher pool boiling heat transfer coefficient compared to water. **Vafaei** [92] experimentally studied the pool boiling behavior of alumina nanofluids on a flat copper plate. In his work, the pool boiling heat transfer coefficient was measured on rough and smooth surfaces inside water and alumina nanofluid with various concentrations. Results have shown that the pool boiling heat transfer coefficient was improving and degraded depends on the variation of different parameters such as heat flux, concentration and surface roughness. **Diao et al.** [93] examined the pool boiling performance of Cu nanoparticles based R141b nanorefrigerant at atmospheric pressure. They used surfactant with prepared nanorefrigerant to study the pool boiling heat transfer coefficient. Their results have shown that the Cu nanoparticles based R141b nanorefrigerant with a surfactant can enhance the pool boiling heat transfer.

Again **Cieśliński and Kaczmarczyk** [94] studied the pool boiling heat transfer coefficient on smooth and porous stainless steel heated tubes with different pressures. Their results showed that the heat transfer was enhanced for both nanofluids with the smooth tube while it was deteriorated on the porous tube. **Sarafraz and Hormozi** [95] conducted an experimental study of pool boiling heat transfer using aqueous multi-walled carbon nanotubes (MWCNTs) nanofluids for modified heater surfaces up to the critical heat flux limit. Several surface properties with diamond-shaped micro-finned have been examined during their investigation; their results showed that the pool boiling heat transfer coefficient on the plain surface was degraded. While for micro-finned surfaces, it was improved up to 56% and 77% for 0.1 and 0.3 % mass concentration, respectively. However, the formation of a fouling layer at the heater surface observed, which created a vast thermal resistance layer and a significant decrease in the heat transfer coefficient. **He et al.** [96] experimentally investigated the pool boiling heat transfer coefficient behavior of ZnO nanoparticles based on deionized water and ethylene glycol nanofluids in a cylindrical vessel under atmospheric pressure. Their results demonstrated that increasing heat flux makes the heat transfer coefficient of nanofluids growing significantly.

Moreover, enhancement of critical heat flux for nanofluids observed due to surface wettability reduction and nanoparticle coating on the heater surface. **Xing et al.** [97] studied the influence of covalent functionalization groups on the pool boiling heat transfer performance of MWCNTs nanofluids experimentally. The heat transfer coefficient of pool boiling heat transfer on flat plate surface examined under different volumetric concentrations for both nanofluids. Their results show the maximum PBHTC enhancements ratio could reach about (53.4%) for covalent functionalization nanofluids compared to the conventional fluid.
In another study, Sarafraz et al. [98] experimentally presented the pool boiling heat transfer of aqueous alumina nanofluid up to critical heat flux point on a circular surface with different volume concentration and nanoparticles size. The two-step method used to prepare their nanofluid and to get stable nanofluid for an extended period, they added non-ionic surfactants. Results have shown that the enhancement of heat transfer coefficient over the microstructure surface and the main reason for this increase is the increase of the heat transfer area in comparison with the unattractive surface. The results of plain surface reported a deterioration of the heat transfer coefficient, and this is ascribable to the continual fouling formation of nanoparticles on the surface, which increased the static contact angle of nanofluid on the porous layer and later cut down the act of active nucleation sites. Sarafraz et al. [99] introduced another work regarding the pool boiling heat transfer performance using zirconia nanofluid on a discoid heater. Their results showed that the PBHTC was enhanced up to 12% at 0.1% Vol. Sarafraz et al. [100] studied the pool boiling heat transfer coefficient of functionalized carbon nanotube and non-functionalized carbon nanotube at high-heat flux conditions up to the critical heat flux point experimentally. Results demonstrated that there was a considerable enhancement for the pool boiling heat transfer coefficient.

Sayahi and Bahrami [101] conducted three sets of experiments to examine the three types of nanofluids with different parameters such as nanomaterial type, size, and adding a surfactant to nanofluids. Their results have shown that the heat transfer coefficient was enhanced and decreased depending on these parameters. Akbari et al. [102] conducted an experimental study to investigate the influence of silver nanoparticle deposition in re-entrant inclined mini-channels and inclined mini-channels on bubble dynamics for pool boiling heat transfer. Results indicated that by increasing the nanofluid concentration to reach the nanocoated-polished surface, the heat transfer coefficient (HTC) of pool boiling increased. It was also observed that inclination and reentrance enhanced pool-boiling performance in comparison with polished copper. Manetti et al. [103, 104] presented experimentally the pool boiling heat transfer coefficient of deionized water and Al₂O₃- water-based nanofluid at saturation conditions. They used different volume concentrations for nanoparticles based deionized with smooth and roughness surfaces as a test section. Results observed that an increase in the heat transfer coefficient up to 75 %, and 15% for the smooth and roughness surfaces, respectively, in comparison to that of water. Moreover, they examined the effect of time on PBHTC and they revealed that during the 240 min of boiling there was no effect on PBHTC.

Salimpour et al. [105] studied the boiling heat transfer performance of iron oxide/deionized water nanofluid on a flat copper surface experimentally under atmospheric pressure. They reported during their study the effects of nanofluid concentration, surface type, surface roughness, sedimentation thickness, and heat flux on the roughness of the surface after boiling experiments. Results observed that after the boiling test on the rough surface, boiling heat transfer of nanofluids reduced at low heat fluxes, while it is increased in high heat fluxes. Kiyomura et al. [106] studied the effects of surface roughness and nanoparticle deposition on the contact angle, surface wettability, and pool boiling heat transfer coefficient. They reported that increase the concentration of magnetite nanoparticles used in their study increased the surface roughness of the heating surface. Besides, the highest heat transfer coefficient was obtained for the smooth surface with the deposition of nanoparticles at low mass concentrations. Ciloglu [107] experimentally investigated the nucleate pool boiling heat transfer of SiO₂ nanofluid in atmospheric pressure and saturated conditions. His results showed that the nucleate pool boiling heat transfer coefficient (PBHTC) of the nanofluids is lower than
that of deionized water, especially with high heat fluxes. Ali et al. [108] studied the titanium oxide nanoparticles based water nanofluids with two mass concentrations (12% and 15% wt.) at atmospheric pressure. They found that the pool boiling heat transfer coefficient ratio increased by about (1.24 and 1.38%) with above mass concentration, respectively.

Karimzadehkhoei et al. [109] studied the pool boiling of two types of nanofluids (TiO2/water and CuO/water) on the flat copper heater at atmospheric condition. Their results have shown that for TiO2/water nanofluids, the pool boiling heat transfer coefficient was increased at dilute volume fraction (i.e., 15% at 0.001% wt.). Besides, the CuO/water nanofluid PBHTC was about (35%) compared to water as a baseline case. Ham et al. [110] carried out an experimental study on pool boiling heat transfer performance of alumina nanofluids. They used different concentrations of nanofluids and two values of surface roughness 177.5 nm, 298.8 nm. Their results demonstrated that the pool boiling heat transfer coefficient depends on concentrations and roughness as well. In their study, PBHTC was decreased with increasing volume concentrations.

Salari et al. [111] investigated the pool boiling heat transfer of iron oxide nanofluid as a coolant on a flat disc heater under the pool boiling condition. Their results demonstrated that the pool boiling heat transfer coefficient increases with increasing the mass concentration and the applied heat flux. Shoghl et al. [112] experimentally investigated the effect of three types of nanofluids on pool boiling heat transfer coefficient from a horizontal stainless steel tube. Their results have shown that with Al2O3 and ZnO based water nanofluids, there was a reduction in PBHTC, while the CNT based water nanofluid with the presence of surfactant there was enhancement compared to the base fluid. Hu et al. [113] examined the silica (SiO2) based water nanofluid on pool boiling heat transfer characteristics with different mass concentrations. They revealed that the heat transfer coefficient of pool boiling decreased when increasing the concentration of nanoparticle in comparison with pure water. Rostamian and Etesami [114] also tested the silica-based water nanofluid on circular flat plate heater to investigate the variation of heater surface and characteristics of nanofluid pool boiling at periods. The results demonstrated that as the boiling time increases, the nanofluid boiling behavior differs from the boiling of pure water. The heater surface roughness in different periods showed that the surface roughness increases with time duration of boiling. Besides, it was found that the boiling heat transfer coefficient enhanced with nanofluid concentration (< 0.01% Vol.) and indicated an optimum in (0.007% Vol), especially at a higher period. With an interesting study,

Aizzat et al. [115] carried out an experimental research on pool boiling heat transfer performance of Al2O3 and SiO2 nanoparticles based water and their hybrid nanofluids. They used different volume concentrations as well as different mixing ratios of the mono nanofluids to see the effect of hybrid nanofluids on the boiling process. Their results showed that there was an enhancement or deterioration which depend on some parameters such as concentration, type and time of boiling using nanofluids. Yaghem and Venkatachalapathy [116] studied the pool boiling performance of alumina and copper oxide-based water hybrid nanofluid at various concentrations. Results revealed that the PBHTC is enhanced by 7.1 and 6.72% for 0.01 and 0.03% volume concentrations compared to water and starts to decrease with increasing volume concentrations. Akbari et al. [117] conducted an experiment on pool boiling heat transfer of graphene nanofluids on a flat heater surface under the saturated boiling and atmospheric pressure. Their results indicated that the pool boiling heat transfer coefficient enhanced considerably via increasing the concentration of graphene sheets. Norouzipour et al. [118]
experimentally studied the effect of silica nanoparticles size based water on pool boiling heat transfer coefficient during atmospheric pressure. The results obtained for nanofluid pool boiling on the copper surface indicates that at all the considered concentrations and nanoparticle sizes (except nanoparticle size of 70 nm size and concentration of 0.1% Vol.), the pool boiling heat transfer coefficient for the nanofluid was reduced compared to the pure water. The findings have shown that by increasing the diameter of silica nanoparticles from 11 to 70 nm, the pool boiling heat transfer coefficient was increased. Sarafraz et al. [119] studied the pool boiling performance of iron-based water nanofluids with the presence of a constant magnetic field. Results showed that the pool boiling heat transfer coefficient could enhance with a magnetic field while it was reduced with increasing the concentration of nanoparticles. Recently, Modi et al. [120] experimentally investigated the pool boiling performance of alumina nanofluid. Results showed that an increase in PBHTC was observed with an increase in the concentration of nanoparticles as well as for the nanoparticles-deposited surfaces. From all the above reported experimental studies, it can be concluded that the pool boiling heat transfer performance represented by PBHTC considerably depends on several parameters related to thermophysical properties as well the surface topology. The contradiction of the results introduced from researchers paid us to future investigate the mechanism behind the enhancement or the degradation of boiling performance. Fig. (1.5). Shows the main factors that affect the pool boiling heat transfer coefficient using nanofluids. Table (1.2) summarized essential experimental studies, which reported in the literature regarding pool boiling heat transfer performance using nanofluids.

![Figure (1.5) Factors affect the pool boiling heat transfer performance.](image-url)
Table 1.2 Summarized experimental studies on pool boiling of nanofluids.

<table>
<thead>
<tr>
<th>Reference/ year</th>
<th>Nanofluid type</th>
<th>Concentration</th>
<th>Particles size (nm)</th>
<th>Heating surface type</th>
<th>Pool boiling heat transfer coefficient behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yang and Maa [74]/1984</td>
<td>Al₂O₃/ water</td>
<td>0.1-0.5% wt.</td>
<td>50, 300, 1000</td>
<td>Horizontal stainless steel tube</td>
<td>Enhanced</td>
</tr>
<tr>
<td>Das et al. [63]/2003</td>
<td>Al₂O₃/ water</td>
<td>1-4% wt.</td>
<td>58.4</td>
<td>Horizontal tubes</td>
<td>Deteriorated for narrow and large tubes.</td>
</tr>
<tr>
<td>Kathiravan et al. [75]/2009</td>
<td>Cu/distilled water</td>
<td>0.25-1% wt.</td>
<td>10</td>
<td>Stainless steel tube</td>
<td>Decreased with increasing concentration, and increase with adding surfactant</td>
</tr>
<tr>
<td>Suriyawong and Wongwises [76]/2009</td>
<td>TiO₂/ R141b</td>
<td>0.01-0.05% Vol.</td>
<td>21</td>
<td>Horizontal copper heated tube</td>
<td>Decreased with increasing particles concentration</td>
</tr>
<tr>
<td>Suriyawong and Wongwises [77]/2010</td>
<td>TiO₂/ water</td>
<td>0.0001-0.01% Vol.</td>
<td>21</td>
<td>Discoid copper and aluminum heaters</td>
<td>Enhanced and decreased, depending on the heater type and concentrations of nanofluids.</td>
</tr>
<tr>
<td>Cieśliński and Kaczmarczyk [78, 79]/2011</td>
<td>Al₂O₃/ water Cu/ water</td>
<td>0.01-1% wt.</td>
<td>47 and 48</td>
<td>Horizontal copper and stainless steel heated tubes</td>
<td>Enhanced and decreased depends on heater materials, operating pressure, and concentration</td>
</tr>
<tr>
<td>Kole and Dey [80]/2012</td>
<td>ZnO/ EG</td>
<td>0.35-2.6 Vol. %</td>
<td>30-40</td>
<td>Horizontal copper tube</td>
<td>Enhanced about 22% at concentration 1.6% Vol. decreased with high concentration.</td>
</tr>
<tr>
<td>Ahmed and Hamed [81]/2012</td>
<td>Al₂O₃/ water</td>
<td>0.01-0.5% Vol.</td>
<td>40-50</td>
<td>Flat copper surface</td>
<td>Enhanced for water during nanoparticles deposition for high concentration</td>
</tr>
<tr>
<td>Sarafraz et al. [82]/2013</td>
<td>Al₂O₃/water-glycerol</td>
<td>0.5-1.5% Vol.</td>
<td>49-50</td>
<td>Horizontal stainless steel tube</td>
<td>Increased with increasing volume fraction</td>
</tr>
<tr>
<td>Duangthongsuk et al. [83]/2013</td>
<td>Al₂O₃/ water</td>
<td>0.00005-0.03% Vol.</td>
<td>120</td>
<td>Horizontal copper tube</td>
<td>Decreased with increasing volume fraction compared to water</td>
</tr>
<tr>
<td>Kim et al. [84]/2013</td>
<td>Al₂O₃/ water</td>
<td>0.00001-0.1% Vol.</td>
<td>40-50</td>
<td>Copper flat plate</td>
<td>Decreased with increased volume concentration</td>
</tr>
<tr>
<td>Authors</td>
<td>System</td>
<td>Concentration/Volume Fraction</td>
<td>Temperature</td>
<td>Device</td>
<td>Result</td>
</tr>
<tr>
<td>-------------------------</td>
<td>---------------------------------</td>
<td>-------------------------------</td>
<td>-------------</td>
<td>-------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Raveshi et al. [85]/2013</td>
<td>$\text{Al}_2\text{O}_3/\text{water-EG}$</td>
<td>0.05-0.75% Vol.</td>
<td>20-30</td>
<td>Discoid copper heater</td>
<td>Enhanced with increasing volume fraction</td>
</tr>
<tr>
<td>Shahmoradi et al. [86]/2013</td>
<td>$\text{Al}_2\text{O}_3/\text{distilled water}$</td>
<td>0.001-0.1% Vol.</td>
<td>40</td>
<td>Discoid copper heater</td>
<td>Reduced with increasing volume fraction</td>
</tr>
<tr>
<td>Shoghl and Bahrami [87]/2013</td>
<td>CuO and ZnO/ water</td>
<td>0.01-0.02 wt. %</td>
<td>-</td>
<td>Horizontal stainless steel tube</td>
<td>Increased with increasing surfactant and decreased without surfactant</td>
</tr>
<tr>
<td>Sarafraz and Hormozi [88]/2013</td>
<td>$\text{Al}_2\text{O}_3/\text{EG}$</td>
<td>0.1-0.3 wt. %</td>
<td>45-50</td>
<td>Horizontal stainless steel tube</td>
<td>Decreased with increasing concentration</td>
</tr>
<tr>
<td>Hegde et al. [89]/2014</td>
<td>CuO/ distilled water</td>
<td>0.1-0.5 g/l</td>
<td>50</td>
<td>Vertical tube</td>
<td>Deteriorated with concentration, and does not affect with pressure</td>
</tr>
<tr>
<td>Cieśliński and Kaczmarczyk [90]/2014</td>
<td>$\text{Al}_2\text{O}_3/\text{water}$</td>
<td>0.01-1 % wt.</td>
<td>47 and 48</td>
<td>Horizontal copper and stainless steel heated tubes</td>
<td>Improved and deteriorated depends on heater porosity, operating pressure, and concentration</td>
</tr>
<tr>
<td>Sarafraz and Hormozi [91]/2015</td>
<td>CuO/ water</td>
<td>0.1-0.4 wt. %</td>
<td>50</td>
<td>Horizontal stainless steel tube</td>
<td>Increased with the presence of surfactant and decreased without surfactant compared to water</td>
</tr>
<tr>
<td>Vafaei [92]/2015</td>
<td>$\text{Al}_2\text{O}_3/\text{water}$</td>
<td>0.001-0.1% Vol.</td>
<td>20-150</td>
<td>Copper flat plate</td>
<td>Decreased and increased depend on concentration, heat flux and surface roughness</td>
</tr>
<tr>
<td>Diao et al. [93]/2015</td>
<td>Cu/ R141b</td>
<td>0.008-0.05% Vol.</td>
<td>30</td>
<td>Discoid copper heater</td>
<td>Enhanced with presence of surfactant</td>
</tr>
<tr>
<td>Cieśliński and Kaczmarczyk [94]/2015</td>
<td>$\text{Al}_2\text{O}_3/\text{Cu/ water}$</td>
<td>0.01-1 % wt.</td>
<td>47 and 48</td>
<td>Horizontal stainless steel tube</td>
<td>Enhanced with a smooth tube, while decreased with a porous tube.</td>
</tr>
<tr>
<td>Sarafraz and Hormozi [95]/2016</td>
<td>MWCNTs/ DI-W</td>
<td>0.1-0.3 wt. %</td>
<td>Average diameter 10-20 nm and tube length of 1.5-2 μm</td>
<td>Discoid copper heater</td>
<td>Degraded for plain surface and enhanced for roughness surfaces.</td>
</tr>
<tr>
<td>He et al. [96]/2016</td>
<td>ZnO/ DI-W and EG with (75:25, 85:15 and 95:5 by volume)</td>
<td>0-8.25 wt. %</td>
<td>30</td>
<td>Ni-Cr wire heater</td>
<td>Enhanced</td>
</tr>
<tr>
<td>Xing et al. [97]/2016</td>
<td>MWCNTs/ DIW</td>
<td>0.1-1 wt. %</td>
<td>Average diameter 10-30 nm and tube length of 30 μm</td>
<td>Discoid copper heater</td>
<td>Improved with covalent functionalization MWNTs</td>
</tr>
<tr>
<td>Reference</td>
<td>Fluid System</td>
<td>Nanofluid Concentration</td>
<td>Average Diameter/Tube Length</td>
<td>Heat Transfer Surface</td>
<td>Impact</td>
</tr>
<tr>
<td>----------------------------</td>
<td>-------------------------------------</td>
<td>-------------------------</td>
<td>-------------------------------</td>
<td>-----------------------</td>
<td>--------</td>
</tr>
<tr>
<td>Sarafraz et al. [98]/2016</td>
<td>Al$_2$O$_3$/ DI-W</td>
<td>0.1-0.3 wt. %</td>
<td>20 and 50</td>
<td>Discoid copper heater</td>
<td>Deteriorated for plain heater surface and enhanced for micro-structured surface</td>
</tr>
<tr>
<td>Sarafraz et al. [99]/2016</td>
<td>ZrO$_2$/ water-EG (50:50)</td>
<td>0.025-0.1% Vol.</td>
<td>20-25</td>
<td>Discoid copper heater</td>
<td>Enhanced up to 12% at 0.1% Vol.</td>
</tr>
<tr>
<td>Sarafraz et al. [100]/2016</td>
<td>CNT/ water</td>
<td>0.1-0.3 wt. %</td>
<td>Average diameter 10-20 nm and tube length of 1.5-2 μm</td>
<td>Discoid copper heater</td>
<td>Enhanced for functionalized carbon nanotubes</td>
</tr>
<tr>
<td>Sayahi and Bahrami [101]/2016</td>
<td>Al$_2$O$_3$, SiO$_2$ and ZnO/ water</td>
<td>0.03 wt. %</td>
<td>10, (10 and 25), and 10</td>
<td>Horizontal stainless steel tube</td>
<td>Reduced and increase depending on the type, size, and surfactant</td>
</tr>
</tbody>
</table>
| Akbari et al. [102]/2017   | Ag/ water                           | 0.025-0.05 Vol. %       | The average diameter of 20    | Discoid copper heater | Enhanced up to 90% for the coated surface with high concentration, both inclined and re-entrant inclined surfaces enhanced HTC up to 60%.
<p>| Manetti et al. [103, 104]/2017 | Al$_2$O$_3$/ DI-W                   | 0.0007-0.007 Vol. %     | The average diameter of 10    | Discoid copper heater | Increased up to 75 %, and 15% for the smooth and rough surfaces, respectively |
| Salimpour et al. [105]/2017 | Fe$_3$O$_4$/ DI-W                   | 0.1-0.5 Vol. %          | 25                            | Discoid copper heater with SS rods cartridge | Enhanced and deteriorated with heat flux and concentration for both smooth and roughness surfaces. |
| Kiyomura et al. [106]/2017 | Fe$_2$O$_3$/ DI-W                   | 0.029 g/l and 0.29 g/l  | 10                            | Discoid copper heater | Deteriorated with high concentration, increased incrementally with low concentration. |
| Ciloglu [107]/2017         | SiO$_2$/ water                      | 0.01-0.1% Vol.          | 414                           | Hemispherical surface | Degraded with high heat fluxes. |
| Karimzadehkhouei et al. [109]/2017 | TiO$_2$/ water, CuO/ water         | 0.001-0.2 wt. %, TiO$_2$ = 20-50, CuO = 10-20 | Aluminum Plate heater. | Increased at dilute mass friction and deteriorated with high mass fraction for TiO$_2$-water nanofluid. Increased with increasing mass fraction for CuO-water nanofluid. |</p>
<table>
<thead>
<tr>
<th>Authors</th>
<th>Nanofluid</th>
<th>Volume Range</th>
<th>Temperature</th>
<th>Type of Heater</th>
<th>Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ham et al. [110] / 2017</td>
<td>Al₂O₃/ water</td>
<td>0-0.1% Vol.</td>
<td>50</td>
<td>Discoid copper heater</td>
<td>Enhanced and degraded depend on surface roughness and concentrations.</td>
</tr>
<tr>
<td>Salari et al. [111] / 2017</td>
<td>Fe₃O₄/ DI-W</td>
<td>0.1-0.3 wt. %</td>
<td>20</td>
<td>Discoid copper heater</td>
<td>Increased with increasing concentrations.</td>
</tr>
<tr>
<td>Shoghl et al. [112] / 2017</td>
<td>αAl₂O₃, MWCNTs and ZnO/ water</td>
<td>0.01-0.05 wt. %</td>
<td>80, (10-20 nm) and length of 10-30 μm, and 10-30</td>
<td>Horizontal stainless steel tube</td>
<td>Deteriorated for alumina and ZnO nanofluids while enhanced with CNT with adding surfactant.</td>
</tr>
<tr>
<td>Hu et al. [113] / 2018</td>
<td>SiO₂/ water</td>
<td>0.081-0.325 wt. %</td>
<td>98</td>
<td>Platinum wire</td>
<td>Decreased in the nucleate region with increasing concentration.</td>
</tr>
<tr>
<td>Rostamian and Etesami [114] / 2018</td>
<td>SiO₂/ water</td>
<td>0.005-0.01% Vol.</td>
<td>7-14</td>
<td>Discoid copper heater</td>
<td>Increased for all concentrations.</td>
</tr>
<tr>
<td>Aizzat et al. [115] / 2018</td>
<td>Al₂O₃, SiO₂ and (Al₂O₃+SiO₂)</td>
<td>0.00025-0.001% Vol.</td>
<td>13, 20</td>
<td>Discoid copper heater</td>
<td>Enhanced and decreased depending on time, concentration, and type of nanofluid.</td>
</tr>
<tr>
<td>Yagnem and Venkatachalapathy [116] / 2019</td>
<td>(Al₂O₃+CuO)</td>
<td>0.01-0.1% Vol.</td>
<td>Less than 50</td>
<td>Discoid copper heater</td>
<td>Enhanced up to 7.1% at 0.01% Vol. and decreased with increasing concentration.</td>
</tr>
<tr>
<td>Akbari et al. [117] / 2019</td>
<td>Graphene/ water</td>
<td>0.01-0.1 wt. %</td>
<td>diameter of 1-20 μm, thickness of&lt;40 nm</td>
<td>Discoid stainless steel heater</td>
<td>Enhanced with increasing concentration.</td>
</tr>
<tr>
<td>Norouzipour et al. [118] / 2019</td>
<td>SiO₂/ water</td>
<td>0.01-1% Vol.</td>
<td>11, 50, and 70</td>
<td>Discoid copper heater</td>
<td>Enhanced and decreased depending on particle size and concentration.</td>
</tr>
<tr>
<td>Sarafraz et al. [119] / 2020</td>
<td>Fe₃O₄/ DI-W</td>
<td>0.05-0.2 wt. %</td>
<td>20</td>
<td>Discoid copper heater</td>
<td>Enhanced with a magnetic field and decreased with increasing concentration.</td>
</tr>
<tr>
<td>Modi et al. [120] / 2020</td>
<td>Al₂O₃/ water</td>
<td>0.005-0.015 Vol.</td>
<td>13</td>
<td>borofloat glass substrate</td>
<td>Increased with increasing concentration.</td>
</tr>
</tbody>
</table>
1.5.3.2 Computational fluid dynamic (CFD) studies

Pool boiling using nanofluids has been investigated extensively during the last decade, but knowledge on the modeling of pool boiling of nanofluid still limited. The contradiction in the experimental studies have shown that the boiling heat transfer of nanofluid is a complex mechanism and depends on many parameters; hence, more experimental studies are needed to cover the lack of understanding of this phenomenon. On the other hand, due to the dependency of nucleate boiling process on various nucleate boiling parameters, such as nucleation sites density, bubble growth rates, bubble frequency, temperature field in liquid/solid, etc., which makes the numerical investigations more complicated especially with using nanofluids [121-123]. Table 3, summarized essential numerical studies, which reported in the literature regarding pool boiling heat transfer using nanofluids. Aminfar et al. [124] numerically studied the nucleate pool boiling of SiO2 and Al2O3 nanoparticles based nanofluids on a flat plate heating surface. They used in their simulation two and three phases mixture models to mimic pool boiling using nanofluids; their results showed that the two phases model was able to predict this mechanism more accurately than three phases model using effective thermophysical properties for nanofluids.

Li et al. [125, 126] investigated the pool boiling of dilute silica-based water nanofluid numerically from flat plate heating surface. They studied the effects of thermophysical properties on boiling heat transfer performance due to the existence of nanoparticles in the basefluid as well the effects of the nanoparticle material and size, improved surface wettability induced by nanoparticle deposition during the boiling process. Their results demonstrated that through appropriate considering the modifications caused by nanoparticle deposition, the heat flux partitioning HFP model achieved a satisfactory agreement with the experimental data available in the literature and provided a more feasible and mechanistic approach than the classic Rohsenow correlation for predicting nucleate pool boiling of nanofluids. Niknam et al. [127] introduced a numerical study to see the effect of particle size, surface roughness on nucleate pool boiling of nanofluid. They considered the nucleation site density ratio, and a correlation was derived based on experimental literature data.

Moreover, the heat flux partitioning model under the Eulerian-Eulerian multiphase models was employed to evaluate the proposed model for boiling heat transfer. The validity was assessed by comparing their results with experimental data in the literature. They concluded that the nucleation site density ratio could predict heat transfer enhancement of nanofluids. Qi et al. [128] numerically and experimentally studied the pool boiling heat transfer of TiO2 based water nanofluids. They used the mixture model for boiling heat transfer of nanofluid by considering mass transfer and energy transfer between the liquid phase and the vapor phase. Their results simulated by the mixture model, have a good agreement with the experimental results, which proves the validity of the simulation method. Kim et al. [129] adopted a numerical simulation of saturated water and Al2O3 based water nanofluid on a vertical surface using the volume of the fluid model. They used different superheated temperatures with a range of (5 − 20 K) and various concentrations for nanoparticles. Their results found that there was an agreement for the size and shapes of vapor bubbles between the numerical results and the experimental measurements for all superheat temperatures.

Moreover, the void fraction and the temporal heat flux increased with increasing superheat temperatures, and this is due to the enhancement of thermal conductivity with the higher volume fraction of nanoparticles. Mortezazadeh et al. [130] used the eulerian-eulerian framework to predict the nucleate pool boiling of ferrofluid with a magnetic field. They also
modified the heat flux-partitioning model under the boiling model to including the boiling parameters in their account. Their results showed that using nanoparticles causes degradation in the boiling heat transfer performance and void fraction. Moreover, using the magnetic field enhanced those reductions. Mahdavi et al. [131] studied the pool boiling of nanofluid behavior numerically on two horizontal tubes with the various inclination and pitch distance by adopting the Eulerian-Lagrangian approach. They implemented new closure correlations in their model as a user-defined function for nucleation sites density and bubble departure diameter based on the nanoparticle deposition effect and surface roughness enhancement for nanofluids.

On the other hand, they model the particle effect by tracking them everywhere in the physical domain via the Lagrangian approach by using the discrete phase model. Their results detected that the percentage of deposition is dependent on heat flux and particle volume fraction. Besides, heat transfer performance increases with increasing the pitch distance of the tubes. Moreover, the numerical results show good agreement to those of experimental study in literature. Salehi and Hormozi [132] studied numerically the pool boiling heat transfer of water and water–silica nanofluid using the Eulerian multiphase approach. They considered in their study the nucleation site density and bubble frequency by using various correlation to insert them in the boiling model. Results demonstrated that the nanoparticle deposition on the heater surface was a critical factor that could change the heat transfer performance in the boiling of nanofluid. Therefore, proper investigation of bubble dynamics behavior in nucleate boiling of nanofluids is a necessary concern to be focused on future modeling studies.

Gupta et al. [133] carried out a numerical investigation using a 2D geometrical domain to calculate values of heat transfer coefficient for different constant heat flux applied on the heater at atmospheric as well as sub-atmospheric pressures. They used a transient Eulerian multiphase involving a boiling model that was used along with various sub-models including drag, lift, heat, and mass transfer models. Their results for the heat transfer coefficient were compared and validated from the experimental results. From all the above-reported works, we can conclude that the numerical studies regarding pool boiling heat transfer of nanofluids are rare. However, future investigations on pool boiling heat transfer by focusing on bubble dynamics behavior are necessary to develop a predictive model. It was reported that surface modification during the pool boiling process due to particle deposition is a crucial factor that could affect the pool boiling performance. Hence, a more experimental investigation is significant to understand the mechanism of the surface topology during nanoparticle deposition, which, in turn, influence bubble dynamics behavior during the boiling of nanofluid. Moreover, it was noticed that the boiling model represented by heat flux partitioning model RPI under the eulerian-eulerian approach could predict this mechanism if it comes with proper closure correlations for bubbles dynamics during boiling of nanofluids.
Table (1.3) Summary of CFD studies of pool boiling using nanofluids.

<table>
<thead>
<tr>
<th>Reference/ year</th>
<th>Nanofluid type</th>
<th>CFD model/ sub-model</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aminfar et al. [124]/ 2012</td>
<td>Al₂O₃ and SiO₂/ water</td>
<td>Multiphase mixture model/ boiling heat flux partitioning model RPI</td>
<td>Two-phase simulation in which effective parameters has been used is more accurate than three-phase simulation.</td>
</tr>
<tr>
<td>Le et al. [125, 126]/ 2014 and 2015</td>
<td>SiO₂, Al₂O₃, TiO₂, ZrO, and ZnO/ water</td>
<td>Multiphase Eulerian-Eulerian model/ boiling heat flux partitioning model RPI</td>
<td>The effects of improved surface wettability due to nanoparticle deposition, materials type, and nanoparticles size during the boiling process were taken into account when developing new closure correlations for the bubble dynamics parameters.</td>
</tr>
<tr>
<td>Niknam et al. [127]/ 2015</td>
<td>Al₂O₃/ water</td>
<td>Multiphase Eulerian-Eulerian model/ boiling heat flux partitioning model RPI</td>
<td>The effect of particle size, surface roughness on nucleation sites density was considered in their study.</td>
</tr>
<tr>
<td>Qi et al. [128]/ 2016</td>
<td>TiO₂/ water</td>
<td>Multiphase mixture model/ boiling heat flux partitioning model RPI with in house code</td>
<td>They used unsteady segregated solvers in their simulation. A UDFs program is developed to solve the mass and energy transfer between the liquid phase and the vapor phase.</td>
</tr>
<tr>
<td>Kim et al. [129]/ 2017</td>
<td>Al₂O₃/ water</td>
<td>Multiphase volume of fluid (VOF) model/</td>
<td>The explicit volume of fluid (VOF) method based on tracking the fluid interface, as well as the transient laminar model, is used in their study.</td>
</tr>
<tr>
<td>Mortezazadeh et al. [130]/ 2017</td>
<td>Fe₂O₃/ water</td>
<td>Multiphase Eulerian-Eulerian model/ boiling heat flux partitioning model RPI</td>
<td>They extended the wall partitioning model to consider the boiling surface modification by the nanoparticle deposition on the heated surface.</td>
</tr>
<tr>
<td>Mahdavi et al. [131]/ 2018</td>
<td>Al₂O₃/ water</td>
<td>Multiphase Eulerian-Eulerian model/ boiling heat flux partitioning model RPI</td>
<td>They considered the surface modification during pool boiling of nanofluid. To include these effects, new correlations are implemented as a user-defined function UDFs for nucleation site density and bubble departure diameter.</td>
</tr>
<tr>
<td>Salehi and Hormozi [132]/ 2018</td>
<td>SiO₂/ water</td>
<td>Multiphase Eulerian-Eulerian model/ boiling heat flux partitioning model RPI</td>
<td>They used various correlations to determine nucleation site density, bubble departure frequency and the best equation was found.</td>
</tr>
<tr>
<td>Gupta et al. [133]/ 2019</td>
<td>Al₂O₃/ water</td>
<td>Multiphase Eulerian-Eulerian model/ boiling heat flux partitioning model RPI</td>
<td>They used various sub-models involving drag, lift, heat, and mass transfer models to validate their experimental results.</td>
</tr>
</tbody>
</table>
CHAPTER 2

“NUMERICAL INVESTIGATION”

2.1 Introduction

In this chapter, computational fluid dynamic CFD analysis with Eulerian- Eulerian multiphase approach using wall heat flux partitioning model HFP, which is under the wall boiling model presented to investigate the pool boiling heat transfer performance of deionized water and nanofluids at atmospheric pressure. The results obtained from this model are validated to those of experimental results in the literature as well as present experimental study for silica and cerium oxide nanoparticles based water nanofluids. Moreover, the numerical simulations results regarding the vapor volume fraction, vapor velocity vectors from the horizontal heated tube helped me to get an insight to the boiling process then to design the proper experimental test rig, which will be discussing in the next chapter. For example, to chose a adequate condenser to condensate the vapor rising the chamber and control the liquid capacity inside the pool boiling chamber as well as to keep the atmospheric pressure, the prediction of vapor velocity was critical to know during the design stage.

2.2 Model discerption

2.2.1 Geometry structure

In this research, three physical geometries are chosen for simulations. Tables (2.1) and (2.2) shows the simulation cases that adopted for pool boiling heat transfer of water and nanofluids with different dimensions and boundary conditions. The first simulation was for a rectangular boiling chamber with a horizontal copper heated tube according to experimental work of [78], while the second one was also for the pool boiling chamber as a rectangular chamber with stainless steel flat plate heated surface according to experimental work of [117]. The last simulation was for pool boiling test rig for a horizontal copper heated tube for the present experimental facility that will be explaining in the next chapter. Fig. (2.1) illustrates the structures of the geometries which are used in these simulations. All the simulations were done for validation and predicting purpose of the experimental works in literature as well as the present experimental work for pool boiling heat transfer from different heater geometry and materials. The wall boiling model under the eulerian-eulerian multiphase model was used to predict the boiling process of pure water and nanofluids in this study. More details regarding the model and sub-models used in the present simulations will be in the next sub-sections.

Table (2.1) Dimensions of the computational domain for pool boiling chamber in present simulations.

<table>
<thead>
<tr>
<th>Simulation Number</th>
<th>Length (mm)</th>
<th>Width (mm)</th>
<th>Heated wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.1</td>
<td>150</td>
<td>100</td>
<td>$D_{out} = 10$ mm</td>
</tr>
<tr>
<td>No.2</td>
<td>300</td>
<td>150</td>
<td>$L_h = 40$ mm</td>
</tr>
<tr>
<td>No.3</td>
<td>120</td>
<td>120</td>
<td>$D_{out} = 22$ mm</td>
</tr>
</tbody>
</table>

*L_h = length of the heated wall (mm)
2.2.2 Eulerian- Eulerian multiphase model formulation

In nature, multiphase flow regimes can be classified into five groups: liquid-liquid flow, gas-liquid flow, liquid-solid flow, gas-solid flow, and three-phase flow that contains any three-phase flow regimes. **Fig. (2.2)** shows the main multiphase flow types with some examples of these multiphase systems. In the Eulerian multiphase model (Eulerian boiling model), the liquid behaves as the continuous phase, and vapor bubbles are the disperse phase. Therefore, there are various kinds of coupling between the phases in this model. The pressure is shared by all the existing phases, whereas the continuity, momentum, and energy equations are solved for each phase in this model. The volume of each existing phase is calculated by integrating its volume fraction throughout the domain, while the summation of all the volume fractions is equal to unity [134, 135].
Table (2.2) Number of simulations for various cases changing in geometry structures, working fluids, boundary conditions, and investigated parameters.

<table>
<thead>
<tr>
<th>Number of simulations</th>
<th>Geometry structure</th>
<th>Working fluids</th>
<th>Model/ sub-model</th>
<th>Boundary conditions (B.Cs)</th>
<th>Purpose of simulation</th>
<th>Studied parameters</th>
</tr>
</thead>
</table>
| Simulation No.1       | 2-D rectangular chamber with a horizontal copper heated tube [78]. | - Water-two-phase vapor flow | E-E’ multiphase model/ heat flux partitioning model with bubble waiting time coefficient correction | $\Delta T_{sup} = 5 - 10 \text{ K}$ $q = 29 - 87 \text{ kW/m}^2$ | • Validation | • Pool boiling curves  
• PBHTC  
• V-V-F** contours prediction  
• V-V*** vectors prediction  
• Heat flux partitioning components |
|                       |                    | - Water-two-phase vapor flow | E-E’ multiphase model/ heat flux partitioning model with bubble waiting time coefficient correction | $\Delta T_{sup} = 6 - 32 \text{ K}$ $q = 35 - 1100 \text{ kW/m}^2$ $\varphi = 0.01\% Vol.$ $Ra_{nf} = 1 \mu m$ $\theta_{nf} = 22^\circ$ | • Validation | • Pool boiling curves  
• PBHTC  
• V-V-F**  
• Void fraction |
| Simulation No.2       | 2-D rectangular chamber with stainless steel flat plate [117]. | - Water-two-phase vapor flow Silica nanofluids-two-phase vapor flow | E-E’ multiphase model/ heat flux partitioning model with bubble waiting time coefficient correction | $\Delta T_{sup} = 3.9 - 14.1 \text{ K}$ $q = 21 - 117 \text{ kW/m}^2$ $\varphi = 0.007\% Vol.$ $\varphi = 0.01\% Vol.$ $Ra_{nf} = 0.115 \mu m$ $\theta_{nf} = 31^\circ$ | • Validation | • Pool boiling curve  
• PBHTC  
• Heat flux partitioning portion  
• V-V-F** |

* E-E: Eulerian-Eulerian, ** V-V-F: Vapor volume fraction, *** V-V: Vapor velocity
2.2.2.1 Governing equations

Two sets of conservation equations governing the balance of mass, momentum, and energy of each phase are presented in Eqs. (2.1) – (2.3) as follows [132, 136, 137]:

**Continuity equation:**
\[
\frac{\partial (\rho_k \alpha_k)}{\partial t} + \nabla \cdot \rho_k \alpha_k \vec{v}_k = \dot{m}_{kp} - \dot{m}_{pk} \tag{2.1}
\]

**Momentum equation:**
\[
\frac{\partial (\rho_k \alpha_k \vec{v}_k)}{\partial t} + \nabla \cdot \rho_k \alpha_k \vec{v}_k \vec{v}_k = -\alpha_k \nabla P + \rho_k \alpha_k \vec{g} + \nabla \tau_k + \left( \dot{m}_{kp} \vec{v}_k - \dot{m}_{pk} \vec{v}_k \right) + S_{1k} \tag{2.2}
\]

**Energy equation:**
\[
\frac{\partial (\rho_k \alpha_k E_k)}{\partial t} + \nabla \cdot (\rho_k \alpha_k \vec{v}_k E_k) = \alpha_k \frac{\partial p}{\partial t} + \nabla \dot{q}_k + Q_{\text{exchange} pk} + (\dot{m}_{kp} E_k - \dot{m}_{pk} E_p) + S_{2k} \tag{2.3}
\]

where: the subscripts of \( k \) denotes \( k \)-th phase \((k = l\) for the liquid phase and \( k = g \) for vapor phase). \( P \), is represented to the pressure. \( \rho_k, \alpha_k, \vec{v}_k \) are the density, volume fraction and velocity of the \( k \)-th phase, respectively. \( \dot{m}_{kp} \) is interfacial mass transfer in the liquid phase on the surface heater. In the bulk liquid, this quantity is equal to zero. This is because pool boiling begins at saturation temperature. \( \left( \dot{m}_{kp} \vec{v}_k + \dot{m}_{pk} \vec{v}_k \right) \), in the momentum equation represents the momentum transfer due to liquid evaporation or vapor condensation. Besides, \( \left( \dot{m}_{kp} E_k + \dot{m}_{pk} E_p \right) \) in the energy equation stands for the energy transfer due to phase change. Additionally, the terms of \( \vec{g}, \dot{q}_k, S_{1k}, S_{2k} \) and \( Q_{\text{exchange} pk} \) are the gravitational acceleration, heat flux, the inter-phase momentum transfer term, the inter-phase energy transfer term and is the direct heat transfer to phase “\( k \)” and it can be calculated from Eq. (2.4) as follows:

\[
Q_{\text{exchange} pk} = h_{\text{interfacial}} A_{\text{interfacial}} (T_p - T_k) \tag{2.4}
\]

where: \( h_{\text{interfacial}}, A_{\text{interfacial}} \) and \( T \) are the interface heat transfer coefficient, interfacial area, and fluid temperature, respectively. In the present simulations, to solve the governing equations formulating the phase interaction that related to interfacial momentum, heat and mass transfer are included. Firstly, for the viscous model, there are two typical flow regimes, which are the laminar and the turbulent models; due to the physical nature of vapor bubbles and the dynamics related to them, it was considered a chaotic phenomenon, and then the rough model with well-known realizable two equations \( K - \epsilon \) model is selected as it is recommended by previous works [132, 136, 138] due to the suitable performance for pool boiling heat transfer. Eqs. (2.5)–(2.7) shows the formulation of this model.

\[
\frac{\partial (\alpha_k \rho_k \theta_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \theta_k \vec{v}_k) = \nabla \cdot \left( \alpha_k \frac{\mu_{T,k}}{\sigma_k} \nabla \theta_k \right) + \alpha_k \frac{\tau_{T,k}}{\sigma_k} \nabla \vec{v}_k - \alpha_k \rho_k \epsilon_k + S_{K,k} \tag{2.5}
\]

\[
\frac{\partial (\alpha_k \rho_k \epsilon_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \epsilon_k \vec{v}_k) = \nabla \cdot \left( \alpha_k \frac{\mu_{T,k}}{\sigma_k} \nabla \epsilon_k \right) + \alpha_k \frac{\epsilon_k}{K_k} \left( \epsilon_k \tau_{T,k} \nabla \vec{v}_k - \epsilon_k C_{e1} \tau_{T,k} \nabla \vec{v}_k - C_{e2} \rho_k \epsilon_k \right) + S_{\epsilon,k} \tag{2.6}
\]

\[
\tau_{T,k} = \mu_{T,k} \left[ \nabla \vec{v}_k + (\nabla \vec{v}_k) - \frac{2}{3} (\nabla \cdot \vec{v}_k) I \right] - \frac{2}{3} \rho_k K_k I \tag{2.7}
\]
In Eqs. (2.5) and (2.6), $K$ and $\varepsilon$ are denoted the turbulence kinetic energy and dissipation rate, respectively. $\mu_{T,k} = C_\mu K^2/\varepsilon$ is the turbulent viscosity coefficient, $S_{\text{int},k}^k$, $S_{\varepsilon,k}^k$ are the source terms related to the interaction of nucleate bubbles with the turbulent fluid flow of the liquid. The constants in Eqs. (2.5) and (2.6) are, as in works of [138, 139, 140], which are set to as follows: $C_\mu = 0.09$, $\sigma_K = 1.0$, $\sigma_\varepsilon = 1.3$, $C_{\varepsilon 1} = 1.44$, $C_{\varepsilon 2} = 1.92$.

### 2.2.2.2 Phase interaction mechanism

The interaction between the liquid-vapor phases could induce some forces such as viscous drag force $F_{k,\text{drag}}$, lift force $F_{k,\text{lift}}$, wall lubrication force $F_{k,\text{LW}}$, virtual mass force $F_{k,\text{VM}}$ and turbulent dispersion force $F_{k,\text{dispersion}}$. The term $S_{1k}$ is the inter-phase momentum transfer term, which is written on the left side of the momentum governing equation represents all the above interaction forces [136]. The Eq. (2.8) shows the forces during the inter-phase interaction.

$$S_{1k} = F_{k,\text{drag}} + F_{k,\text{lift}} + F_{k,\text{VM}} + F_{k,\text{dispersion}} + F_{k,\text{LW}} \tag{2.8}$$

In the present simulations, a detailed formulation of all the interfacial forces is introduced in Table (2.3) [141-150]. For heat transfer between the continuous phase (water) and the dispersed phase (vapor) was included, and this transferred energy could accrue due to the non-thermal equilibrium across the interphase [132]. To determine the heat transfer coefficient between the continuous and dispersed phases ($h_{\text{interface}} = k_L Nu_g/d_{\text{bubble}}$), the Ranz-Marshall model [149, 150] was selected in these simulations to model the heat transfer via phase interaction, the following expression Eq. (2.9) represented this model.

$$Nu_g = 2.0 + 0.6 Pr_l^{0.333} Re_g^{0.5} \tag{2.9}$$

where: $Re_g$ is the relative Reynolds number based on the diameter of the dispersed phase (bubble diameter), and relative velocity, and $Pr_l$ is the Prandtl number of the continuous phase (water), as shown in Eq. (2.10).

$$Pr_l = \frac{C_{p,l} \mu_l}{k_l} \tag{2.10}$$

where: $C_{p,l}$, $\mu_l$, and $k_l$ are the specific heat, viscosity, and thermal conductivity of continuous phase (water), respectively.

### Table (2.3) Models used in these simulations for the interfacial exchange of heat and mass transfer (phase interactions).

<table>
<thead>
<tr>
<th>Physics</th>
<th>Model/ Reference</th>
<th>Formulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtual mass forces</td>
<td>Explicit source term/ [141]</td>
<td>$F_{VM} = C_{VM} \alpha_g \rho_l \left( \frac{d_i \vec{v}_l}{dt} - \frac{d_j \vec{v}_g}{dt} \right)$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>where: $C_{VM}$ is the virtual mass coefficient, and by default, it is equal to 0.5. the term $\frac{d_j}{dt}$ denotes the liquid phase time derivative.</td>
</tr>
<tr>
<td>Drag force</td>
<td>Schiller-Naumann/ [142]</td>
<td>$f = \frac{C_p Re}{24}$</td>
</tr>
</tbody>
</table>

[36]
\[ C_D = \begin{cases} 
\frac{24(1 + 0.15Re^{0.687})}{Re} & \text{Re} \leq 1000 \\
0.44 & \text{Re} > 1000 
\end{cases} \]

where: \( Re_1 \) is the relative Reynolds number for the liquid phase and \( \mu_{rg} = \alpha_g \mu_g + \alpha_r \mu_r \) is the mixture viscosity of vapor and liquid.

Ishii/ [143]

\[ C_D = \min\{C_{D,\text{vis}}, C_{D,\text{dis}}\} \]

where: \( C_D \) is the drag coefficient and is determined by selecting the minimum of \( C_{D,\text{vis}}, C_{D,\text{dis}} \) which are the viscous regime and the distorted regime coefficients, respectively.

\[ C_{D,\text{vis}} = \frac{24}{Re_g} \left( 1 + 0.15Re_g^{0.75} \right) \]

\[ C_{D,\text{dis}} = \frac{2}{3} \left( \frac{d_{\text{bubble}}}{\sigma} \right) \sqrt{G \left( \rho_l - \rho_g \right)} \]

\[ F_{k,\text{lift}} = -C_L \alpha_g \rho_l (\vec{v}_l - \vec{v}_g) (\nabla \vec{v}_l) \]

where: \( C_L \) is the lift coefficient.

\[ C_I = \begin{cases} 
\min\{0.288\tanh(0.121Re_g), f(E\dot{\theta}_{\text{modif}})\} & E\dot{\theta}_{\text{modif}} \leq 4 \\
\max\{0.00105E\dot{\theta}_{\text{modif}}^3 - 0.0159E\dot{\theta}_{\text{modif}}^2 + 0.020E\dot{\theta}_{\text{modif}} + 0.474 & E\dot{\theta}_{\text{modif}} > 4 \}
\end{cases} \]

where: \( E\dot{\theta} \) is modified Eotvos number, and it is expressed as:

\[ E\dot{\theta}_{\text{modif}} = \frac{g(\rho_g - \rho_l) d_h^3}{\sigma} \]

\[ d_h = d_{\text{bubble}} \left( 1 + 0.163E\dot{\theta}_{\text{modif}}^{0.75} \right)^{\frac{1}{3}} \]

where: \( d_h, d_{\text{bubble}} \) are deformable bubbles and bubble diameter.

\[ E\dot{\theta} = \frac{g(\rho_g - \rho_l) d_{\text{bubble}}^2}{\sigma} \]

\[ F_{l,\text{dispersion}} = -F_{g,\text{dispersion}} = C_{TD} \rho_l K_l \nabla \alpha_g \]

where: \( C_{TD} \) is a user-modified constant, by default equal to 1, and \( K_l \) is the turbulent kinetic energy in the liquid phase. \( \nabla \alpha_g \) is the gradient of the vapor phase volume fraction.

\[ F_{k,\text{LW}} = C_{WL}\rho_l \alpha_g \left( \vec{v}_l - \vec{v}_g \right) \left( \nabla \vec{v}_l \right) \]

where: \( C_{WL}, \nabla \vec{v}_l \) are the wall lubrication coefficient and the normal unit pointing away from the wall.

\[ C_{WL} = \max \left( 0, \frac{C_{W1}}{d_{\text{bubble}}} + \frac{C_{W2}}{y_w} \right); \]

\[ C_{W1} = -0.01, C_{W2} = 0.05 \]

\[ \text{are non-dimensional coefficients, and they equal to} \]

\[ \sigma_{k,k}^{\text{int}} = C_{ke} \sum_{p=1}^{M} K_{gi} \left| \vec{v}_i - \vec{v}_g \right|^2 \]

[37]
2.2.2.3 Heat flux partitioning model HFP

The heat and mass transfer during the nucleate pool boiling of pure liquids has been commonly predicted by using the Rensselaer Polytechnic Institute RPI model [151, 152]. In this classical wall boiling model, the total heat flux $\dot{q}_{\text{total}}$ from the heating surface is governed by three heat transfer mechanisms [132], as shown in Fig. (2.3). First, the heat flux due to the natural convection that represented by the energy transfer from the formation bubbles to the bulk liquid $\dot{q}_{\text{conv}}$. Second, the heat flux due to the latent heat of vaporization $\dot{q}_{\text{evap}}$, the last term is the heat flux due to quenching $\dot{q}_{\text{quen}}$, which is the process of the periodic averaged transient energy transfer related to liquid filling the wall vicinity after bubble separation. The Eqs. (2.11)- (2.14) shows the three parts of heat fluxes that are applied in this model.

$$\dot{q}_{\text{total}} = \dot{q}_{\text{conv}} + \dot{q}_{\text{evap}} + \dot{q}_{\text{quen}} \quad (2.11)$$

Where: $\dot{q}_{\text{conv}}$, $\dot{q}_{\text{evap}}$ and $\dot{q}_{\text{quen}}$ represent the total heat flux components transferred by natural convection, evaporation, and quenching, respectively.

$$\dot{q}_{\text{conv}} = A_{\text{conv}} \times h_{\text{conv}} \times (T_w - T_i) \quad (2.12)$$

$$\dot{q}_{\text{evap}} = V_{\text{bubble}} N_a \rho_g h_{lg} f = \frac{\pi}{6} d_b^3 \rho_g f N_a h_{lg} \quad (2.13)$$

$$\dot{q}_{\text{quen}} = C_w \frac{2k_i}{\sqrt{\pi \alpha_t w}} (T_w - T_i) A_{\text{bubble}} \quad (2.14)$$
where, \( \Delta t_{\text{bubble}} \), \( f \), \( N_\text{a} \), \( A_\text{conv} \), \( A_\text{quen} \) and \( t_w \) are the bubble departure diameter, bubble frequency, active nucleation sites, the area fractions of the heater surface related to convection and quenching mechanisms, and the bubble waiting time, respectively. \( C_w \) is the bubble waiting time coefficient, and the default value supposed in Ansys Fluent solver to be 1 and there is a possibility of modifying this value as need. In the next section, nucleate boiling parameters will be discussing in detail.

2.2.2.4 Nucleate boiling parameters

All the equations mentioned above for the heat flux partitioning model including three heat fluxes mechanisms need closure for boiling parameters that used for predicting the nucleate boiling process. Therefore, there are vast correlations in the literature that described the pool boiling parameters of pure liquids and those correlations were succeed in validating the boiling of conventional fluids. According to our best knowledge, nucleate pool boiling parameters, especially the nucleation sites density for bubbles and the bubbles departure diameters could be affected during pool boiling of nanofluids due to the deposition of nanoparticles on the heating surface. Therefore, efforts should be put to take into account the modification of the heating surface to find new closure correlations related to bubble dynamics parameters through a pool boiling phenomenon. Table (2.4) shows the nucleate pool boiling parameters that are used in our simulations to predict the pool boiling of deionized water and the nanofluids [153-158].

<table>
<thead>
<tr>
<th>Boiling parameters</th>
<th>Working fluid/Reference</th>
<th>Closure correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleation sites density, ( N_\text{a} )</td>
<td>Water / Lemmert and Chawla [153].</td>
<td>( N_\text{a} = C^n(T_w - T_{\text{sat}})^n ) where: ( n = 1.805 ); ( C = 210 ) are the empirical parameters. Note: The nucleate site density usually correlated based on superheat wall temperature.</td>
</tr>
<tr>
<td>Nanofluid / Ganapathy and Sajith [154].</td>
<td>( N_\text{a} = 218.8 \frac{1}{\gamma} P r_t^{1.63} \left{ 14.5 - 4.5 \left( \frac{P R_a}{\sigma} \right) \right}^{0.5} \beta^{-0.4} \Delta T_{sup} ) where: ( P ), ( R_a ) and ( d_p ) stand for the pressure, average surface roughness, and nanoparticle diameter, respectively. Moreover, ( \gamma ) is the wall-liquid interaction parameter determined by the surface and liquid materials, and ( \beta ) is the surface wettability improvement parameter described as follow: ( \beta = \frac{1 - \cos \theta}{1 - \cos \theta^<em>} ) where: ( \theta ) and ( \theta^</em> ) are the liquid contact angles on the nanocoated and clean surface, respectively. Note: this semi-empirical correlation applicable for flat plate heating surface.</td>
<td></td>
</tr>
<tr>
<td>Nanofluid / Das et al. [155].</td>
<td>( N_\text{a} = \frac{512}{\gamma} P r_t^{1.63} \left{ 14.5 - 4.5 \left( \frac{P R_a}{\sigma} \right) \right}^{0.5} \beta^{-0.4} \xi \left( \frac{R_a}{d_p} \right)^{0.4} \Delta T_{sup}^{3} )</td>
<td></td>
</tr>
</tbody>
</table>
\[
\xi \left( R_a / d_p \right) = \begin{cases} 
0.275 \left( R_a / d_p \right)^{-1.2} & \left( R_a / d_p \right) \leq 1.0 \\
0.275 + 0.7911 \left( R_a / d_p \right)^{0.68} & \left( R_a / d_p \right) > 1.0
\end{cases}
\]

where: \( \gamma \) is the wall-liquid interaction parameter that was defined below, and it is re-defined in the above correlation due to the deposition of the nanoparticles layer.

\[
\gamma = \sqrt{\frac{k_p \rho_p c_{p,p}}{k_l \rho_l c_{p,l}}}
\]

**Note:** Authors showed that heat transfer by nanofluids was degraded when \( R_a / d_p \) value reaches 1.0; otherwise, heat transfer enhanced as \( R_a / d_p \) was away from 1.0. They proposed when \( R_a / d_p \) was near 1.0, deposited nanoparticles reduce the active site density. Otherwise, when the surface roughness and particle size were slightly far from more active site density would be created. Therefore, so that the effects of particle size relative to the surface roughness could be adequately considered.

\[
N_a = 1.206 \times 10^4 (1 - \cos \theta) \Delta T_{sup}^{0.206}
\]

where: \( \theta \) is the liquid contact angle on the nanocoated surface. **Note:** this correlation applicable only to nanofluid with a low contact angle.

**Bubble departure diameter, \( d_{bubble} \):**

- **Water / Tolubinski and Kostanchuk [156].**
  \[
d_{bubble} = \min\left(0.0014, 0.0006 e^{(T_w - T_{sat})/45.0}\right)
\]
  **Note:** This correlation is a default bubble departure diameter for the RPI model.

- **Nanofluid/ Li et al. [126].**
  \[
d_{bubble} = -1.91 \times 10^{-3} + 4.21125 \times 10^{-4} \Delta T_{sup} - 1.70945 \times 10^{-2} \Delta T_{sup}^2 + 2.03938 \times 10^{-7} \Delta T_{sup}^3
\]
  **Note:** this polynomial correlation was used based on fitting data of experimental work for silica-based water nanofluid.

**Bubble departure frequency, \( f \):**

\[
f = \frac{4g(\rho_l - \rho_g)}{3\rho_l d_{bubble}^2}
\]

where: \( g \) are the bubble waiting time and the gravity acceleration force, respectively. **Note:** This parameter was reported to be decreased by increasing the bubble departure diameter. This fact is physically reasonable because the massive bubble needs a longer time to grow.

**Area of Influence, \( A_{bubble} \):**

\[
A_{bubble} = \min\left(1, U \frac{N_a \pi d_{bubble}^2}{4}\right)
\]

\[
U = 4.8 e^{(-ja_{sub} / \rho g)}, ja_{sub} = \frac{h c_p \Delta T_{sub}}{\rho g h g}
\]

where: The value of the empirical constant \( U \) is usually set to 4, \( ja_{sub} \), \( \Delta T_{sub} \) are the subcooled Jacob number and subcooled temperature \( \Delta T_{sub} = T_{sat} - T_i \)
2.3 Numerical method and assumptions

In this research, the numerical simulations of pool boiling heat transfer from horizontal heated copper tube and stainless steel flat plate heating surface were performed to investigate the pool boiling performance. The physical geometries were created in 2-D via (Design Modeler Toolbox), and the structural grids were also built through the meshing tool available in the toolbox of Ansys software. In this numerical study, the Finite Volume Method (FVM) was used to discretize the computational domain spatially and to convert the partial differential equations into a linear algebraic system of equations. Therefore, the governing equations for mass, momentum and energy for each phase are solved using the finite volume method in ANSYS FLUENT software. A phase coupled SIMPLE method (PC-SIMPLE) was selected to handle the pressure-velocity coupling. In this algorithm, the velocities are solved coupled by phases in a segregated manner whereas; the pressure correction equation is built based on total continuity. Hence, the coefficients of the pressure correction equations come from the coupled per phase momentum equations in this method. A second-order upwind scheme was used to approximate the momentum, turbulent kinetic energy and turbulent dissipation rate whereas the first-order upwind scheme selected for energy equation, and the gradient of all flow variables was calculated using the least-square cell-based method. Moreover, to solve the vapor volume fraction equation in a multiphase flow solver, the upwind scheme is generally undesirable for interface tracking because of the overly diffusive nature which results in the unphysical thickening of the fluid interfaces. While, downwind differencing scheme is usually able to keep the sharpness of the interface, but it is also unbounded and often give unphysical oscillatory results. Hence, to take advantage of the stability of upwind differencing and the accuracy of down winding for interface tracking, a modified scheme of the HRIC scheme is used for the current simulations as recommended by [136]. The simulation process continued until the scaled residuals reach the convergence criterion of $10^{-4}$ for all the components. Moreover, the grid independence test is examined for all simulations cases; further mesh refinement did not result in any significant changes to the mean values of the vapor volume fraction around the heating surface. Hence, the moderate mesh elements number were taken to make the balance between the time and the accuracy of the obtained results. More details will be discussed in the next chapter regarding this issue. The following assumptions are considered for the present simulations:

- The current simulations are transient and turbulence fluid flow.
- The properties of water and vapor phases are assumed to be constant under the specified operating pressure and temperature.
- Due to near molecular mixing between the dilute concentration of nanoparticles and the base fluid, a nanofluid hydro dynamically behaves as basefluid. Then, a single-phase modeling for nanofluid is reasonable to assume during those simulations.
- It was also believed that the vapor-phase is not dense enough to hold the nanoparticles within. Hence, we assumed that the stable nanoparticles did not influence the thermal properties of the vapor phase.
- Due to the low volume concentration of nanoparticles used in these simulations (Simulation No.2 and Simulation No.3), we assumed that there no bulk property modification happens with this type of nanofluids. The negligibility assumption is approved by models of thermo-physical properties with dilute volume concentration,
which are used and discussed in the next section. Hence, the effective properties of nanofluid do not deviate significantly from that of pure water.

- Surface tension property for nanofluid was considered to be the same as pure water due to the dilute volume concentration used in this work.
- The saturation temperature of nanofluid is near that of basefluid (water), and the assumption was approved by measuring the saturation temperature of ceria nanofluid for both concentrations used in the third simulation. It was found to be (±0.2 °C), and this was within the error of temperature logger.
- A time step size of (1 ms) selected for the present work. Moreover, the maximum iterations number per time step was set to be 100 after try and error procedure to assure that the solution is converged at each time step.

### 2.4 Boundary conditions

In the present simulations, the aforementioned governing equations are subjected to the following boundary conditions, as shown in Eqs. (2.15) – (2.17).

- A constant temperature assumed to be at the heating surface of the horizontal tube.

\[ T = T_w, \quad (2.15) \]

- Heat flux is zero at the adiabatic walls of the boiling chamber.

\[ q'' = -k_w \frac{dT}{dx} = 0, \quad (2.16) \]

- At the top of the boiling chamber, the pressure is assumed to be atmospheric pressure.

\[ P = P_{atm}, \quad (2.17) \]

### 2.5 Thermo-physical properties of nanofluids

The thermo-physical properties of pure water, nanofluids, and vapor at saturation temperature of 100 °C [159] are shown in Table (2.5). The following effective thermal properties correlations for nanofluids which are available in the literature were chosen with acceptable accuracy and cover the range of concentrations utilized in the present simulations.

- Density, used by [125]

\[ \rho_{nf} = \frac{m_{nf}}{V_{nf}} = \varphi \rho_{np} + (1 - \varphi) \rho_f \quad (2.18) \]

- Heat capacity, used by [22-24]

\[ C_{p,nf} = \frac{\varphi (\rho C_p)_{np} + (1 - \varphi) (\rho C_p)_f}{\varphi \rho_{np} + (1 - \varphi) \rho_f} \quad (2.19) \]

- Thermal conductivity, introduced by [34]
\[
\frac{K_{nf}}{K_f} = \left[ \frac{K_p + 2K_f + 2\phi(K_p - K_f)}{K_p + 2K_f - 2\phi(K_p - K_f)} \right] 
\]
(2.20)

- Viscosity, introduced by [50]

\[
\frac{\mu_{nf}}{\mu_f} = 1 + 2.5\varphi + 6.25\varphi^2
\]
(2.21)

**Table (2.5) Thermo-physical properties of working fluids used in present simulations at saturation temperature condition (100 °C).**

<table>
<thead>
<tr>
<th>Property</th>
<th>Water [159]</th>
<th>Vapor [159]</th>
<th>Silica Nanofluid (0.01% Vol.)</th>
<th>Ceria Nanofluid (0.007% Vol.)</th>
<th>Ceria Nanofluid (0.01% Vol.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [kg m(^{-3})]</td>
<td>958.35</td>
<td>0.59817</td>
<td>958.47 ↑</td>
<td>959.03 ↑</td>
<td>959.21 ↑</td>
</tr>
<tr>
<td>Specific heat [J kg(^{-1}) K(^{-1})]</td>
<td>4215.7</td>
<td>2080</td>
<td>4215 ↓</td>
<td>4214.93 ↓</td>
<td>4214.82 ↓</td>
</tr>
<tr>
<td>Thermal conductivity [W m(^{-1}) K(^{-1})]</td>
<td>0.67909</td>
<td>0.02509</td>
<td>0.67909 ↑</td>
<td>0.67924 ↑</td>
<td>0.67929 ↑</td>
</tr>
<tr>
<td>Dynamic viscosity [Pa s]</td>
<td>0.000281</td>
<td>0.0000122</td>
<td>0.000281 ↔</td>
<td>0.000283 ↑</td>
<td>0.000283 ↑</td>
</tr>
<tr>
<td>Surface tension [N m(^{-1})]</td>
<td>0.0589</td>
<td>-</td>
<td>0.0589 ↔</td>
<td>0.0589 ↔</td>
<td>0.0589 ↔</td>
</tr>
</tbody>
</table>

↑ Increased; ↓ Decreased; ↔ Not changed

### 2.6 Results and discussion

#### 2.6.1 Results of simulation No.1

In this simulation, the pool boiling heat transfer of pure water from the horizontal copper heated tube at atmospheric pressure was investigated numerically. The main aim of the present simulation is to predict with an extended RPI model the pool boiling heat transfer performance of water from horizontal copper tube to study the vapor volume fraction contours, vapor velocity vectors and water velocity streamlines inside the pool boiling chamber. New proposed polynomial function regarding the bubble waiting time coefficient was introduced by to correct the quenching heat flux partition under the wall boiling model by fitting this coefficient data to superheat temperature after modifying this coefficient by trying and error procedure as suggested by [160]. The bubble waiting time coefficient was introduced in quenching heat flux term to correct the waiting time between the departures of consecutive bubbles. Next, subsections describe the validation, results, and discussion of current simulation.

#### 2.6.1.1 Grid sensitivity test

A grid independence test was done to check the mesh sensitivity of the present numerical results. Different structured uniform grid elements were performed in this simulation (i.e., 10696, 15668, and 48906 elements) to verify the average vapor volume fraction around the heated tube at superheat temperature (\(\Delta T_{sup} = 6 \) K). The maximum relative error for average vapor volume fraction was less than 2% between the second and third grids number; hence,
the second grid size (15668 elements) selected to balance between the time and accuracy of the solution as shown in Table (2.6).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Grid elements</th>
<th>Relative error %</th>
<th>Grid elements</th>
<th>Relative error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average vapor volume fraction</td>
<td>0.292</td>
<td>2.3%</td>
<td>0.304</td>
<td>1.64%</td>
</tr>
<tr>
<td></td>
<td>15668 elements</td>
<td></td>
<td>48906 elements</td>
<td></td>
</tr>
</tbody>
</table>

### 2.6.1.2 Results validation

The results of the pool boiling curve and pool boiling heat transfer coefficient PBHTC of water from the horizontal copper heated tube are presented in Fig. (2.4) and (2.5). The present simulation results were validated with the results of the experimental study of [78] and the numerical results of [136]. As can see from Fig. (2.4) and (2.5), comparison between the results of pool boiling curve and pool boiling heat transfer coefficient against heat fluxes for the present model and the experimental work of [78] are shown a good agreement, which corroborates the accuracy and reliability of the current numerical results. This is because we used the same geometry structure and boundary condition of experimental work of [78] while the numerical work has a different structure and boundary conditions as those of our present simulation.

The total heat flux was found to be close to experimental heat flux after taking in our consideration the uncertainties of the mentioned experimental work. The maximum average absolute deviation A.A.D% found to be less than 7% for the superheat temperature (8.5 K) in this simulation, which means that this simulation with a correction of a bubble waiting time coefficient model was quite acceptable to predict this phenomenon. In this simulation, the chapman sigmoidal function for the bubble waiting time coefficient was proposed by fitting this coefficient to superheat temperatures with ($R^2 = 0.9992$), and this could be valid for the range of parameters used in this study, see table (2.2). The Eq. (2.22) introduced the bubble waiting time coefficient $C_w$ with the best curve fitting as shown in Fig. (2.6).

$$C_w = 0.1017 + 0.8336\left(1 - e^{(-1.1894\Delta T_{sup})}\right)^{28748098} \tag{2.22}$$

where: $C_w$ is a bubble waiting time coefficient, which was introduced in the quenching heat flux partition to correct the waiting time between the departures of consecutive bubbles. The default value for this coefficient is equal to 1. However, Ansys fluent users guide [160] suggested to modify this coefficient as needed, and this coefficient can only be as a constant value. $\Delta T_{sup}$ is the superheat temperature [K], which is the difference between the wall temperature and the saturation temperature of the liquid.
Figure (2.4) Pool boiling curve of water for present simulation against experimental work [78].

Figure (2.5) Pool boiling heat transfer coefficient of water against heat flux for present simulation and experimental work [78].

Figure (2.6) Bubbles waiting time coefficient vs. superheat temperature proposed in the simulation No.1 to correct the quenching heat flux part for pool boiling of water.
2.6.1.3 Contours of vapor volume fraction

Fig. (2.7) and (2.8) depicted the formation of the bubbles represented by vapor volume fraction contours at various time and the different superheat temperatures. Fig. (2.7) shown the formation of bubbles at the variation of time steps and constant superheat temperatures. At the time \( t = 200 \text{ ms} \) and constant superheat temperature for example \( (7.5 \text{ K}) \), the bubbles begin to take shape on the circular horizontal heated tube, and we can see that those groups of bubbles start to sliding from bottom to sides of the tube then at a specific location they detached together and escapes to the top of the heated surface. As time increased to \( (t = 500 \text{ ms}) \) and \( (t = 600 \text{ ms}) \) bubbles start to travel the heated surface to the bulk fluid, and this is due to the buoyancy effects (vapor density less than water phase), which lifted the bubble to the top of the chamber. The height of this pool boiling was chosen according to experimental of [78] as mentioned in the previous section and due to the short distance between the heated tube and the surface of fluid the bubbles could not deform or shaped inside the bulk liquid to other forms then they were deformed in the top surface. Fig. (2.8) demonstrated the motion of bubbles at time \( (t = 600 \text{ ms}) \) with various superheat temperature, as can be seen from the contours the vapor volume fraction there was an increase with increasing the superheat temperatures and for superheat \((10 \text{ K})\), the bubbles formed as a column and this due to the quantity of bubble that were created from the tube from various nucleation sites (increasing superheat temperature led to increasing the densities of the nucleation sites then increased bubbles formation). The mechanism of sliding bubbles from the horizontal tube was reported in the literature [136, 161], and our simulation was physically matched this bubbles layer. It can be concluded that the increase of superheat temperature significantly increases the nucleation sites density which, in turn, led to increasing the bubbles number and the agitation of the fluids hence, the heat transfer coefficient increase during this nucleate boiling regime.

![Figure (2.7)](image)

**Figure (2.7)** Contours of vapor volume fraction with different time and superheat temperature \((7.5 \text{ K})\):
- A \((200 \text{ ms})\),
- B \((400 \text{ ms})\),
- C \((500 \text{ ms})\), and
- D \((600 \text{ ms})\).
2.6.1.4 Vectors of vapor velocity

Fig. (2.9) and (2.10) illustrates the vectors of vapor velocity at different time steps and various superheat temperatures. Fig (2.9) shows the velocity of bubbles during the growth and sliding stages from the tube, and this was introduced in terms of the vapor velocity vector at different time steps and superheat for example (7.5 K). The velocity of bubbles at the bottom tube region was high enough to slide on both sides of the tube to take away to the top of the boiling chamber. It can be seen that from velocity distribution during bubbles formation at the heated surface start to increase as superheating temperature increase at the same time step, as shown in Fig. (2.10), and this due to the intensified bubbles columns from the sides tube. Line arrows demonstrated that vapor velocity increased with escaping time and increasing superheat temperature. It worth to mention that the velocity of bubbles at a circular heated tube starts to increase at both sides of the heated tube then forms unify column of those bubbles which are vertically elapsed to the top bulk fluids surface. This was captured by visualizing study in literature [161], and hence we can say that our model results match the experimental study by means physically during the pool boiling from the horizontal tube. Knowing the vapor velocity is very important during the condensation stage to understand a proper cooling process to meet the heat exchange system application.
Figure (2.9) Velocity vectors of vapor phase with different time steps and superheat temperature (7.5 K): A (200 ms), B (400 ms), C (600 ms), D (800 ms), and E (1000 ms).
Figure (2.10) Velocity vectors of vapor phase at time (500 ms) with different superheat temperatures; A (7.5 K), B (8.5 K), and C (10 K).

2.6.2 Results of simulation No.2

In the present work, the pool boiling heat transfer of pure water and silica-based water nanofluid from stainless steel flat plate heating surface at atmospheric pressure was studied numerically. The main aim of the present simulation is to predict with an extended heat flux partitioning model the pool boiling heat transfer performance by considering the surface modification during pool boiling of silica nanofluid that represented by surface roughness and wettability put into the account in this simulation. New proposed correlation regarding the bubble waiting time coefficient was introduced by modify the quenching heat flux partition under the wall boiling model and found the best curve fit this coefficient to superheat temperature after correct this coefficient by trying and error procedure as suggested by [160] to improve the results of this simulation. The numerical results validated with experimental works in literature, and they revealed good agreements for both pure water and nanofluids. The results found that when improve the heat flux partitioning model HFP by considering the correcting of quenching heat flux partition as well as the surface modification of nucleate pool boiling parameters, it will give more mechanistic sights compared to the classical model, which is used for predicting of boiling heat transfer of pure liquid. Next, sub-sections describe the validation, results, and discussion of current simulation.
2.6.2.1 Grid independence test

The effect of cells number on the total heat flux along the flat plate heating surface was performed to check the mesh independence of the current simulation results. Different number of quadrilateral cells have been chosen in this simulation (i.e., 75×120, 100×190, and 200×190 elements) to verify the total heat flux of pure water along the heated surface at superheat temperature ($\Delta T_{\text{sup}} = 10$ K). The maximum relative error for total heat flux was less than 3%; hence, the first elements number (9000 elements) was selected to save the computing time without losing the accuracy of present numerical results.

2.6.2.2 Results validation

In the present simulation, the RPI boiling model to predict the pool boiling of pure water with two forms so-called: the classical RPI model using the default value of bubble waiting time coefficient ($C_w = 1$), and that the extended RPI boiling model by mean of correcting quenching heat flux part using a modified bubble waiting time coefficient $C_w$ according to the proposed polynomial function, as shown in Eq. (2.23) was adopted. To validated the present model with other works, the experimental data of [117] and the well-known Rohesnow correlation [19] for pool boiling heat transfer were chosen in this work. Fig (2.11) presents the heat flux against superheat temperatures for pure water at atmospheric pressure, which is called (pool boiling curve) during the nucleate boiling regime. Results revealed a reasonable agreement with pool boiling curve experimental results and Rohesnow correlation of pure water with an absolute average deviation A.A.D about 7.7% and 3.3 % in low and high heat fluxes respectively. As mentioned in the previous section, the HFP model depends on quenching heat flux partition which is model the cyclic averaged transient energy transfer associated with the fluid filling on the wall vicinity after the bubble detachment with a certain period. Therefore, for the first time, a bubble waiting time coefficient $C_w$ was corrected to modifying for quenching heat flux model under the RPI boiling model by fitting the experimental data of pure water [117]. A sigmoidal function was found to be the best fitting for those data with ($R^2 = 0.9986$) as shown in Fig (2.12) and Eq. (2.23). The results seem to be more acceptable with experimental data for the total heat flux against the superheat temperature, while the model with the default value of this bubble waiting time coefficient correction model was mainly over prediction to experimental data as depicted in Fig (2.11).

$$C_w = 0.102 + 2.5448\left(1 + e^{\left(-\left(\Delta T_{\text{sup}} - 21.1792\right) / 2.6439\right)}\right)^{-1} \tag{2.23}$$

where: $C_w$ is a bubble waiting time coefficient, which was introduced in the quenching heat flux partition to correct the waiting time between the departures of consecutive bubbles. The default value for this coefficient ($C_w = 1$); however, Ansys Fluent guide suggested modifying this value as needed [160]. $\Delta T_{\text{sup}}$ is the superheat temperature [K].
Moreover, it was widely reported in the literature that the nucleation site density and bubble departure diameter are a critical boiling parameter, and the boiling of nanofluids could change the surface characteristics then might increase or reduce the number of the nucleation sites and bubble departure diameter. In this simulation, we examined those parameters to validate our model. The active nucleation sites density in the present extended HFP model was obtained from fitting the experimental data for pool boiling of silica-based water nanofluid [162] and used by [125, 126]. The nucleation site density and bubble departure diameter in [125, 126] were inserted as UDFs within parallel bubble departure diameter in the boiling parameters list of the present model, and the results show good agreement with experimental results in the literature as depicted in Fig (2.13). Bubble departure diameter of nanofluids increased when the superheat going to grow at a certain level, and then, it will be decreasing as superheat temperature continues to increase, and this trend noticed by Gerardi et al. [162]. Predicting of bubble departure diameter in the present model was successfully done by comparison of the incorporated UDFs for the current extended model and the experimental data of [162], which

Figure (2.11) The boiling curve of pure water for the present model compared to experimental data of Akbari et al. [117], and Rohesnow correlation [19].

Figure (2.12) Bubbles waiting time coefficient vs. superheat temperature proposed in the simulation No.2 to modify the quenching heat flux part for pool boiling of water.

Figure (2.13) Pool boiling heat transfer coefficient of nanofluids against heat flux for present extended RPI model and experimental work [162].
are used for silica and graphene nanofluids under atmospheric pressure condition. It can be concluded that the nucleation site density and bubble departure diameter were inserted in this model from experimental works in literature for flat plate heating surface could predict the surface modification well when using nanofluids during the boiling process.

2.6.2.3 Void fraction and PBHTC results

Fig (2.14) shows the vapor velocity vectors at the time (1000 ms), during the nanofluids/vapor phase change. As can be seen from the curves, the velocity of bubbles starts from the center of the enclosure from the heated surface, and on the corners, there is no bubbles formation to avoid the effect of sidewall force on bubbles motion. The velocity of bubbles increases as superheat temperature increases, and this is due to the increasing bubbles formations from sites of the nucleation process on the heated surface. The motion of bubbles column form the center of the heated wall at superheating temperature ($\Delta T_{sup} = 20$ K) accelerate when the bubble becomes like mushroom shape, which makes it significant with a velocity slower than the velocity of the upward bubbles column because of the resistance of effect bulk fluid over it. The velocity of vapor during the boiling process is considered an important issue due to the dependence of condenser functionality in the two-phase condensation process. Hence, the predicting of vapor velocity could be useful for pool boiling experiments using nanofluid. Fig (2.15) illustrates the vapor void fractions along the vertical direction from the center of the heating wall to the top of the boiling chamber for both water and silica-based water nanofluids. It can be seen that the volume fraction for all cases (water and nanofluids) increased with increasing the superheat temperature, and this could be attributed to the formation of more bubbles with high frequencies and size. On the other hand, the void fraction of nanofluid noted to be less than the void fraction of water, and this is due to the interaction of nanoparticles with vapor bubbles in bulk fluid, and this trend was studied by [163, 164]. Besides, the void fraction near the heating surface (voided region) was more predominant than another area, and this is due to the high heat flux in this region. It can be seen that for nanofluid with small contact angle about ($23^\circ$), which is used in this study as suggested by [162], the wettability was enhanced through the decrease in contact angle due to the surface modification during the boiling of silica nanofluid. Hence, less void fraction in this region than pure water, and this is due to the deposition of nanoparticles during the boiling process, which, in turn, modified the surface contact angle via enhancing the capillary wicking force and reducing the nucleation sites by filled the microcavities in surface structure.

In the present extended model, results obtained for pool boiling heat transfer coefficient against applied heat flux for water and silica-based water nanofluids are shown in Fig (2.16). It can be seen from the curves that the PBHTC for nanofluids was degraded compared to pure water especially for high heat flux values and this trend noted by experimental data of [162], while the finding of [117] detected that the nanofluids could enhance the heat transfer coefficient and this contradictory in results may be due to the type of nanofluids and the thermophysical properties that be used in their studies as well the concentration of nanoparticles. The main influence mechanism that could affect the reduction of HTC for nanofluid is that the deposition of nanoparticles on the heating surface during the boiling process. The deposition of those nanoparticles build up the porous nano-layer on the heating surface, and this nano-layer mainly created due to the microlayer evaporation process, which in turn, modified the surface characteristics that could enhance wettability by reducing the contact angle between the liquid and surface. Also, the porous nanolayer on the heating surface
could be a thermal resistance layer that could hinder the rate of heat transfer from the surface to a liquid.

Figure (2.14) Vectors of a vapor velocity of silica-based water nanofluid at different superheat temperatures. (i) $\Delta T_{sup} = 10$ K, time = 1000 ms; (ii) $\Delta T_{sup} = 20$ K, time = 1000 ms.

Figure (2.15) The void fraction of the vapor phase for pure water and (0.01% Vol.) silica-based water nanofluid along the vertical distance with various superheat temperatures.

Figure (2.16) Pool boiling heat transfer coefficient against heat flux for pure water and (0.01% Vol.) silica nanofluid predicted by the present model.
2.6.3 Results of simulation No.3

The pool boiling heat transfer of deionized water and cerium oxide CeO$_2$ nanoparticles based deionized water nanofluids from a typical horizontal heated copper tube at atmospheric condition was numerically investigated. The present simulation aims to validate with an extended heat flux partitioning (RPI) model the pool boiling heat transfer performance of deionized water and ceria based deionized water nanofluids at two-volume concentrations (0.007% and 0.01% Vol.). An experimental pool boiling apparatus was built in our department to investigate the boiling process using nanofluids as working fluids, and more details will be discussed in detail in the next chapter. New proposed polynomial correlations regarding the bubble waiting time coefficient were introduced to correct the quenching heat flux partition under the wall boiling model by modifying this coefficient and correlate it to superheat temperature. The following sub-sections describe the grid independence test, validation, obtained results, and discussion of current simulation.

2.6.3.1 Mesh sensitivity test

The pool boiling heat transfer of deionized water and cerium oxide CeO$_2$ nanoparticles based deionized water nanofluids from a typical horizontal heated copper tube at atmospheric pressure was numerically studied. Different numbers of elements were selected in this simulation (29276, 46256 and 82154), and to achieve a minimum number of cells with accurate results. The grids were compared by the total heat flux and average vapor volume fraction around the circular tube for deionized water at superheat temperature ($\Delta T_{sup} = 6.4$ K). The results shown that they are not sensitive to the resolution of mesh, especially for first and second elements number the maximum relative error between was less than 2.4%, and therefore the best grid to balance between the accuracy and time saving was grid (29276) as shown in Fig. (2.17).

Figure (2.17) Grid independence test for present model for pool boiling of deionized water.
2.6.3.2 Validation of the present model with experimental data

To validate the accuracy of the present simulation results, the current experimental data of pool boiling heat transfer for deionized water and cerium oxide CeO$_2$ nanoparticles based deionized water nanofluids at atmospheric pressure was compared to the present numerical results. The results of the pool boiling curves and pool boiling heat transfer coefficient for deionized water and cerium oxide-based deionized water nanofluids for volume concentrations (0.007% and 0.01% Vol.) were validated in Figs. (2.18) and (2.19). The comparison was made by adopted two types of heat flux partitioning models; the classical HFP model and the extended HFP model. The classic one used the build-in multiphase interaction sub-models inside Ansys fluent solver in parallel with the default value of the bubble waiting time coefficient $C_w = 1$, while the second one so-called corrected heat flux partitioning model was extended using a modifying bubble waiting time coefficient. In case of nanofluids and due to the absence of closure correlations related to boiling parameter (bubble dynamics) in literature and the limitation in the current experimental measurements regarding those parameters, we considered the bulk transport properties for the nanofluids that represented by thermophysical properties for cerium oxide nanoparticles based deionized water nanofluids with two dilute volume concentrations as shown previously in Table (2.5) at saturation temperature. Results obtained from Figs. (2.18) and (2.19) demonstrated that for deionized water case the numerical results were in good agreement with the experimental data when using the properties of water and modifying the bubble waiting time coefficient according to the polynomial regression to correlate this coefficient to superheat temperature $\Delta T_{sup}$. Therefore, this means that the extended heat flux partitioning model using the modified bubble waiting time coefficient to correct the waiting time between the departures of consecutive bubbles during the nucleate pool boiling regime gives a good prediction for boiling of pure water as well the ceria nanofluids without the closure of pool boiling parameters during boiling of nanofluids. The following polynomial functions were determined with a best-fitting for this coefficient as shown in Fig. (2.20).

- For water case, ($R^2 = 0.994$)

$$C_w = 0.0002\Delta T_{sup}^2 + 0.0718\Delta T_{sup} - 0.3613 \quad (2.24)$$

- For (0.007% Vol.) CeO$_2$ based water nanofluids, ($R^2 = 0.9711$)

$$C_w = -0.005\Delta T_{sup}^2 + 0.1675\Delta T_{sup} - 0.4228 \quad (2.25)$$

- For (0.01% Vol.) CeO$_2$ based water nanofluids, ($R^2 = 0.9844$)

$$C_w = -0.0028\Delta T_{sup}^2 + 0.1234\Delta T_{sup} - 0.359 \quad (2.26)$$

Where: $C_w$ is the bubble waiting time coefficient [-], $\Delta T_{sup}$ is the superheat temperature [K]. The above correlations are valid for a range of superheat temperature ($3.9 \leq \Delta T_{sup} \leq 14.1$ K), and atmospheric pressure.
Figure (2.18) The boiling curve of pure water for the present model compared to present experimental data for deionized water and ceria nanofluids.

Figure (2.19) The pool boiling heat transfer coefficient against the heat flux for deionized water and ceria nanofluids for the present model.

Figure (2.20) Bubbles waiting time coefficient vs. superheat temperature proposed in the simulation No.3 to modify the quenching heat flux part for pool boiling of deionized water and ceria nanofluids.

2.6.3.3 The portion of RPI model components

Fig. (2.21) shows the components of the heat flux partitioning model which are convective heat flux \( q_{conv} \), evaporation heat flux \( q_{evap} \), and the quenching heat flux \( q_{quen} \) for the present classical RPI model \( (C_w = 1) \) and extended RPI model with modified bubble waiting time coefficient correction (corrected \( C_w \)) to modify the quenching part for a heat flux partitioning model (RPI) that has been introduced in Eq. (2.14). The heat flux-partitioning model shown that the quenching heat flux plays a significant role, among other heat fluxes mechanisms especially at the high heat flux region. It can be seen that the heat removal from the heating wall more significant compared to evaporating and convection heat flux for values of total heat flux > 35 kW/m\(^2\) and this could be attributed to the nucleate pool boiling regime. The situation with the classical heat flux partitioning model was quite different before the modification of the bubble waiting time coefficient; it can be seen that when using the classical model, the amount of quenching heat flux was close to convective heat flux and this means that the convective take place in this region of heat flux and this was corrected in case of ceria
nanofluids to by means of correcting quenching heat flux. The portion of convective heat flux was dominated after modifying bubble waiting time coefficient and this due to the existing of natural convective heat flux in the range of heat flux $21 \text{--} 35 \text{ kW/m}^2$, and this was also observed in our experimental study with this type of nanofluids at volume fraction (0.007 Vol.). Besides, in the present model, we focused on the convective and nucleate boiling regimes, and this agrees well with finding that reported by previous studies [165, 166]. It can be concluded that the quenching and convective heat fluxes play a significant role in the regions of low and moderate heat fluxes, and this was investigated in this study. Moreover, to validate the present model it should be taken into account the pool boiling parameters during the boiling of nanofluid or correct the quenching heat flux by modifying the bubble waiting time coefficient as needed to control the quenching process in case the absence of closure correlations related to the boiling parameters such as the nucleation site density, waiting time, growth time, bubble departure diameter. The obtained pool boiling results from the extended RPI model were in good agreement with experimental data for pool boiling heat transfer coefficient for ceria based water nanofluids.

![Figure (2.21)](image)

**Figure (2.21)** The Portion of heat flux components of the classical RPI model and extended RPI model against the total heat flux for (0.007% Vol.) ceria nanofluid.

### 2.6.3.4 Further discussion

In the present simulation, the vapor volume fraction contours were captured to see the motion of bubbles during the two-phase simulation for deionized water and ceria based deionized water nanofluids. **Fig. (2.22)** shown the formation of bubbles at the variation of time steps and constant superheat temperatures. For deionized water, at the time ($t = 100 \text{ ms}$) and constant superheat temperature for example ($6.4 \text{ K}$), the bubbles begin to form on the circular horizontal heated tube and we can notice that those groups of bubble start to sliding from bottom to sides of the tube as time escape, then at a specific location, they detached together and escaped to the top of the heated surface. As time increased to ($t = 300 \text{ ms}$) and ($t = 500 \text{ ms}$), bubbles becomes apart from the weak of the heated tube to traveling to the bulk fluid, and this is due to the difference in the densities of the liquids (vapor density less than water phase), which led to lifting the bubble to the top of the boiling chamber. In the current simulation, the height of this pool chamber was chosen according to present experimental setup, and as mentioned in the previous section and due to the short distance
between the heated tube and the surface of fluid the bubbles could not deform or shaped inside bulk liquid to other forms then they were deformed in the top surface. In the case of ceria nanofluids, we can see from contours of vapor volume fraction that the vapor bubble reduced compared to the boiling of water and at the same time steps ($t = 100$ ms), the bubbles delayed to form and their size becomes smaller than the water case. This trend could be attributed to the wettability effect due to the deposition of nanoparticles of the heating surface as well as the interaction between the nanoparticles inside the bulk fluids.

Figure (2.22) Contours of vapor volume fraction with different time and superheat temperature for water and (0.007% Vol.) ceria nanofluids.
CHAPTER 3

“EXPERIMENTAL INVESTIGATION”

3.1 Introduction

This chapter deals with an experimental investigation on pool boiling heat transfer performance of deionized water and different types of nanofluids at the atmospheric pressure condition. The pool boiling chamber setup and heating element fabrication was done at the laboratory of the Energy Engineering Department to build up the pool boiling apparatus. During the fabrication stage, great endeavors have been taken to fixing the thermocouples on the outer surface of the heating element to ensure proper surface temperatures measurements. All the preparing samples of nanofluids were formed by the two-step method as the dry powders were dispersed into deionized water by using physical techniques. Seven types of nanofluids with different volume concentrations and nanomaterials types and sizes were investigated in this research. One type of investigated nanofluids pool boiling tests was used to validate the results of new extended multiphase model to predict the pool boiling heat transfer of ceria based water nanofluid with two-volume concentrations and various heat fluxes as a part of this work to justify the use of the CFD as a design tool for predicting pool boiling heat transfer using nanofluid from horizontal heated typical tube.

3.2 Experimental Methodology

3.2.1 Pool boiling chamber setup

Pool boiling facility with instrumentations used in the present experimental investigation schematically and photographically illustrated in Fig. (3.1) (A) and (B), respectively. The pool boiling chamber used for this study is a stainless steel vessel with dimensions (Length = 155 mm, Width = 120 mm, Height = 310 mm). Fireproof and heat resistance ceramic glass (Supplied by Poly M Hungary Ltd.) used to visualize the bubbles' motion during the pool boiling process. The glass installed for the front and back sides of the chamber by using a proper adhesive material, and due to the essential characteristics and high transparency of this type of glass, we can easily see the whole boiling and bubble formation process with the presence of LED from the backside. All the boiling chamber excluding two windows with an area of (0.0256 m²) used for visualization and light source purpose covered with two layers of insulation materials, the first layer was an insulation sheet with high reflective one side material solflex (Thermofoam company. OBI store, Hungary), the second layer was the 10 mm thermal insulation sheet to minimize the heat losses. The pool boiling chamber is sandwiched by two Teflon plates (PTEF) of 10 mm thickness provided from (Balisz.hu Company) to prevent the vapor leakage from the chamber. Moreover, cooling condenser (Allihn type NS29/32) with a jacket length 400 mm supplied from (aalabor.hu), which has minimal thermal expansion during the temperature change used to condense the vapor and keep the atmospheric pressure condition as well as the fluid capacity inside the apparatus.
The instrumentations used in this experiment are the temperature data logger (Type: Omega, HH378) and energy data logger (Type: Voltcraft, Energy data logger 4000) to measure temperatures and the applied power, respectively. Besides, both loggers connected to the computer to collect all necessary data to calculate heat transfer performance in this study. The main item in this facility is the heating element, which is a horizontal copper tube with a typical external diameter (22 mm), and tube thickness (1 mm) filled with copper sleeve fabricated in
the department laboratory to holding the cartridge heater as shown in Fig. (3.2). The sleeve made from the rigid copper shaft and three grooves fabricated along the axial distance with different radial angles and locations. Four K-Type thermocouples are calibrated and used to measure the bulk and surface temperatures along the heating surface. Great efforts have been made to fix the thermocouples in a proper way to measure the surface temperatures without any effect on the surface characteristics of the external tube. Cartridge heater with a power 1 kW and diameter (12.5 mm), length (100 mm) manufactured by (Cartridge heaters, UK) inserted to the inside diameter of the copper sleeve to supply the heat flux. All facility above was designed, fabricated, and collected to build up our pool boiling apparatus at the laboratory of the Energy Engineering Department at (Budapest University of Technology and Economics, Hungary).

\[\text{Figure (3.2) Heating element assembly and sleeve configuration used in this experiment.}\]

### 3.2.2 Experimental procedure

Prior to starting the tests, the pool boiling chamber was cleaned with a water jet and dried to remove all the dirt stuck. Next, the roughness of the heating surface was measured by the surface tester (Type: Mitutoyo SJ-400) to obtain the roughness of the polished copper tube before the boiling process. The average of six measurements along the tube with different radial and axial locations taken to calculate the arithmetic mean roughness parameter ($R_a$), the roughness for two surfaces was measured to be (0.115 μm and 0.382 μm), and the surface profile was plotted as shown in Fig. (3.3). Afterward, working fluid injected through an injection hole from the top of the chamber. Following this, to raise the temperature of the working fluid to a boiling point, the auxiliary heater has a capacity (400 W) was switched on. When the temperature of bulk fluid reached the saturation temperature, the boiling process kept for (10 min) to remove all those dissolving bubbles. In this experiment, the boiling points at the atmospheric condition were measured for both deionized water and nanofluids in the same condition. Therefore, measurements detected that the deionized water boiling point was higher than a nanofluid boiling point by about (0.2 °C), and this was within the range of the error of the temperature logger. Hence, the boiling point for both deionized water and nanofluid
has been assumed to be the same, and this was also observed in earlier works of \([63, 68]\). The next stage was to switch on the cartridge heater with low heat flux and keep the auxiliary heater at a specific power about (20-35 W) to maintain the saturation temperature during the initial heat flux stage. The reading of electrical power and temperatures were taken via data acquisition programs after reaching a steady-state condition (about 5 min). The capacity of the working fluids measured before and after the boiling tests to examine the functionality of the cooling condenser, which is used in this system. The maximum power for cartridge heater used in this experiment was about (1000 W) as mentioned above hence, our tests conducted under the critical heat flux point, which indicates that our scope of this study is to calculate the pool boiling heat transfer coefficient for different working fluids (water and nanofluids). All the measured data for this experiment were taken three times, and the average value calculated to ensure the repeatability of the results and the average values used to calculate the applied heat flux and temperatures and find out the PBHTC.

### Figure (3.3) Roughness profiles for two polished copper tubes in the present work.

**3.2.3 Nanofluids preparation method**

The formation of nanofluids is considered as a crucial stage during the nanofluids experimental studies. Nanofluids are principally formed via two procedures: the two-step method and one-step method. The two-step method is widely used in the preparation of nanofluids by mixing conventional fluids with commercially available nanomaterials that obtained from several physical, mechanical, and chemical processes \([167]\). In the one-step method, the nanoparticle dispersion avoided to minimize nanoparticle agglomeration and increase the fluid stability of prepared nanofluids. In the present research, deionized water and different types of metals oxide and nitride nanoparticles and their composites are prepared by the first method to investigate the pool boiling heat transfer performance. Two-step method applied in this experimental study to make different types of mono and hybrid nanofluids at various dilute volume concentrations (0.001 up to 0.5 Vol. %). In this procedure, the first step is to scale the desired quantity of the dry nanopowder via accurate digital balance has an accuracy (0.001 grams), then the scaled amount of nanopowder added and mixing to a desired volume of the water. Next, the amount of nanopowder mixing with deionized water by means physical methods such as stirrer or ultra-sonication process. Finally, the stability of prepared suspensions will be checking, and the final suspension will be used for heat transfer boiling application. **Fig. (3.4)** illustrates the steps for our procedure to prepare a stable nanofluid during these experiments. Moreover, all the working fluids utilized in the present work to investigate
the boiling heat transfer performance, which contains the deionized water and the prepared nanofluids with different types of nanomaterials, size, and concentrations, are summarized and listed in Table (3.1).

Table (3.1) Types of working fluids used to investigate pool boiling heat transfer in this research.

<table>
<thead>
<tr>
<th>Test number</th>
<th>Nanomaterial type</th>
<th>Basefluid</th>
<th>Nanofluids NFs</th>
<th>Preparation method</th>
<th>Number of measured data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline Test No.1</td>
<td>-</td>
<td>DI-W** Surface roughness (115 nm)</td>
<td>-</td>
<td>-</td>
<td>36</td>
</tr>
<tr>
<td>Baseline Test No.2</td>
<td>-</td>
<td>DI-W** Surface roughness (382 nm)</td>
<td>-</td>
<td>-</td>
<td>36</td>
</tr>
<tr>
<td>NFs’ Test No.1</td>
<td>Cerium oxide, CeO₂</td>
<td>DI-W**, (115 nm)</td>
<td>50 nm</td>
<td>0.001-0.04 % Vol.</td>
<td>60</td>
</tr>
<tr>
<td>NFs Test No.2</td>
<td>Tungsten oxide, WO₃</td>
<td>The thickness of nanoflakes 30 nm</td>
<td></td>
<td>0.005-0.05% Vol.</td>
<td>36</td>
</tr>
<tr>
<td>NFs Test No.3</td>
<td>Magnesium oxide, MgO</td>
<td></td>
<td>40 nm</td>
<td>0.001-0.04 % Vol.</td>
<td>Two-step method</td>
</tr>
</tbody>
</table>
The desired volume concentration of the nanofluids is calculated by using conversion formula, which is used by [168, 169], as shown in Eq. (3.1).

$$\phi_v = \left[\frac{1-\phi_m}{\phi_m} \frac{\rho_p}{\rho_l} + 1\right]^{-1}$$ (3.1)

Where: $\phi_v$, $\phi_m$ are the volume and mass concentrations, respectively. whereas $\rho_p$, $\rho_l$ are the nanopowder and water densities, respectively. The details about the nanopowder quantities calculations are presented in Appendix (A). The next section gives details about the nanomaterials used in the current research and their characterization.

### 3.2.3.1 Nanopowder types and the supplier

During the stage of selecting the nanomaterials, I was in contact with various companies that are responsible for producing the nanomaterials for research purposes. After a wide route from inquiries from those companies to check the price and the quality of the desired nanopowders. Finally, nanomaterials are purchased from (US Research Nanomaterials, Inc. USA). Five types of nanopowders were chosen according to the quality, price, thermal, and chemical properties (i.e., $\text{Al}_2\text{O}_3$, $\text{CeO}_2$, $\text{MgO}$, $\text{WO}_3$, and $\text{AlN}$). To check the supplier specifications, scanning electron microscope SEM for all nanomaterials was used to capture the size and the shapes of nanopowders (see Appendix B). It can be seen that a reasonable agreement between the shape and size of the images and those obtained from the vendor specification.

| Table (3.2) Specifications of the nanopowders from the supplier (US Research Nanomaterials, Inc.) |
|-----------------------------------|---|---|---|---|---|
| Specifications | $\text{Al}_2\text{O}_3$ | $\text{CeO}_2$ | $\text{MgO}$ | $\text{AlN}$ | $\text{WO}_3$ |
| Purity | 99+% | 99.97% | 99+% | 99.5% | 99.95% |
| Appearance particle size APS | 20 nm | 50 nm | 40 nm | 65-75 nm | Thickness 30nm |
| SSA ($m^2.g^{-1}$) | $>138$ | 30-35 | ~ 45 | - | 85-105 |
| Morphology | nearly spherical | nearly spherical | polyhedral | hexagonal | flaky |
| Color | white | light yellow | white | white to gray | yellow |
| Density ($kg. m^{-3}$) | 3890 | 7132 | 3580 | 3260 [170] | 7160 [171] |
3.2.3.2 Dispersion process and stability checking

One of the most critical steps during the two-step nanofluid preparation method is the dispersion process of the nanopowder into basefluid to obtain a stable suspension. Different techniques have been used in literature to make homogeneous dispersion nanofluids, and one of those techniques is the physical treatment technique involving the magnetic stirrer, the ultrasonic bath, the ultrasonic probe, and the high-pressure homogenizer. Hence, the aims of using the two-step method to break up the agglomerated nanoparticles clusters to make a homogeneous suspension. In the present work, I focused on utilizing the magnetic stirrer as well as the ultra-sonication probe to mixing the nanofluids at a different period. It is worth to notice that during the present study no surfactant or pH controlling used to enhance the dispersion process to avoiding the change might happen in the chemical properties for the working fluids especially the boiling point (saturation temperature), and this was also stated in studies [63, 68]. In this regard, the ultra-sonication homogenizer probe type (Type: Bandelin, SONOPULS, Germany) with maximum power 200 W and ultrasound frequency 20 kHz ± 500 Hz with continuous ultrasound mode utilized to disperse the agglomerates and make a stable suspension.

Moreover, the magnetic stirrer was used to mixing the nanoparticles within the conventional fluid. To check the stability of the suspension (nanofluids) after the dispersion processes, two techniques were applied in this study, which is the sedimentation-time checking by the naked eye and the zeta potential measurements via (PALS Zeta potential analyzer Version. 3.37 from Brookhaven Instruments). Table (3.3) summarized the details of preparation procedures employed in the present work. All visualizations have been presented to show that the prepared nanofluid has been stable after a period since no visible sedimentation was observed by naked eyes (see Appendix C).

Table (3.3) The details of nanofluids formation methods and stability checking.

<table>
<thead>
<tr>
<th>Nanofluid Type</th>
<th>Stirring conditions</th>
<th>Ultra-sonication conditions</th>
<th>Stability conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test No.1 CeO₂/NFs</td>
<td>Speed: 800 rpm Time: 90 min</td>
<td>Time: 30 min</td>
<td>Zeta-potential**: -30.45 mV Sediment time: After 1 day</td>
</tr>
<tr>
<td>Test No.2 WO₃/NFs</td>
<td>Speed: 800 rpm Time: 60 min</td>
<td>Time: 45 min</td>
<td>Zeta-potential: NR*** Sediment time: After 3 days</td>
</tr>
<tr>
<td>Test No.3 MgO/NFs</td>
<td>Speed: 800 rpm Time: 60 min</td>
<td>Time: 60 min</td>
<td>Zeta-potential: NR*** Sediment time: After 2 days</td>
</tr>
<tr>
<td>Test No.4 AlN/NFs</td>
<td>Speed: 800 rpm Time: 90 min</td>
<td>Time: 30 min</td>
<td>Zeta-potential: NR*** Sediment time: After 1 day</td>
</tr>
<tr>
<td>Test No.5 Al₂O₃/NFs</td>
<td>Speed: 800 rpm Time: 90 min</td>
<td>Time: 60 min</td>
<td>Zeta-potential: -38.55 mV Sediment time: After 3 days</td>
</tr>
<tr>
<td>Test No.6 Hybrid (Al₂O₃+CeO₂) NFs</td>
<td>Speed: 800 rpm Time: 60 min</td>
<td>Time: 45 min</td>
<td>Zeta-potential: -31.53 mV Sediment time: After 1 days</td>
</tr>
<tr>
<td>Test No.6 Hybrid (Al₂O₃+MgO) NFs</td>
<td>Speed: 800 rpm Time: 60 min</td>
<td>Time: 30 min</td>
<td>Zeta-potential: NR*** Sediment time: After 3 days</td>
</tr>
</tbody>
</table>

NFS*: Nanofluids; Zeta-potential**: After sonication process; NR***: Not recorded
### 3.2.3.3 Thermal conductivity measurements

To characterize the produced nanofluids, one of the most crucial transport properties is the thermal conductivity of the working fluid. In the present research, thermal conductivities of all types of nanofluids were measured. Transient Plane Source Method (TPS) is a new technology to measure the thermal conductivity of materials, which was developed based on the hot transient wire method [172]. Transient Plane Heat Source sensor (Type: SKZ1061C) from (SKZ Industrial Co., Ltd) was used as a thermal conductivity tester for both deionized water and nanofluids, as shown in Fig. (3.5). The test time was (5 seconds) and the accuracy of the sensor within a range of (± 5%). All the measured data repeated three times for each test, and the average value was taken. Thermometer utilized to measure the temperatures with hot water insulated vessels after heating the samples for the desired temperature and the accuracy of this thermometer (±1%) of reading temperature. The thermal conductivity tester was calibrated using deionized water, by comparison, the measured thermal conductivity data for deionized water with those obtained from National Institute for Standard and Technology NIST under various temperatures [159], the validation of the obtained results after calibration has shown high accuracy behavior with NIST thermal conductivity data, all details regarding the validation as well the measurements results will be discussed in the upcoming section related to the thermal conductivity results.

![Image](TPS Sensor.png)

**Figure (3.5)** Thermal conductivity tester used in the present work.

### 3.3 Data reduction and uncertainty analysis

To estimate the pool boiling heat transfer coefficient in this research, the applied heat flux on the heating element should be calculated by knowing the applied electric power and surface area of the tube, as shown in Eq. (3.2).

\[
q' = \frac{V \cdot J}{\pi D_{\text{out}} L_{\text{tube}}} = \frac{E}{\pi D_{\text{out}} L_{\text{tube}}}
\] 

(3.2)

Where: \( E \) is the power in (W), \( D_{\text{out}}, L_{\text{tube}} \) are the outer diameter and length of copper tube in (m), respectively. The surface temperatures were taken from the three thermocouples, which

[66]
are installed on the outer tube surface. Efforts have been made in this experiment to fix the
thermocouples in the proper position on the tube surface and avoiding the surface effects on
temperature reading. So, the average of the surface temperatures values for top, side, and
bottom thermocouples calculated as shown in Eq. (3.3).

\[
T_{s,\text{ave}} = \frac{T_{\text{top}} + T_{\text{side}} + T_{\text{bottom}}}{3}
\] (3.3)

Where: \(T_{\text{top}}\), \(T_{\text{side}}\) and \(T_{\text{bottom}}\) are the surface temperatures of the top, side, and bottom
thermocouples locations, respectively. The pool boiling heat transfer coefficient PBHTC
calculated from the above-mentioned physical quantities, as shown in Eq. (3.4).

\[
P\text{BHTC} = \frac{q'}{\Delta T_{\text{sup}}} = \frac{q'}{(T_{s,\text{ave}} - T_{\text{sat}})}
\] (3.4)

Where: \(T_{s,\text{ave}}\), \(T_{\text{sat}}\) the average surface temperature and saturation temperature,
respectively. \(\Delta T_{\text{sup}}\) is the superheat temperature, which is the difference between surface and
saturation temperatures. The uncertainty analysis for multiples measured variables for this
experiment calculated according to [173], as shown in Eq. (3.5).

\[
\Delta U = \sqrt{\left(\frac{\partial U}{\partial X_1} \Delta X_1\right)^2 + \left(\frac{\partial U}{\partial X_2} \Delta X_2\right)^2 + \left(\frac{\partial U}{\partial X_3} \Delta X_3\right)^2}
\] (3.5)

Where: \(X_1\), \(X_2\) and \(X_3\) are the variables. \(\Delta X_1\), \(\Delta X_2\) and \(\Delta X_3\) are the uncertainties given by
instrument data-sheets. Therefore, the relative uncertainties for the applied heat flux and pool
boiling heat transfer coefficient calculated as shown in Eqs. (3.6) and (3.7).

\[
\Delta q' = \sqrt{\left(\frac{\partial q'}{\partial P} \Delta P\right)^2 + \left(\frac{\partial q'}{\partial D_{\text{out}}} \Delta D_{\text{out}}\right)^2 + \left(\frac{\partial q'}{\partial L} \Delta L\right)^2}
\] (3.6)

\[
\Delta PBHTC = \sqrt{\left(\frac{\partial PBHTC}{\partial q'} \Delta q'\right)^2 + \left(\frac{\partial PBHTC}{\partial T_{\text{sup}}} \Delta T_{\text{sup}}\right)^2}
\] (3.7)

The maximum relative uncertainties for the applied heat flux and pool boiling heat transfer
coefficient in this study were found to be ± 1.1% and ± 5.5%, respectively.
3.4 Results and discussion

3.4.1 Results of thermal conductivity for nanofluids

Prior to measuring the thermal conductivity of the prepared nanofluids, the thermal conductivity tester was calibrated using deionized water, and this stage was very important by validating the results with other well-known thermal conductivity data [159]. The results obtained for deionized water was also a reference to comparing with the nanofluids measured data. The validation of the obtained results for a temperature range (32 – 90 ºC) after calibration shows high accuracy behavior with National Institute for Standard and Technology NIST thermal conductivity data for deionized water, as presented in Fig. (3.6).

![Figure (3.6) The validation of thermal conductivity results for deionized water with NIST data [159].](image)

After we finished the verification stage, our prepared nanofluids were measured at different volume concentrations and various temperatures. Three types of nanofluids were chosen to present their thermal conductivities and assess the results by comparing the measured data with deionized water thermal conductivity, and this was represented as the thermal conductivity enhancement ratio $k_{ratio}$, which is defined as Eq. (3.8).

$$K_{ratio} = \frac{k_{nf}}{k_f}$$ (3.8)

Where: $k_{nf}$, $k_f$ are the thermal conductivity of nanofluids and deionized water, respectively. Thermal conductivity of CeO$_2$ based deionized water nanofluid, Al$_2$O$_3$ based deionized water nanofluid, and their hybrid (Al$_2$O$_3$+CeO$_2$) 50:50 by volume-based deionized water nanofluid with different volume concentrations (0.01, 0.05, 0.1, and 0.5% Vol.) at various temperatures (35, 40, 45, and 50 ºC) were measured in this study. Fig. (3.7) illustrates the thermal conductivity enhancement ratio for ceria nanofluid against the temperatures for different volume concentrations. It can be seen that the thermal conductivity ratio increases linearly with increasing the temperature; the maximum ratio was (1.033) at higher temperature and volume concentration compared to the deionized water baseline case. However, for all measured data, it can be noticed that the thermal conductivity was a function of volume concentrations and temperatures. The enhancement was attributed to the higher thermal conductivity of ceria nanoparticles compared to deionized water, and this results in higher thermal conductivity of the nanofluid. Fig. (3.8) shows the comparison between the measured results and data obtained from the other theoretical model of Crosser and Hamilton [35].
Thermal conductivity of alumina nanoparticles based deionized water nanofluids was measured at various temperatures (35 °C) up to (50 °C), and different dilute volume concentration (0.01% Vol. to 0.5% Vol.). Fig. (3.9) presents the experimental relative thermal conductivity enhancement ratio of alumina nanofluid compared to previous theoretical models at a constant temperature 50 °C when the experimental thermal conductivity of water at this temperature equals 0.6475 (W/m. K). Thermal conductivity enhancement results showed a good agreement trends with previous models according to increase volume concentration, while our obtained experimental results show slight increase compared with previous general models; this referred to examine the general models at high temperature while these model were estimated under room temperature so that those models show underestimated results compared with our present work, as mentioned in various previous study the temperature has a significant effect so should be engaged in various models [46]. The validation with the previous general model occurred because there is no particular experimental work under dilute volume concentration that can be used to verify our experimental results. Hence, to bypass this issue, our experimental results were compared under volume concentration 0.5% and variable temperatures with Esfe et al. [46], this regarding the use of this concentration on both studies. Fig. (3.10) shows the thermal conductivity ratio with a variety of temperatures for different volume concentrations. The results demonstrated that the ratio increased linearly with increasing temperature and got more enhancement when the concentration increased. However, the enhancement ratio was (1.0285) at the higher volume concentration (0.5 Vol.) and temperature (35 °C), while the maximum enhancement ratio was (1.0534) at volume concentration (0.55 Vol.) and temperature (50 °C). The enhancement ratio at low temperature has a small variation between maximum and minimum concentration equal (0.013), while it's equal to (0.028) at high temperature, which means the effect of increased concentration has an impact in enhancing thermal conductivity at high-level temperature. For more validation, Fig. (3.11) presents our measured results that proved high accuracy with previous work of [46] within a margin of deviation equal (1.32%). This small variation can be referred to as the nanoparticle size that uses in different studies. Besides, the preparation methods that were used and the experimental conditions. Finally, the thermal conductivity ratio was introduced for hybrid (Al₂O₃+CeO₂) 50:50 by volume-based deionized water nanofluid at various concentrations and temperatures.
Figure (3.7) Thermal conductivity ratio results of ceria nanofluids against temperatures at different volume concentrations.

Figure (3.8) The comparison between measured thermal conductivity ratio results of ceria nanofluid and theoretical H-C model [35].

Figure (3.9) Thermal conductivity of alumina nanofluid compared to other theoretical models [35, 36].

Figure (3.10) Thermal conductivity ratio results of alumina nanofluids with temperatures at different volume concentrations.

Figure (3.11) The comparison between measured data of alumina nanofluid and Esfe et al. [46] at volume concentration (0.5% Vol.).
Fig. (3.12) presents the ratio of the thermal conductivity of hybrid nanofluids against the temperatures under various volume concentration. It can be seen that the thermal conductivity enhancement ratio increased with increasing the concentrations and the temperatures as expected. At low temperature (35 °C) and volume concentration (0.5% Vol.), the thermal conductivity ratio was (1.0307), whereas at high temperature and volume concentration (0.55 Vol.), the maximum enhancement ratio was considerably noticed to be (1.0888). The results indicated that the hybrid nanofluids lead to higher thermal conductivity at the same condition compared to the previous two types of mono-nanofluids (Alumina and ceria nanofluids). This might be attributed to the well-mixing process between the hybrid nanoparticles, which leads to good stability for such kinds of nanofluids. Moreover, the interaction between the two sizes of the nanoparticles resulted in a high collision; then, high conductive could accrue during the molecules of the liquid. Fig. (3.13) shows the comparison of thermal conductivity ratio for tested nanofluids against volume concentrations at temperature equal (50 °C), it can be seen that the hybrid nanofluid has higher relative thermal conductivity value compared with other two mono-nanofluids at high concentration (i.e., 1.088 for hybrid nanofluids, 1.053 for Al₂O₃ nanofluid, and 1.033 for CeO₂ nanofluid). The combination of those two types of nanoparticles with different size of (20, 50 nm) for alumina and ceria nanoparticles within a range of volume concentration used in this research lads to increase the collision rate of molecules and the Brownian motion of nanoparticles due to the high kinetic energy which, in turn, improved the thermal conductivity of hybrid nanofluids compared to single nanofluids and deionized water [174].

Based on literature for the thermal conductivity of mono and hybrid nanofluids, there is still no model to predict the ceria and alumina-based water hybrid nanofluids with a dilute volume concentration. Hence, this work effort has been made to propose a correlation for (alumina+ceria) hybrid nanofluid with different volume fraction and working temperatures. Fig. (3.14) illustrates the curve fitting method for (3-D) plot of thermal conductivity ratio as a function of two dependent variables which are the volume fraction and temperature with the above-mentioned experimental conditions to find the best fit of thermal conductivity ratio that depends on those two parameters. The correlation introduced as follows:
\[ k_{\text{ratio}} = 1.21 - 0.009581T - 0.223\varphi + 0.0001223T^2 + 0.006598 \times T \times \varphi \] (3.9)

Where: the \( T \), \( \varphi \) are the temperature and volume fraction of nanofluid, respectively. To check the accuracy of the proposed correlation, the following parameter, referred to a Margin of Deviation, is defined:

\[
\text{Margin of deviation (\%)} = \frac{K_{\text{exp}} - K_{\text{corr}}}{K_{\text{exp}}} \times 100,
\] (3.10)

Where: \( K_{\text{exp}} \) referred to thermal conductivity results obtained from measured data while \( K_{\text{corr}} \) related to thermal conductivity obtained from the proposed correlation. The margin of deviation was not exceeding 4.2 \%, as shown in Fig. (3.15), which means the reasonable accuracy of the introduced correlation to predict the thermal conductivity ratio of hybrid nanofluid.

Figure (3.14) (3-D) analysis of thermal conductivity ratio for hybrid nanofluid at various volume fractions and temperatures.

Figure (3.15) The margin of deviation for the proposed correlation and measured data.

Thermal conductivity of another nanofluid so-called tungsten oxide nanoflakes based deionized water was also measured with different volume concentrations and various temperatures. Fig. (3.16) shown the thermal conductivity ratio of \( \text{WO}_3 \) nanofluids relative to water at different concentrations and temperatures. It can be seen from Fig. (3.16) that the maximum enhancement ratio for thermal conductivity was about (1.063) for nanofluids with
volume concentration (0.05% Vol.) and temperature (90 ºC). Moreover, the other nanofluids measured data like aluminum nitride AlN nanoparticles based deionized water nanofluids, Magnesium oxide MgO nanoparticles based deionized water nanofluids, and the new hybrid (Al₂O₃+MgO) 50:50 by volume, the measurements were done at constant temperature (50 ºC) and different volume concentrations. The maximum thermal conductivity enhancement ratio was shown at higher volume concentrations for all samples (i.e., 1.1222, 1.0341, and 1.1168) for AlN, MgO, and (Al₂O₃+MgO) hybrid nanofluids compared to deionized water baseline case, respectively. All the thermal conductivity measured data for other nanofluids were summarized in tables (see Appendix D).

![Figure (3.16) Thermal conductivity ratio of WO₃ nanofluids relative to deionized water at different volume concentrations and temperatures.](image)

3.4.2 Results of pool boiling heat transfer performance for nanofluids

Before introduce and discuss our obtained results regarding the pool boiling tests, the pool boiling apparatus and procedure should be validated to ensure the accuracy of the present findings. The results of pool boiling curves and pool boiling heat transfer coefficient for deionized water compared to those well-known correlations in literature called Rohesnow correlation [19] Eqs. (3.11), and Gorenflo Correlation [175] Eqs. (3.12) to (3.15), and the experimental works reported in the literature such as Das et al. [63], Suriyawong and Wongwises [77] as well as Shoghl et al. [112] with horizontal heated tubes. The reason behind using deionized water for the validation of our obtained results that this type of liquids has well-known and high accurate thermophysical properties in literature [159]. Therefore, our experimental results for deionized water with various runs validated, as can be seen from Fig. (3.17) and Fig. (3.18) that the experimental results compare reasonably well with predicted correlations as well the experimental studies for pool boiling curves and pool boiling heat transfer coefficient.

\[
q = \mu_l h_{lw} \left[ \frac{\sigma}{g(\rho_l-\rho_v)} \right]^{-0.5} \left( \frac{1}{\lambda_{sf}} \right)^{1/0.333} Pr_l^{1/0.333} \left[ \frac{C_p l \Delta T_{sup}}{h_{lw}} \right]^{1/0.333} \tag{3.11}
\]

Where: \( \mu_l \), \( \rho_l \), \( C_{p,l} \) are the viscosity, density, and specific heat for liquid. \( h_{lw} \), \( \sigma \), \( \rho_v \) are the latent heat of vaporization, the surface tension of the liquid, and density of the vapor,
respectively. \( C_{sf} \) is a constant that depends on surface characteristics, and in this study considered to be (0.0128) for polished copper tube.

\[
PBHTC = PBHTC_0 \times F_p \times F_q \times F_{SR}
\]

(3.12)

\[
F_p = 1.73P_r^{0.27} + (6.1 + 0.68 \frac{1}{1-P_r}) \times pr^2
\]

(3.13)

\[
F_q = \left(\frac{q}{q_0}\right)^n, \quad n = 0.9 - 0.3pr^{0.15}
\]

(3.14)

\[
F_{SR} = \left(\frac{Ra}{Ra_0}\right)^{0.133}
\]

(3.15)

Where: \( pr \), \( q \), \( Ra \) are the reduced pressure ratio \( pr = p/p_c \), heat flux (kW/m\(^2\)) and average surface roughness for heating surface [\( \mu m \)], respectively. The reference conditions for pure water used in this correlation are \( PBHTC_0 = 5600 \) (kW/m\(^2\).K), \( q_0 = 20 \) (kW/m\(^2\)), \( Ra_0 = (0.4 \, \mu m) \), as stated in [175].

![Figure (3.17) The comparison between the pool boiling curve for present experimental work and literature work for deionized water as a working fluid.](image)

![Figure (3.18) The comparison between the pool boiling heat transfer coefficient PBHTC for present experimental work and literature works for deionized water.](image)

3.4.2.1 Test No. 1 (CeO\(_2\) based DI-W nanofluid)

The results of the pool boiling curves for deionized water DI-W and cerium oxide-based DI-W at various volume concentrations were plotted in Fig. (3.19). It can be seen that the pool boiling curves for all volume concentrations were shifted to the left side compared to the deionized water curve, which means that at the same range of heat fluxes, the superheat temperatures reduced for nanofluids compared to those of DI-W. This behavior means that the heat flux was removed with large heat in relatively small superheat temperatures; hence, the heat transfer performance was improved. However, the enhancement of the boiling curves at low concentrations (i.e., 0.004% and 0.007% Vol.) achieved better improvement compared to other concentrations as well as DI-W as the baseline case. The pool boiling heat transfer
coefficient PBHTC of water and dilute cerium oxide nanofluids at different volume concentrations were presented in Fig. (3.20). It can be noticed that the PBHTC for all cases increased when applied heat flux increased, and this due to the developed pool boiling nucleation regime, which includes the formation and interaction of the bubbles with bulk liquids [103], [106]. According to Fig. (3.20), the highest enhancement in pool boiling heat transfer coefficient of nanofluid with concentration (0.007% Vol.) was found to be (70%) compared to the DI-W baseline case. Because the experiment was conducted on the smooth heating surface with a roughness (0.115 μm) and the size of the nanoparticle was about (50 nm), it is expected that the smooth surface with low particles concentration leads to obtain high heat transfer performance, and this was also stated in studies [103], [109]. The deposition of nanoparticles on the smooth heating surface at lower nanoparticle concentration makes the surface rougher than before which, in turn, increased the creation of new nucleation sites density hence, increasing the number of onset bubbles during the pool boiling process and then the heat transfer rate. However, the increment in the volume fraction of nanofluid from (0.007% Vol.) to (0.04% Vol.) leads to noticeable degradation in pool boiling heat transfer coefficient compared to other nanofluids concentrations, while it is still better than of DI-W, especially at low heat fluxes. The reason for that is the nanoparticle deposition layer concerning high heat fluxes as well as the boiling time, and this was reported with studies of [88], [99].

The pool boiling heat transfer coefficient enhancement ratios of cerium oxide-based DI-W nanofluid at different concentrations concerning DI-W was illustrated in Fig. (3.21). It can be seen that the improvement up to (70%) can be found at a nanofluid volumetric fraction (0.007% Vol.) with low applied heat flux compared to DI-W. For all applied heat fluxes in this test, the heat transfer coefficients for nanofluids with all volumetric fractions were higher than of DI-W. This trend was also reported in the study of [109] for the range of heat fluxes (50 – 100 kW/m²). However, the heat transfer coefficient ratios distinctly drop beyond the heat fluxes for all nanofluids concentrations except the dilute one (i.e., 0.001% Vol. at heat fluxes 50 – 70 kW/m²). This may be due to the nucleate boiling at this range of heat fluxes, which related to the formation of bubbles and the interactions between bubbles, solid particles, and surface heating.

Figure (3.19) Pool boiling curves of deionized water and cerium oxide nanofluids at different volume concentrations.

Figure (3.20) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and cerium oxide nanofluids at different volume concentrations.
Figure (3.21) Pool boiling heat transfer coefficient ratio of cerium oxide nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.

Next, results of surface roughness around the horizontal heated copper tube before and after boiling of cerium oxide-based water nanofluids at different concentrations were plotted in Fig (3.22). Three locations were considered to measure the surface roughness of the heated tube are upper, sides, and bottom parts. As aforementioned in the previous section, the distribution and formation of bubbles from the horizontal tube during the pool boiling are different from those of flat plate or vertical tubes heaters.

Figure (3.22) Surface roughness against different volume fraction of cerium oxide nanofluids at various tube locations.

Fig (3.22) depicts that the nanoparticles deposition layer of nanofluid has a strong influence on the bottom location of the heated tube, and this has been attributed to the intensity of bubbles formation from this part compared to sides and top regions. It was widely reported that the boiling time has a strong effect on the nanoparticle deposition layer, as stated in the study of [95]. Therefore, the roughness measurements for all nanofluid concentrations were measured after the same time of boiling tests to show the influence of nanoparticle concentrations on the deposition nanolayer roughness at different radial positions of the tube. It can be seen that the highest roughness found at the bottom area for all volumetric fractions of cerium oxide-based water nanofluids (i.e., 0.007% Vol.) has a roughness about (308 nm) compared to the smooth case (before boiling, 115 nm). This concentration (0.007% Vol.) has the highest heat transfer coefficient compared to other concentrations for all range of heat fluxes, as discussed in the
previous section. Hence, it can be concluded that the concentration of nanofluid has a direct influence on the roughness of the deposition nanolayer during pool boiling, especially for the bottom part of the horizontal heated tube. Moreover, the surface roughness of the bottom part decreased after a specific volume concentration (i.e., 0.007% Vol.), and this could be attributed to the low stability of nanofluid at a high volumetric fraction. Fig. (3.23) shows the measurement of the contact angle of a water droplet on the bottom region of the smooth tube and nanoparticles deposition of nanofluid concentration (0.01% Vol.). The formation of this layer was more dominated at the bottom part, and this could be effect the on boiling performance by decreasing the contact angle then enhancement the wettability of the surface. Therefore, the suggested mechanism is convenient with the boiling behavior of cerium oxide-based deionized water nanofluid that discussed in the previous section. Fig. (3.24) presents the formation of the bubbles from the horizontal heated copper tube for DI-W and cerium oxide-based DI-W nanofluid at different heat fluxes (28 – 87 kW/m²). Nanofluid with volume concentration (0.001% Vol.) was visualized due to the visibility of bubbles images at this concentration, while other concentrations are not transparent enough to distinguish the motion of the bubble during pool boiling. As can be noticed from the photos, at a lower range of heat fluxes (i.e., ~28 kW/m²), bubbles start to create on the bottom surface then sliding on the tube sides towards the top, which represent the nucleation boiling regime. Large bubbles are distinguishing at this range of heat flux for both DI-W and nanofluids, and this can be attributed to the low bubbles agitation and weak interaction, which makes them have enough growth time to form and depart from the top of the heated tube as the study of [91], [176] recorded that. As the applied heat flux increased, the superheat temperatures increase, which in turn, enhanced the bubbles interactions due to the intensifying the active sites to nucleate bubbles. Therefore, bubbles with a small size (less diameter) and more intensity could be seen from the horizontal tube. However, with rising the applied heat flux, bubbles from adjoining nucleation sites mix, coalesce and create large unequal bubble shapes as seen in pictures especially with heat flux ranges (43 – 87 kW/m²). For nanofluid, visualization of CeO₂ based- water with concentration (0.001% Vol.) revealed that the bubbles do not coalesce quickly from the heated tube, and discrete bubble regime has taken longer duration even for higher heat flux. With increasing heat flux, nanoparticles settle in nucleation cavities and prevent them from being active in the presence of highly wetting liquid, which leads to a decrease in the bubble intensities. Due to the enhancement wettability due to reducing the contact angle of nanofluids compared with water, the active cavities on the heating surface filled by the nanofluid and tend to be inactive or flooded with liquid, resulting from increasing the value of superheat temperature, which required for the inception of nanofluid boiling [176].

![Figure (3.23) Contact angles of the deionized water droplet on the bottom side of the tube before and after (0.01% Vol.) nanoparticles deposition layer.](image-url)
Deionized water

<table>
<thead>
<tr>
<th>Heat Flux (W/m²)</th>
<th>Cerium oxide CeO₂ NFs</th>
</tr>
</thead>
<tbody>
<tr>
<td>28895.96</td>
<td>28823.61</td>
</tr>
<tr>
<td>43635.75</td>
<td>43177.54</td>
</tr>
<tr>
<td>65755.08</td>
<td>65721.31</td>
</tr>
<tr>
<td>87006.22</td>
<td>87281.14</td>
</tr>
</tbody>
</table>

Figure (3.24) Visualization of pool boiling of DI-W and cerium oxide nanofluids with the volume fraction of (0.001% Vol.) at various heat fluxes.
3.4.2.2 Test No. 2 (WO₃ based DI-W nanofluid)

Tungsten oxide WO₃ nanoflakes based deionized water nanofluids as a new nanofluid has been prepared for different volumetric concentrations to examine the pool boiling heat transfer performance. Fig. (3.25) illustrates the heat flux against the superheat temperature \(\Delta T_{\text{sup}} = T_{\text{w}} - T_{\text{sat}}\), which is called the pool boiling curve for both deionized water and WO₃ based deionized water nanofluids. The maximum applied heat flux used for all tests in this work not exceed \((130 \text{ kW/m}^2)\), which is means all measurements were done under the critical heat flux value due to the power limitation of the cartridge heater used in this study. It can be seen from Fig. (3.25) that for all working fluids with increasing the applied heat flux, the superheat temperature was also increased with relatively small temperature difference, and this is due to the nucleate pool boiling regime represented by the latent heat of vaporization. For minor volumetric concentrations (i.e., 0.005 % and 0.01% Vol.), especially at the low heat flux region used in this study, the boiling curve is shifted to the leftward compared to deionized water pool boiling curve. However, an increase in volume concentration of nanofluids (i.e., 0.05% Vol.) considerably the boiling curve shifted to the right side, and this change was notable especially in high heat flux regions above \((50 \text{ kW/m}^2)\). The higher superheat temperatures at the same applied heat flux mean the pool boiling performance degraded, and this could be attributed to the deposition of the nanoflakes on the heating surface during the boiling process. At high heat flux, the formation of the bubble increased due to the increase of the nucleation site density. Hence, the deposition of the tungsten oxide nanoflakes increases due to the microlayer evaporation mechanism, which occurs during the formation of bubbles.

Fig. (3.26) shows the relationship between the pool boiling heat transfer coefficient and the applied heat flux for both deionized water and nanofluids. It can be seen that the pool boiling heat transfer coefficient for volume concentration (i.e., 0.005% and 0.01% Vol.) slightly increases for low heat flux-region, and this could be attributed to bulk effect for tungsten oxide nanofluids that represented by thermal conductivity enhancement. While the increasing volume concentration led to a reduction in pool boiling heat transfer coefficient compared to water and this reduction attributed to the deposition of nanoflakes on the surface which, in turn, build a resistance thermal layer to transfer the heat from the heating surface to the working fluid and this trend was also reported by some researchers [63, 78, 109]. Moreover, as mentioned above, the deposition of those nanoflakes decreased the boiling heat transfer by deactivate the number of nucleation sites and then changed the bubble formation and their dynamic behavior during the boiling process. Fig. (3.27) presents the pool boiling heat transfer coefficient ratio \(\frac{PBHTC_{\text{nf}}}{PBHTC_{\text{water}}}\) of nanofluid relative to pure water at various volume concentrations. It can be seen that there is an enhancement in this ratio up to (6.7%) for dilute concentration (i.e., 0.01% Vol.) of WO₃ nanoflakes based water nanofluid at low heat flux. Besides, it can be observed that the behavior of pool boiling heat transfer coefficient of nanofluid at low heat flux (free convection regime) was better than water case, especially for volume concentrations (0.005% and 0.01% Vol.) where the bulk effect dominates in this region. For high heat fluxes \(> 40 \text{ kW/m}^2\), which means at the nucleate pool boiling regime, there is a considerable decrease in pool boiling heat transfer coefficient of nanofluid compared to deionized water at all volume concentrations used in this study. The maximum reduction in pool boiling heat transfer coefficient ratio was about (15%) at volume fraction (0.05% Vol.) relative to pure water case. It was reported in the literature that pool boiling heat transfer performance could be affected by the modification of the heating surface (i.e., surface roughness, wettability, and capillary wicking forces) as well as the bulk effect that associated
to thermal properties (i.e., thermal conductivity, viscosity and surface tension). However, a surface modification that resulted from the deposition of the nanopowder during the boiling process has a significant role in causing degradation or improvements for the boiling heat transfer performance of nanofluids. Many parameters have a direct influence on pool boiling heat transfer coefficient, such as the heating surface materials, pressure system, nanomaterials type, shapes, size, and concentrations [78- 109]. The size and shape of nanomaterials considered to be essential parameters that might affect the surface characteristics during the boiling process. Those parameters have a direct interlink with surface roughness through surface particle interaction parameter, which introduces and discussed by [169].

**Figure (3.25)** Pool boiling curves of deionized water and tungsten oxide nanofluids at different volume concentrations.

**Figure (3.26)** Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and tungsten oxide nanofluids at different volume concentrations.

**Figure (3.27)** Pool boiling heat transfer coefficient ratio of tungsten oxide nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.

Fig. (3.28) (A) and (B) shows schematically and photographically the deposition of WO₃ nanoflakes on the heating surface during the pool boiling heat transfer process. It can be observed from Fig. (3.28) (A) that the deposition of those nanoflakes on the heating surface could cause the deactivation of the nucleation site by lying those nanoflakes on the
microcavities of the surface, which in turn, resulted in a reduction in bubbles formation and distribution especially at nucleate boiling region. On the other hand, the deposition of this nanomaterial created a porous nanolayer on the heating surface, which could work as a thermal resistance layer that hinders the heat transfer from the surface toward the bulk fluid. Thus, for better understanding regarding this hypothesis, photos were taken to capture the deposition of that nanopowder on the horizontal heat tube that used as a heating element in present work. **Fig. (3.28) (B)** illustrates the deposition of the WO$_3$ nanoflakes after the pool boiling test with a volume concentration (0.05% Vol.), which considered a higher concentration in this study. The built nanolayer from three directions of the horizontal heated tube was detected and it can be seen that the yellow layer on the heated tube has dominated action on the bottom side and this could be attributed to the nature of the bubble formation and sliding from horizontal tube where the bubbles start to form from the bottom side going to grow and then sliding on both sides of tube and finally at a certain point elapse from the tube towards to the bulk fluid as studied by work of [177]. According to findings of [68], the deposition of nanopowder led to created the nanoporous layer on the heating surface that makes the heating surface hydrophilic, which in turn, increases the wettability and decreases the contact angle. As mentioned above, the porous structure may enhance or deteriorate the pool boiling process depending on the surface particle interaction parameter. In the present study, it was hypothesized that the deposition of the nanoflakes changes the surface characteristics (decrease the roughness of the surface), as shown in **Fig. (3.28) (A)**, and this was proven, as shown in **Fig. (3.28) (B)**. It can be concluded that the deposition of nanoflakes on heating surfaces reduced the number of nucleation sites by filled the cavities then decrease the surface roughness of the tube. On the other hand, this deposition with such shape and size of nanopowder creates an extra thermal resistance layer that is responsible for preventing the heat from solid to the liquid. Hence, these two observation reasons were enough to reduce the heat transfer performance during the pool boiling of tungsten oxide-based water nanofluid.

![Figure 3.28 (A) Schema of nanoflakes deposition on the heating surface, (B) Deposition nanolayer of WO$_3$ nanoflakes on different radial and axial locations at 0.05% Vol. nanofluid concentration.](image)
3.4.2.3 Test No. 3 (MgO based DI-W nanofluid)

Pool boiling heat transfer performance using magnesium oxide MgO nanoparticles based deionized water from the horizontal heated copper tube was experimentally investigated. Different dilute volume concentrations with a range of (0.001% - 0.04% Vol.) were used to prepare the nanofluids. The surface roughness of the heated copper tube was measured by surface roughness tester and the arithmetic average roughness ($R_a = 0.382 \mu m$). Fig. (2.29) shows the pool boiling curve represented by the heat fluxes against the superheat temperatures for deionized water as a baseline case and for magnesium oxide-based deionized water nanofluids. It can be seen that the pool boiling curves for dilute concentrations (i.e., 0.001%, 0.004%, and 0.007% Vol.) were shifted to the left side of the deionized water pool boiling curve, and this means that the pool boiling heat transfer was enhanced by reducing the superheat temperatures as same heat flux values. However, an increase in volume concentration of magnesium oxide nanofluids (i.e., 0.01% and 0.04% Vol.), noticeably, the boiling curves were shifted to the right side, and this change was notable especially in high heat flux regions (above 60 kW/m²). Fig. (2.30) depicts the pool boiling heat transfer coefficient against heat flux for deionized water and magnesium oxide nanoparticles based deionized water nanofluids at different volume concentrations. We can see from those curves that the pool boiling heat transfer coefficient considerably increased for nanofluids with volume concentration (0.001%, 0.004%, and 0.007% Vol.) compared to pool boiling heat transfer coefficient of deionized water. However, using concentration above (0.007% Vol.) leads to a reduction in heat transfer coefficient of MgO nanofluids especially at moderate and high heat fluxes. It was widely reported in the literature that the pool boiling heat transfer could be affected by the bulk properties of the liquid and surface modification during the presence of the nanoparticles during the nucleate boiling regime. Hence, in case of low concentrations that resulted in the enhancement of PBHTC, we supposed that both effects contributed to improving the pool boiling behavior. The slightly increased thermal conductivity at volume concentration (i.e., 0.004% and 0.007% Vol.) and the deposition of nanoparticles after a period of the boiling process resulted in improving the surface characteristics for a horizontal heated tube in the present case. The average size of the magnesium oxide nanoparticles was observed via scanning electron microscope (see Appendix B) to be in the range of (80-100 nm) while the average roughness for the heater was measured by surface profile meter to be 382 nm in this test. Therefore, the deposition of nanoparticles creates new cavities which lead to increase nucleation sites and in turn, more bubbles were formed during the nucleate pool boiling regime. The interaction and the mixing between the bubbles led to increasing the collision of these nanoparticles then increase the Brownian motion during the boiling process. Fig. (2.31) shows the pool boiling heat transfer coefficient enhancement ratio ($\frac{PBHTC_{nf}}{PBHTC_{water}}$) relative to deionized water at various heat fluxes and volume concentration of magnesium oxide nanofluids. It can be seen that the maximum enhancement was (1.22) for volume concentration (0.004% Vol.) at higher heat fluxes region while there was a reduction in this ratio for high volume concentration used in this test of nanofluids. The decrease was attributed to the deposition of the nanoparticles during the pool boiling process even at low heat flux; the stability of the nanofluid in this concentration was also a vital issue to contribute with this deterioration. However, it was found that the thermal resistance increased with an increase in the volume concentration of the MgO nanofluids above 0.007% Vol. This was due to the increase of deposition of nanoparticles on the heating surface, which formed a porous resistance layer on the wall, which may reduce the bubble creation followed by a reduction in
the quantity of heat transfer from the heating surface to the bulk of the fluid and this trend was also observed in other related studies [109], [178].

Figure (3.29) Pool boiling curves of deionized water and Magnesium oxide MgO nanofluids at different volume concentrations.

Figure (3.30) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and Magnesium oxide MgO nanofluids at different volume concentrations.

Figure (3.31) Pool boiling heat transfer coefficient ratio of Magnesium oxide MgO nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.

3.4.2.4 Test No. 4 (AlN based DI-W nanofluid)

Recently, reported studies in the literature have shown that the AlN nanofluids have a potential application, especially in heat transfer systems due to its high thermal conductivity compared to other oxide nanoparticles [179]. A new type of nanofluid so-called aluminum nitride-based deionized water nanofluid was tested as a working fluid to assess the pool boiling heat transfer performance at atmospheric conditions. The pool boiling heat transfer performance using different volume concentrations of AlN nanofluid with various heat fluxes from a horizontal heated copper tube with a surface roughness ($R_a = 0.382 \, \mu m$) was experimentally studied. Fig. (3.32) shows the relationship between the heat flux and superheat temperature ($\Delta T_{sup} = T_w - T_{sat}$), which is called the pool boiling curve for deionized water and various volume concentrations of aluminum nitride AlN nanoparticles based deionized water nanofluids. It can be seen that this type of nanofluids have a potential enhancement for
pool boiling curve by shifted this curve to the left side of deionized water curve (baseline case) and this improvement was detected with volume concentrations (i.e., 0.001%, 0.01%, and 0.1% Vol.) while, other concentrations have been shown a considerable reduction in pool boiling heat transfer performance represented by shifted the curve to the right side of baseline case curve. This trend was also stated in other related studies but for different types of nanofluids [109]. It should be mention here that to assess the pool boiling performance using nanofluids, and there is a necessity to measure some thermal transport properties and evaluate the surface characteristics due to the interlink between those effects on the pool boiling manner. We can see from the thermal conductivity measurements that this type of nanofluid has a liner increase for the thermal conductivity enhancement ratio with increasing the volume fraction. Hence, the maximum thermal conductivity enhancement ratio was (1.1222) at temperature (50 °C) as shown in tables (see Appendix D), however, it was found that the bulk effect associated with thermal conductivity enhancement plays a significant role in enhancing the pool boiling heat transfer performance especially at low heat flux values (natural convection region). Fig. (3.33) illustrates the pool boiling heat transfer coefficient against heat flux for deionized water and different volume concentrations of AlN nanofluids. It was found that when using volume concentration lower than (0.2% Vol.) of nitride aluminum nanofluid, the pool boiling heat transfer coefficient was increased by about 33% compared to deionized water at heat flux (28.954 kW/m²) for volume concentration (0.01% Vol.). This improvement was attributed to the high thermal conductivity of the nanofluids at mentioned volume concentration compared to the thermal conductivity of deionized water, and this was reported in other studies for thermal conductivity measurements of aluminum nitride-based ethylene glycol basefluid [180], [181]. Moreover, the surface modification accrued during the deposition of AlN nanoparticles throughout the pool boiling process due to the microevaporation sub-phenomenon might also be another reason for this enhancement. However, with relatively higher volume concentration (i.e., 0.2% and 0.5% Vol.), the PBHTC was shown to decrease relative to deionized water.

![Figure (3.32) Pool boiling curves of deionized water and Aluminum nitride AlN nanofluids at different volume concentrations.](image1)

![Figure (3.33) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and Aluminum nitride AlN nanofluids at different volume concentrations.](image2)
Figure (3.34) shows the pool boiling heat transfer coefficient enhancement ratio for AlN nanofluids at different volume concentrations. It can be demonstrated that improvement up to 33% can be achieved with dilute AlN nanoparticles (0.01% Vol.) based deionized water nanofluids at low heat flux (28.954 kW/m²). It was also shown that a reduction up to (18%) for higher volume concentration of AlN nanofluids (0.5% Vol.) at lower heat flux and this deterioration fluctuated with increased applied heat flux. The PBHTC enhancement ratio for a concentration of 0.2% Vol. was found to nearly form deionized water values, as depicted in Fig. (3.34). However, the mechanism of boiling heat transfer using nanofluids is very complicated due to the non-linear interaction between the nucleate boiling parameters and the presence of nanoparticles, as reported in literature increase this complexity [109], [126]. The present results were found to agree with [109] for low concentration of TiO₂ nanofluids at low heat flux but contradict CuO nanofluids at the same conditions. Hence, the behavior of pool boiling heat transfer depends on the type of nanofluids and the interaction between the nanoparticles and the liquid molecules.

### 3.4.2.5 Test No. 5 (Al₂O₃ based DI-W nanofluid)

Pool boiling heat transfer performance of alumina Al₂O₃ based deionized water nanofluids from a horizontal heated copper tube at atmospheric pressure was studied. Many researchers have been studied the boiling performance of alumina nanofluids with different loading, particles size, basefluids and heat transfer operation conditions [63], [78], [81-85], [88], [90], [94], [110] and [112]. Research on pool boiling of alumina nanofluids has been shown conflicting results in pool boiling heat transfer coefficient PBHTC; hence, such trends have been attributed to the bulk and surface modification effects during boiling of nanofluids. The aim of this test was to investigate the pool boiling behavior of alumina-based deionized water nanofluids (20 nm) within a volume concentration of (0.01%, 0.05%, 0.1% and 0.5% Vol.), and heat fluxes between (14 – 118 kW/m²) from a typical horizontal heated copper tube with an outer diameter of (22 mm). Fig. (3.35) illustrates the pool boiling curves for deionized water and alumina nanofluids at different volumetric fractions from the horizontal copper heater with a surface roughness ($R_a = 0.382 \mu m$) and particle size (20 – 30 nm). It can be seen that the pool boiling curve of (0.01% Vol.) alumina nanofluid was shifted leftward compared to
deionized water curve except for the last data point (higher heat flux), while other volumetric concentrations have shown the contrary trend by moving to the rightward direction of deionized water curve. The enhancement was accrued with 0.01% Vol. alumina nanofluids by decreasing the superheat temperatures at nearly heat flux of deionized water, and this was expected as the thermal conductivity ration of this concentration was higher than the deionized water by (1.0258) and also in term of surface modification the deposition of this type of nanoparticles at present concentration resulted in more cavities, which in turn increases the formation of bubbles during nucleate pool boiling regime. Fig. (3.36) shows the relationship between the PBTHC and heat fluxes for deionized water as a baseline case and different concentrations of alumina nanofluids. Generally, the PBHTC increased for both deionized water and alumina nanofluids with increasing heat flux and this because the region of nucleate pool boiling and the formation of bubbles resulted in increasing the pool boiling heat transfer coefficient. The higher PBHTC was found at low heat flux (15.251 kW/m²) and volume concentration (0.01% Vol.) and this value was (4.766 kW/m²·K) compared to deionized water value (3.405 kW/m²·K). While the volume concentration of (0.05% Vol.) at lower heat fluxes the PBHTC was same deionized water values and the values were found to be deteriorated at high heat fluxes above (50 kW/m²) for volume concentrations (i.e., 0.05%, 0.15 and 0.2% Vol.). The deterioration trend was found for the same nanofluids at nearly volume concentrations, as detected in the study of [63], [81]. The contradictory results in the literature regarding this type of nanofluids pushed us to investigate it again with the different conditions to see the behavior of pool boiling heat transfer using alumina nanofluids. Fig. (3.37) shows the pool boiling heat transfer enhancement ratio of alumina nanofluids relative to deionized water. It can be seen that the maximum enhancement ratio was (1.40) at low heat flux for (0.01% Vol.) volume fraction of Al₂O₃ nanofluids compared to the baseline case. Whereas the maximum reduction ratio was (0.83) compared to deionized water for higher concentration used in this test. It can be concluded from this investigation that the best volume concentration of alumina nanofluids could be used to achieve a high heat transfer rate was (0.01% Vol.) at a low heat flux region. Otherwise, degradation was reported for other volume concentrations used in present tests.

![Figure (3.35) Pool boiling curves of deionized water and Aluminum oxide Al₂O₃ nanofluids at different volume concentrations.](image1)

![Figure (3.36) Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and Aluminum oxide Al₂O₃ nanofluids at different volume concentrations.](image2)
3.4.2.6 Test No. 6 (Hybrid Al₂O₃+CeO₂ based DI-W nanofluid)

The pool boiling heat transfer performance using a new nanofluid so-called hybrid nanofluid (Al₂O₃+ CeO₂) from the horizontal heated copper tube was investigated. Different particle loading (0.01%, 0.05% and 0.1% Vol.) were obtained by mixing (50:50) percent ratio to prepare our new nanofluids. According to the best knowledge, and based on the experimental studies reported in the literature, there was no study concerned about this type of hybrid nanofluid. Some interesting studies have been shown the effect of hybrid nanofluid on pool boiling heat transfer coefficient behavior using nanofluids [115], [116]. Fig. (3.38) shows the heat flux against superheat temperatures, which are called pool boiling curve for deionized water and various volume fractions for hybrid nanofluids. It can be seen that the pool boiling curves for hybrid nanofluids for all volume concentrations were shifted leftward to the pool boiling curve of deionized water at nearly heat fluxes value. This means that the pool boiling performance was increased to nanofluids compared to the baseline case of deionized water.

Figure (3.37) Pool boiling heat transfer coefficient ratio of Aluminum oxide Al₂O₃ nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.

Figure (3.38) Pool boiling curves of deionized water and (Al₂O₃+CeO₂) hybrid nanofluids at different volume concentrations.

Figure (3.39) Pool boiling heat transfer coefficient PBHTC against applied heat fluxes for deionized water and (Al₂O₃+CeO₂) hybrid nanofluids at different volume concentrations.
Fig. (3.39) illustrates the pool boiling heat transfer against heat fluxes for deionized water and various volume fractions of hybrid nanofluids. It was also found that the PBHTC for nanofluids increased compared to the baseline case but this increase was not proportional to increased volume fractions. The maximum PBHTC was found to be (7.718 kW/m².K) at (44.769 kW/m²) for volume fraction (0.05% Vol.) of nanofluid compared to deionized water at the same heat flux. Fig. (3.40) shows the pool boiling heat transfer coefficient enhancement ratio (PBHTC<sub>nf</sub> / PBHTC<sub>water</sub>) of the hybrid nanofluid relative to the deionized water baseline case. It can be seen from this figure that the maximum enhancement ratio was (1.363) for nanofluid with (0.05% Vol.) at moderate heat flux-region (nucleate boiling regime), while this ratio was (1.343) for nanofluid with (0.015 Vol.) at low heat flux. It was also found that this ratio was going to reduce with increasing heat flux after a period of pool boiling process. The PBHTC is influenced by the surface characterization that represented by surface roughness. In the present test, 0.382 μm rough copper heated tube was used. This roughness was kept constant for all the volume concentrations of working fluids. Furthermore, the thermal conductivity of the hybrid nanofluid was measured, and it was found to be higher than the unitary nanofluids and this enhancement was a temperature and volume concentration-dependent. However, the present test was shown an increase for pool boiling heat transfer behavior for all volume fraction of tested hybrid nanofluid, and this improvement was higher at volume concentration (0.05% Vol.) especially at moderate heat fluxes compared to deionized water. The reason behind this enhancement was supposed to the deposition of the hybrid nanoparticles on the heater surface that have different sizes of nanoparticles' diameter. The deposition of those composite leads to create new cavities on the heater surface which makes more bubbles to be formed with higher frequencies which resulted in this improvement in heat transfer rate in parallel with higher transport properties for these nanofluids. Moreover, deterioration of nucleation sites and bubble dynamics on the heating surface was the main reason for decreasing PBHTC with increased heat flux and the boiling period, as suggested by other studies [63], [116]. It can be concluded that this type of nanofluids with this range of volume fractions led to enhance the pool boiling heat transfer performance. To get better understand a comparison between this type of nanofluids, the pool boiling test of mononanofluids of (Al<sub>2</sub>O<sub>3</sub>) and (CeO<sub>2</sub>) based deionized water nanofluids at constant volume concentration (0.01% Vol.) was made in the present research. Figs. (3.41), (3.42) and (3.43)
show the pool boiling curves, PBHTC, and the pool boiling heat transfer enhancement ratio respectively for deionized water ceria nanofluids, alumina nanofluid and their hybrid at (0.01% Vol.) with various applied heat fluxes. It can be seen that the pool boiling performance for hybrid nanofluid and the alumina nanofluid was improved compared to deionized water as well the ceria nanofluid and this was contrary to what was expected for ceria nanofluids. The enhancement or the degradation in pool boiling heat transfer strongly depends on the surface roughness and it is interaction with the nanoparticles. However, in the present test, the behavior of alumina nanoparticles and the hybrid nanofluids have shown better performance than the ceria nanofluids especially in the low and moderate heat fluxes region. The size of the mentioned nanoparticles was different for each one. Hence the deposition of those nanoparticles makes more nucleation for bubble formation and then improve the heat transfer rate during the boiling process. The maximum pool boiling enhancement ratio was (1.40) for alumina nanofluids at low heat flux as shown in Fig. (3.43), while the maximum reduction was reported for ceria nanofluid to be (0.88).

![Graph showing pool boiling curves of deionized water, Alumina, Ceria, and their hybrid nanofluids at volume concentrations (0.01% Vol.).](image1)

**Figure (3.41)** Pool boiling curves of deionized water, Alumina, Ceria, and their hybrid nanofluids at volume concentrations (0.01% Vol.).

![Graph showing pool boiling heat transfer coefficient PBHTC against applied heat fluxes for deionized water, Alumina, Ceria, and their hybrid nanofluids at volume concentrations (0.01% Vol.).](image2)

**Figure (3.42)** Pool boiling heat transfer coefficient PBHTC against applied heat fluxes for deionized water, Alumina, Ceria, and their hybrid nanofluids at volume concentrations (0.01% Vol.).
**Figure (3.43) Pool boiling heat transfer coefficient ratio of deionized water, Alumina, Ceria, and their hybrid nanofluids at volume concentrations (0.01% Vol.).**

3.4.2.7 Test No. 7 (Hybrid Al₂O₃+MgO based DI-W nanofluid)

Following the test No. 6, other new prepared nanofluids which consist of two types of nanoparticles so-called aluminum oxide (Al₂O₃) and magnesium oxide (MgO) based deionized water nanofluids by (50:50) of volume concentration, to investigate the pool boiling performance from horizontal heat copper tube at atmospheric pressure condition. **Fig. (3.44)** presents the pool boiling curves for deionized water and hybrid nanofluids at various volume concentrations and different applied heat flux. It can be seen that all curves for testes volume concentrations of hybrid nanofluid were shifted to the left side of the deionized water curve, and this means that the nanofluids enhanced the pool boiling performance compared to the deionized water baseline case. It was demonstrated form **Fig. (3.45)** that the PBHTC was found to be (8.170 kW/m² K) at (44.118 kW/m²) for volume fraction (0.05% Vol.) of hybrid nanofluid compared to deionized water at a close value of heat flux. This enhancement was attributed to the interaction of hybrid nanoparticles at this heat flux region with surface characteristics. The size of the MgO nanoparticles was found to be in range (80-100 nm) from scanning electron microscope image, as shown in (Appendix B), whereas the size of alumina nanoparticles was in range (20-30 nm). The deposition of those composite was the main reason to increase the cavities on the heater surface and then, the possibility to create more bubbles become high. On the other hand, the higher thermal conductivity might be another reason for this improvement for this nanofluid type, and this enhancement was decreased with increase volume concentration (i.e., 0.1% Vol.) compared to low concentration while it is still improved compared to the deionized water baseline case. **Fig. (3.46)** shows the pool boiling heat transfer coefficient enhancement ratio (\(\frac{PBHTC_{nf}}{PBHTC_{water}}\)) of hybrid nanofluids with various volumetric concentrations relative to deionized water. It can be seen from **Fig. (3.46)** that the maximum enhancement ratio was (1.443) for hybrid nanofluid with volume concentration (0.05% Vol.) at moderate heat flux (44.118 kW/m²) compared to the baseline case. The enhancement ratio was found to decrease with increase volume concentration at same heat flux value (i.e., become 1.314 at 43.886 kW/m²) for volume fraction (0.1% Vol.) and this due to the deposition of nanoparticles during this concentration. The method of preparation of the nanofluid and the stability criteria in parallel with other factors related to surface interaction were the main reasons for enhancement or deterioration of the pool boiling heat transfer when
using nanofluids. It can be stated that this type of nanofluid was quite good for the application of pool boiling and two-phase flow with the abovementioned conditions.

**Figure (3.44)** Pool boiling curves of deionized water and (Al₂O₃+MgO) hybrid nanofluids at different volume concentrations.

**Figure (3.45)** Pool boiling heat transfer coefficient PBHTC against the applied heat fluxes for deionized water and (Al₂O₃+MgO) hybrid nanofluids at different volume concentrations.

**Figure (3.46)** Pool boiling heat transfer coefficient ratio of (Al₂O₃+MgO) hybrid nanofluid with respect to deionized water at various volumetric concentrations and applied heat fluxes.
CHAPTER 4

“CONCLUSION AND RECOMMENDATIONS FOR FUTURE RESEARCH”

4.1 Conclusion

Boiling heat transfer plays a significant role in transporting heat from one medium to another in many heat exchange systems. As one of the most efficient boiling heat transfer regimes, nucleate boiling involved in numerous industrial applications to remove high heat flux in relatively small superheat temperature, which, in turn, make these systems more durable and efficient. Therefore, enhancement of boiling heat transfer performance has been a subject of numerous studies during the past century to present, see [1]- [6], [16- 21], [63], [74- 121], [123- 169]. It wildly reported in the literature that the boiling heat transfer is a complicated phenomenon even for the boiling of pure liquids, and this was attributed to the many non-linear subprocesses which are involved during the boiling heat transfer. Nanofluids are new engineered thermo-fluids that consist of dispersing nano-scaled solid materials into conventional liquids. Numerous investigations in literature reported that the nanofluid thermophysical properties especially, the thermal conductivity has beenenhanced when adding those nanomaterials into conventional fluids, and this is due to the higher thermal conductivity of solid particles which, in turn, increase the conductive between the solid particles and liquid molecules [30]- [47].

In the present research, numerical and experimental investigation on boiling heat transfer performance using different types of stable nanofluids were studied. In particular, this research was focused on pool boiling heat transfer performance that represented by pool boiling curves and pool boiling heat transfer coefficient enhancement ratio of nanofluids relative to deionized water as baseline case from a typical horizontal heated copper tube at atmospheric pressure condition. A numerical CFD boiling model so-called heat flux partitioning model (RPI boiling model) was extended to simulate the deionized water and nanofluids from horizontal heated copper tubes and stainless steel flat plate heating surface at atmospheric pressure. The obtained numerical results were validated with experimental studies in the literature (simulation No.1 and simulation No.2) as well as an experimental test rig, which is built in the department laboratory for pool boiling from typical horizontal heated copper tube (simulation No.3) as described in chapter 3. The simulations were shown that to predicting pool boiling heat transfer using nanofluids; efforts should be paid to take into account the bulk properties effect of suspended nanoparticles and the surface modification effect during the deposition of nanoparticles on the heater surface. However, significant efforts have been made to modify the bubble waiting time coefficient to correct the quenching heat flux partition for pure water and nanofluids and correlate this coefficient to superheat temperature, as presented in chapter 2. Moreover, the numerical results have been shown that quenching heat flux plays a significant role among other heat fluxes mechanisms. Finally, to introduce a comprehensive model of pool boiling using nanofluids, more data from experimental studies should be taken in the account in the future to obtain new closure correlations related to the bubble dynamics (boiling parameters) and surface modification during pool boiling of nanofluids.
The present experimental setup was performed on pool boiling heat transfer performance of deionized water and different types of fairly stable mono-nanofluids (CeO$_2$, WO$_3$, MgO, AlN, Al$_2$O$_3$), and hybrid nanofluids so-called (Al$_2$O$_3$+CeO$_2$, Al$_2$O$_3$+MgO 50:50 by volume) based deionized water nanofluids from a typical horizontal heated copper tube at atmospheric pressure. The nanofluids were prepared by a two-step method with various volumetric concentrations, and then the stability was checked in two ways, which are called sedimentation time method and zeta-potential measurements and all prepared nanofluids were revealed relatively stable criteria at less during the experiments. Before introducing the pool boiling heat transfer results, the thermal conductivity measurements were done for nanofluids via the plate source transient method. The results have been shown the thermal conductivity of nanofluids enhanced compared to deionized water a baseline case, and this enhancement was increased with increasing the volume concentration and temperature. The obtained results for pool boiling tests demonstrated that using nanofluids as working fluids in the pool boiling heat transfer process might degrade or enhance the pool boiling heat transfer coefficient. The pool boiling heat transfer coefficient enhancement ratio was improved and deteriorated depending on the nanomaterials type, size, concentration, and the heating surface characteristics and configuration. The new kind of nanofluids, so-called hybrid nanofluids which are produced by adding complex nanopowders (hybrid ones) or by mixing two different nanofluids were prepared to investigate the pool boiling behavior in the present research. Results have shown that for both types of hybrid nanofluids that are used in this work, the pool boiling heat transfer performance was enhanced when using dilute volume concentrations.

4.2 Recommendations for future research

The following are some future directions for the topic of pool boiling heat transfer using nanofluids by means both numerically and experimentally:

- **First**, to introduce a comprehensive model of pool boiling using nanofluids, more data from experimental studies should be taken into account in the future work to obtain new closure correlations related to the bubble dynamics due to the surface modification during the deposition of nanoparticles using of boiling of nanofluids. Furthermore, pool boiling with different pressure systems and applied heat flux should be taken into consideration in future numerical works.
- **Second**, a potential improvement of the boiling model using nanofluids is to incorporate both the effects of bulk properties (thermophysical properties) and surface modification when adding nanoparticles into pure liquids.
- **Third**, three-phase simulations are recommended for future numerical analysis to predict the boiling of nanofluids, especially when using moderate or high solid concentration.
- **Fourth**, the detailed and physically correct modeling of the nucleate boiling using nanofluids represents another possible improvement of the heat flux partitioning model. Hence, incorporate both modifying bubble waiting time coefficient and implementing new closure for boiling parameters by taking the surface modification effect due to the nanoparticle deposition during the boiling process will give accurate results.
• **Fifth**, the long-term stability of prepared nanofluids is a crucial issue and must be demonstrated under realistic field operation conditions that involve high-pressure and temperature system. Besides, developing new technologies make nanofluid stable as long as possible, especially for application in which boiling takes place is highly recommended.

• **Sixth**, more efforts should be directed toward inventing non-toxic and low-cost nanomaterials with high impact to meet quickly with the market needs. Besides, to release the potential of real-life application of nanofluids in boiling heat transfer, sufficient large-scale, low-cost manufacturing methods for nanofluids must be developing in the future.

• **Seventh**, various micro-structure surfaces with different orientations and shapes should be testing during the boiling heat transfer process. Furthermore, combining the application of boiling using nanofluids and micro-structured surfaces may provide superior heat removal.

• **Eighth**, to split the bulk effect (transport properties effect) of suspended nanoparticles inside basefluid from the impact of surface modification (nanoparticles deposition on heater surface) during the boiling process. I recommend doing the nanofluids pool boiling test firstly; afterward, the pool boiling experiment of deionized water should be following to see the pool boiling heat transfer behavior before and after the nanoparticle deposition during pool boiling process.

• **Ninth**, correlating the bubble dynamics parameters to superheat temperature by using different types of nanofluids is crucial; only a few closure correlations regarding this topic are available, and they are related to the flat plate surface. A systematic experimental study should be conducted to measure some bubbles parameters (i.e., bubble diameter, frequency, and nucleation site density) by using nanofluids from horizontal and vertical tubes.

• **Tenth**, measuring the transport properties such as surface tension and contact angle for different types of nanofluids at various concentrations could help to develop empirical models and get a better understanding of the boiling of nanofluids mechanism.

• **Last**, hybrid nanocomposites with two or more nanoparticles types should be applying in parallel with a mixture of conventional liquids, for example, ethylene glycol+water or glycerine+water in various concentrations. Besides, new eco-friendly and highly efficient nanofluids (i.e., nano-salt-fluids) should be prepared and tested for the boiling heat transfer process.
CHAPTER 5

“THE THESSES”

The present chapter summarizes the main contributions from this research in the form of theses as listed below:

**Thesis 1**

The heat flux partitioning (RPI) model was used to predict the pool boiling heat transfer of water from the horizontal heated copper tube. The quenching heat flux partition was modified by correcting the bubble waiting time coefficient $C_w$ according to the following sigmoidal function with the coefficient of determination ($R^2 = 0.9992$):

$$C_w = 0.1017 + 0.8336\left(1 - e^{(-1.1894\Delta T_{sup})}\right)^{2874.8098}$$  \hspace{1cm} (5.1)

Where: $C_w$ is the bubble waiting time coefficient [-], and it was introduced to correct the waiting time between the departures of sequential bubbles. The default value for this coefficient ($C_w = 1$) used in Ansys fluent solver; however, it is possible to correct this value as needed, but it can only set as a constant value. $\Delta T_{sup}$ is the superheat temperature [K]. The above correlation is valid for pool boiling of water from a horizontal heated copper tube with a range of superheat temperature ($5 \leq \Delta T_{sup} \leq 10$ K) at atmospheric pressure condition. **Related publications [P5, P13, P17]**.

**Thesis 2**

In case of pool boiling heat transfer from stainless steel flat plate surface using water and silica-based water nanofluid at atmospheric pressure. The bubble waiting time coefficient was corrected and correlated with superheating temperature to validate the RPI model for pool boiling of water. Moreover, the closure correlations from the literature regarding the pool boiling parameters of silica nanofluid were inserted as a user-defined function to validate the pool boiling using silica nanofluid. The following correlation was proposed for bubble waiting time coefficient with ($R^2 = 0.9986$):

$$C_w = 0.102 + 2.5448\left[1 + e^{\left(-\frac{(\Delta T_{sup} - 21.1792)}{2.6439}\right)}\right]$$  \hspace{1cm} (5.2)

Where: $C_w$ is the bubble waiting time coefficient [-], and this coefficient was introduced to correct the waiting time between the departures of sequential bubbles. The default value for this coefficient utilized in Ansys fluent was ($C_w = 1$); however, it is possible to correct this value as needed, but it can only locate as a constant value. $\Delta T_{sup}$ is the superheat temperature [K]. The above correlation is valid at atmospheric pressure for a range of superheat temperature ($6 \leq \Delta T_{sup} \leq 32$ K). **Related publications [P6, P16, P18]**.
Thesis 3

A horizontal typical heated copper tube with an outer diameter (22 mm) was used to examine the pool boiling heat transfer of deionized water and ceria-based deionized water nanofluids at atmospheric pressure. The quenching heat flux partition was modified by correcting the bubble waiting time coefficient for deionized water and ceria nanofluids and correlating this coefficient to superheat temperature as a boundary condition to validate the extended RPI model with experimental data for water and ceria-based water nanofluids. The following quadratic polynomial functions were determined as follows:

- For water case, \(R^2 = 0.994\)

\[
C_w = 0.0002\Delta T_{sup}^2 + 0.0718\Delta T_{sup} - 0.3613
\]  

(5.3)

- For (0.007% Vol.) CeO\(_2\) based water nanofluids, \(R^2 = 0.9711\)

\[
C_w = -0.005\Delta T_{sup}^2 + 0.1675\Delta T_{sup} - 0.4228
\]  

(5.4)

- For (0.01% Vol.) CeO\(_2\) based water nanofluids, \(R^2 = 0.9844\)

\[
C_w = -0.0028\Delta T_{sup}^2 + 0.1234\Delta T_{sup} - 0.359
\]  

(5.5)

Where: \(C_w\) is the bubble waiting time coefficient [-], and it was introduced to correct the waiting time between the departures of consecutive bubbles. The default value for this coefficient is \((C_w = 1)\) in Ansys fluent solver; however, it is possible to correct this value as needed, but it can be only as a constant value. \(\Delta T_{sup}\) is the superheat temperature [K]. The above correlations are valid for a range of superheat temperatures \((3.9 \leq \Delta T_{sup} \leq 14.1 \text{ K})\) and atmospheric pressure conditions.

Thesis 4

Thermal conductivity of three types so-called nanofluids (aluminum oxide, cerium oxide and their hybrid (50:50) by volume) based deionized water nanofluids at the range of dilute volume concentrations (between 0.01% - 0.5% Vol.) and various temperatures (35, 40, 45 and 50 °C) was measured. Results demonstrated that the higher thermal conductivity enhancement ratio \((k_{nf}/k_f)\) for Al\(_2\)O\(_3\), CeO\(_2\), and their hybrid nanofluids were 1.053, 1.033, and 1.083 respectively at a higher volume concentration (0.5% Vol.) and a higher temperature (50 °C) compared to the deionized water case. Proposed correlation for thermal conductivity enhancement ratio of hybrid nanofluid was introduced, and it shows good accuracy with measured experimental data with the maximum margin of deviation of 4.2% as following:

\[
\frac{k_{nf}}{k_f} = 1.21 - 0.009581T - 0.223\varphi + 0.0001223T^2 + 0.006598 \times T \times \varphi
\]  

(5.6)

Where: \(k_{nf}\), is the thermal conductivity of nanofluids, \(k_f\) is the thermal conductivity of water, \(T\) is the temperature of the nanofluids, and \(\varphi\) is the volume fraction. Related publication [P8].
**Thesis 5**

It was found that the thermal conductivity of tungsten oxide WO$_3$ nanoflakes based deionized water nanofluid increased by increasing the volume concentration and temperature of the nanofluids. The thermal conductivity enhancement ratio ($K_{nf}/K_f$), was revealed to be (1.066) at higher volume concentration (0.05% Vol.) and temperature (90 °C) compared to deionized water as a baseline case. Related publication [P10].

**Thesis 6**

The pool boiling heat transfer performance using cerium oxide (CeO$_2$), nanoparticle-based water nanofluids from the horizontal heated copper tube at atmospheric pressure was experimentally investigated. The pool boiling heat transfer coefficient PBHTC measurements revealed that the maximum PBHTC ratio ($PBHTC_{nf}/PBHTC_{water}$) was 1.7 compared to the deionized water baseline case at dilute volume concentration 0.007% Vol. and low heat flux (15 kW/m$^2$) when the surface roughness of the heated tube was ($R_a = 0.115 \mu m$). The results also demonstrated that the PBHTC enhancement ratio decreased as volume concentrations increased (i.e., 0.01% and 0.04% Vol.), whereas it was still improving compared to the deionized water case.

\[
PBHTC \text{ enhancement ratio} = \frac{PBHTC_{nf}}{PBHTC_{water}}
\]  

(5.7)

Where: $PBHTC_{nf}$ and $PBHTC_{water}$ are the pool boiling heat transfer coefficients of nanofluids and deionized water, respectively. Related publication [P7].

**Thesis 7**

Dilute volume concentrations within a range of (0.001% to 0.5% Vol.) were tested to investigate the pool boiling heat transfer performance of different types of mono nanofluids so-called aluminum oxide Al$_2$O$_3$, aluminum nitride AlN, magnesium oxide MgO nanoparticles as well as tungsten oxide WO$_3$ nanoflakes based deionized water nanofluids with a tube surface roughness of ($R_a = 0.382 \mu m$) at atmospheric conditions. The pool boiling performance represented by pool boiling heat transfer coefficient PBHTC ratio was measured. The obtained results indicated that the PBHTC ratio ($PBHTC_{nf}/PBHTC_{water}$) was enhanced for dilute volume concentration (i.e., less than 0.01% Vol.) for all prepared nanofluids, and the maximum PBHTC enhancement ratio was (1.40, 1.33, 1.22, and 1.067) at heat fluxes (15.251, 28.954, 102.952, and 14.527 kW/m$^2$) for Al$_2$O$_3$, AlN, MgO nanoparticles, and WO$_3$ nanoflakes -based deionized water nanofluids, respectively. Related publications [P9, P10].

**Thesis 8**

Under the atmospheric pressure conditions, the pool boiling heat transfer performance from a typical horizontal heated copper tube with a surface roughness ($R_a = 0.382 \mu m$) using different types of mono nanofluids, which are aluminum oxide Al$_2$O$_3$, aluminum nitride AlN, magnesium oxide MgO nanoparticles, and tungsten oxide WO$_3$ nanoflakes -based deionized water nanofluids was studied. The influence of various dilute volumetric concentrations within a range of (0.001% to 0.5% Vol.), and applied heat flux ranging from (14 – 120 kW/m$^2$) for pool boiling heat transfer coefficient and pool boiling curve were studied. It was revealed that
the PBHTC ratio \( \frac{PBHTC_{nf}}{PBHTC_{water}} \) was degraded for volume concentrations (i.e., above 0.01% Vol.) for all types of nanofluids, and the maximum PBHTC reduction ratio was (0.83, 0.82, 0.85, and 0.85) at heat fluxes (65.504, 14.933, 14.397, and 87.140 kW/m\(^2\)) for Al\(_2\)O\(_3\), AlN, MgO nanoparticles, and WO\(_3\) nanoflakes based deionized water nanofluids, respectively. Related publications [P9, P10, P15].

**Thesis 9**

A new types of nanofluids, so-called hybrid nanofluids, which consists of two kinds of nanopowders (aluminum oxide Al\(_2\)O\(_3\) and cerium oxide CeO\(_2\) 50:50 by volume) and (aluminum oxide Al\(_2\)O\(_3\) and magnesium oxide MgO, 50:50 by volume) with different volume concentrations (0.01%, 0.05% and 0.1% Vol.), were prepared via two-step method. The effect of volume concentration and applied heat flux were studied to assess the pool boiling heat transfer coefficient enhancement ratio from a typical horizontal heated copper tube with a surface roughness \( R_a = 0.382 \mu m \) and atmospheric pressure conditions. Results demonstrated that both hybrid nanofluids enhanced the pool boiling performance for all concentrations, compared to the deionized water baseline and the maximum PBHTC enhancement ratio was (1.37 and 1.44) at moderate heat flux (44 kW/m\(^2\)) and volume concentration (0.01% Vol.) for Al\(_2\)O\(_3\)+CeO\(_2\) and Al\(_2\)O\(_3\)+MgO hybrid nanofluids, respectively. Related publication [P11].
LIST OF PUBLICATIONS

- **Journals publications**


**Conference proceeding and abstracts publications**


**Others**


REFERENCES


For example, to calculate (2000 ml) of deionized water as a basefluid, the density was (997.52 kg m⁻³) at room temperature (23.1 °C). Hence, the mass of deionized water was calculated to be:

\[
\text{mass (kg)} = \text{density (kg m}^{-3}\text{)} \times \text{volume (m}^3\text{)}
\]  

\[
997.52 \frac{kg}{m^3} \times 2000 \frac{ml}{l} \times 0.001 \frac{l}{ml} \times 0.001 \frac{m^3}{l} \times 1000 \frac{gram}{kg} = 1995.04 \text{[gram]}
\]

Therefore, to calculate the desired mass for cerium oxide (CeO₂) nanoparticles at volume concentration (0.001% vol.), we can use the following formula for mono and hybrid nanofluids:

\[
\varphi_v = \left[ \frac{\left( \frac{m_p}{\rho_p} \right)}{\left( \frac{m_p}{\rho_p} + \frac{m_f}{\rho_f} \right)} \right] \times 100
\]  

\[
\varphi_v = \left[ \frac{\left( \frac{m_{p1}}{\rho_{p1}} + \frac{m_{p2}}{\rho_{p2}} \right)}{\left( \frac{m_{p1}}{\rho_{p1}} + \frac{m_{p2}}{\rho_{p2}} + \frac{m_f}{\rho_f} \right)} \right] \times 100
\]

where; \( m_p \), \( m_f \), \( \rho_p \), \( \rho_f \) are the mass of nanoparticles, mass of basefluid, density of nanoparticles and density of basefluid, respectively.

\[
0.00001 = \left[ \frac{\left( \frac{X}{7132} \right)}{\left( \frac{X}{7132} \right) + \left( \frac{1995.04}{997.52} \right)} \right]
\]

\[
0.00001 = \left[ \frac{\left(1.4021 \times 10^{-4}X\right)}{\left(1.4021 \times 10^{-4}X\right) + (2)} \right]
\]

\[
4.021 \times 10^{-10}X + 2 \times 10^{-5} = 1.4021 \times 10^{-4}X
\]

\[
2 \times 10^{-5} = 1.40209 \times 10^{-4}X
\]

\[
X = 2 \times 10^{-5} / 1.40209 \times 10^{-4} = 0.1426 \text{[gram]}
\]

By applying the same procedure above for the other volume concentrations the mass of nanomaterials in each concentration were calculated as shown below in a Table (1.A).
Table (1.A) Calculation of nanopowders quantities in (grams) used to prepare the nanofluids for each concentration in the present study.

<table>
<thead>
<tr>
<th>NPs Type</th>
<th>Density of nanoparticles [kg. m(^{-3})]</th>
<th>Density of DI-W [kg. m(^{-3})]</th>
<th>Quantity of DI water [gram]</th>
<th>Desired volume Concentration</th>
<th>Quantity of required nanoparticles in [gram]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CeO(_2)</td>
<td>7132</td>
<td>997.52</td>
<td>1995.04</td>
<td>0.00001</td>
<td>0.1426</td>
</tr>
<tr>
<td>CeO(_2)</td>
<td>7132</td>
<td>997.52</td>
<td>1995.04</td>
<td>0.0004</td>
<td>5.7079</td>
</tr>
<tr>
<td>CeO(_2)</td>
<td>7132</td>
<td>997.52</td>
<td>1995.04</td>
<td>0.0007</td>
<td>9.9918</td>
</tr>
<tr>
<td>CeO(_2)</td>
<td>7132</td>
<td>997.52</td>
<td>1995.04</td>
<td>0.0001</td>
<td>1.4265</td>
</tr>
<tr>
<td>CeO(_2)</td>
<td>7132</td>
<td>997.52</td>
<td>1995.04</td>
<td>0.0004</td>
<td>5.7079</td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>3890</td>
<td>997.17</td>
<td>1994.34</td>
<td>0.0001</td>
<td>0.7781</td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>3890</td>
<td>997.17</td>
<td>1994.34</td>
<td>0.0005</td>
<td>3.8919</td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>3890</td>
<td>997.17</td>
<td>1994.34</td>
<td>0.001</td>
<td>7.7878</td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>3890</td>
<td>997.17</td>
<td>1994.34</td>
<td>0.002</td>
<td>15.5912</td>
</tr>
<tr>
<td>MgO</td>
<td>3580</td>
<td>997.52</td>
<td>1995.14</td>
<td>0.00001</td>
<td>0.0716</td>
</tr>
<tr>
<td>MgO</td>
<td>3580</td>
<td>997.52</td>
<td>1995.14</td>
<td>0.00004</td>
<td>0.2864</td>
</tr>
<tr>
<td>MgO</td>
<td>3580</td>
<td>997.52</td>
<td>1995.14</td>
<td>0.00007</td>
<td>0.5012</td>
</tr>
<tr>
<td>MgO</td>
<td>3580</td>
<td>997.52</td>
<td>1995.14</td>
<td>0.0004</td>
<td>2.8651</td>
</tr>
<tr>
<td>AlN</td>
<td>3260</td>
<td>995.22</td>
<td>1990.44</td>
<td>0.0001</td>
<td>0.6521</td>
</tr>
<tr>
<td>AlN</td>
<td>3260</td>
<td>995.22</td>
<td>1990.44</td>
<td>0.001</td>
<td>6.5265</td>
</tr>
<tr>
<td>AlN</td>
<td>3260</td>
<td>995.22</td>
<td>1990.44</td>
<td>0.002</td>
<td>13.0661</td>
</tr>
<tr>
<td>AlN</td>
<td>3260</td>
<td>995.22</td>
<td>1990.44</td>
<td>0.005</td>
<td>32.7638</td>
</tr>
<tr>
<td>WO(_3)</td>
<td>7160</td>
<td>995.22</td>
<td>1990.44</td>
<td>0.00005</td>
<td>0.7160</td>
</tr>
<tr>
<td>WO(_3)</td>
<td>7160</td>
<td>995.22</td>
<td>1990.44</td>
<td>0.0001</td>
<td>1.4321</td>
</tr>
<tr>
<td>WO(_3)</td>
<td>7160</td>
<td>995.22</td>
<td>1990.44</td>
<td>0.0005</td>
<td>7.1636</td>
</tr>
</tbody>
</table>
APPENDIX (B)

“Scanning electron microscope images for nanomaterials”

Scanning electron microscopic SEM images for nanopowders used in present work.

Al₂O₃ nanoparticles
MgO nanoparticle
AlN nanoparticle
CeO$_2$ nanoparticles
WO₃ nanoflakes
APPENDIX C

“Stability checking of the prepared nanofluids”

Pictures inserted below related to stability checking via sedimentation-time method for prepared nanofluids in this research.

Figure (1) Stability of CeO$_2$ based deionized water nanofluids at different periods (A) Deionized water; (B) 0.001% Vol.; (C) 0.04% Vol.
Figure (2) Stability of WO₃ based deionized water nanofluids at different periods.
Figure (3) Stability of MgO based deionized water nanofluids at different periods
(A) Deionized water; (B) 0.001% Vol.; (C) 0.004% Vol.; (D) 0.04% Vol.
Figure (4) Stability of AlN based deionized water nanofluids at different periods (A) Deionized water; (B) 0.001\% Vol.; (C) 0.5\% Vol.
Figure (5) Stability of Al₂O₃ based deionized water nanofluids at different periods (A) Deionized water; (B) 0.01% Vol.; (C) 0.1% Vol.; (D) 0.2% Vol.
Figure (6) Stability of (Al$_2$O$_3$+CeO$_2$) hybrid based deionized water nanofluids at different periods. (A) 0.5% Vol. (B) 0.01% Vol.
Figure (7) Stability of (Al₂O₃+MgO) hybrid based deionized water nanofluids at different periods. (A) 0.01% Vol. (B) 0.1% Vol.
APPENDIX D

“Thermal conductivity measurements for nanofluids”

Tables inserted below illiterate the results of thermal conductivity measurements for deionized water and nanofluids in the present work.

*Table (1.D)* Validation of measured thermal conductivity and data from NIST for deionized water at various temperatures.

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Thermal conductivity measured Data, [W/m·K]</th>
<th>Thermal conductivity from NIST Data [159], [W/m·K]</th>
<th>Percentage of error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>32</td>
<td>0.6012</td>
<td>0.6187</td>
<td>-2.83</td>
</tr>
<tr>
<td>35</td>
<td>0.6187</td>
<td>0.6233</td>
<td>-0.74</td>
</tr>
<tr>
<td>40</td>
<td>0.6291</td>
<td>0.6306</td>
<td>-0.24</td>
</tr>
<tr>
<td>45</td>
<td>0.6351</td>
<td>0.6373</td>
<td>-0.35</td>
</tr>
<tr>
<td>50</td>
<td>0.6475</td>
<td>0.6436</td>
<td>0.61</td>
</tr>
<tr>
<td>55</td>
<td>0.6536</td>
<td>0.6492</td>
<td>0.68</td>
</tr>
<tr>
<td>60</td>
<td>0.6614</td>
<td>0.6543</td>
<td>1.08</td>
</tr>
<tr>
<td>70</td>
<td>0.6712</td>
<td>0.6631</td>
<td>1.23</td>
</tr>
<tr>
<td>80</td>
<td>0.6807</td>
<td>0.6700</td>
<td>1.59</td>
</tr>
<tr>
<td>90</td>
<td>0.6977</td>
<td>0.6753</td>
<td>3.32</td>
</tr>
</tbody>
</table>

*Table (2.D)* Thermal conductivity enhancement ratio data for Aluminum nitride AlN based deionized water nanofluids at different concentrations and temperature (50 °C).

<table>
<thead>
<tr>
<th>Volume concentration Vol. [%]</th>
<th>Thermal conductivity measured Data for nanofluids, [W/m·K]</th>
<th>Thermal conductivity of water at temperature (50 °C), [W/m·K]</th>
<th>$\frac{k_{nf}}{k_{water}}$, [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>0.6593</td>
<td>0.6475</td>
<td>1.0182</td>
</tr>
<tr>
<td>0.01</td>
<td>0.6730</td>
<td>0.6475</td>
<td>1.0394</td>
</tr>
<tr>
<td>0.1</td>
<td>0.6980</td>
<td>0.6475</td>
<td>1.0780</td>
</tr>
<tr>
<td>0.2</td>
<td>0.7158</td>
<td>0.6475</td>
<td>1.1055</td>
</tr>
<tr>
<td>0.5</td>
<td>0.7452</td>
<td>0.6475</td>
<td>1.1508</td>
</tr>
</tbody>
</table>

*Table (3.D)* Thermal conductivity enhancement ratio data for Magnesium oxide MgO based deionized water nanofluids at different concentrations and temperature (50 °C).

<table>
<thead>
<tr>
<th>Volume concentration Vol. [%]</th>
<th>Thermal conductivity measured Data for nanofluids, [W/m·K]</th>
<th>Thermal conductivity of water at temperature (50 °C), [W/m·K]</th>
<th>$\frac{k_{nf}}{k_{water}}$, [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>0.6490</td>
<td>0.6475</td>
<td>1.0023</td>
</tr>
<tr>
<td>0.004</td>
<td>0.6513</td>
<td>0.6475</td>
<td>1.0058</td>
</tr>
<tr>
<td>0.007</td>
<td>0.6545</td>
<td>0.6475</td>
<td>1.0108</td>
</tr>
<tr>
<td>0.01</td>
<td>0.6585</td>
<td>0.6475</td>
<td>1.0169</td>
</tr>
<tr>
<td>0.04</td>
<td>0.6696</td>
<td>0.6475</td>
<td>1.0341</td>
</tr>
</tbody>
</table>
**Table (4.D)** Thermal conductivity enhancement ratio data for Cerium oxide CeO$_2$ based deionized water nanofluids at different concentrations and various temperatures.

<table>
<thead>
<tr>
<th>Vol. [%]</th>
<th>Temperatures [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>0.01</td>
<td>1.0041</td>
</tr>
<tr>
<td>0.05</td>
<td>1.0055</td>
</tr>
<tr>
<td>0.1</td>
<td>1.0061</td>
</tr>
<tr>
<td>0.5</td>
<td>1.0090</td>
</tr>
</tbody>
</table>

**Table (5.D)** Thermal conductivity enhancement ratio data for Aluminum oxide Al$_2$O$_3$ based deionized water nanofluids at different concentrations and various temperatures.

<table>
<thead>
<tr>
<th>Vol. [%]</th>
<th>Temperatures [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>0.01</td>
<td>1.0139</td>
</tr>
<tr>
<td>0.05</td>
<td>1.0179</td>
</tr>
<tr>
<td>0.1</td>
<td>1.0218</td>
</tr>
<tr>
<td>0.5</td>
<td>1.0290</td>
</tr>
</tbody>
</table>

**Table (6.D)** Thermal conductivity enhancement ratio data for hybrid (Al$_2$O$_3$+ CeO$_2$) 50:50 by volume based deionized water nanofluids at different concentrations and various temperatures.

<table>
<thead>
<tr>
<th>Vol. [%]</th>
<th>Temperatures [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>35</td>
</tr>
<tr>
<td>0.01</td>
<td>1.0102</td>
</tr>
<tr>
<td>0.05</td>
<td>1.0168</td>
</tr>
<tr>
<td>0.1</td>
<td>1.0218</td>
</tr>
<tr>
<td>0.5</td>
<td>1.0308</td>
</tr>
</tbody>
</table>

**Table (7.D)** Thermal conductivity enhancement ratio data for hybrid (Al$_2$O$_3$+MgO) 50:50 by volume based deionized water nanofluids at different concentrations and temperature (50 °C).

<table>
<thead>
<tr>
<th>Volume concentration Vol. [%]</th>
<th>Thermal conductivity measured Data for nanofluids, [W/m . K]</th>
<th>Thermal conductivity of water at temperature (50 °C), [W/m . K]</th>
<th>$\frac{k_{nf}}{k_{water}}$, [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>0.6543</td>
<td>0.6475</td>
<td>1.0105</td>
</tr>
<tr>
<td>0.004</td>
<td>0.6695</td>
<td>0.6475</td>
<td>1.0340</td>
</tr>
<tr>
<td>0.007</td>
<td>0.6946</td>
<td>0.6475</td>
<td>1.0728</td>
</tr>
<tr>
<td>0.01</td>
<td>0.7231</td>
<td>0.6475</td>
<td>1.1168</td>
</tr>
</tbody>
</table>

**Table (8.D)** Thermal conductivity enhancement ratio data for Tungsten oxide WO$_3$ based deionized water nanofluids at different concentrations and various temperatures.

<table>
<thead>
<tr>
<th>Vol. [%]</th>
<th>Temperatures [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>50</td>
</tr>
<tr>
<td>0.005</td>
<td>1.0018</td>
</tr>
<tr>
<td>0.01</td>
<td>1.0049</td>
</tr>
<tr>
<td>0.05</td>
<td>1.0091</td>
</tr>
</tbody>
</table>