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TURBULENT TWO-PHASE FLOW OF GRANULAR MATERIAL IN STRAIGHT CHANNELS OF NON-CIRCULAR CROSS-SECTION

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Abstract

In the paper has been considered the numerical simulation of pneumatic transport in straight channels of noncircular cross section. The considered turbulent two-phase flow is air - solid particles type. The numerical simulation has been performed by using CFD commercial code PHOENICS 3.3.1. Reynold stress model has been used for turbulence modelling. All numerical experiments has been performed for the same initial flow conditions and the uniqe uniform grid has been adapted. The fluid flow has been considered in the straight channels with quadratic cross section. During the simulation, the numerical grid convergence has been achieved, and all results are grid independent. The velocity distributions of transported particles have been shown, from which it can be seen that the subsidence of particles does not occur.

Keywords*: computer simulation, pneumatic transport, solid particles, two-phase flows*.

1 INTRODUCTION

Transport of any solid material can be made by movable or immovable transportmeans.Under the movable transport means it is understood road, air or seatransport, while under the immovabletransport means usual it is understood pipeline and ribbon transport.Transport of small amount of material with movable transportmeans has an advantage in the case of fast and occasional transport.However, if it comes to the need of continuous material supply, then the pipeline or ribbon transport are preferred.In engineering practice often meets pipeline transport of solid particles usually movement by air flow in channels with a non-circular cross-section.

Transported material move due to the fact that air flow act on them by aerodynamic forces, which become strong enough at appropriate air velocities for the material particles to be carried by gas flow.The movement of solid particles in pneumatic transport is chaotic, wherein the particles at one time dropping to the bottom of the channel then the lifted and often colliding or hitting the walls of the channel, but is essentially moving in the direction of the pipeline axis with the based component of the velocity, which is slower than velocity of thetransporting air.

In the paper discusses the two-phase flow are characterized by a special complex of flow phenomena which are the consequences of the interaction between the gas and solid phase, chemical reactions between the phases, elaborate heat flows with the volumetric effects of gas radiation and surface effects of particle radiation, etc.Such flows have an important influence in the complete mechanism of mass, momentum, and heat transfer in the channel and its environment.The large momentum transfer towards the channel causes large gradients of transverse velocities in the cross-sectional plane of the channel.

In this case, except the basic flow along the channel, which is extremely turbulent, in the case of developed turbulent flow in these channels flow are occurs a new phenomenon: and this is a secondary flow.The secondary flow occurs in the plane of the channel cross-section.In curved channels, where the centrifugal force acts perpendicularly on the primary flow direction inducing pressure difference in the channel cross-section, which results in the appearance of secondary flow.Also in the case of different temperatures channel walls, ie the existence of strong temperature gradients in the cross-sectional plane of the channel results in the appearance of the secondary flow.Such secondary flows are known as Prandtl's secondary flows of the first kind and are characteristic of both the turbulent and laminar flow, as well as for channels with a circular cross-section.

In the case of the developed turbulent flow, in thestraight channels with a non-circular cross-section, occurs a specificflow phenomenon in the cross-section of channel known Prandtl's secondary flow of the second kind.Even though the level of velocity of the secondary flow of this kind is only 2-3% of the average velocity of the main flow, it still has an important influence on the momentum, heat and mass transfer in the channel and its environment.

This secondary flow is the consequence of transverse gradients of primary shear stresses in the area ofchannel vertices and produces increased shear stresses towards the channel verticesby which greatly influences on the level of intensity of heat transfer from the fluid to the channel wall and vice versa.

The importance of secondary flow of the second kind definitely exerts lesser influence than the secondary flow of the first kind, however, it cannot be neglected, particularly in the cases of the two-phase gas-solid type flow with a high Stokes number, i. e. the cases of pneumatic transport of solid particles with a small diameter. In the paper is to determine the velocities of solid particles of the transported materialused a full Reynolds stress model of turbulence, where each component of Reynolds stresses is determined from its own transport differential equation.Transport solved differential equations are not exact equations of conservation but they already modeled.The basic principle used to obtain these equations is to retain the correlations in their original form up to the second order, and to model the terms which contain the third- or higher-order correlations, of same or different physical quantities, using the gradient method, i. e. express them through the gradients of known physical quantities and model constants.

2 PHYSICAL MODEL OF THE GAS AND SOLID PHASE

The basic cause of all difficulties and the most influential factor in the investigation process of momentum, heat and mass transfer is turbulence.By its nature, the turbulence is unsteady, non-linear, irreversible, stochastic and 3-D phenomenon.

The basic problem in the case of turbulent flows are consists of need for very fine discretization fields of fluid in space and time in order to meet the numerical network sufficiently dense and the smallest turbulent structures.

Turbulence also and the main cause that leads to development of secondary flow.Generating secondary flow of second kind depends primarily on the turbulent fluctuations of the velocity field.In the case of a stationary and incompressible flow, the transport equation for the vorticity component perpendicular to the plane of the cross-section Ω_1 when are all gradients along the axis of the main flow equal to zero[2,3], has the following form:

$$\begin{aligned} &\overbrace{U_2 \frac{\partial \Omega_1}{\partial x_2} + U_3 \frac{\partial \Omega_1}{\partial x_3}}^{A_1} = \\ &= \underbrace{\frac{\partial^2}{\partial x_2 \partial x_3}\left(\overline{u_3 u_3} - \overline{u_2 u_2}\right)}_{A_4} - \underbrace{\left(\frac{\partial^2}{\partial x_3^2} - \frac{\partial^2}{\partial x_2^2}\right)\overline{u_2 u_3}}_{A_5} + \underbrace{\nu\left(\frac{\partial^2 \Omega_2}{\partial x_2^2} + \frac{\partial^2 \Omega_1}{\partial x_3^2}\right)}_{A_6} \end{aligned} \quad (1)$$

The physical sense of the terms of transport eq. (1), for the vorticity component perpendicular to the plane of the cross-section Ω_1 is:A_1 - the convective transport of the vorticity component$\Omega_1$in the main fluid flow, A_4 andA_5 - the influence of turbulent stresses on the production or destruction of the vorticity component$\Omega_1$andA_6 - the process of viscous dissipation of the vorticity componentΩ_1. By analyzing the terms of the previous equation for turbulent vorticityΩ_1, one can reach a conclusion that the turbulent terms$A_4$and$A_5$are of the same order, have a dominant role, opposite signs and are separately much larger than the convective termA_1.The viscous term$A_6$is negligibly small, except in the wall zone of channel vertices.This leads to the conclusion that the difference lies between the turbulent termsA_4andA_5which are of the same order as the convective termA_1, which finally implies that that difference between the relatively large turbulent terms is the mechanism which generates secondary flow.

Will be considered fully developed turbulent flow, which means that the velocity profiles,*i. e.*velocityin the cross-sections of the channel is settled *i. e.* not changing, in the right horizontal channel of square cross-section whose walls have a constant temperature.

Two-phase flows, in the general casegas-solid particles, are characterized by a complex of a large number of mutually connected, in themselves elaborate phenomena, which are the consequences of the influence between the phases. In the consideration of such flows with the interaction between the phases, a combined approach to the solution of the flow field is adopted in flow modelling. The gas phase is solved by applying the Euler approach – the concept of continuum, while the solid phase is solved by applying the Lagrange approach – the concept of monitoring particles trajectories.The interphase interaction between the gas and solid phase is obtained through the iterative procedure of problem solution:

First step:	At the beginning of the integration of conservation equations, the gas phase is first solved without the presence of interphase terms.
Secondstep:	After a certain number of iterations, the obtained gas current field is frozen and particles are run through it. On the basis of the obtained particles trajectories, the interphase terms of the interaction between the solid and gas phase are determined.
Thirdstep:	Particles trajectories are frozen and the gas phase flow field is solved again, but now with the interphase terms obtained in the previous step.
Fourth step:	If the solution convergence is not achieved, steps two and three are repeated successively until the pre-set criterion of the solution convergence is reached.

To define a mathematical model of the gas phase, the following assumptions are adopted: the flow is steady, 3-D, incompressible, isothermal and chemically inert.To define a mathematical model of the solid phase, the following assumptions are adopted: particles are of varying dimensions, particles do not change their mass while travelling through the channel, particles have a constant temperature in the channel, the influence of particle collisions is neglected, particles lose a certain degree of momentum upon hitting the channel walls and internal obstacles and particles move stochastically.

3 MATHEMATICAL MODEL OF THE GAS PHASE

The mathematical model of the gas phase is formed for a 3-D fully developed turbulent flow in a straight channel with a square cross-section, and this fully developed turbulent flow implies that the velocity profiles in cross-sections are not changing.Steady, incompressible, turbulent flow is assumed where the channel walls have a constant temperature, different from the environmental temperature. Gravity volume force and temperature buoyancy effects are neglected.In such a case, the general equation of momentum, heat and mass transfer for the gas phase is identical to the generally known field conservation equation (Reynolds)[1,2,9], for a single-phase fluid with the addition of the interphase term:

$$\frac{\partial}{\partial t}(\rho \Phi) + U_j \frac{\partial}{\partial x_j}(\rho \Phi) - \frac{\partial}{\partial x_j}\left(\Gamma_\Phi \frac{\partial \Phi}{\partial x_j}\right) = S_\Phi + S_\Phi^{IF} \quad (2)$$

Under the conditions of isothermal flow, the effects of buoyant flow, caused by the temperature gradients, are negligible, and the density of the gas phase can be considered constant.Thus, according to the adopted assumptions of the physical model, the averaged equations of momentum, heat and mass conservation have the following forms:

- continuity equation: $\frac{\partial U_j}{\partial x_j} = 0$ (3)
- momentum equation:

$$U_j \frac{\partial U_i}{\partial x_j} - \frac{\partial}{\partial x_j}\left(\nu \frac{\partial U_i}{\partial x_j}\right) = -\frac{1}{\rho}\frac{\partial P}{\partial x_j} - \frac{\partial \overline{u_i u_j}}{\partial x_j} + S_{Ui}^{IF} \qquad 4)$$

- energy equation:

$$U_j \frac{\partial T}{\partial x_j} - \frac{\partial}{\partial x_j}\left(a \frac{\partial T}{\partial x_j}\right) = -\frac{\partial \overline{\theta u_j}}{\partial x_j} \qquad (5)$$

4 TURBULENT MODELS

The starting basis for the formation of a stress model of turbulence is the transport equation which defines the dynamics of Reynolds stresses, [2,5]:

$$\overbrace{\frac{\partial \overline{u_i u_j}}{\partial t}}^{a} + \overbrace{U_k \frac{\partial \overline{u_i u_j}}{\partial x_k}}^{b} = \overbrace{\left(\overline{f_i u_j} + \overline{f_j u_i}\right)}^{c} - \overbrace{\left(\overline{u_i u_k}\frac{\partial U_j}{\partial x_k} + \overline{u_j u_k}\frac{\partial U_i}{\partial x_k}\right)}^{d} - \underbrace{2\nu \overline{\frac{\partial u_i}{\partial x_k}\frac{\partial u_j}{\partial x_k}}}_{e} + \underbrace{\overline{\frac{p}{\rho}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)}}_{f} - \frac{\partial}{\partial x_k}\Big[\underbrace{\overline{u_i u_j u_k}}_{g^1} + \underbrace{\overline{\frac{p}{\rho}\left(u_i\delta_{jk}+u_j\delta_{ik}\right)}}_{g^2} - \underbrace{\nu\frac{\partial \overline{u_i u_j}}{\partial x_k}}_{g^3}\Big] \qquad (6)$$

The stress turbulence model implies a simultaneous solution of transport eq. (7), with the momentum eq. (5) in the Reynolds averaged form.Turbulent stresses model involves simultaneously solving the previous transport equationwhich defines dynamicsof Reynolds stresses, with equation of momentum inReynoldsaveraged form.However, in its exact form only these terms can be treated (a, b, d, andg^3, and$c$), while the other terms (e, f, g^1andg^2), represent the correlations which have to be modelled in the function of the available dependent variables.Dependent variables that are available for the modelling,for which the transport equations are solved, in the stress turbulence model are:the averaged velocity U_i, the turbulent stresses $\rho\overline{u_i u_j}$ and the velocity of the dissipation of the turbulent kinetic energy: $\varepsilon = \nu\,\overline{(\partial u_i/\partial x_k)^2}$.

The modelling of the terms in transport eq., leads to the closed form of the transport equation for Reynolds stresses:

$$U_k \frac{\partial \overline{u_i u_j}}{\partial x_k} = \frac{\partial}{\partial x_k}\left(C_g^{'} \frac{k}{\varepsilon}\overline{u_k u_n}\frac{\partial \overline{u_i u_j}}{\partial x_n}\right) + \mathsf{P}_{ij} + \Phi_{ij,1} + \Phi_{ij,2} + \Phi_{ij,z} - \frac{2}{3}\delta_{ij}\varepsilon \qquad (7)$$

where are, [1,11]:

$$\mathsf{P}_{ij} = -\overline{u_i u_k}\frac{\partial U_j}{\partial x_k} - \overline{u_j u_k}\frac{\partial U_i}{\partial x_k}\,;\; \Phi_{ij,1} = -C_1\frac{\varepsilon}{k}\left(\overline{u_i u_j} - \frac{2}{3}\delta_{ij}k\right);$$

$$\mathsf{D}_{ij} = -\overline{u_i u_k}\frac{\partial U_k}{\partial x_j} - \overline{u_j u_k}\frac{\partial U_k}{\partial x_j}\,;\; \mathsf{P} = -\overline{u_i u_j}\frac{\partial U_i}{\partial x_j}\,;$$

$$\Phi_{ij,2} = -\alpha\left(\mathsf{P}_{ij} - \tfrac{2}{3}\delta_{ij}\mathsf{P}\right) - \beta k\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right) - \gamma\left(\mathsf{D}_{ij} - \tfrac{2}{3}\delta_{ij}\mathsf{P}\right)$$

$$f_z = \frac{C_\mu^{0.75}k^{1.5}}{0.417\cdot\varepsilon}\cdot\frac{1}{x_{nz}}\,,\; \Phi_{ij,z} = \Phi_{ij,z1} + \Phi_{ij,z2}\,;$$

$$\Phi_{ij,z1} = C_{z1}\left(\overline{u_k u_m}\delta_{ij}n_k n_m - \frac{3}{2}\overline{u_k u_i}n_k n_j - \frac{3}{2}\overline{u_k u_j}n_k n_i\right)\cdot f_z\cdot\frac{k}{\varepsilon}\,;$$

$$\Phi_{ij,z2} = C_{z2}\left(\Phi_{km,2}\delta_{ij}n_k n_m - \frac{3}{2}\Phi_{ki,2}n_k n_j - \frac{3}{2}\Phi_{kj,2}n_k n_i\right)\cdot f_z$$

The closing of the stress model for Reynolds stresses, eq. (7), is performed by an additional transport differential equation for the dissipation of the kinetic energy of turbulence, so that ε is the dissipation of the kinetic energy of turbulence appears as a new additional variable which is determined from its own transport equation:

$$U_k\frac{\partial\varepsilon}{\partial x_k} = \frac{\partial}{\partial x_k}\left(C_\varepsilon\frac{k}{\varepsilon}\,\overline{u_k u_j}\,\frac{\partial\varepsilon}{\partial x_j}\right) + \frac{\varepsilon}{k}\left(C_{\varepsilon1}\mathsf{P} - C_{\varepsilon2}\,\varepsilon\right) \qquad (8)$$

Table1 The empirical coefficients of the turbulence model for Reynolds stresses

$C_g^{'}$	C_1	C_2	C_{z1}	C_{z2}	C_μ	C_ε	$C_{\varepsilon1}$	$C_{\varepsilon2}$
0.21	1.50	0.40	0.50	0.06	0.09	0.15	1.44	1.90

The transport differential equation of turbulent temperature fluxes also can not be solve in the exact form, but it is necessary as well as in solving the transport equation for the Reynolds stresses its modeling.The modelling of the terms in transport equation forturbulent temperature fluxes, it’s get the closing form of transport equation:

$$U_k\frac{\partial\overline{\theta u_i}}{\partial x_k} = \frac{\partial}{\partial x_k}\left(C_\theta\frac{k}{\varepsilon}\overline{u_k u_j}\frac{\partial\overline{\theta u_i}}{\partial x_j}\right) + \mathsf{P}_{\theta i} + \Phi_{\theta i} + \Phi_{\theta i,z} + \varepsilon_{\theta i} \qquad (9)$$

where are, [1,11]:

$$\mathsf{P}_{\theta i} = -\overline{u_k u_i}\frac{\partial T}{\partial x_k} - \overline{\theta u_k}\frac{\partial U_i}{\partial x_k}\,;\; \Phi_{\theta i} = -C_{\theta1}\frac{\varepsilon}{k}\overline{\theta u_i} + C_{\theta2}\overline{\theta u_k}\frac{\partial U_i}{\partial x_k}\,;$$

$$\Phi_{\theta i,z} = -C_{\theta1z}\frac{\varepsilon}{k}\overline{\theta u_k}n_i n_k\cdot f_z$$

Table 2 The empirical coefficients of the model of turbulent temperature fluxes

C_θ	$C_{\theta1}$	$C_{\theta2}$	$C_{\theta z1}$
0.11	2.45	0.66	0.80

5 MATHEMATICAL MODEL OF THE SOLID PHASE

The presence of solid particles in gas flows which are encountered in the vast majority of engineering processes complicate the problem to a large extent, both because of the need to model the flow of the discrete phase and due to the interaction between the phases.The presence of particles creates aerodynamic resistances which causes the change in the momentum of both phases.The mathematical model of the solid phase is based on the Lagrange concept of problem solution. The Lagrange concept implies the monitoring of trajectories of the transported material solid particles, wherebycan determine the positions – trajectories of solid particles, their momentum, velocity, temperature as well as mass change along those trajectories, and finally determine the interphase terms in motion eq. (4).

Solid particle positions are determined by solving the following motion equation for each group of particles:

$$\frac{\mathrm{d}\, x_{\mathrm{p}}}{\mathrm{d}t} = \tilde{U}_{\mathrm{p}} \tag{10}$$

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

$$\mathrm{m}_{\mathrm{p}} \frac{\mathrm{d}\tilde{U}_{\mathrm{p}}}{\mathrm{d\,t}} = \underbrace{\Re_{\mathrm{p}}\left(\tilde{U}\text{-}\tilde{U}_{\mathrm{p}}\right)}_{A} + \underbrace{\mathrm{m}_{\mathrm{p}}\,\mathrm{b}\;\mathrm{g}}_{B} - \underset{C}{\mathrm{V}_{\mathrm{p}}\,\nabla \mathrm{P}} \tag{11}$$

In previous equation (11), the first term on the right side of the equals sign*A* - represents the force of resistance to the movement of particles in relation to the gas phase and is the dominant force which acts on the solid particles in the direction of the flow, causing their motion.The second term, B, represents the gravitational force, while the third term, C, represents the buoyancy force.The gravitational and buoyancy forces are perpendicular to the direction of the particle movement, i. e. to the direction of the force of resistance to the relative movement, but are of opposite senses, thus it can be assumed that their actions on a solid particle of the transported material are in equilibrium when solving this problem.Since the vertical forces are in balance, i. e. they do not affect the movement of solid particles, only the force of resistance reaction acts on the particles of the transported material, which causes the solid particles to move along the channel.The other forces that act on the solid particles are neglected: the force due to the increase in the pressure gradient, Basset, Saffman and Magnus force which alsoact on the solid particles of transported material.

In the previous equation, in the expression for the force of resistance reaction, $\Re_{\mathrm{p}}$ - represents the function of the resistance of a solid particle and it is determined from the following expression:

$$\Re_{\mathrm{p}} = 0{,}5\; \rho\, \mathrm{A}_{\mathrm{p}}\, \mathrm{C}_{\mathrm{D}} \left| \tilde{U}\text{-}\tilde{U}_{\mathrm{p}} \right| \tag{12}$$

whereC_D - is the coefficient of the resistance of a solid particle, determined from the expres-sion:

$$\mathrm{C}_{\mathrm{D}} = \frac{24}{\mathrm{Re}}\left(1{+}0{,}15\,\mathrm{Re}^{0{,}687}\right) + \frac{0{,}42}{1{+}4{,}25{\times}10^{4}\,\mathrm{Re}^{-1{,}16}} \tag{13}$$

and applied for spherical particles of the transported material as well as for the Reynolds number$\mathrm{Re}<10^5$.

6 NUMERICAL MODEL

The fundamental problem in the analysis of the two-phase gas-solid turbulent flow is the treatment of the mutual exchange of momentum, energy and mass between the phases due to the chaotic movement of the particles shifting from one vortex to another, whereby this changes must remain in the gas phase.The mathematical model of the gas phase is established on the basis of the models developed for monophasic flow with a correction due to the presence of solid particles.A numerical model was formed for a developed two-phase gas-solid turbulent flow in a horizontal straight channel with a square cross-section, and with the side dimension of 200 mm.In order to form fully developed turbulent flow with stable velocities, and to induce and emphasize the secondary flow, known as Prandtl's secondary flow of the second kind, an $80D_h$, i. e. 18 m long channel was taken and is shown in Figure 2.

The selected numerical grid along the cross-section of the channel is non-uniform, Figure 3, which accounts for different sizes of numerical cells.There are fewer numerical cells in the central part of the channel and they have greater surfaces, while there are more of them closer to the walls and the vertices of the channel and their surface is smaller.The total mass flow ofthe transported material (particles) set through the cross-section of the channel at the entrance, is established as partial flow in the numerical cells proportional to the cell surface.

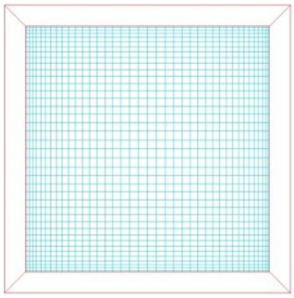

Figure 1. *Numerical grid for the channel cross-section*

Since the numerical cells differ in their surfaces, i. e. the cells close to the channel walls and vertices are smaller, the mass flows of the transported material (particles) are also smaller in them, contrary to the numerical cells situated in the central part of the channel that are larger in themselves and that have larger mass flows. Thus, if one observes the entire cross-section of the channel, one gets a steady distribution of transported solid particles along the entire cross-section.During the simulations, the fineness of the numerical grid was examined, and the paper presents the results from the highest resolution numerical grid above which the fineness of the grid did not affect the obtained results.

The mechanisms which lead to the occurrence of secondary flows in turbulent flow, as already mentioned, are different.To notice the effects of the secondary flow of the second kind in the cross-section of the observed channel, the study includes three simulation cases of the two-phase gas-solid turbulent flow, where the transporting fluid was always air while different particles were used as the transported material, namely, quartz, and flour.

Firstly, like transported material were considered solid quartz particles of 0,5[mm]in diameter and 2500[kg/m^3]in density, and then flour, with the particle diameter of0,20[mm]and density of 1410[kg/m^3]. The transported particles were assigned an initial velocity at the entrance to the channel.

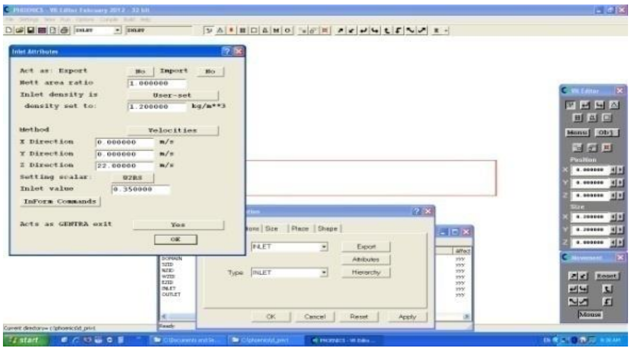

Fig.2 *Initial conditions*

Like initial velocity is taken value of suspension velocity and adopted the same value ranged from2,8[m/s], (where is forquartz2,8[m/s] and for flour 1,2÷1,5[m/s]). Apart from defining the initial velocity of the transported particles of quartz and flour, it was necessary to define the flow velocity of the transporting air at the entrance, which ranged from 12÷22[m/s] [11]. In the paper adopted the value of 22[m/s], while air pressure was taken as 1 bar with the density of 1,2[kg/m^3].

Upon the formation of the mathematical model, the transported particles were equally distributed at the channel entrance along the entire cross-section of the channel. To record the behaviour of the transported material, six groups of particles were selected and distributed along the x- and y-axis.

To perform a comparative analysis of monophasic and two-phase flows in the defined real problem, the simulation of monophasic flow was conducted under the same boundary conditions for the gas phase as in the simulations of two-phase flow for various types of transport of solid particles. Furthermore, the same fineness of the numerical grid was retained.The dominant parameter which influences the secondary flow of the second kind is the turbulent tangential stress in the cross-sectional plane of the channel, thus it was chosen as the parameter for comparing the effects of two-phase flow on the observed phenomenon.

7 RESULTS AND DISCUSSION

The fundamental problem in the consideration of the two-phase gas-solid turbulent flow is based on the change in momentum, energy and mass of the transported material while passing through a certain segment of the flow field.The change in momentum, energy and mass of transported material represents the fundamental problems in consideration of the turbulent two-phasegas-solid typeflow.The change of specified sizes during the passing through an observed control volume is taken as the source or sink of momentum of the continuous – gas phase.For solving the task of two-phase turbulent flow is used a full Reynolds stress model of turbulence,where each component of Reynolds stresses is determined from its own transport differential equation, which are modelled.

The mathematical model is arranged to observe the movement of solid particles of spherical shape, the recommended values of the equivalent diameter and density.How is chosenthe numerical grid withdifferent sizes of numerical cells, the total mass flow ofset through the cross-section of the channel at the entrance, is established as partial flow in the numerical cells proportional to the cell surface.

The formation of the secondary flow of the second kind in a straight channel with a non-circular cross-section during a developed turbulent flow occurs due to the existence of the gradients of Reynolds stresses.The turbulent terms which contain Reynolds stresseshave a dominant role and are of opposite sign in the vorticity equation whose direction perpendicular to the basic flow direction.These terms express the influence of turbulent stresses on the production or destruction of turbulent vorticity.The generation of turbulent normal and shear stresses depends on the size of the velocity gradients of secondary and primary flow.The velocity gradients of secondary flow have a greater influence on the generation ofturbulent shear stresses than the primary velocity gradients in most of the cross-section during a developed turbulent flow. Secondary flow launches the small momentum fluid towards the centre of the channel and produces increased shear stresses towards the channel vertices.

The presence of particles in the gas phase leading to an increase in the difference between the terms which contains turbulent stresses, and thus to more intensive secondary flow.The solid particles affect on changesproperties in flow of the carrier fluid, in this case air and vice versa.The presence of the particles is taken into account via additional terms, which define a source or sink of interphase of momentum, mass or heat, in the gas phase conservation equations.Movement of the transported material particles is achieved the force of the reaction resistance.Besides the reaction forces of resistance which acts in the direction of particles movement and causes them to move, on the particles acting and force in a direction perpendicular to the direction of their movement for which are introduced the assumption that they are balanced.

The task is solved by an iterative procedure, where in the first iterative step only the air current is observed, and conservation equations are solved for it as if there were no solid particles.In second iterative step the obtained flow field of the gas phase is *frozen* and the movement of solid particles is observed within it, because their presence of the dispersed phase causes the appearance of additional sources of the momentum in the gas phase equations.In this *frozen* flow field of the gas phase are determined the trajectories of solid particles.Based on thus obtained trajectories, the interphase terms are determined for the interaction between the transporting air and the transported material – particles.In the third iterative step freezes the obtained trajectories of transported particles from the previous step and solves the flow field of the gas phase again. The solution of the flow field of the gas phase is now performed by taking into consideration the influence of transported particles through the previously obtained interphase interaction terms.If the solution convergence of 0.1% is achieved, the problem is solved, otherwise the iteration procedure continues simultaneously.

In the following figures shows the distribution of the transported solid particles according to the in cross-section of the channel as well as the velocities along the channels and also in cross-section.Solid particles fills the entire cross-section of the channel from input to output, thus achieving their continuous transport, Figures 3a and

4a.Figures 3b and 4b shows the change in particles velocity in the cross section of the channel, and in figures 3c and 4cshows the change in particles velocitythat are in the middle of the channel.

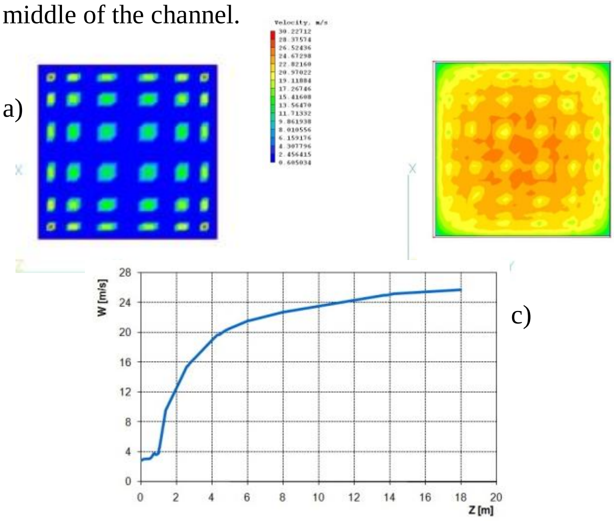

Fig. 3*Particles of flour: a)position of particles,* b)*velocity in cross-section* c)*velocityalong the channel*

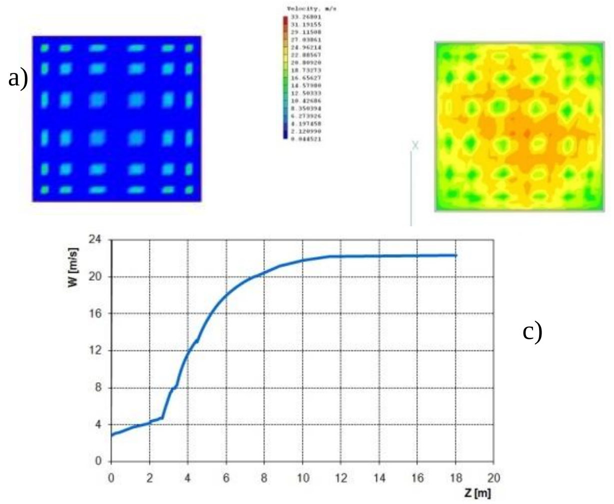

Fig. 4*Particles of quartz a) position of particles,* b) *velocity in cross-section,* c) *velocityalong the channel*

CONCLUSION

It is contemplated a fully developed turbulent flow in the right channels of non-circular cross-section, with isolated secondary flow effects of second kind. The turbulent momentum, heat and mass transfer represent the main characteristic of fluid flow which are faces every day not only in engineering and tech-nical devices as well as natural watercourses and atmospheric flows.Correction of stress turbulence model was made by taking into account the impact of secondary flows induction of second kind due expressed non-isotropyturbulence in the gas phase as well as the impactdamping-promotedinteraction effects of gas and solid phases.For solve two-phase flow its used a full Reynolds turbulence stress model, where is implemented a complete model of turbulent stresses and turbulent temperature flux.Obtained turbulent stresses model describes the physics of turbulence induction of secondary flow in straight channels of non-circular cross section and were determined interphase terms of the interaction between the gas and solid phases.The performed numerical simulations obtained velocity distribution of transported particles from where it can be seen that there will be no precipitation of the transport material in the channel and that the required transport can be achieved.Obtained is a reliable engineering tool on the basis of the numerical calculation approach to the complex phenomena of pneumatic transport of granular materials in channels with a non-circular cross-section.

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