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Thermodynamic analysis of power cycles and their basic processes under non-conventional conditions

Booklet of theses

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1. Introduction of the main topics

Nowadays there is a growing need to produce electricity from sources, which do not pollute the environment significantly. Simultaneously, the rising price and the decreasing availability of the formerly used sources for electricity production make us use these sources more efficiently.

In the thesis, the above-mentioned set of problems from several interrelated aspects are examined. Therefore, the results are presented in two big also interrelated chapters:

(1) Certain heat sources, like geothermal or various types of waste heat are available in relatively great amount, however, their temperatures are not high enough to operate the conventional RANKINE-cycles, which use mostly water as working fluid. In order to exploit these heat sources Organic RANKINE Cycles (ORCs) may be used. It was examined that in the adiabatic expansion process of the cycle, which properties of the working fluid affect the formation of liquid droplets in the expanded steam. Blade erosion depends on the amount of these droplets. Theoretical studies resulted in a correlation which was applied to real working fluids as well and a simple thumb-rule could be created, which enables us to decide whether a working fluid behaves like a wet or a dry-type during a given expansion based on the molar heat capacity of the working fluid. Also, in connection with the organic RANKINE cycle, a database and a novel classification has been created which is more sophisticated than the conventional three-category (wet, dry and isentropic) one. The database and the new categories help to choose working fluid easier for a given heat source. Three papers with impact factor in English and one paper in Hungarian have been published in the topic. In addition, one Wikipedia article has been made for educational or popularising purposes.

(2a) A proper knowledge of the processes is required to accurately describe the entire cycle. These processes (like the already mentioned adiabatic expansion) can often be described by simple or thought to be simple equations. However, it gives you only an idealised version of the processes, which produces sufficiently good results in most cases, but the more extreme the conditions, the less accurate they will be. It was examined whether the currently used descriptions of certain processes (like isobaric heat transfer, isentropic expansion or compression, isochoric heat transfer, isenthalpic expansion), which make up the thermodynamic cycles, are accurate enough when the conditions are extreme (for example in supercritical, near supercritical or metastable fluid states). In most cases, the processes remained accurately described, although in some cases, certain processes, which undergo properly under normal conditions (e.g. adiabatic), but cannot undergo under non-conventional conditions due to the special characteristics of the fluid, while others can (e.g. isochoric). Recognition of the latter helped to determine what the simplest equation of state should be like, which describes at least qualitatively the properties of water. Also, as a result of the same researches, a previously unknown thermodynamic process has been defined in which the volume of a liquid can be changed without boundary work. One paper with impact factor and one in WoS, but with no impact factor have been published so far.

(2b) The entire or part of both conventional and organic RANKINE cycle can undergo in the so-called supercritical region. Within this supercritical region lies the so-called WIDOM region, in which the fluid does not behave like a liquid, like a vapour, nor like something between the two. Since the processes of the cycles may pass through these zones and the anomalies there can affect the entire cycle, these parts for some relevant fluids have been mapped, and examined how these processes pass through the region. Among them, e.g. the isobaric heat transfer or the adiabatic expansion are important as regards the cycles, but knowledge of adiabatic and isenthalpic expansion is essential in accident conditions too. In connection with the latter, it has been proven that in supercritical water cooled reactors during a loss of coolant accident (LOCA) in addition to the already known explosion-like flash-boiling, the phenomenon of steam collapse may occur in the early stage of the accident. Linking the second and third major topics, it has been shown that pseudo-boiling occurring in the supercritical region during isobaric heat addition is not the "smeared" version of normal (subcritical) boiling, but rather a phase transition of a metastable liquid related to the stability limit, which cannot be observed in stable liquids. In these topics two papers with impact factor, one paper in Hungarian and a peer-reviewed conference paper also have been published.

The results are summarised in one to three theses in each topic. The previously planned research have successfully been done, and beyond the examination of the supercritical and the metastable regions, a third topic relating to the organic RANKINE cycle has appeared, which has at least that importance as the previous ones. However, this third topic connects pretty well to the others, so the unity of the research is not violated.

2. The description of the research – history – results – theses

2.1. Entire cycle

Electricity production from low-temperature heat sources (80-300 °C) has been growing significantly over the last few decades. Such low-temperature heat sources include for example geothermal, waste heat, thermal solar or biomass-firing technologies. Due to low-temperatures, power plants based on the conventional RANKINE cycle, using water as working fluid, cannot exploit such heat sources efficiently. An alternative solution is the so-called Organic Rankine Cycle (ORC), which uses non-conventional working fluids (mostly organic ones, although some of them are inorganic, like carbon dioxide). Because of the physical (thermodynamic) properties of the one-component (pure) working fluids, their saturation curve in temperature-entropy diagram are very various. In the 1960's, a classification system was introduced, which sorts the pure working fluids into three categories. A need for introducing a novel classification have arisen owing to the spread of the ORC technology and the theoretical and practical shortcomings of the traditional one.

The traditional classification of working fluids with its three categories (wet, dry, isentropic), is not sufficient to reliably predict or exclude the formation of liquid droplets in the low-pressure stage of the expander of an ORC power plant. In the thesis, a novel, refined classification [1,2] is proposed, which overcomes this problem and which makes it easier to select working fluids for ORC (or other) applications by eliminating the inaccuracy and the shortcomings of the traditional one. The novel classification is based on some well-defined characteristic points (Fig. 1), by which eight categories (sequences) can be distinguished (Fig. 2) [3]. The categories are named after ascending order of the (specific) entropy of the characteristic points. These categories have different thermodynamic characteristics and they require different layouts for ORC machinery. A database was

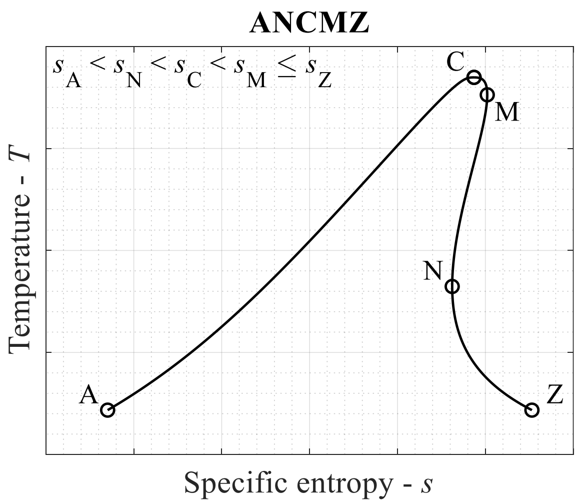

Fig. 1. Introduction of the characteristic points used for the novel classification by an ANCMZ-type, earlier incorrectly categorised as a dry-type working [1,2].

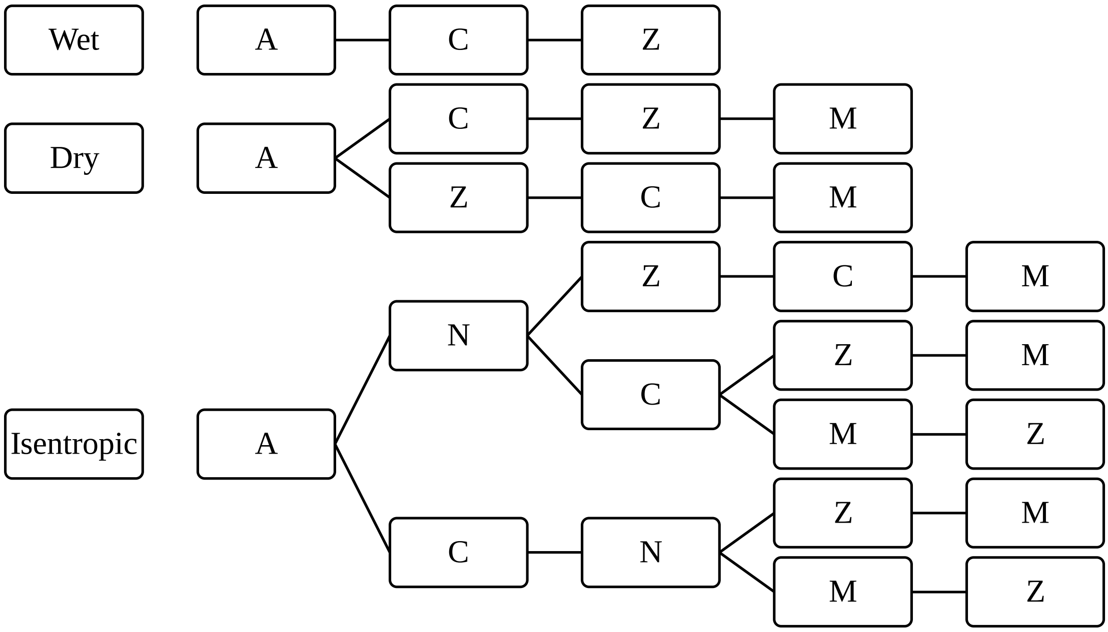

Fig. 2. Possible categories (sequences) of the novel classification
and their compatibility with the traditional one [1,2]

created from the available working fluids to make the choice of optimal working fluid even easier and faster. The database contains 74 fluids (so far) with their significant thermodynamic properties and indicating the categories according to the traditional and novel classification as well. For further practical application, the categories of the working fluids are also available at 15 °C (which is a usual heat rejection temperature value) besides the triple point temperature (points A and Z).

Thesis 1:

1. A novel classification system with eight categories for one component working fluids has been created. The classification is based on the relative location of characteristic points of the liquid-vapour coexistence curve in temperature – specific entropy diagram. The novel classification system is compatible with the traditional three-category (wet, dry and isentropic) one. However, it highlights the differences between the working fluids during the process of expansion, and handles properly the application of the isentropic category for real working fluids. (Related publications: [1,2])

Using the location of the two secondary characteristic points (M and N) in isochoric (molar) heat capacity–reduced temperature space, a rule of thumb can be defined to distinguish between wet and non-wet working fluids. The existence of rule of thumb is based on the recognition that between the new categories, considering a VAN DER WAALS fluid, there is a continuous transition and the place of the transition in the state space is correlated with the molar isochoric heat capacity via a continuous molecular degree of freedom variable [3]. The correlation was first examined on a model system [4]. Later it was expanded to real fluid as well (Fig. 3). If the molar isochoric heat capacity of the saturated vapour phase of the given working fluid is smaller than 80 J/(mol·K) at a temperature 0.74·T_C, then it is most likely a wet fluid (or ACZ according to the novel classification), while fluids with heat capacity values above this limit (at this temperature) are very likely dry or isentropic [5]. Real fluids show the theoretically proven trend that, with the increase of molar isochoric heat capacity, the fluid is more and more probably isentropic or dry. In a similar way, one can assume that all fluids with molar isochoric heat capacity over 165 J/(mol·K) at 0.74·T_C temperature are either dry or ANZCM-type, while the ones with molar isochoric heat capacity over 80 J/(mol·K), but below 105 J/(mol·K) are probably ACNZM-type. These correlations can be seen only when isochoric heat capacities are plotted in molar units [in J/(mol·K)], which shows the importance of molar quantities in comparative analysis.

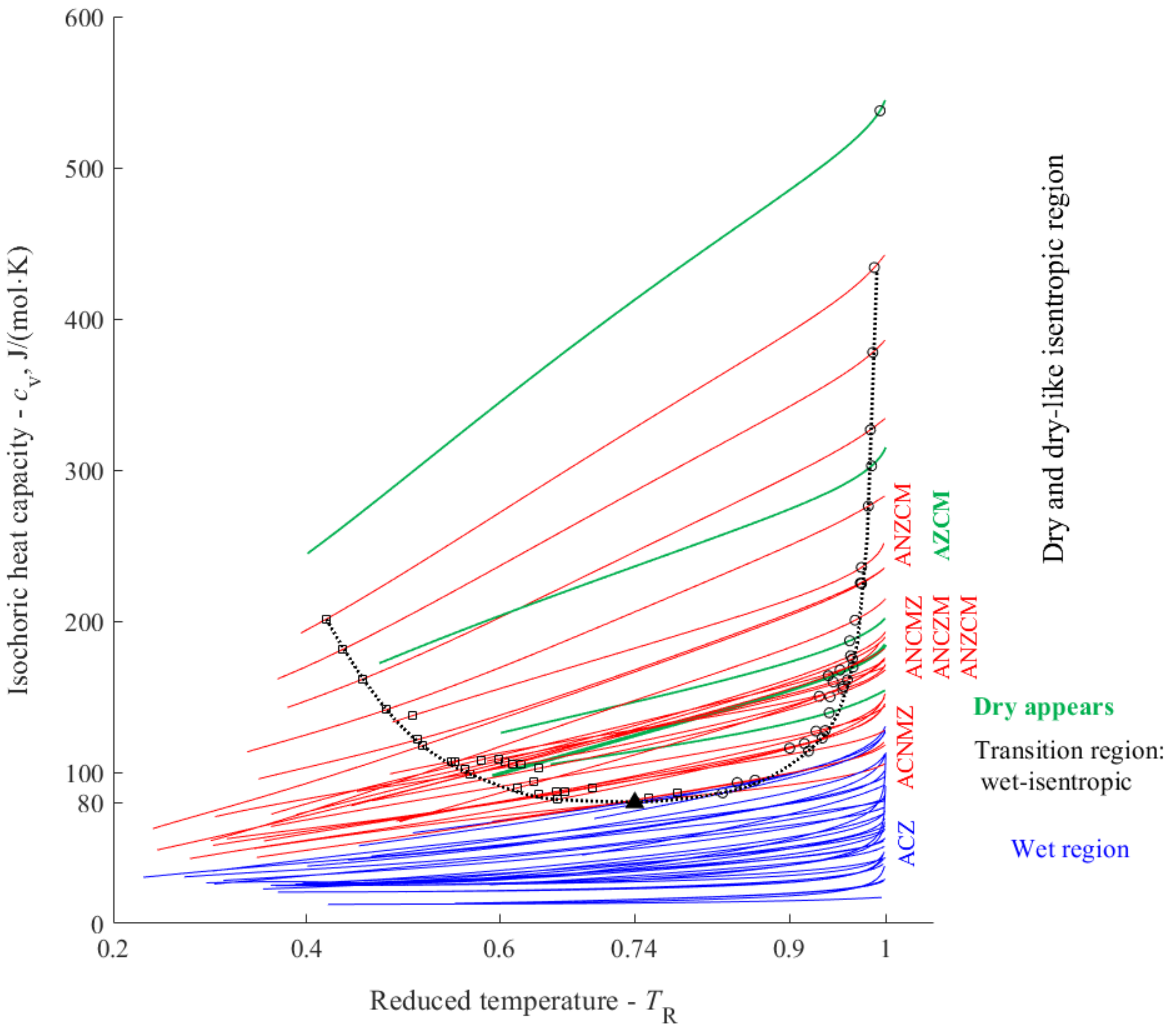

Fig. 3. Molar isochoric heat capacity curves of various working fluids in saturated vapour state. Blue, red, and green curves represent wet, isentropic, and dry fluids, respectively. Squares and circles represent points N (lower temperature) and M (higher temperature). The triangle shows the border between wet and non-wet fluids, located at T_R = 0.74 and c_v = 80 J/(mol·K). The dotted curve represents the outer envelope for points M and N. [5]

It was shown that even dry fluids may have a local entropy maximum (point N), i.e., they might have a low-temperature part on their saturated vapour line (in the *T-s* diagram) with a negative slope. In this case, the temperature of extrapolated point N (Fig. 3) is lower the triple point (solid/frozen state), so it actually occurs only if the working fluid can be subcooled (metastable state) and the equilibrium phase transition can be avoided. In this way dry-type working fluids can reach the two-phase region (the liquid drops are in metastable, subcooled state) during a low-temperature adiabatic expansion in the expander.

Thesis 2:

2a. The transition is continuous between the categories of one component working fluids. The transitions can be connected to molar heat capacity (c_v) values in saturated vapour state at a given reduced temperature. The value of the reduced temperature depends on the used equation of state. A reduced temperature value of 0.74 (T_R) is obtained by using high-precision reference equation of states of real working fluids. If the c_v at this reduced temperature value is smaller than 80 J/(mol·K), the working fluid is of wet category (ACZ), and if it is higher, it is of isentropic or dry category. The boundaries between these categories are not so sharp, but it can be stated that working fluids with c_v values between 80 and 105 J/(mol·K) are most likely to belong to isentropic (ACNZM) category, and above values of 165 J/(mol·K) the working fluid can be only isentropic (ANZCM) or dry (AZCM). (Related publications: [4,5])

2b. If the dry working fluid can be subcooled, so it can exist as a fluid under its triple point (metastable state), then the saturation curve in *T-s* diagram would have new low-temperature endpoints, and the missing fifth characteristic point (N) may appear on the vapour curve of the dry working fluid. Therefore, the dry categories (ACZM and AZCM) become only special subgroups of isentropic categories.
(Related publication: [5])

2.2. Processes of thermodynamic cycles

Thermodynamic cycles are made up of successive processes. These processes are often described by simple equations derived from the behaviour of the ideal gas or a slightly modified versions of them. These formulas are surprisingly accurate in stable phases. However, as a result of technological development it occurs more and more often the working fluid leaves the traditional stable phases under even normal and accident conditions. The development of a new system of thermodynamic formulas would go beyond the reasonable limits of a PhD thesis, therefore, my goal is only to test the correctness of the already existing equations under extreme conditions, such as near supercritical, supercritical or metastable states of the fluid.

These kinds of examinations are particularly justified by the appearance of the trans- and supercritical versions RANKINE and even organic RANKINE cycles. Certain processes of the cycle undergo in the supercritical region and even in its anomalous WIDOM region. Anomalies in this zone may influence the entire cycle, so it is necessary to check the anomalies of the zone, and the correctness of the description of these basic processes. It can be important under normal or even severe accident conditions.

In the thesis the following processes are examined: isobaric heat transfer, isentropic expansion/compression, isochoric heat transfer, and isenthalpic expansion.

2.2.1. Boundary work at zero pressure in liquids and solids

Unlike gases, the pressure of condensed matters (liquids and solids) cannot only be positive, but negative and even zero. Liquids and glasses and in certain cases solids also are in metastable state when their pressure are not positive, so spontaneous boiling (phase transition) can occur at any time.

Boundary work is zero during an isobaric $p = 0$ heat transfer (addition or rejection) according to the conventional equation $\delta W = -p \cdot \mathrm{d}V$. It means that there is a special process at zero constant pressure: macroscopic change in volume (ΔV) can be observed with no boundary work (energy transport between the thermodynamic system and its surroundings), so $\delta W = 0$. Another possible way to calculate boundary work is to introduce a pressure scale, in which the zero reference value is the lowermost limit, where the given phase can exist. This method was proved to be incorrect.

Like reversible adiabatic ($\delta Q = T \cdot \mathrm{d}S = 0$) there are also $\delta W = -p \cdot \mathrm{d}V = 0$ processes, where the boundary work is zero, because there is no change in volume ($\mathrm{d}V = 0$). However, boundary work can also be zero, if the intensive property of the relating interaction (pressure) becomes zero. In this way the thermal interaction (heat) cannot be zero, hence the absolute temperature (relating intensive property) is prohibited to be zero.

These processes are phenomenologically similar to adiabatic ones ($Q = 0$), and however, their technical significance are less, they also deserve a proper name, which is proposed for these $\mathrm{d}V \neq 0$, but $\mathrm{d}W = 0$ processes. The name "aergiatic" processes – after Aergia (Greek: Αεϱγια, "inactivity"), a minor goddess (Daimona) in Greek mythology, a personification of laziness, idleness, and indolence – seems to be a matching, but well-distinguishable name.

The significance of the aergiatic processes that it is possible to make a finite change in volume without boundary work during heat transfer.

Earlier, based on literature, it seemed to be a controversy: while the $p = 0$ itself is not special value, there is at least one process along $p = 0$ which seems to be special ($W = 0$) [6]. It is a little bit similar to the situation of liquid-vapour and vapour-liquid stability lines. By heating or stretching a liquid, and hence by moving first into the stable and then metastable liquid regions, the liquid will not detect the vapour-liquid spinodal, but only its counterpart, the liquid-vapour one. The opposite is also true: coming from the stable vapour side, only the vapour-liquid stability line will have any meaning during the particular processes; the liquid-vapour spinodal remains undetected. In this way, some of the special lines or values will be direction-dependent. The situation is the same with $p = 0$ values. Generally, while crossing or reaching $p = 0$, one cannot detect any peculiarity, except in two "directions" in a pressure-temperature diagram: by isobaric ($p = 0$) heating or by isobaric ($p = 0$) cooling.

Thesis 3:

3. There are processes undergoing at constant zero absolute pressure ($p \equiv 0$), when nonzero change of volume ($\mathrm{d}V \neq 0$) gives no boundary work ($\delta W = 0$). This equality comes from the value of zero pressure. It has no analogy with adiabatic processes ($T \neq 0$). These processes are named aergiatic processes. (Related publication: [6])

2.2.2. Stability of reversible adiabatic processes in the WIDOM region

The supercritical region when defined as all states, where $T > T_C$ and $p > p_C$ is not a homogeneous region. Close to the low-temperature border of this region, supercritical states show rather liquid-like properties, while states close to the low-pressure border are very much vapour-like. Between this liquid- and vapour-like regions, a wedge-shaped region can be seen, where the liquid-like fluid turns to vapour-like and vice versa during the proper change of pressure and temperature. Crossing this region, some of the properties (for example density) change smoothly from liquid-like to vapour-like, suggesting that this is a "neither liquid, nor vapour, but something between them" region, which might be handled in some sense as a mixture (i.e. one can obtain densities seen in this region by mixing normal liquid and vapour into a well-dispersed, two-phase mixture). However, the change of other properties shows entirely different characteristics; for example while crossing this region, one can start from a state with liquid-like isobaric compressibility, reach a vapour-like value on the other side, but within the region, states with enormously high compressibility values can be seen; these are neither liquid-like, nor vapour-like materials; according to these anomalies, they might be considered as a new phase. This anomalous region is called WIDOM region.

Some of these properties have influence on the stability of various processes against external noises. Therefore, relative position of the mapped WIDOM lines and the adiabatic expansion/compression lines have been shown for model and real argon, real water, carbon dioxide and methane (Fig. 4). For some of these materials, concerning regions with

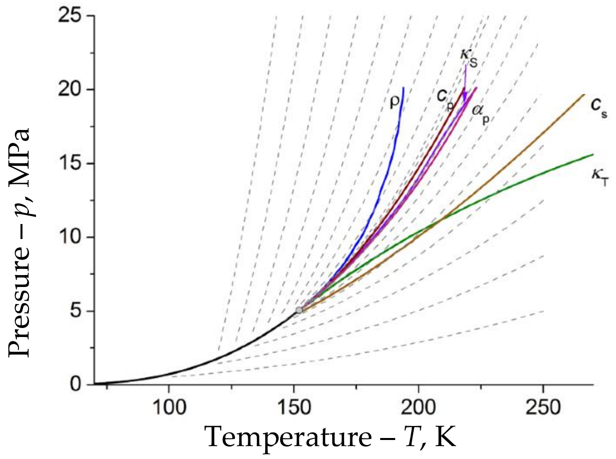

Fig. 4. Several reversible adiabatic (isentropic) lines (dashed) and some Widom lines of VAN DER WAALS argon. [7,8]

slightly above critical pressure, one can find adiabats running close to the WIDOM line of isobaric heat capacity, representing the ridge formed by the c_p -maxima. These adiabats might be more stable against internal heat noises than others, therefore they might have special importance in thermodynamic cycles used for heat-to-work conversion. In contrast, the adiabats running close to the WIDOM line of isothermal compressibility are much less stable against external mechanical noises, so they must be avoided. [7,8]

Thesis 4:

4a. Reversible adiabats in the WIDOM region, which run together with or close to the maxima of the isothermal compressibility (WIDOM line), are much less stable against external mechanical noises than the ones, which run farther from it. There are no such reversible adiabats of working fluids argon, water, carbon dioxide and methane, which run together with or very close to the WIDOM line of isothermal compressibility and are significantly less stable against external mechanical noises than others.
(Related publications: [7,8])

4b. Reversible adiabats in the WIDOM region, which run together with or close to the maxima of the heat capacity at constant pressure (WIDOM line), are much stable against external thermal noises than the ones, which run farther from it. Amongst working fluids argon, water, carbon dioxide and methane, there are only reversible adiabats of carbon dioxide and methane in the pressure region relevant to energy application, which run together with or very close to the WIDOM line of heat capacity at constant pressure and are significantly less stable against external thermal noises than others.
(Related publications: [7,8])

2.2.3. Feasibility of processes in metastable fluid states

Different types of experiments determining the tensile strength of water (i.e., the deepest experimentally attainable negative pressure where the material can stay in liquid phase) are giving contradictory results. Ultrasonic measurements yield values around −30 MPa, while with inclusion-based measurement, values around or slightly below −100 MPa can be reached. These controversial results can be explained by assuming the existence of a second WIDOM region, originated from a second low-temperature critical point, located in the deep metastable region. Due to the compressibility anomalies within this pseudocritical zone, there will be a region in the metastable liquid states, where the probability of bubble nucleation will be much higher than for neighbouring states, which are also metastable. Expansion processes which would cross this region probably would be terminated by cavitation, while processes avoiding it can go deeper and approach the limit of metastability given by the tensile strength (Fig. 5). [9]

At first glance, the result presented here resembles the so-called CARATHEODORY principle of inaccessibility, according to which there are states in the vicinity of any state which cannot be reached adiabatically. The results presented in the thesis differ from this principle in four points. The first difference is that the CARATHEODORY principle is true for all states, whereas the one described here is only true for states which are connected by processes passing through the special anomalous region described above. The second difference is while adiabatic inaccessibility describes an absolute inaccessibility (impossible to get from point A to point B in an adiabatic path), in this case is just simply that it is unlikely to get from certain A points to certain B points (due to cavitation, boiling). The third difference is that the CARATHEODORY principle of inaccessibility only applies to adiabatic processes, whereas the phenomenon presented here also applies to other processes (e.g. isothermal). Finally, the fourth difference is that the principle of adiabatic in-

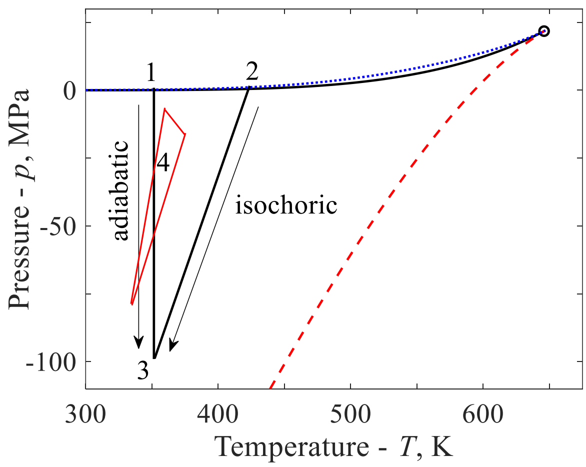

Fig. 5. Blue dotted, black and red dashed lines represent the vapour-liquid stability line, the saturation curve and the liquid-vapour stability line, respectively. All of them are calculated by IAPWS EoS. The red triangle shows estimated location of the anomalous pseudocritical region. As it can be seen, some states cannot be reached through certain paths (processes), while through others they can. [9]

accessibility is independent from the fluid, whereas the phenomenon described here can only occur, if in the liquid phase of the fluid there is an anomalous region with high compressibility such as water.

A qualitative, quintic equation of state is proposed, which could provide a narrow pseudocritical region in the metastable liquid range. Due to the location of this range, adiabatic or nearly adiabatic processes (like the expansion during ultrasonic measurements) could be intersected by this region; therefore, in this measurement, only relatively low tensions (−30 MPa) can be reached, while in inclusion measurement (where the expansion of liquid is nearly isochoric, avoiding the pseudocritical region when aiming the room-temperature limiting tension) the real tensile strength with values around −100 MPa or below can be reached. [9]

Due to the quintic nature of the equation, it is also possible to explain the second (liquid–liquid) critical point proposed by several authors. It is shown here that the reference equation used to describe water (IAPWS) is quasi-quintic in nature, but the location of the low-temperature critical point and the location of the second Widom region connected to the this critical point are misplaced. Additionally, some of the properties predicted by the IAPWS REoS for the second liquid phase—like the giant spinodal strength—are strongly unbelievable. To build a REoS with acceptable accuracy in the metastable region, more experimental data are needed, but good candidates should be quintic, or rather quasi-quintic, in form. [9]

Thesis 5:

5. In the metastable liquid (negative pressure) region of water there are states with low possibility of being reached or which cannot be reached at all experimentally via certain paths. The existence of them can be explained by the appearance of a compressibility anomaly similar to the one in the supercritical region. In order to describe this anomaly, minimally quasi-quintic equations of state or ones behaving like those are necessary. However, recently used IAPWS equation of state behaves like a quintic, it is not qualitatively nor quantitatively suitable to describe this anomalous region. (Related publication: [9])

2.2.4. Potential phase transitions from metastable states during a LOCA

For supercritical water used as working / moderator fluid for reactors, one of the advantage – compared to pressurized water – that under normal conditions, phase transitions can be avoided. It has already been shown that although it is true for normal conditions, by accidents causing pressure loss, sudden phase transitions like flash boiling or steam collapse can be induced [6]. This differs from the pressurized water case, where only flash boiling can be caused directly by these kinds of accidents.

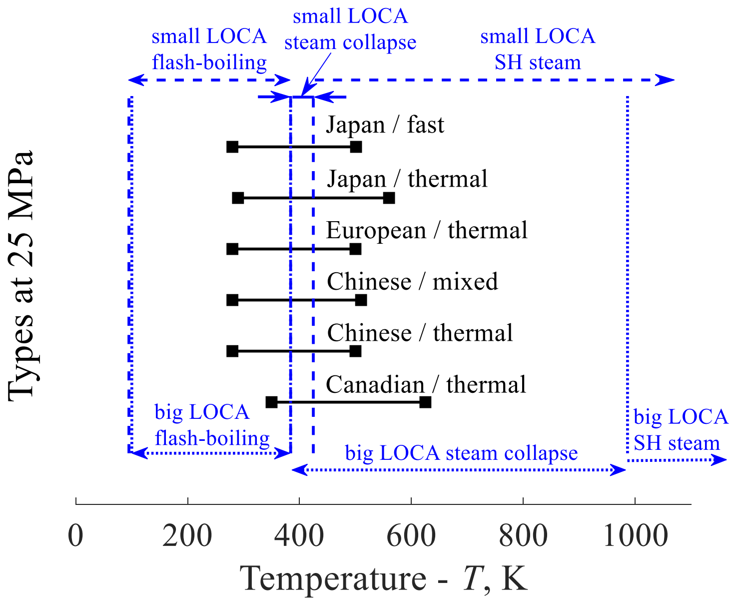

Fig. 6. Temperature ranges belong to different LOCA expansions in case of various nuclear power plant designs. The outcome of the expansions are also indicated (flash-boiling, steam collapse and superheated (SH) steam). The expansions start from supercritical state and end at 0,1 MPa. [10]

Various SCWR designs were analysed comparing their behaviour during an idealized small LOCA (isenthalpic expansion) and big LOCA (isentropic expansion). Replacing the actual reactor designs with a simplified fluid loop, it becomes possible to give the temperature ranges, where sudden phase transitions (flash boiling or steam collapse, followed by pressure surge) can be caused by the various LOCAs; also safe temperature regions, where these phase transitions can be avoided, are estimated. Although only temperature limits are given, assuming steady flow, a location-temperature map can be constructed for real or model loops. In this way, these results (Fig. 6) can be used for the better design of safety features of various SCWR models. [10]

The existence of the two phenomena described (steam collapse and flash boiling) is independent from the layout of the reactor, therefore, real geometries should be taken only for quantitative studies. The flash and steam collapse during LOCA in supercritical loops existence is caused solely by the special physical-chemical properties of the subcritical, supercritical and metastable water. [10]

Accidents connected with pressure loss in various kinds of facilities (extraction columns, supercritical water oxidation reactors, etc.) can also be analysed with similar method using the physical-chemical properties of the given supercritical fluid.

Thesis 6:

6a. Flash-boiling and condensation induced water hammer phenomena can occur in different places of the same supercritical water loop at the same time as a consequence of accidents with pressure drop, unlike a subcritical water loop where only flash-boiling can happen consequently. (Related publication: [10])

6b. Supposing steady-state flow and temperature distribution, there can be parts inside a supercritical water loop, which are safe during small and big loss of coolant accidents (LOCA) with pressure drop, so neither flash-boiling nor condensation induced water hammer occur in these places. (Related publication: [10])

2.2.5. The supercritical pseudo-boiling

At pressures over the critical value, it is possible to get to vapour state from liquid by changing the temperature or more precisely both the pressure and temperature without a sharp phase transition called boiling. Examining certain properties (e.g. density or enthalpy), this phenomenon looks as if it would be a smeared version of boiling over a finite temperature range and called pseudo-boiling. Because of the phenomenological similarity the phenomenon is originated from boiling, assuming that the sharp phase transition is smeared by an unknown effect (Fig. 7). In my thesis it is proven [11] that this explanation is incorrect. Examining the phase transitions of water and argon and the properties of stable and metastable states, it can be shown that sharp phase transitions (boiling and condensation) at low pressures do not transform as the pressure increases, but they completely disappear. However, at higher pressures, the influence of the so-called spinodal anomalies relating to the thermodynamic limits of liquid and vapour states becomes detectable even in the stable liquid and vapour regions. The anomalies relating to the two stability limits merge in the critical point and at higher pressures their traces can be seen in the WIDOM anomalies. At subcritical pressures, besides the less and less dominant phase transition (boiling/condensation) with jump discontinuity, the anomalies cause "smeared" changes (pre- and post-boiling, or pre- and post-condensation) similarly to transitions in the supercritical region, kind of preparing the stable phases for the transition to the other phase.

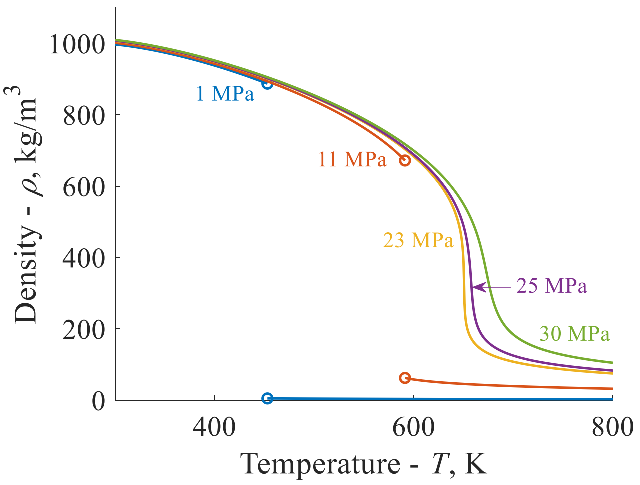

Fig. 7. Density of water as a function of temperature between 300 and 800 K at two subcritical (1 and 11 MPa) and three supercritical pressures (23, 25 and 30 MPa). At subcritical pressures the functions have discontinuity, which are also indicated by the circle markers [11]

Since the mathematical description of anomalies relating to the spinodals and the critical point is already well-known, the description of the WIDOM anomalies in the supercritical region, the pseudo-boiling and the pre- and post-boiling becomes mathematically simpler, as the pseudo-boiling is originated from the spinodal anomalies. With the help of the simpler description, the isobaric processes of transcritical and supercritical cycles can be understood better.

Thesis 7:

7. Liquid-vapour phase change as a consequence of isobaric heat input at supercritical pressure does not undergo at a well-defined temperature with jump discontinuity, but continuously within a temperature range. It is the phenomenon of pseudo-boiling. The origin of pseudo-boiling and traditional (subcritical) boiling is not the same. Pseudo-boiling is not a smeared version of the traditional one caused by some kind of physical effect, but it is caused by the effect of anomalies relating to phase stability boundaries (spinodals). The explanation is also true for its reverse process named pseudo-condensation as a consequence of isobaric heat rejection.
(Related publication: [11])

Own publications

Based on the results of the thesis, six papers with impact factor in English, one paper in the WoS without impact factor, one peer-reviewed conference paper in English and two peer-reviewed paper in Hungarian have been published. As the eleventh [3], I included a strictly non-scientific, but rather an educational and popularising article available at Wikipedia. The reason is that animation in the article helps significantly the understanding of certain parts of the thesis.

[1] Györke G, Deiters U K, Groniewsky A, Lassu I and Imre A R 2018 Novel classification of pure working fluids for Organic Rankine Cycle *Energy* **145** 288–300

[2] Györke G, Groniewsky A and Imre A 2019 Egykomponensű munkaközegek újszerű osztályozása ORC technológiához *Energiagazdálkodás* **60** 34–45

[3] Györke G, Groniewsky A and Imre A R 2018 Working fluid selection - Wikipedia (elérhető: https://en.wikipedia.org/wiki/Working_fluid_selection)

[4] Groniewsky A, Györke G and Imre A R 2017 Description of wet-to-dry transition in model ORC working fluids *Appl. Therm. Eng.* **125** 963–71

[5] Györke G, Groniewsky A and Imre A 2019 A Simple Method of Finding New Dry and Isentropic Working Fluids for Organic Rankine Cycle *Energies* **12** 480

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