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BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS
FACULTY OF MECHANICAL ENGINEERING
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A booklet of theses entitled

Modeling gas-solid fluidized beds of energy industrial relevance

For partial fulfilment of the doctor of philosophy degree

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Motivation

The title contains three interesting keywords which are modeling, fluidized bed, and industrial relevance and based on them I classified the main challenging problems under 4 main areas: Fluidization, Segregation, Heat transfer, and Macroscopic modeling. In the fluidization process, the gas bubbles act like the mixing impellers and throughout the process, the gas and the solids phases interact and influence each other.

Segregation is the phenomenon subjected to fluidized beds containing two different types of solid species of different density and sizes and this composition causes non-homogeneity of the bed material. An example is the mixing of the fuel and bed material in fluidized bed combustors.

Excellent heat transfer is one of the interesting characteristics of fluidized beds. For example, the heat transfer of fluidized bed exceeds 12 times the heat transfers in packed beds. However, the heat transfer coefficient of solid suspension is much larger than the heat transfer coefficient of individual sphere.

Finally, the macroscopic modeling is one of the commonly used methods for modeling of large scale industrial units. There are macroscopic comprehensive models based on the Two-Phase Theory and include different aspects such as solids density, heat transfer, and reaction kinetics.

Objectives

I formulated my goal this way "To analysis and find out solutions to the main challenging problems of modeling of fluidized beds for energy industrial relevance. And my main objectives are these:

- Surveying the literature on the modeling approaches
- Highlighting the research gaps
- Analysis of the available models
- Development of the exciting models
- Making experimental investigations of some aspects that are difficult to model using the numerical models

Literature survey

I carried out a comprehensive literature review to be updated with the recent research advances related to modeling of fluidized bed. For example:

In fluidization modeling, I found the Gas-solid drag is the hot topic with many publications referring to it. The mojor gas-solid models used in these studies were the Gidaspow and EMMS models. In the other hand, few publications studied the solid-solid drag and the viscosity closure.

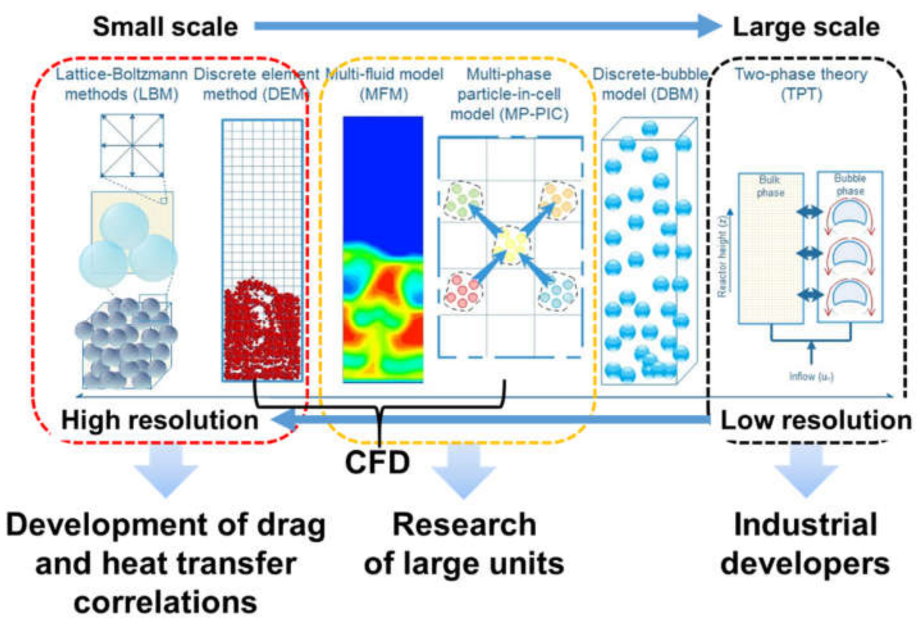
In the segregation modeling, the majority of the literature reseach studies binary-mixtures of Geldart B-B particles. However, only few studied the Geldart B-D mixture with is related to the energy industrial applications. Moreover, the effect of active particle sphericity on the mixing weren't studied.

In the heat transfer modeling, I found that the apparent thermal conductivity model is the most commonly used in the CFD modeling of the thermal field. On the other hand, the effect of the thermo-physical properties on the thermal field didn't got enough interest.

In the macroscopic modeling, I found that the macroscopic comprehensive models didn't include submodels for the segregation of binary-mixture fluidized bed. On the other hand, the Gibilaro-Rowe model was one of the most cited macroscopic models. There is no overall solution of Gibilaro-Rowe model in the literature.

Theoretical models

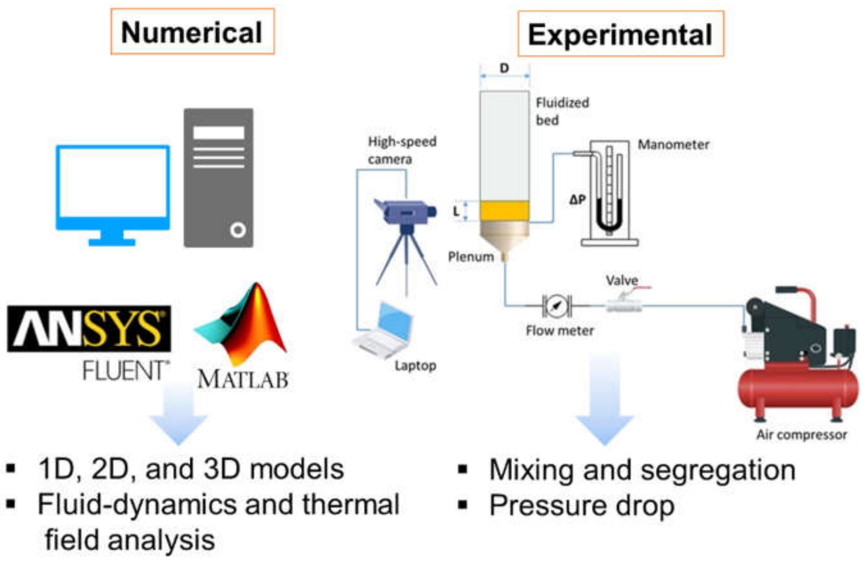
These are the available theoretical models in the literature for modeling of fluidized beds. As you can see they are order from right to left from the lowest resolution to highest resolution and from the left to the right from the smallest scale to the highest scale. The two-phase theory models also called the macroscopic models are used by the industrial manufacturers of fluidized bed combustors. The Two-Fluid model and the Multi-Phase Particle-in-cell are the mesoscopic models used currenly in research and development of large units. While, the Discrete-Element Model and the Lattice-Boltzmann model are limited to development of the drag and heat transfer correlations.



Methods

These are the two methods I used in my study: numerical and experimental.

I used two popular softwares in the numerical modeling: ANSYS FLUENT and MATLAB with student free licence. On the other hand, the schematic view shows the experimental test-rig which I used in the experimental measurements.



The numerical simulations included 1D, 2D, and 3D modeling of the fluid-dynamic and thermal fields, while the experimental measurements were carried out to investigate the phenomena which are difficult of analyse by the current numerical capabilities.

Findings

The following is illustration of the most significant findings from the present dissertation. The findings can be classified into three main categories:

- Theses related to models assessment such as Thesis 1, Thesis 5, and Thesis 6
- Theses related to models adjustment such as Thesis 2 and Thesis 3
- Theses related to new methods such as Thesis 1, Thesis 6, Thesis 7, Thesis 8, Thesis 9, and Thesis 10

Theses

Thesis I

The EMMS gas-solid model is a steady-state system-dependent model. It is scaled with a transient drag model such as the Wen-Yu model, and the resultant scaling function is called the heterogeneous index function. The EMMS model is the most verified gas-solid model for simulations of fluidized beds containing Geldart A systems. The conventional EMMS heterogeneous function is a function of the system properties. **A new general, system-independent formula of the heterogeneous index for Geldart A systems** is given as follows:

$$log(H_\mathrm{d}) = \begin{cases} 0.56p_1 - p_2, & \text{for } \varepsilon_\mathrm{g} \leq 0.56 \\ p_1\varepsilon_\mathrm{g} - p_2, & \text{for } 0.56 < \varepsilon_\mathrm{g} \leq \varepsilon^* \\ p_1\varepsilon^* - p_2, & \text{for } \varepsilon_\mathrm{g} > \varepsilon^* \end{cases}, \varepsilon^* = \begin{cases} 1.0, & \text{for } u_\mathrm{g}/u_\mathrm{mf} \leq 90 \\ 0.86, & \text{for } u_\mathrm{g}/u_\mathrm{mf} > 90 \end{cases}$$

where p_1 and p_2 are coefficients and they can be estimated from the fluidization velocity ratio as follows:

$$p_1 = 35.23\frac{u_\mathrm{g}}{u_\mathrm{mf}}^{-0.9752} + 7.645$$

$$\frac{|p_2|}{p_1} = 3.788\frac{u_\mathrm{g}}{u_\mathrm{mf}}^{0.03075} - 3.471$$

This new general formula makes the system-dependent EMMS model applicable in simulations of reactive particulate systems where the physical properties change with time, such as combustion and gasification modeling.

Part of the dissertation related to this thesis [section 2.2, subsection 4.1.1, subsection 4.1.3]
Publication related to this thesis [P7, P8]

Thesis II

The existence of SRF particles in binary SRF-sand packed beds reduces the overall pressure drop of the bed in the fixed state and the fluidized condition as well, even with small SRF concentrations of X = 2.1 - 5.2*%wt*. While the cylindrical biomass pellets do not have a significant influence on bed homogeneity in the range of biomass concentration of X = 15.1 - 26.3*%wt*. As a result, **the viscous and kinetic loss coefficients in the Ergun pressure drop equation should be modified according to the following relation:**

$$A(X) = 150e^{-0.154X}$$

$$B(X) = 1.75e^{-0.322X}$$

where A and B are the viscous and kinetic loss coefficients in the generally-used Ergun equation, X is the amount of SRF *%wt* in the binary bed with sand as inert material.

Part of the dissertation related to this thesis [section 3.2, subsection 4.2.1]
Publication related to this thesis [P13]

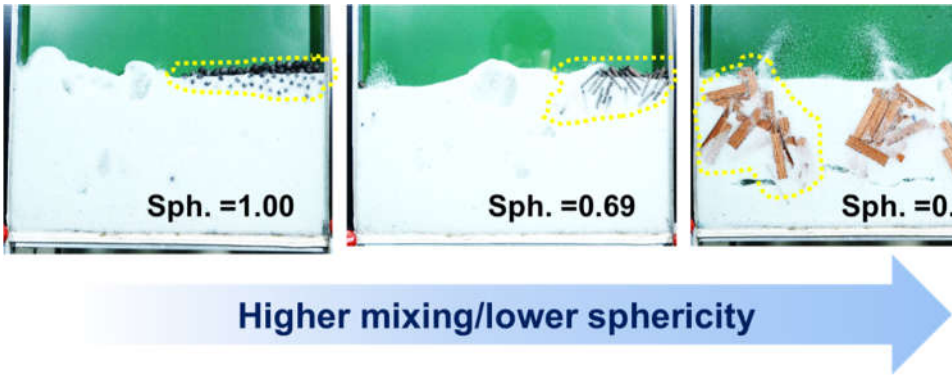
Thesis III

In numerical modeling of irregular-shaped large-size SRF in binary bubbling fluidized beds, the Gidaspow drag model is suitable for the simulation of SRF segregation in the bubbling beds when using the Haider and Levenspiel drag coefficient. 0.23 is the disk sphericity ratio, which characterizes the SRF particles the best with an acceptable agreement with the experimental data with an error less than 32% at the elevated fluidization velocities u_g/u_{mf} = 1.6 - 2.0.

Part of the dissertation related to this thesis [subsection 4.2.2]
Publication related to this thesis [P7, P8]

Thesis IV

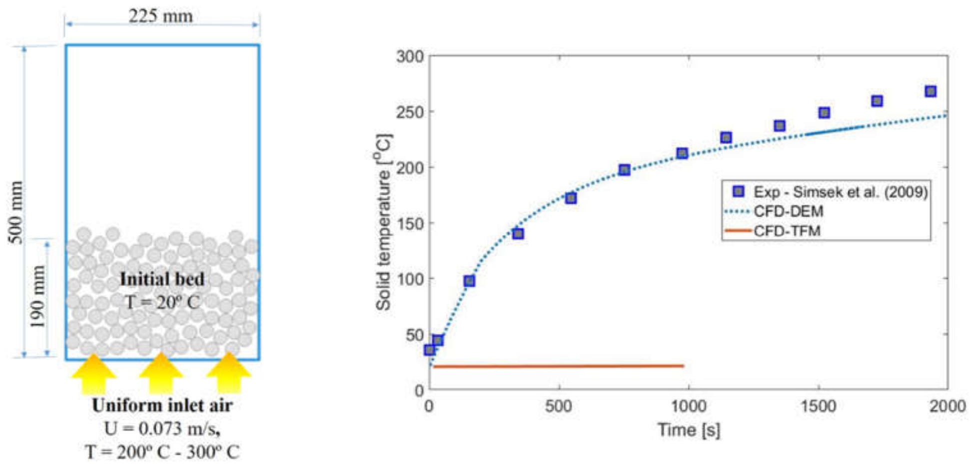
When equal-sized, non-spherical wood particles are fluidized in sand, the lower is the sphericity ratio of the wood particles the higher is the mixing. Above the wood particles' sphericity of 0.86, its actual value on the wood concentration profile can be neglected at fluidization velocities of u_g/u_{mf} = 1.2 - 2.4.



Part of the dissertation related to this thesis [subsection 4.2.3]
Publication related to this thesis [P7, P8]

Thesis V

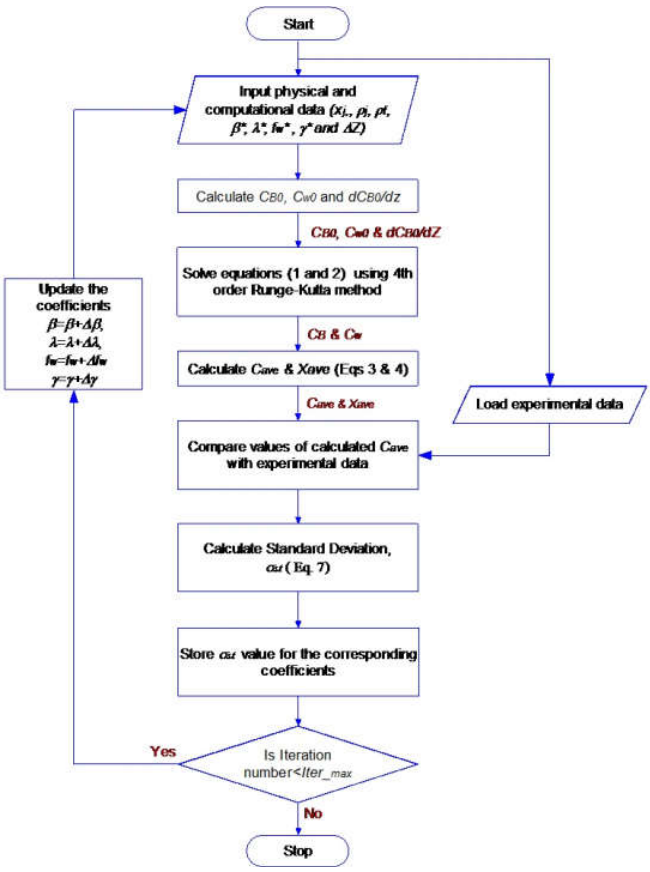
The Two-Fluid Model (TFM), which is widely used in CFD simulations of fluidized beds, is not valid for the simulation of heat transfer in packed beds. The CFD Discrete-Element Model (DEM) gives agreement with the experimental data of the thermal field of packed beds, but it requires at least ten times the computational time of the TFM method.



Part of the dissertation related to this thesis [subsection 4.3.1]
Publication related to this thesis [P4, P8]

Thesis VI

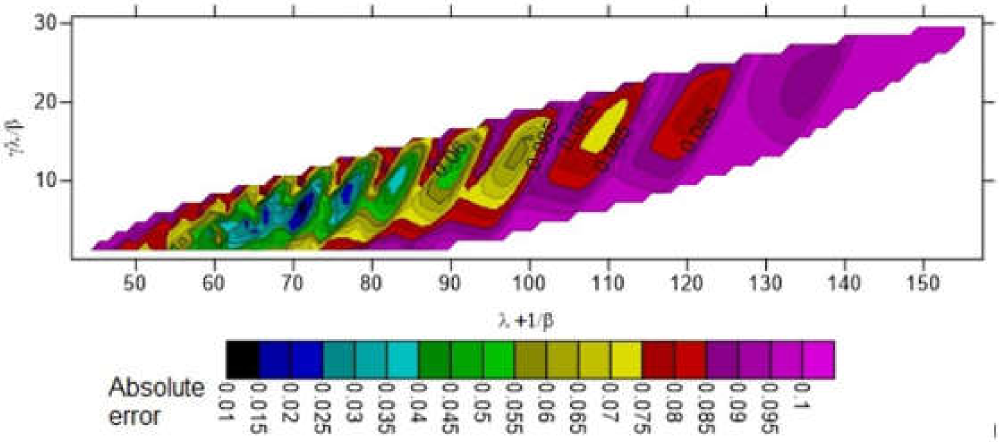
The macroscopic segregation model of Gibilaro and Rowe (G-R) gives high accuracy prediction of the segregation profile of the binary mixture fluidized beds if an adequate set of coefficients are applied. **The optimum set of coefficients of the G-R model can be obtained by executing the following numerical program:**



Part of the dissertation related to this thesis [subsection 4.4.1]
Publication related to this thesis [P1]

Thesis VII

A new method based on the binary system properties was developed. A new set of semi-empirical correlations was obtained using **an advanced fitting method in which a group of minimum-error solution points is used** to represent a given system instead of one optimum point as shown in the following figure:



Part of the dissertation related to this thesis [subsection 4.4.2]
Publication related to this thesis [P5]

Thesis VIII

The specific G-R model gives better prediction results compared to the previous 1D models and the CFD 2D/3D models as well. Besides, the overall model is faster in computation compared to the CFD models. These advances were achieved by using **the new set of coefficients given as follows:**

$$f_{\mathrm{w}} = 0.25289 X_{\mathrm{fw}}, \qquad X_{\mathrm{fw}} = x_{\mathrm{j}}^{1.662} (\rho_{\mathrm{j}}/\rho_{\mathrm{f}})^{-0.223} (d_{\mathrm{j}}/d_{\mathrm{f}})^{0.493} e^{0.539 \frac{u-u_{\mathrm{mf}}}{u_{\mathrm{mf}}}}$$

$$\beta = 0.01331 X_{\beta}^{-0.10125}, \qquad X_{\beta} = e^{-2.404 x_{\mathrm{j}}} (\rho_{\mathrm{j}}/\rho_{\mathrm{f}})^{-0.471} e^{0.5 \frac{d_{\mathrm{j}}}{d_{\mathrm{f}}}} e^{0.140 \frac{u-u_{\mathrm{mf}}}{u_{\mathrm{mf}}}}$$

$$\lambda = \beta (32.09753 X_{\lambda}), \qquad X_{\lambda} = x_{\mathrm{j}}^{1.143} (\rho_{\mathrm{j}}/\rho_{\mathrm{f}})^{0.655} (d_{\mathrm{j}}/d_{\mathrm{f}})^{0.677} e^{0.534 \frac{u-u_{\mathrm{mf}}}{u_{\mathrm{mf}}}}$$

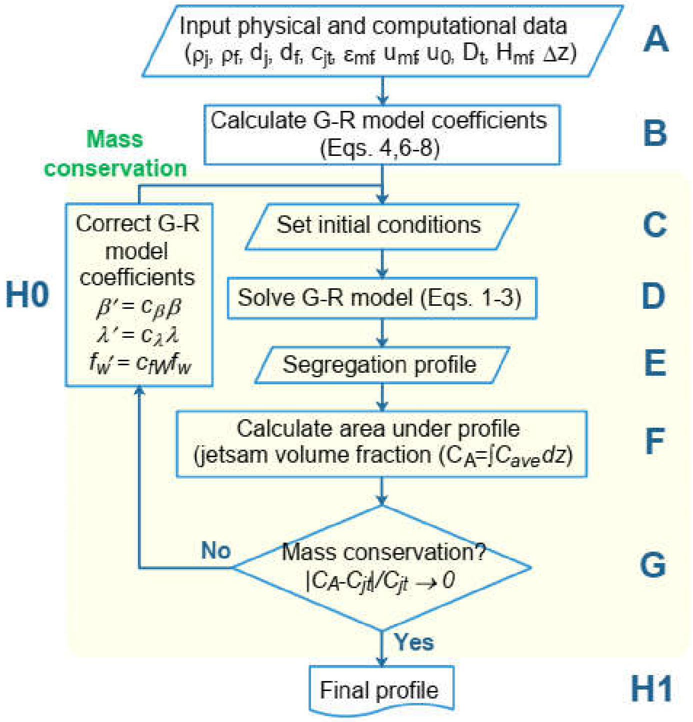
$$\gamma = \frac{\beta (1.72223 X_{\gamma})}{\lambda}, \qquad X_{\gamma} = x_{\mathrm{j}}^{1.319} (\rho_{\mathrm{j}}/\rho_{\mathrm{f}})^{1.120} (d_{\mathrm{j}}/d_{\mathrm{f}})^{-0.063} e^{0.712 \frac{u-u_{\mathrm{mf}}}{u_{\mathrm{mf}}}}$$

Part of the dissertation related to this thesis [subsection 4.4.2]
Publication related to this thesis [P5]

Thesis IX

The conservative calculation method of the G-R model gives overall realistic jetsam profile prediction. **This calculation method uses the mass**

conservation to correct the G-R model coefficients iteratively by creating multiple solutions and choosing the solution which satisfies the mass conservation. The flowchart of this conservative G-R model calculation is shown as follows:



Part of the dissertation related to this thesis [subsection 4.4.3]

Thesis X

The segregation layer height represents the bottom layer of the bed containing 100% jetsam. **A new expression for the segregation layer height as a function of the fluidization velocity ratio is given as follows:**

$$\frac{Y_i}{C_{jt}} = \begin{cases} 15.589(\frac{u_0}{u_{mf}})^{3.76} exp[-3.275(\frac{u_0}{u_{mf}})^{4.76}] & \text{for } u_0 \leq u_{mf,j} \\ -0.8 & \text{for } u_0 > u_{mf,j} \end{cases}$$

where Y_i is the segregation layer height and C_{jt} is the total volumetric jetsam concentration within the bed. Here, the negative value is no more than a mathematical indicator, which represents the strong mixing cases where there is no segregation appears at the bed bottom.

Part of the dissertation related to this thesis [subsection 4.4.3]

Publications

The publications related to the present thesis are as follows:

[**P1**] M. S. Alagha and P. Szentannai. 1D numerical model for prediction of jetsam concentration in segregating fluidized beds. Therm. Sci., 23(2b):1173-1187, 2019.

[**P2**] M. S. Alagha and P. Szentannai. Comparative Study of Homogeneous and Sub-grid Drag Models in Simulation of Fluidized Beds Containing Geldart A & B Particles. in Innovative Fluidized Bed Conversion Technology for a Sustainable Development, B1-4:9 p, Seoul, Korea, 2018.

[**P3**] M. S. Alagha and P. Szentannai. CFD Simulations of Segregation in Binary Fluidized Beds Composed of Geldart B Particles. in Innovative Fluidized Bed Conversion Technology for a Sustainable Development, B8-1:10 p, Seoul, Korea, 2018.

[**P4**] M. S. Alagha and P. Szentannai. Study of Heat Transfer Mechanism in Granular Thermal Energy Storage. in Innovative Fluidized Bed Conversion Technology for a Sustainable Development, B5-2:10 p, Seoul, Korea, 2018.

[**P5**] M. S. Alagha and P. Szentannai. An Efficient Model for Predicting the Segregation Profile of Binary Fluidized Beds. Period. Polytech. Chem. Eng., 63(1):147-159, 2019.

[**P6**] M. S. Alagha and P. Szentannai. Approaches for Modeling Fluidized Beds of Energy Industrial Relevance - An Analytical Review. HEEP conference, M´atraf`ured, Hungary, 2019.

[**P7**] M. S. Alagha, B. Szucs and P. Szentannai. Mixing of Solid Refused Fuel Particles in a Bubbling Fluidized Bed: Experimental and Numerical Studies. 2nd Journal of Thermal Analysis and Calorimetry Conference, Budapest, Hungary, 2019.

[**P8**] M. S. Alagha, B. Szucs and P. Szentannai. Numerical study of mixing and heat transfer of SRF particles in a bubbling fluidized bed. Journal of Thermal Analysis and Calorimetry, 00(00):00-00, 2019.

[**P9**] M. S. Alagha and P. Szentannai. Analytical Review of Fluid-Dynamic and Thermal Modeling Aspects of Fluidized Beds for Energy Conversion Devices. International Journal of Heat and Mass Transfer, 147:118907, 2020.

[**P10**] M. S. Alagha and P. Szentannai. Numerical Simulations of Dense Fluidized Beds using the EMMS Gas-Solid Drag Model. INFUB12, Porto, Portugal, 2020.

[**P11**] M. S. Alagha, B. Szucs and P. Szentannai. Mixing of an Iron-Sand Binary Mixture in a 2D Pseudo Bed: Experimental and Numerical Studies. INFUB12, Porto, Portugal, 2020.

[**P12**] M. S. Alagha, B. Szucs and P. Szentannai. A study on the influence of sphericity on the mixing of wood particles in a binary fluidized bed. INFUB12, Porto, Portugal, 2020.

[**P13**] M. S. Alagha, B. Szucs and P. Szentannai. Pressure drop of packed bed containing binary mixture with non-spherical active particles. INFUB12, Porto, Portugal, 2020.