doi: 10.5937/SimTerm24356M

A Model of Two-Phase Flow in Pneumatic Transport of Powder Material

Saša Milanović [a], ***Veljko Begović*** [b], ***Miloš Jovanović*** [c], ***Boban Nikolić*** [d], ***Živan Spasić*** [e], ***Petar Miljković*** [f]

[a] *Faculty of Mechanical Engineering, Niš, RS, sasa.milanovic@masfak.ni.ac.rs*
[b] *Faculty of Mechanical Engineering, Niš, RS, veljko.begovic@masfak.ni.ac.rs*
[c] *Faculty of Mechanical Engineering, Niš, RS, milos.jovanovic@masfak.ni.ac.rs*
[d] *Faculty Mechanical Engineering, Niš, RS, boban.nikolic@masfak.ni.ac.rs*
[e] *Faculty Mechanical Engineering, Niš, RS, zivan.spasic@masfak.ni.ac.rs*
[f] *Faculty Mechanical Engineering, Niš, RS, petar.miljkovic@masfak.ni.ac.rs*

Abstract: The paper presents a numerical simulation of two-phase turbulent flow in straight horizontal channels with a square cross-section, with the dimensions of 200x200 mm and the length of 80D_h. The flow of solid particles of quartz, flour and ash using air was chosen for the two-phase flow simulation. During the modelling of the flow, the transported particles were observed as spherical. The turbulence was modelled using a full Reynolds stress model, while the complete model was used to examine turbulent stresses and turbulent temperature fluxes. The same initial flow conditions and a single uniform grid were employed in all numerical experiments. The fineness of the numerical grid was tested during the simulation, and the paper shows the results of the numerical grid of the highest resolution beyond which the fineness did not affect the obtained results. The paper also presents the change in the velocity of the transported material by air in the cross-section and along the channel.

Keywords: Computer Simulation, Pneumatic Transport, Solid Particles, Channel, Two Phase Flow.

1. Introduction

Pneumatic transport is the transport of loose, granular or powder material mainly by using the flow of air or some other gas. This transport is made possible by the fact that aerodynamic forces are exerted on solid particles by the air flow, and when such forces become sufficiently strong at certain air velocities they can lift and move the transported material particles. Pneumatic transport is characterized by a chaotic motion of particles of material full of collisions, however, the motion still possesses a basic component of velocity along the channel that is lower than the velocity of the transporting air.

There are numerous examples of two-phase flows of the air-solid type in channels with a non-circular cross-section in engineering. The most common instances are found in systems of pneumatic transport of granular and powder material, air conditioning and ventilation systems, process and energy systems, etc. Two-phase flows comprise a multitude of flow phenomena that stem from interactions between the gas and the solid phase. These flows play a very important role in the whole mechanism of matter, impulse and heat transport in a channel and its surroundings. High intensity impulse transfer in the channel yields high gradients of transversal velocities in the cross-sectional plane.

Besides the main flow along the channel, in horizontal channels with a square cross-section secondary flows are also induced in the cross-sectional plane of the channel during a developed turbulent flow. A secondary flow known as secondary flow of the first kind occurs due to centrifugal forces in both laminar and turbulent flow in channels of arbitrary cross-sections. In straight channels with a square cross-section, and only in the completely developed turbulent flow mode, a secondary flow known as secondary flow of the second kind is induced in the cross-section of the channel. Secondary flows are a result of transversal gradients of primary shear stresses, and they produce increased shear stresses, significantly affecting the intensity of heat transfer from the fluid to the wall of the channel and vice versa. Gas-particle multiphase flow, which may include a solid or liquid particle, is a significant phenomenon in natural and industrial engineering. The interaction between the particles and the gas is difficult to establish because of the diversity and complexity of problems involved. Numerical simulation is a powerful tool for examining the characteristics of gas-particle multiphase flow thanks to the development of computers. Three models, namely, Euler-Euler two-fluid model (TFM), Euler-Lagrange discrete particle model (DPM), and Lagrange-Lagrange pseudo-particle model, are widely used in these numerical simulations.

The inability of TFM to trace the path of individual particles was the main reason behind the development of Euler-Lagrange DPM. The soft-sphere model or discrete element model (DEM) is a granular dynamics simulation technique proposed by Cundall and Strack [1] and first presented in the open literature. Subsequently, a two-dimensional (2D) soft-sphere approach was applied to gas-fluidized beds [2]. On the other hand, the hard-sphere approach assumes that the interactions between particles are pair-wise additive and instantaneous. Campbell and Brennen [3] first studied granular systems using hard-sphere discrete particle simulation (DPM). Tanaka et al. [4] introduced DSMC (Direct Simulation Monte Carlo) to calculate particle collisions in gas–solid flows. Numerical simulations were performed for a dispersed gas–solid flow in a vertical channel [5] and fluidized beds using the DSMC method. This method is suitable for large-scale simulations. Paper [6] presented a modified model for the prediction of the erosion rate in pipe flows, on the basis of the simulation of fluid fluctuating velocities using the Discrete Random Walk model. Pneumatic conveying of spherical particles in a horizontal channel with a rectangular cross-section was numerically simulated and presented in [7].

This paper employs a full Reynolds stress model of turbulence, which implies that each of the components of turbulent stress is calculated from its own transport differential equation. These equations are modelled and not exact [8]. The modelled equations were obtained by keeping the correlation of the second order in its original form, while the members that contain correlations of the higher order were modelled using the gradient method.

2. Physical model

Turbulence is the most important factor and the cause of all the difficulties in the processes of matter, momentum and heat transport. It is a non-stationary, non-linear, irreversible, stochastic and three-dimensional phenomenon [9,10]. For a fully developed turbulent flow, in the case of a stationary and incompressible current, the transport equation of the vorticity component perpendicular to the cross-sectional plane Ω_1 [11], has the following form:

$$\underbrace{U_2\frac{\partial \Omega_1}{\partial x_2}+U_3\frac{\partial \Omega_1}{\partial x_3}}_{A_1}=\underbrace{\frac{\partial^2}{\partial x_2 \partial x_3}\left(\overline{u_3u_3}-\overline{u_2u_2}\right)}_{A_4}-\underbrace{\left(\frac{\partial^2}{\partial x_3^2}-\frac{\partial^2}{\partial x_2^2}\right)\overline{u_2u_3}}_{A_5}+\underbrace{\nu\left(\frac{\partial^2\Omega_2}{\partial x_2^2}+\frac{\partial^2\Omega_1}{\partial x_3^2}\right)}_{A_6} \tag{24}$$

This implies that the difference between the turbulent members A_4 and A_5, which are of the same order of magnitude as the convective member A_1, stems directly from the mechanism generating secondary flow, that is, secondary flow is a consequence of the transverse gradients of the primary shear stresses in the region of the channel vertices. Thus it is necessary to model all Reynolds stresses as accurately as possible to provide a realistic simulation of secondary flow of the second kind in a straight channel with a square cross-section during a developed turbulent flow.

Two-phase flows are characterized by numerous interconnected complex phenomena that occur due to the mutual influence between the phases. While modelling such flows, one has to use a combined approach to solve the flow field. The Euler approach (the concept of continuum) is adopted to solve the gas flow, while the Lagrange approach (the concept of tracking the particle trajectories) is applied in solving the solid phase. An iterative task-solving procedure yields the interphase interaction of the gas and the solid phase.

On the one hand, the mathematical model of the gas phase is defined under the following assumptions: the flow is stationary, three-dimensional, incompressible, isothermal and chemically inert. On the other, the mathematical model of the solid phase is defined under the following assumptions: particles are of various dimensions, particles do not change their mass while travelling through the channel, particles have a constant temperature through the channel, the influence of particle collisions is neglected, particles lose a certain level of impulse upon hitting the channel walls and internal obstacles, particles move stochastically.

3. Mathematical model of the gas phase

The mathematical model is created for a three-dimensionally fully developed turbulent flow in a straight horizontal channel with a square cross-section. The turbulent flow is assumed to be stationary and incompressible, while the channel walls have a constant temperature. With the volumetric forces of gravity neglected, the general equation of conservation of impulse, matter and energy for the gas phase correlates to the equation of field conservation for a single-phase flow, with the addition of the interphase member, thus obtaining the following form [8,11]:

$$\frac{\partial}{\partial t}(\rho\Phi)+U_j\frac{\partial}{\partial x_j}(\rho\Phi)-\frac{\partial}{\partial x_j}\left(\Gamma_\Phi\frac{\partial\Phi}{\partial x_j}\right)=S_\Phi+S_\Phi^{IF} \tag{25}$$

Based on the adopted assumptions of the physical model, the averaged equations of conservation of matter, impulse and heat have the following forms:

- the continuity equation:

$$\frac{\partial U_j}{\partial x_j}=0 \tag{26}$$

- the equation of motion:

$$U_j\frac{\partial U_i}{\partial x_j}-\frac{\partial}{\partial x_j}\left(\nu\frac{\partial U_i}{\partial x_j}\right)=-\frac{1}{\rho}\frac{\partial P}{\partial x_j}-\frac{\partial\overline{u_iu_j}}{\partial x_j}+S_{U_i}^{IF} \tag{27}$$

- the energy equation:

$$U_j\frac{\partial T}{\partial x_j}-\frac{\partial}{\partial x_j}\left(a\frac{\partial T}{\partial x_j}\right)=-\frac{\partial\theta u_j}{\partial x_j} \tag{28}$$

3.1 Model of Reynolds stresses

The starting point of the stress model of turbulence is a transport equation that defines the dynamic of Reynolds stresses [11]. The tress model of turbulence presumes the simultaneous solution of the transport equation of Reynolds stresses and the motion equation in the Reynolds averaged form. The exact form can only deal with particular components of the transport equation for Reynolds stresses, with the rest of the components being merely correlations to be modelled in the function of the available dependently variable values [11,12]. These values are as follows: averaged velocity, tensor of turbulent stresses, and velocity of dissipation of turbulent kinetic energy.

By modelling the components in the transport equation that defines the dynamics of Reynolds stresses, one can obtain the closed form of the transport equation for Reynolds stresses:

$$U_k\frac{\partial\overline{u_iu_j}}{\partial x_k}=\frac{\partial}{\partial x_k}\left(C_g'\frac{k}{\varepsilon}\overline{u_ku_n}\frac{\partial\overline{u_iu_j}}{\partial x_n}\right)+P_{ij}+\Phi_{ij,1}+\Phi_{ij,2}+\Phi_{ij,z}-\frac{2}{3}\delta_{ij}\,\varepsilon \tag{29}$$

The stress model for Reynolds stresses (6) is closed by an additional transport differential equation for the dissipation of turbulent kinetic energy ε:

$$U_k\frac{\partial\varepsilon}{\partial x_k}=\frac{\partial}{\partial x_k}\left(C_\varepsilon\frac{k}{\varepsilon}\overline{u_ku_j}\frac{\partial\varepsilon}{\partial x_j}\right)+\frac{\varepsilon}{k}\left(C_{\varepsilon1}P-C_{\varepsilon2}\,\varepsilon\right) \tag{30}$$

where the members in equations (6) and (7) are determined by modelling [13].

3.2 Model of turbulent temperature fluxes

Modelling the components in the transport equation for turbulent temperature fluxes leads to the following transport equation:

$$U_k\frac{\partial\overline{\theta u_i}}{\partial x_k}=\frac{\partial}{\partial x_k}\left(C_\theta\frac{k}{\varepsilon}\overline{u_ku_j}\frac{\partial\overline{\theta u_i}}{\partial x_j}\right)+P_{\theta i}+\Phi_{\theta i}+\Phi_{\theta i,z}+\varepsilon_{\theta i} \tag{31}$$

where the members in equation (8) are determined by modelling [13].

4. Mathematical model of the solid phase

In the vast majority of technical processes, the presence of particles in flows produces aerodynamic resistances that condition the change in the momentum of both phases. The mathematical model of the solid phase is based on the Lagrange concept of task solution, and it gives a more realistic picture of the particle motion in the air. The position of particles is determined by solving the equation of motion:

$$\frac{\mathrm{d}x_{\mathrm{p}}}{\mathrm{d}t}=\widetilde{U}_{\mathrm{p}} \tag{32}$$

The current velocity vector of solid particles $\widetilde{U}_{\mathrm{p}}$ is determined from the equation of the solid phase impulse:

$$m_{\mathrm{p}}\frac{\mathrm{d}\widetilde{U}_{\mathrm{p}}}{\mathrm{d}t}=\Re_{\mathrm{p}}\left(U-\widetilde{U}_{\mathrm{p}}\right)+m_{\mathrm{p}}\,b\,g-V_{\mathrm{p}}\,\nabla P \tag{33}$$

where $\Re_{\mathrm{p}}$ is the function of the resistance of a solid particle and it is determined using the expression:

$$\Re_{\mathrm{p}}=0{,}5\rho\,A_{\mathrm{p}}C_{\mathrm{D}}\left|U-\widetilde{U}_{\mathrm{p}}\right| \tag{34}$$

where C_D is the coefficient of resistance for spherical particles and Reynolds number $Re<10^5$ [13].

When considering two-phase turbulent flows of the gas-solid particles type, the basic problem lies in the treatment of the mutual exchange of momentum, energy and mass between the phases, bearing in mind that the particles travel from one vortex to another. The presence of disperse phase during the modelling of the two-phase turbulent flow causes the occurrence of additional sources of momentum, energy and mass in the gas phase equations. The interphase components of interaction are determined on the basis of the division of the flow field into numerical cells, which are each taken as a control volume.

The mathematical model of the continual phase draws upon the models developed for a pure fluid – air, along with the correction caused by the presence of solids. When a particle flows through a numerical cell, the interphase interactions of changing the impulse, energy or mass occur. This means that if a particle moves with a speed larger than its surroundings, the particle slows down because of the interactions of phases, while the velocity of the gas phase in the surroundings of the solid particle increases. Interactions between phases are defined by interphase components, which are added in the equation of motion of the gas phase. The interphase components of interactions describe the changes in the momentum of the transported material particles, that is, the change in the momentum of the gas phase due to the presence of solid particles. The interphase component of the interaction in equation (4) represents the force of resistance to the motion of the particle in the air flow. It is assumed that the forces perpendicular to the trajectory of particles are balanced. This means that the interaction between the phases is given by the intensity of forces acting in the direction of particle motion, and the interphase component of the interaction is determined by integrating equations of particle motion:

$$m_{\mathrm{p}}\frac{\mathrm{d}\widetilde{U}_{\mathrm{p}}}{\mathrm{d}t}=S_{U_i}^{IF} \tag{1}$$

Equation (12) is integrated for each numerical cell, taking into account the Lagrange time step so as to integrate each numerical cell.

5. Numerical model

When considering two-phase flows the basic problem comes from the change in the momentum, energy and mass of particles as they pass through a certain segment of the flow field. A change in the momentum of particles while they are passing through the observed numerical control volume is considered the source or sink of the momentum of the gas phase. In this case, the mathematical model of the gas phase is set for the single-phase flow with the correction related to the presence of particles.

To solve the problem, a two-phase air-solid particle turbulent flow is observed in a straight channel with a square cross-section, and with the side dimensions of 200x200 mm. A channel of $80D_h$ in length, which amounts to 18 m, is taken to form a fully developed turbulent flow. The non-uniform numerical grid is chosen, causing the numerical cells to be of various sizes. The central numerical cells have larger surfaces, while the cells closer to the channel walls and vertices have smaller surfaces. The mass flow of solid particles through the cross-section of the channel is taken as a partial flow in the numerical cells, proportional to the surface of the cells. The partial flows differ due to the fact that the numerical cells are of different surfaces. In such a case, a balanced distribution of transported particles is present along the entire cross-section. In the simulation, the influence of the fineness of the numerical grid was examined for three different numerical grids (30×30×180, 35×35×180, and 40×40×180). The paper presents the results of the highest resolution of the numerical grid above which the fineness of the grid did not affect the obtained results, with the number of cells in the $x^1 \equiv x$, $x^2 \equiv y$, and $x^3 \equiv z$ directions being 40×40×180, respectively.

To solve the problem, the following particles were transported: quartz particles of 0.5 mm in diameter and 2500 kg/m^3 in density, ash particles of 0.14 mm in diameter and 1800 kg/m^3 in density, and flour particles of 0.20 mm in diameter and 1410 kg/m^3 in density. The same initial particle velocity at the entrance to the channel of 2.8 m/s was adopted, matching the flying velocity of quartz particles. Besides defining the initial velocities of the transported particles, it was necessary to define the velocity of air at the entrance, which amounted to 12÷22 m/s for transporting quartz particles, 12÷20 m/s for ash particles, and approximately 20 m/s for flour particles [14]. To solve the problem, the adopted air velocity at the entrance was 22 m/s, with the pressure of 1 bar and 1,2 kg/m^3 in density for all three models of two-phase flow.

The isothermal, stationary and three-dimensional flow of the transporting air was observed to simulate the two-phase turbulent flow, assuming that the mass and the temperature of the solid particles, which move stochastically along the channel, did not change during the transport process. In addition, the influence of mutual collisions of particles and collisions of particles with the walls were neglected.

The solution of the mathematical model was performed in the iterative manner until the solution convergence of 0.1% was reached. The iterative procedure comprised four successively repeated steps. In the first iterative step only the airflow field was considered, and the gas phase conservation equations were calculated as if the dispersed phase was absent. The integration conservation equation of the gas phase was carried out as if the existence of particles did not influence the gas phase flow field. The presence of the dispersed phase caused the appearance of additional terms in the gas phase momentum equation, as the sink term and the source term in the solid phase, due to the interaction between the gas and the solid phase. In the second iterative step the computed gas phase flow field was “frozen” with respect to time, and the forces by which the gas phase flow field acted on solid particles was calculated. Thus, the trajectories of solid particles were computed in the “frozen” gas phase flow field. On the basis of the obtained trajectories of the particles, it was possible to determine the interphase interaction sink term in the momentum equation of the gas phase and the source term in the solid phase momentum equation. In the next, third iterative step the gas phase flow field was again calculated but this time taking into account the interphase interaction sink term obtained on the basis of the calculated trajectories of the solid phase, which was temporarily “frozen”. The second and third iterative steps were repeated until the desired solution convergence criteria of 0.1% was achieved.

6. Results and discussion

For the sake of a comparison between the results of single-phase and two-phase flow, the numerical simulations of single-phase gas flow and two-phase flow were carried out for the same boundary conditions of the gas phase flow but for several different solid particles dispersed in the gas flow, with the mesh density kept unaltered. The dominant parameters that influence the secondary flow of the second kind are turbulent shear stresses in the channel cross-section, and they were chosen as the parameters for the two-phase flow comparison with different solid particles [13].

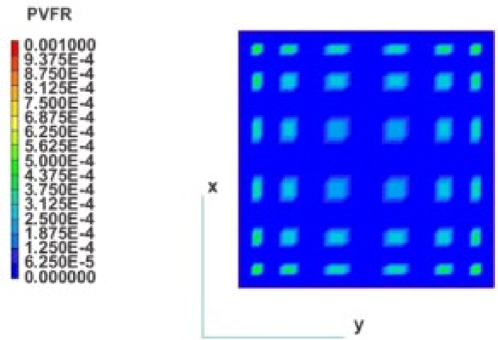
When the Reynolds equations are averaged in time, correlations of fluctuation parts of different physical quantities occur, and they are modelled in the function of the available dependently variable values: averaged velocity, tensor of turbulent stresses and velocity of dissipation of turbulent kinetic energies, which define the mathematical model. The Reynolds stress model assumes that each component of Reynolds stress is determined from its own modelled differential equation. The mathematical model observes the motion of the spherical particles of the recommended values with equivalent diameters and densities. Since the chosen numerical grid is not uniform, the total mass flow given at the entrance fits the partial mass flows in the cells proportionally to the size of the cells. For the central numerical cells, where the sizes are larger, the flows are also larger, while the partial flows of the cells in the vicinity of the walls are lower, proportionally to the size of the cells.

The formation of the secondary flow of the second kind in a straight channel with a square cross-section during the fully developed turbulent flow causes the occurrence of the gradients of Reynolds stresses. The turbulent tangential stresses in the transversal plane of the channel are the dominant parameters that influence the secondary flow of the second kind. These members exert the effect of turbulent stresses on the production and destruction of turbulent vorticity.

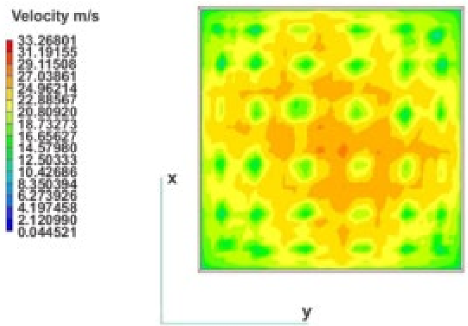
Two-phase flows are generally characterized by numerous mutually related phenomena, as the consequences of multicomponentness of a mixture. The transported material particles move because of the action of the resistance reaction force. Besides said force that acts in the direction of the particle motion, the particles are also subjected to the forces perpendicular to the direction of their movement. If the vertical forces are not balanced, the disturbance of the particle motion may occur, and it can cause the precipitation and even the discontinuation of the transport. Here it is assumed that the vertical forces are balanced, which prevents the disturbance of the particle motion. The numerical simulations yielded a reliable stress model of turbulence and adequate interphase members of interaction in the two-phase flow systems.

Figures 1b, 2b and 3b show the distribution of particles (partial mass flow) at the entrance to the channel, while figures 1a, 2a and 3a show the particle trajectories. It can be seen that particles fill the entire cross-section of the channel from its entrance to its exit, which is how their transport is achieved. Figures 1c, 2c and 3c show the change in the velocity of particles in the cross-section, in the middle of the channel, from which one can observe that the velocity of central particles is greater than the velocity of particles closer to the walls and vertices of the channel. Figures 1d, 2d and 3d show the change in the velocity of particles along the channel as follows: the blue curve for central particles and the red curve for particles closer to the channel wall.

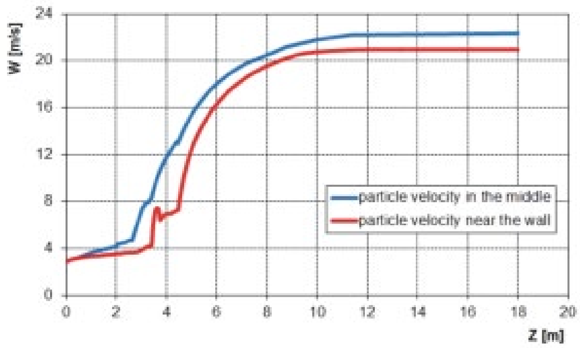
a)



b)

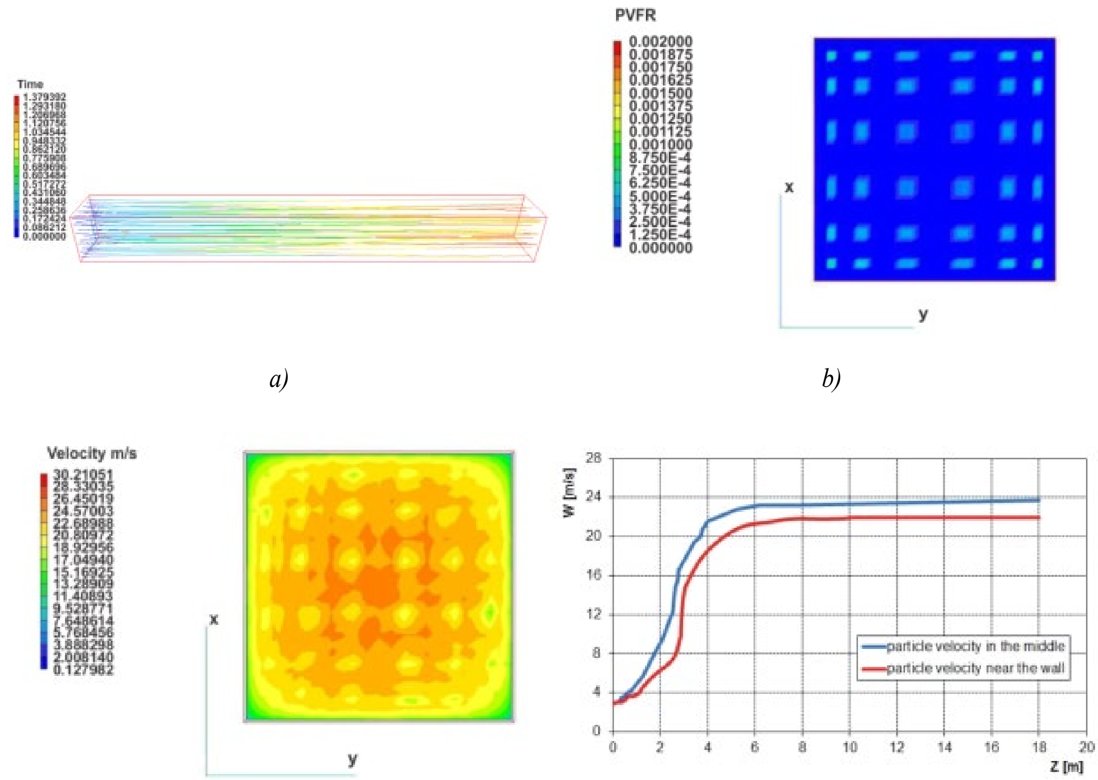


c)



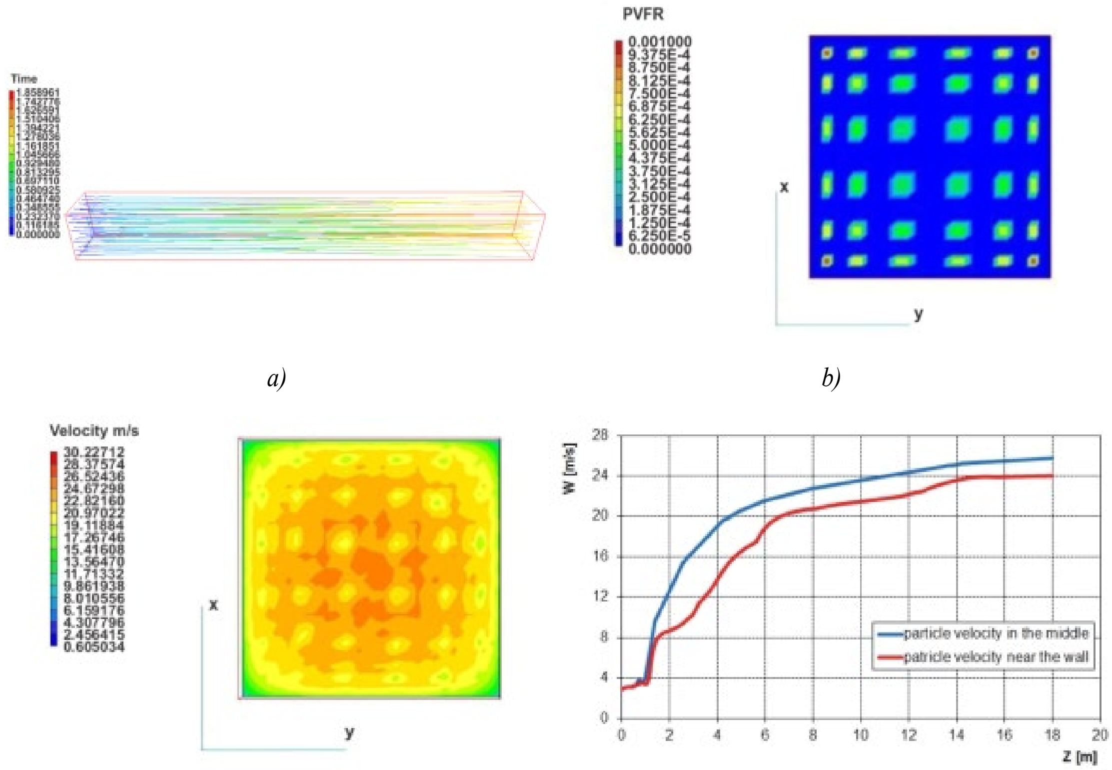
d)

Figure 1. Motion of quartz particles



a) b) c) d)

Figure 2. Motion of ash particles



a) b) c) d)

Figure 3. Motion of flour particles

7. Conclusions

The paper considered a fully developed turbulent flow in straight channels with a square cross-section, with the isolated effect of the secondary flow of the second kind. Numerical simulations of transport processes, matter and momentum during the turbulent two-phase flow were conducted using the PHOENICS 3.3.1 software package, which is based on the control volume method. The same initial flow conditions were used for all numerical experiments. A correction of the stress model of turbulence was performed taking into account the effect of damping-promoting interactions of the gas and the solid phase. The two-phase flow was solved using the full Reynolds stress model of turbulence, while the complete model was employed for turbulent stresses and turbulent temperature fluxes. The conducted numerical simulations yielded the distribution of the velocities of transported particles, showing that no precipitation occurred in the channel and proving that the desired transport could be realized.

Nomenclature

Latin symbols

A	–	cross-section surface, [m^2]
a	–	heat diffusion coefficient, $a = \lambda/\rho c_p$
b	–	buoyancy force coefficient
c_p	–	specific heat, [$Jkg^{-1}K^{-1}$]
g	–	solid particles diameter, [m]
k	–	kinetic turbulence energy, [m^2s^{-2}]
m	–	particle mass, [kg]
P	–	averaged pressure, [Nm^{-2}]
∇P	–	continuous phase pressure gradient
$\widetilde{P}$	–	current pressure, [Nm^{-2}]
Re	–	Reynolds number,
S	–	source term,
T	–	averaged temperature, [K]
t	–	time step, [s]
U	–	averaged velocity, [ms^{-1}]
$\widetilde{U}$	–	current velocity vector, [ms^{-1}]
$\overline{u_i u_j}$	–	components of turbulent stresses,
V	–	particle volume, [m^3].

Greek symbols

Γ	–	transport, diffusion parameter coefficient
ε	–	dissipations of turbulent kinetic energy, [m^2s^{-3}]
η	–	flow of number of particles per one cell, [s^{-1}]
$\overline{\theta u_j}$	–	turbulent temperature flux, [$kgKm^{-2}s^{-1}$]
λ	–	heat transfer coefficient, [$Wm^{-1}K^{-1}$]
ν	–	kinematic viscosity, [m^2s^{-1}]
ρ	–	density, [kgm^{-3}]
Φ	–	gas phase universal parameter,
Ω	–	vorticity, [s^{-1}].

Superscripts

i, j, k	–	vector component,
n	–	end of time step,
p	–	particle,
$\vec{x}, \vec{y}, \vec{z}$	–	position vector,
0	–	beginning of time step

Subscripts

IF	–	interphase term of gas and solid phase interaction.

Acknowledgements

This research was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia (Contract No. 451-03-65/2024-03).

References

[1] Cundall, P.A., Strack, O.D.L., A discrete numerical model for granular assemblies, Géotechnique, 29 (1979), 1, pp. 47–65
[2] Tsuji, Y., Kawaguchi, T., Tanaka, T., Discrete particle simulation of two-dimensional fluidized bed, Powder Technology, 77 (1993), 1, pp. 79–87
[3] Campbell, C.S., Brennen, C.E., Computer simulations of granular shear flows, Journal of Fluid Mechanics, 151, (1985), pp. 167–188
[4] Tanaka, T., Yonemura, S., Kiribayashi, K., Tsuji, Y., Cluster formation and particle-induced instability in gas–solid flows predicted by the DSMC method, International Journal of JSME, 39 (1996), 2, pp. 239–245
[5] Fuzhen, C., Hongfu, Q., Han, Z., Weiran G., Coupled SDPH-FVM method for gas-particle multiphase flow: Methodology, International Journal for Numerical Methods in Engineering, 109 (2017), 1, pp.73-101
[6] Jafari, M., Mansoori, Z., Saffar Avval, M., Ahmadi, G., Ebadi, A., Modelling and numerical investigation of erosion rate for turbulent two-phase gas-solid flow in horizontal pipes, Powder technology, 267 (2014), pp. 362–370
[7] Lain, S., Study of turbulent two-phase gas-solid flow in horizontal channels, Indian Journal of Chemical Technology, 20 (2013), 2, pp. 128-136
[8] Mathematical models of turbulent transport processes, (in Serbian), Collection of papers dedicated to the Academician Muhamed Riđanović, Academy of Sciences and Arts of Bosnia and Herzegovina, Sarajevo, 1984.
[9] Hinze, J.O., Turbulence, McGraw-Hill, New York, 1959
[10] Bird B.R, Steward E.W., Lightfoot N.E., Transport Phenomena, Now York, 2001
[11] Stevanović Ž., Numerical aspects of turbulent impulse and heat transfer, (in Serbian), Faculty of Mechanical Engineering, University of Niš, Niš 2008
[12] Sijerčić M., Mathematical modelling of complex turbulent transport processes (in Serbian), Yugoslav Society of Thermal Engineers – Edition: Scientific research achievements, Belgrade 1998.
[13] Milanović S., Research into the turbulent two-phase flow in straight channels with a non-circular cross-section during the pneumatic transport of granular materials, PhD Thesis, Faculty of Mechanical Engineering, University of Niš, Niš, 2014
[14] Bogdanović B., Milanović S., Bogdanović-Jovanović J., Flying Pneumatic Transport (in Serbian), Faculty of Mechanical Engineering, University of Nis, Nis, 2009