Abstract

This PhD dissertation is focused on the analysis of the process of heat and mass flow through beds of granular materials. Special attention was paid to the development and verification of a method for the simulation of heat and mass flow through this type of bed. The work uses advanced numerical methods allowing for a thorough analysis of the influence of the granular material type, its parameters and distribution on the flow parameters. The present state of the art in the area of heat and mass transfer through granular material beds is described with particular emphasis on the physics of the flow process and research methods. The mathematical model and the computational algorithm used for numerical simulations are described in detail. The proposed method was verified using the ANSYS Fluent program, available literature data and self-performed laboratory experiments. The key task of the experiment was to investigate the influence of external temperature changes on the temperature distribution inside the layers depending on their structure and physical properties. The obtained results indicated a very complex flow and heat transfer inside the layers. It was shown that the temperature inside the layers can be effectively altered and controlled by the parameters of the air flowing through them.

The paper presents a novel computational algorithm for modelling heat and mass transfer processes around single elements and inside granular layers. Complex layer structures were modelled using the Immersed Boundary (IB) technique, which allows the use of Cartesian grids for objects with very complex shapes and in any form of contact (point-to-point, point-to-surface, etc.). Spatial discretisation was performed using the higher-order compact difference method and applying the Weighted Essentially Non-Oscillatory (WENO) scheme on computational grids in which the positions of nodes storing velocity, density and temperature values were partially shifted with respect to the position of pressure nodes. Compared to the conventional arrangement of nodes, the present approach has a stabilising effect. That is highly desirable in case of a sudden change in geometry inside the computational grids, especially when using high-order discretisation. Indeed, a weakness of higher-order methods is that they become unstable when the flow field is characterised by large velocity and temperature gradients or discontinuities in the solution domain. In the case of granular layers, such discontinuities are caused by solid granular elements embedded in the computational regions of the flow. This dissertation shows that the proposed method based on the immersed boundary (IB) method is stable and can be used to solve flow problems in real configurations. To the best of the author's knowledge, the combination of the high-order discretization method with the IB method is novel and can be implemented in any numerical code.

The research part of the paper is divided into three parts. In the first part, attention was paid to the analysis of the flow process around single elements. Relatively simple flow configurations around single elements were chosen as test cases to verify the chosen computational method. The results obtained with this method turned out to be almost identical to those obtained using ANSYS Fluent with element-matched grids and available data taken from the literature.

The second part of the work focused on the issues of heat and mass flow through beds of granular materials. The flow behaviour was analysed for idealised beds with an assumed structure consisting of spheres arranged symmetrically and for real beds with randomly placed spheres, cylinders and Raschig rings, which are commonly used in industry. The analysis has shown that the flow behaviour, both in and behind the granular material layer, depends to varying degrees on parameters such as granular alignment, granular size, temperature, and flow velocity. It is shown that by changing bed parameters, the process of heat and mass flow through

beds of granular materials can be controlled and the distributions and maximum values of parameters such as temperature, velocity or vorticity can be significantly influenced. It is shown that flows in granular material beds are characterised by a very complex structure (recirculation and stagnation areas) and that the configuration of granular layers significantly affects the mixing and heat transfer efficiency. Among other things, it has been found that the use of smaller spheres and their alternation in successive layers of structured beds promotes heat transfer between the granular bed and the flow. In contrast, cylindrical elements in 'random' beds introduced the highest values of vorticity and magnitude of velocity components behind the granular layer, but also the highest values of pressure drop. The existence of different-sized recirculation areas developing behind the bed elements was demonstrated. Their identification is extremely important, as they determine the heat transfer process between the solid phase and the flowing medium. Due to the fact that granules are often used to increase the wall surface area for better heat transfer, the third part of the study additionally focuses on the use of granular material for surface formation. Perpendicular channels in which one wall had corrugation or roughness (spherical objects, spheres) in different alignment configurations were analysed. The effect of different surface topologies (2D and 3D) on flow was investigated. It was found that the higher the amplitude of the corrugated surface, the higher the turbulence intensity production. It was observed that in the 3D configuration, there was a smaller increase in all components of velocity fluctuations and a smaller increase in velocity compared to the 2D case at comparable wall corrugation amplitude. For the roughness cases, it was found that increasing the diameter of the spheres resulted in a higher drag force, which was attributed to a greater blockage of the channel cross-section and the occurrence of recirculation between the large diameter spheres. The velocity profiles in the vicinity of the balls were highly dependent on the diameter of the balls and local velocity values increased with increase. It was found that the distribution of spheres plays an important role only when the spheres are large and the resulting recirculation zones behind them are characterised by different intensities and sizes. In such cases, the distribution of the spheres can be considered as a control parameter affecting the local surface friction and thus the drag force occurring on the surface of the spheres and the turbulence intensity.