Bubbling gas-solid fluidized beds with BDIM

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Abstract

A numerical scheme based on Boundary Domain Integral Method (BDIM) is being developed to model the bubbling behaviour of fluidized beds by using the Eulerian approach. Each phase is described by a modified Navier-Stokes equation. While modified Helmholtz fundamental solution has been used for the kinematics, the elliptic diffusion-convective one has been used for the kinetics of the both components motion. A gas-phase is described by its physical properties, but the solid-phase needs additional physical models. The most promising set of the equations in the sense of fast numerical convergence is presented in present work.

1 Introduction

Fluidized multiphase reactors are of increasing importance in nowadays chemical industries. Although the tools for applying single phase flow Computational Fluid Dynamics (CFD) are widely available, application of multiphase CFD is still complicated from both a physical and numerical point of view. In the past there was a lot of attempts to explain the hydrodynamics behaviour of complex gas-solid multiphase flow. Some sets of partial differential equations were written and a lot of laboratory experiments have been done. Even there appear difficult problems - the scale up from laboratory towards industrial equipment is always a problem. For example, equations describing the bubble behaviour in gas-solid fluidized beds are
(semi)empirical and often determined under laboratory conditions. For that reason there is little unifying theory describing the bubble behaviour in fluidized beds. In the last period CFD is becoming more and more an engineering tool to predict flows in various types of apparatus on industrial scale. In literature little attempt has been made to verify experimentally Eulerian-Eulerian gas-solid model simulations of bubbling fluidized beds using well known numerical techniques. In following contribution a new scheme based on BDIM is explained to extend the applicability of boundary element method.

2 Governing Equations

In spite of the increasing computational power, the number of particles in gas-solid flow in large scale equipment is still much too large to handle each particle separately. Therefore the Eulerian approach is applied in this work. The CFD model is based on a Two Fluid Model (TFM) extended with the kinetic theory of granular flow as derived from the kinetic theory of gases. In TFM both phases are considered to be continuous and fully interpenetrating.

The continuity equation or mass balance for phase \( p \) (\( g \) for gas and \( s \) for solid) reads

\[
\frac{\partial}{\partial t} (\varepsilon_p \rho_p) + \frac{\partial}{\partial x_i} (\varepsilon_p \rho_p v_{pi}) = 0 \quad \text{and} \quad \sum_{p=g,s} \varepsilon_p = 1, \quad (1)
\]

where \( \varepsilon_p \) is the volume fraction of each phase, \( v_{pi} \) the velocity, and \( \rho_p \) density. The momentum balances are given by the Navier-Stokes equation, modified to include an interphase momentum transfer term

\[
\frac{Dv_{gi}}{Dt} = \frac{1}{\varepsilon_g \rho_g} \frac{\partial \tau_{gij}}{\partial x_j} + g_i + \frac{1}{\varepsilon_g \rho_g} \frac{\partial p}{\partial x_i} - \frac{\beta}{\rho_g \varepsilon_g} (v_{gi} - v_{si}), \quad (2)
\]

\[
\frac{Dv_{si}}{Dt} = \frac{1}{\varepsilon_s \rho_s} \frac{\partial \tau_{sij}}{\partial x_j} + g_i - \frac{1}{\varepsilon_s \rho_s} \frac{\partial p^*_s}{\partial x_i} - \frac{1}{\rho_s \varepsilon_s} \frac{\partial p}{\partial x_i} + \frac{\beta}{\rho_s \varepsilon_s} (v_{gi} - v_{si}), \quad (3)
\]

where \( \beta \) is the interphase momentum transfer coefficient. \( \tau_{pij} \) is the viscous stress tensor, \( g_i \) is the gravity acceleration and \( p \) is the thermodynamic pressure. In solid-phase momentum balance \( p^*_s \) is the solids pressure obtained from the kinetic theory of the granular flow. Both the shear and bulk viscosity should be used in viscous strain tensor in general, but under certain circumstances, as discussed below, only the shear part of the viscosity is sufficient. With \( \varepsilon_g = 1 \) and \( \beta = 0 \) Eq. (2) becomes the classical Navier-Stokes equation.
Taking the curl operator directly on the vorticity definition [Škerget (1995)]
\[ \omega_{pi} = e_{ijk} \frac{\partial v_{pk}}{\partial x_j}, \quad \frac{\partial \omega_{pi}}{\partial x_i} = 0 \]  
(4)
and applying the reformed continuity Eq. (1) with \( \rho_p = \text{const.} \)
\[ \frac{\partial v_{pi}}{\partial x_i} = -\frac{1}{\epsilon_p} \left( \frac{\partial \epsilon_p}{\partial t} + v_{pj} \frac{\partial \epsilon_p}{\partial x_j} \right), \]  
(5)
the kinematics of both components motion is carried out
\[ \frac{\partial^2 v_{pi}}{\partial x_j \partial x_j} + e_{ijk} \omega_{pk} = \frac{\partial}{\partial x_i} \left[ -\frac{1}{\epsilon_p} \left( \frac{\partial \epsilon_p}{\partial t} + v_{pj} \frac{\partial \epsilon_p}{\partial x_j} \right) \right]. \]  
(6)
Computational domain is partitioned in subdomains. If the volume fraction of each phase \( \epsilon_p \) is supposed to be constant over each subdomain called macroelement, the set of governing equations could be rewritten in a simple manner, but a lot of physics is then moved to the boundary conditions. The result is the parabolic equation with false transient approach (\( \alpha \) is the relaxation parameter) describing the kinematics of both phases motion
\[ \frac{\partial^2 v_{pi}}{\partial x_j \partial x_j} - \frac{1}{\alpha} \frac{\partial v_{pi}}{\partial t} + e_{ijk} \omega_{pk} = 0. \]  
(7)
In gas-solid systems shear viscosity \( \eta_p^* \) and bulk viscosity \( \lambda_p^* \) are in the same order of magnitude. Therefore the bulk viscosity should not be neglected. But if the volume fraction of each component is supposed to be constant over the macroelement the viscous strain tensor
\[ \frac{\partial \tau_{pij}}{\partial x_j} = \eta_p^* \frac{\partial^2 v_{pi}}{\partial x_j \partial x_j} + \left( \frac{1}{3} \eta_p^* + \lambda_p^* \right) \frac{\partial}{\partial x_i} \left( \frac{\partial v_{pi}}{\partial x_i} \right), \]  
(8)
is simplified in following expression
\[ \frac{\partial \tau_{pij}}{\partial x_j} = \eta_p^* \frac{\partial^2 v_{pi}}{\partial x_j \partial x_j}. \]  
(9)
Vorticity transport equations are obtained as a curl of the momentum balances Eqs. (2) and (3)
\[ \frac{D \omega_{gi}}{Dt} = \omega_{gj} \frac{\partial v_{gi}}{\partial x_j} + \frac{\eta_g^*}{\phi_g \phi_s} \frac{\partial^2 \omega_{gi}}{\partial x_j \partial x_j} + \frac{\omega_{gi}}{\phi_s \phi_g} \frac{\partial \phi_g}{\partial t} \frac{\partial \epsilon_s}{\partial t} - \beta \left( \omega_{gi} - \omega_{si} \right), \]  
(10)
\[ \frac{D \omega_{si}}{Dt} = \omega_{sj} \frac{\partial v_{si}}{\partial x_j} + \frac{\eta_s^*}{\phi_s \phi_g} \frac{\partial^2 \omega_{si}}{\partial x_j \partial x_j} + \frac{\omega_{si}}{\phi_s \phi_s} \frac{\partial \phi_s}{\partial t} \frac{\partial \epsilon_s}{\partial t} + \beta \left( \omega_{gi} - \omega_{si} \right). \]  
(11)
3 Integral Representation

In general the linear time dependent diffusion-convective equation, describing transport of an arbitrary scalar quantity $u$, defined in a solution domain $R = \Omega \times Q$ representing the product of space $\Omega$ and the time interval $Q(t_0, t)$ acquire the form of

$$\frac{a}{\partial x_j \partial x_j} \frac{\partial^2 u}{\partial t} - \frac{\partial u}{\partial t} - \frac{\partial v_j u}{\partial x_j} + I = 0,$$  \hspace{1cm} (12)

where $v_j$ is the local velocity field, the variable $u$ can be equated with velocity or vorticity (gas or solid phase) and will be refereed to as a potential, while the effective diffusivity $a$ and the source term $I$ are some monotonic space and potential dependent functions. Equation (12) represents a parabolic initial boundary value problem, thus some boundary (e.g. Dirichlet or Neumann) and initial conditions have to be known to complete the mathematical description of the problem [Skerget (1995)].

3.1 Kinematics

By using a finite difference approximation of the field function time derivative the Eq.(12) can be written in a nonhomogenous modified Helmholtz PDE form

$$\frac{\partial^2 u}{\partial x_j \partial x_j} - \frac{u}{a \Delta t} + b = 0.$$  \hspace{1cm} (13)

Considering that each component of the velocity vector $v_{pi}$, Eq. (7) obeys the nonhomogeneous Eq. (12), we obtain

$$\frac{\partial^2 v_{pi}}{\partial x_j \partial x_j} - \frac{v_{pi}}{\alpha \Delta t} + b_{pi} = 0,$$  \hspace{1cm} (14)

with the following corresponding integral representation

$$c(\xi)v_{pi}(\xi) + \int_{\Gamma} v_{pi} \frac{\partial u^*}{\partial n} d\Gamma = \int_{\Gamma} \frac{\partial v_{pi}}{\partial n} u^* d\Gamma + \int_{\Omega} b_{pi} u^* d\Omega,$$  \hspace{1cm} (15)

where the variable $u^*$ is the modified Helmholtz fundamental solution. The nonhomogeneous term $b_{pi}$ stands for pseudo-body force vector which equals to the expression

$$b_{pi} = e_{ijk} \frac{\partial \omega_k}{\partial x_j} + \frac{1}{\alpha \Delta t} v_{pi,F-1},$$  \hspace{1cm} (16)
with the following corresponding integral representation

\[
\frac{c(\xi)}{v_{pi}(\xi)} + \int_{\Gamma} v_{pi} \frac{\partial u^*}{\partial n} d\Gamma = \int_{\Gamma} \left( \frac{\partial v_{pi}}{\partial n} + e_{ijk} \omega_k n_j \right) u^* d\Gamma - \int_{\Omega} e_{ijk} \omega_k \frac{\partial u^*}{\partial x_j} d\Omega \\
+ \frac{1}{\alpha \Delta t} \int_{\Omega} v_{pi,F-1} u^* d\Omega,
\]  

(17)

where \( v_{pn} = v_{pj} n_j \).

For 2D simulation the integral equations are written because of the boundary conditions for normal and tangential direction. It is possible then to prescribe appropriate boundary conditions for both, tangential and normal velocities

\[
\frac{c(\xi)}{v_{pn}(\xi)} + \int_{\Gamma} v_{pn} \frac{\partial u^*}{\partial n} d\Gamma = \int_{\Gamma} \frac{\partial v_{pn}}{\partial n} u^* d\Gamma - n_x \int_{\Omega} \omega_p \frac{\partial u^*}{\partial y} d\Omega \\
+ n_y \int_{\Omega} \omega_p \frac{\partial u^*}{\partial x} d\Omega + \frac{1}{\alpha \Delta t} \int_{\Omega} v_{pn,F-1} u^* d\Omega,
\]

(18)

\[
\frac{c(\xi)}{v_{pt}(\xi)} + \int_{\Gamma} v_{pt} \frac{\partial u^*}{\partial n} d\Gamma = \int_{\Gamma} \left( \frac{\partial v_{pt}}{\partial n} - \omega_p \right) u^* d\Gamma + n_y \int_{\Omega} \omega_p \frac{\partial u^*}{\partial y} d\Omega \\
+ n_x \int_{\Omega} \omega_p \frac{\partial u^*}{\partial x} d\Omega + \frac{1}{\alpha \Delta t} \int_{\Omega} v_{pt,F-1} u^* d\Omega.
\]

(19)

3.2 Kinetics

Integral representation describing kinetics of both components motion can be formulated by using the fundamental solution of steady diffusion-convective PDE with reaction term. Since it exists only for the case of constant coefficients, the velocity field \( v_{pj}(r_k, t) \) has to be decomposed into an average constant vector \( \bar{v}_{pj}(t) \) and perturbated one \( \tilde{v}_{pj}(r_k, t) \), such that \( v_{pj} = \bar{v}_{pj} + \tilde{v}_{pj} \). Again a non-symmetric finite difference approximation of the time derivative can be applied. This approach permits to rewrite eq.(12) in the following diffusion-convective nonhomogeneous PDE form

\[
a \frac{\partial^2 u}{\partial x_j \partial x_j} - \frac{\partial \bar{v}_{pj} u}{\partial x_j} - \frac{1}{\Delta t} u + b = 0.
\]

(20)

Considering that each component of the vorticity vector \( \omega_{pi} \), Eqs. (10) and (11), obeys the nonhomogeneous Eq. (20), we obtain

\[
K_p \frac{\partial^2 \omega_{pi}}{\partial x_j \partial x_j} - \frac{\partial \bar{v}_{pj} \omega_{pi}}{\partial x_j} - \frac{1}{\Delta t} \omega_{pi} + b_{pi} = 0.
\]

(21)
The above differential formulation can now be transformed into an equivalent integral statement by Green's theorems for scalar functions, e.g.

\[
c (\xi) \omega_{pi} (\xi) + K_p \int_{\Gamma} \omega_{pi} \frac{\partial u^*_p}{\partial n} d\Gamma = \int_{\Gamma} \left( K_p \frac{\partial \omega_{pi}}{\partial n} - \omega_{pi} \bar{v}_p \right) u^*_p d\Gamma + \int_{\Omega} b_{pi} u^*_p d\Gamma.
\]  

(22)

The pseudo-body term \( b_{pi} \) includes the convective flux for the perturbated velocity field \( \tilde{v}_{pj} \), deformation, initial conditions, vorticity change on account of the bubble formation and interphase momentum exchange term, e.g.

\[
b_{pi} = - \frac{\partial \tilde{v}_{pj} \omega_{pi}}{\partial x_j} + \frac{\partial \omega_{pj} v_{pj}}{\partial x_j} + \frac{\omega_{pi,F-1}}{\Delta t} + \frac{\omega_{pi}}{\varepsilon_p \Delta t} (\varepsilon_{p,F-\varepsilon_p,F-1}) \mp \beta (\omega_{gi} - \omega_{si}),
\]  

(23)

rendering the following final integral representation

\[
c (\xi) \omega_{pi} (\xi) + \int_{\Gamma} \omega_{pi} \frac{\partial U^*_p}{\partial n} d\Gamma = \frac{1}{K_p} \int_{\Gamma} \left( K_p \frac{\partial \omega_{pi}}{\partial n} - \omega_{pi} v_{pn} + \omega_{pn} v_{pi} \right) U^*_p d\Gamma
\]

\[
+ \frac{1}{K_p} \int_{\Omega} \left( \omega_{pi} \tilde{v}_{pj} - \omega_{pi} v_{pj} \right) \frac{\partial U^*_p}{\partial x_j} d\Omega \mp \frac{\beta}{\eta^*_p} K_p \int_{\Omega} (\omega_{gi} - \omega_{si}) U^*_p d\Omega
\]

\[
+ \frac{1}{K_p \Delta t} \int_{\Omega} \omega_{pi,F-1} U^*_p d\Omega + \frac{1}{\varepsilon_p K_p \Delta t} \int_{\Omega} \omega_{pi} (\varepsilon_{p,F-\varepsilon_p,F-1}) U^*_p d\Omega,
\]  

(24)

with \( K_p = \eta^*_p/\varepsilon_p \varepsilon_p \) and \( U^*_p = K_p u^*_p \).

In case of plane (2D) simulations the kinetics reads

\[
c(\xi) \omega_p (\xi) + \int_{\Omega} \omega_p \frac{\partial U^*_p}{\partial n} d\Omega = \frac{1}{K_p} \int_{\Gamma} \left( K_p \frac{\partial \omega_p}{\partial n} - \omega_p v_{pn} \right) U^*_p d\Gamma
\]

\[
+ \frac{1}{K_p} \int_{\Omega} \omega_p \tilde{v}_{pj} \frac{\partial U^*_p}{\partial x_j} d\Omega \mp \frac{\beta}{\eta^*_p} K_p \int_{\Omega} (\omega_g - \omega_s) U^*_p d\Omega + \frac{1}{K_p \Delta t} \int_{\Omega} \omega_{p,F-1} U^*_p d\Omega
\]

\[
+ \frac{1}{\varepsilon_p K_p \Delta t} \int_{\Omega} \omega_p (\varepsilon_{p,F-\varepsilon_p,F-1}) U^*_p d\Omega.
\]  

(25)

4 Boundary conditions

For the two-dimensional motion in \( x - y \) plane, the following relation can be derived relating vorticity values with normal and tangential velocity component fluxes, e.g.

\[
\omega = \frac{\partial v_t}{\partial n} - \frac{\partial v_n}{\partial t}.
\]  

(26)
Appropriate boundary conditions derived from the conservation laws are:

- **kinematics**
  \[
  \{v_{pt}\}^1_I = -\{v_{pt}\}^2_I, \quad (27)
  \]
  \[
  \{v_{pn}\varepsilon_p\}^1_I = -\{v_{pn}\varepsilon_p\}^2_I, \quad (28)
  \]
  \[
  \left\{\frac{\partial v_{pt}}{\partial n}\right\}_I = -\left\{\frac{\partial v_{pt}}{\partial n}\right\}_I^2, \quad (29)
  \]
  \[
  \left\{\varepsilon_p\frac{\partial v_{pn}}{\partial n}\right\}_I = -\left\{\varepsilon_p\frac{\partial v_{pn}}{\partial n}\right\}_I^2; \quad (30)
  \]

- **kinetics**
  \[
  \{\omega_p\varepsilon_p\}^1_I = \{\omega_p\varepsilon_p\}^2_I, \quad (31)
  \]
  \[
  \left\{\varepsilon_p\frac{\partial \omega_p}{\partial n}\right\}_I = -\left\{\varepsilon_p\frac{\partial \omega_p}{\partial n}\right\}_I^2. \quad (32)
  \]

5 **Gas-solid physical models**

Both phases - gas and solids - in presented contribution are treated as separated interpenetrating fluids. A gas-phase can be described by its real physical properties, but the solid-phase needs additional physical models to calculate in the solid-phase momentum balance required quantities.

5.1 **Radial distribution function**

The radial distribution function $g_0$ is the equilibrium radial distribution at particle contact derived from statistical mechanics. It can be interpreted as the probability of a particle touching another particle. In literature [Boemer (1995)] there is agreement only on the fact that $g_0$ must increase with increasing solid volume fraction, but the formulations for $g_0$ differ considerably. In this work the correlation of Ding and Gidaspow (1990) is preferred

\[
  g_0 = \frac{3}{5} \left[ 1 - \left( \frac{\varepsilon_s}{\varepsilon_{s,max}} \right)^{\frac{1}{3}} \right]^{-1}, \quad (33)
\]

where $\varepsilon_{s,max}$ is the maximum solids packing.

5.2 **Granular temperature**

Granular temperature $\Theta_s$ describes the fluctuation kinetic energy of the solid phase and it can be compared with the thermodynamic temperature of a gas due to the fluctuations of its molecules. Instead
of solving the complete balance of the solids fluctuating energy an algebraic expression was proposed by Boemer et al. (1995). That algebraic equation was confirmed also by Van Wachem et al. (1998).

5.3 Drag model

The interphase momentum transfer due to the gas-solid drag is described by the drag function $\beta$. In this work the interphase drag function of Syamlal et al. (1993) is used

$$\beta = \frac{3}{4} C_D \frac{\varepsilon_s (1 - \varepsilon_s) \theta_g}{V_T^2 d_s} \cdot |v_{gi} - v_{si}|,$$

with

$$C_D = \left(0.63 + 4.8 \sqrt{\frac{V_T}{Re}}\right)^2,$$

$$V_T = 0.5 \left(K_6 - 0.06 Re + \sqrt{(0.06 Re)^2 + 0.12 Re (2K_7 - K_6) + (K_6)^2}\right),$$

$$K_6 = (1 - \varepsilon_s)^{4.14},$$

$$K_7 = \begin{cases} 0.8 (1 - \varepsilon_s)^{1.28} & \text{if } \varepsilon_s \geq 0,15 \\ (1 - \varepsilon_s)^{2.65} & \text{if } \varepsilon_s < 0,15 \end{cases},$$

$$Re = \frac{d_s \theta_g \cdot |v_{gi} - v_{si}|}{\eta_g},$$

where $C_D$ is the drag coefficient, $V_T$ is the ratio of terminal velocity of a group of particles to that of an isolated particle. $Re$ is the particle Reynolds number and $\eta_g$ is the gas viscosity.

5.4 Solid-phase viscosity model

Since a solid-phase in fact is no continuous fluid like a gas or a liquid, its viscosity is not a real physical property. But it was shown that it is possible to combine the different interparticle forces and use a momentum balance similar to that of a real continuous fluid.

A solid-phase shear viscosity function can be written $\eta_s^* = \eta_s \cdot \varepsilon_s$ with $\eta_s$ being the shear viscosity of the solid-phase analogous to the shear viscosity of the gas-phase $\eta_g$. Models from the literature [Boemer et al. (1995)] can be divided into a common term $\eta_s^*_{\text{dense}}$ prevailing in the dense region and a term $\eta_s^*_{\text{dilute}}$ which is of major
importance in the dilute region $\eta_s^* = \eta_{s,dense}^* + \eta_{s,dilute}^*$. The common term found in literature for the dense region is

$$\eta_{s,dense}^* = \frac{4}{5} \varepsilon_s^2 \varepsilon_s d_s g_0 (1 + e) \sqrt{\frac{\Theta_s}{\pi}},$$

while for the dilute region Gidaspow et al. (1992) used the equation

$$\eta_{s,dilute}^* = \frac{2 \sqrt{\frac{\pi}{96}} \varepsilon_s d_s \sqrt{\Theta_s}}{(1 + e) g_0} \left[ 1 + \frac{4}{5} g_0 \varepsilon_s (1 + e) \right].$$

### 6 Numerical Solution

For the numerical approximate solution of field functions (velocity and vorticity for both phases), the corresponding boundary domain integral representation is written in a discretized manner. The discretisation of integral representations could be readily obtained from the corresponding integral equations (18), (19) and (25). For the plane case the equations are:

- **Kinematics - normal direction**

$$c(\xi) v_{pn}(\xi) + \sum_{e=1}^{E} \{h\}_T \{v_{pn}\}_n = \sum_{e=1}^{E} \{g\}_T \left\{ \frac{\partial v_{pn}}{\partial n} \right\}_n - \sum_{e=1}^{C} \{d_y\}_T \{n_x \omega_p\}_m$$

$$+ \sum_{e=1}^{C} \{d_x\}_T \{n_y \omega_p\}_m + \frac{1}{\alpha \Delta t} \sum_{e=1}^{C} \{b_p\}_T \{v_{pn,F-1}\}_m,$$

- **Kinematics - tangential direction**

$$c(\xi) v_{pt}(\xi) + \sum_{e=1}^{E} \{h\}_T \{v_{pt}\}_n = \sum_{e=1}^{E} \{g\}_T \left\{ \frac{\partial v_{pt}}{\partial n} \right\}_n - \sum_{e=1}^{E} \{g\}_T \{\omega_p\}_n$$

$$+ \sum_{e=1}^{C} \{d_y\}_T \{n_y \omega_p\}_m + \sum_{e=1}^{C} \{d_x\}_T \{n_x \omega_p\}_m + \frac{1}{\alpha \Delta t} \sum_{e=1}^{C} \{b_p\}_T \{v_{pt,F-1}\}_m,$$

- **Kinetics**

$$c(\xi) \omega_p(\xi) + \sum_{e=1}^{E} \{H_p\}_T \{\omega_p\}_n = \frac{1}{K_p} \sum_{e=1}^{E} \{G_p\}_T \left\{ K_p \frac{\partial \omega_p}{\partial n} - \omega_p v_{pn} \right\}_n$$

$$+ \frac{1}{K_p} \sum_{e=1}^{C} \{D_{pj}\}_T \{\omega_p \tilde{v}_{pj}\}_m \pm \frac{\beta}{\eta_p} K_p \sum_{e=1}^{C} \{B_p\}_T \{\omega_g - \omega_s\}_m$$

$$+ \frac{1}{K_p \Delta t} \sum_{e=1}^{C} \{B_p\}_T \{\omega_p (\varepsilon_{p,F} - \varepsilon_{p,F-1})\}_m.$$
7 Conclusion

The boundary domain integral method is used to simulate the two dimensional bubbling behaviour of fluidized gas-solid systems. The velocity-vorticity approach in combination with modified Navier-Stokes equations is employed which allows the separation of the kinematic and kinetic part from the pressure part, respectively. The set of governing equations is simplified under assumption that volume fraction of each component is constant in each macroelement. The jump at interfaces is overcome by proper selection of boundary conditions. The advantage of the proposed scheme is reduced number of gas-solid physical models. Numerical model, incorporated into the existing program BEMFLOW, is in the phase of evaluation and testing.

References


