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# Comparison of the standard Euler–Euler and hybrid Euler–Lagrange approaches for modeling particle transport in a pilot-scale circulating fluidized bed

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ABSTRACT

Particle transport phenomena in small-scale circulating fluidized beds (CFB) can be simulated using the Euler–Euler, discrete element method, and Euler–Lagrange approaches. In this work, a hybrid Euler–Lagrange model known as the dense discrete phase model (DDPM), which has common roots with the multiphase particle-in-cell model, was applied in simulating particle transport within a mid-sized experimental CFB facility. Implementation of the DDPM into the commercial ANSYS Fluent CFD package is relatively young in comparison with the granular Eulerian model. For that reason, validation of the DDPM approach against experimental data is still required and is addressed in this paper. Additional difficulties encountered in modeling fluidization processes are connected with long calculation times. To reduce times, the complete boiler models are simplified to include just the combustion chamber. Such simplifications introduce errors in the predicted solid distribution in the boiler. To investigate the consequences of model reduction, simulations were made using the simplified and complete pilot geometries and compared with experimental data. All simulations were performed using the ANSYSFLUENT 14.0 package. A set of user defined functions were used in the hybrid DDPM and Euler–Euler approaches to recirculate solid particles.



## 1. Introduction

Circulating fluidized bed (CFB) and bubbling fluidized bed boilers are popular alternatives to the traditional pulverized coal boilers because of their maturity and insensibility to the quality of fuel. Numerical simulations of the flow conditions inside such devices require solving complex multiphase transport equations in mixtures of gases and particles with high solid mass loadings. Methods used for the granular flow simulations differ by the temporal and spatial scales covered in flow phenomena (Myohanen & Hyppanen, 2011). Because scales range from the small-scale molecular up to large-scale system levels, differing by many orders of magnitude, the computational effort is much different in these approaches. It is attractive to tend toward small-scale models which describe the flow system on fundamental grounds that inherently cover the large-scale phenomena. However, these models are not affordable for large industrial facility simulations. The large-scale systems need to be modeled using less general and experimentally supported approaches. As computer power increases, more detailed and computationally expensive methods are being applied more frequently. The approaches discussed in this paper can be termed meso-scale models (Myohanen & Hyppanen, 2011) and cover time and length scales greater than the particle level. The methods under consideration can be divided by the way the dispersed phase is treated (Wischnewski, Ratschow, Hartge, & Werther, 2010).

High concentration of the particulate matter in the fluidization units results in a significant increase in the influence of mutual particle interactions on the flow conditions. The available numerical models used for solving the particle transport and their interactions can be divided into two main groups, namely Euler–Euler and Euler–Lagrange approaches. The Eulerian models have been derived based on the assumption that a solid phase can be treated as a continuous medium with representative properties similarly as for a fluid.

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The second approach is known as the Euler–Lagrange, where the fluid phase is treated as a continuum while the dispersed phase is tracked in the Lagrangian reference frame. The disadvantages of this approach are that it does not take into account the particle–particle collisions and it is not applicable for modeling dense fluidized beds. However, the Lagrangian model in comparison to the Eulerian approach gives a possibility of predicting particle size distributions (PSDs) with relatively low computational cost. Using the Euler–Euler continuum model, each of the characteristic diameters representing the PSD has to be defined by a separate dispersed phase, which is numerically intensive. However, accurately resolved particle distribution has high impact on calculated field variables and cannot be omitted. To link advantages of both methodologies the hybrid Euler–Lagrange approach (Andrews & O'Rourke, 1996), known as multiphase particle-in-cell (MP-PIC) method, was developed. In this approach, groups of particles known as parcels are tracked in a Lagrangian frame of reference, while parcel properties are mapped to the Eulerian grid where the interactions between particles are calculated and then transferred back to the parcel positions. The hybrid model is applicable to both dilute flows, where particle–particle interactions are of little importance, and dense flows, where the particle–particle collisions control the behavior of the dispersed phase (Snider, O'Rourke, & Andrews, 1998). Nowadays in the literature several variations of the hybrid Euler–Lagrange model can be found dedicated to different applications. One of the newest can be found in ANSYS Fluent CFD code, where the hybrid model, known as dense discrete phase model (DDPM), was implemented. The DDPM approach uses the kinetic theory of granular flow (KTGF) (Chapman & Cowling, 1970) for calculating interactions between particles, whereas the MP-PIC technique uses simple stress–strain relations.

This paper presents a practical application of the hybrid Euler–Lagrange approach for modeling gas-particulate flow in a model experimental circulating fluidized bed facility. The results concern a 3D model of a 0.1 MW pilot-scale CFB installation built at Czestochowa University of Technology used mainly for coal combustion research. Validation of the numerical results is based on pressure drop data delivered by researchers from Czestochowa University of Technology. Besides the pressure–drop comparison, the influence of mass loading on evaluated pressure drop is also investigated. In this work, the usability of the Euler–Lagrange approach in future applications to simulation of large-scale industrial CFB units is also considered.

## 2. The numerical models

In this section, a background of the Euler–Euler and hybrid Euler–Lagrange approaches used for modeling particle transport in fluidized bed boilers are briefly described. Additionally, the governing equations of the model are presented and the applied closure terms are summarized. References to the specific literature where these are described are given.

### 2.1. The Euler–Euler approach

The Euler–Euler approach for describing particle transport in isothermal conditions (cold flow) without mass transfer between phases uses a set of transport equations including the conservation of mass and momentum. Eqs. (1) and (2) are the continuity equations for gaseous and solid phases, respectively, whereas Eqs. (3) and (4) define the momentum changes of the fluid and solid phases, respectively. The transport equations are presented in instantaneous form without terms responsible for mass transfer between phases. The reader is referred to Anderson and Jackson (1967) and Gidaspow (1994) for detailed derivation of these governing equations:

$$\frac{\partial}{\partial t}(\varepsilon_f \rho_f) + \nabla \cdot (\varepsilon_f \rho_f \mathbf{u}_f) = 0, \tag{1}$$

$$\frac{\partial}{\partial t}(\varepsilon_s \rho_s) + \nabla \cdot (\varepsilon_s \rho_s \mathbf{u}_s) = 0, \tag{2}$$

$$\frac{\partial}{\partial t}(\varepsilon_f \rho_f \mathbf{u}_f) + \nabla \cdot (\varepsilon_f \rho_f \mathbf{u}_f \mathbf{u}_f) = -\varepsilon_f \nabla p + \nabla \cdot \tau_f + \varepsilon_f \rho_f \mathbf{g} + F + \sum_{q=1}^{N} [K_{qf}(\mathbf{u}_f - \mathbf{u}_q)], \tag{3}$$

$$\frac{\partial}{\partial t}(\varepsilon_s \rho_s \mathbf{u}_s) + \nabla \cdot (\varepsilon_s \rho_s \mathbf{u}_s \mathbf{u}_s) = -\varepsilon_s \nabla p + \nabla \cdot \sigma_s + \varepsilon_s \rho_s \mathbf{g} + F + \sum_{q=1}^{N} [K_{qs}(\mathbf{u}_q - \mathbf{u}_s)], \tag{4}$$

where $\mathbf{g}$ is the standard gravity, subscripts f and s denote gaseous and solid phases respectively, $\varepsilon$ denotes the phase volume fraction, $\rho$ density, $\mathbf{u}$ velocity vector, $p$ pressure shared by all phases, $\tau_f$ stress tensor which represents viscous forces in the fluid or gaseous phase, and $K$ represents the interphase exchange coefficients between phases with subscript $q$ standing for the $q$-th solid phase of a total number $N$. The set of multiphase transport equations is solved by the CFD code in an average form (Crowe et al., 2011). The phase volume fractions $\varepsilon_f$ and $\varepsilon_s$ are determined using averaging procedures such as phase volume or ensemble averaging described by Syamlal, Rogers, and O'Brien (1993), and Pannala, Syamlal, and O'Brien (2011).

### 2.2. The Euler–Lagrange approach

Instead of using the Euler–Euler approach, the hybrid Euler–Lagrange technique can be applied for granular flow modeling in fluidized beds facilities. In this work, we use the DDPM, which uses a four-way coupling technique to take into account the relationship between continuous and dispersed phases in mass and momentum transfer, as well as the interaction between particles in the dispersed phase. The impact of particle motion on the gaseous phase is contained in the governing equation by source terms. The hybrid model assumes that the interaction between particles in dispersed phase is calculated explicitly on the Eulerian grid based on the volume fraction of solid phase mapped from particle positions. The evaluated solid stress tensor is then used to map back into particle positions.

The DDPM approach does not solve the momentum equation for individual particles. The solver tracks groups of particles called parcels. Each parcel contains several particles characterized by the same mass, velocity, and position. The number of individual particles contained in the injected parcel can be easily calculated from the following relation,

$$n_p = \frac{\dot{m}_{parcel} \Delta t}{m_p}, \tag{5}$$

where $\Delta t$ is the time step in transient calculation, $\dot{m}_{parcel}$ mass flow rate of a single parcel, and $m_p$ mass of an individual particle evaluated based on the particle diameter and density. The equations of mass and momentum conservation for the gaseous phase solved by the DDPM approach are

$$\frac{\partial}{\partial t}(\varepsilon_f \rho_f) + \nabla \cdot (\varepsilon_f \rho_f \mathbf{u}_f) = S_{mass}, \tag{6}$$

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