TECHNICAL TRANSACTIONS | **CZASOPISMO TECHNICZNE**
MECHANICS | MECHANIKA

1-M/2015

ŁUKASZ MIKA*, BOGUSŁAW GÓRSKI**, RYSZARD KANTOR*

FLOW MODELLING OF SLURRY ICE IN A CONTROL VALVE

MODELOWANIE PRZEPŁYWU ZAWIESINY LODOWEJ W ZAWORZE REGULACYJNYM

A b s t r a c t

The paper presents the results of simulations of the flow of slurry ice through a control valve. The study focused on a HERZ Strömax-M DN20 control valve. The mass share of ice crystals in the studied slurry ice ranged from 5% to 20%. The results of experimental studies confirmed that the simulations were correct.

Keywords: *slurry ice flow*, *control valve*, *simulation calculating*

S t r e s z c z e n i e

W artykule przedstawiono wyniki badań symulacyjnych przepływu zawiesiny lodowej w zaworze regulacyjnym. W badaniach wykorzystano przelotowy zawór regulacyjny DN20 firmy HERZ typu Strömax-M. Udziały masowe drobinek lodu w zawiesinie w badaniach wynosiły od 5 do 20%. Wyniki badań doświadczalnych potwierdziły poprawność wyników badań symulacyjnych.

Słowa kluczowe: *przepływ zawiesiny lodowej*, *zawór regulacyjny*, *obliczenia symulacyjne*

* Ph.D. D.Sc. Eng. Łukasz Mika, Ph.D. Eng. Ryszard Kantor, Institute of Thermal and Process Engineering, Faculty of Mechanical Engineering, Cracow University of Technology.

** Ph.D. Eng. Bogusław Górski, ProBiotics Polska.

1. Introduction

Slurry ice is most often produced from carrier liquids other than pure water. Such liquids may include: aquatic solutions of ethanol; propylene glycol; ethylene glycol; even aquatic solutions of table salt (or other salts). In particular devices and applications, the initial concentration of such solutions varies. Depending on the production method, the size of the ice crystals in the slurry may also vary, in industrial installations these typically range from 0.1 mm to 0.5 mm.

As slurry ice contains ice crystals, its flow through a partially closed valve is highly unstable. Due to the ice particles in the slurry, it is quite likely that the valve may temporarily become partially or fully clogged. In light of the above, the practical use of these kind of valves to control the flow of slurry ice with a significant content of ice is highly limited.

CFD (Computational Fluid Dynamics) based modelling was used with the aim of applying a numerical model to the simulation of the flow of slurry ice through a poppet valve. Therefore, the model was expected to ensure sufficient consistency of the results of calculations with the results of experimental studies of slurry ice flow.

In the Ansys Fluent software chosen for the modelling, two approaches to the multi--phase flow problem are offered: a discrete model – i.e. an Euler-Lagrange model and an Euler-Euler model. Lagrange's method is used to describe the movement of particles, while Euler's method is applied to describe the continuous phase. An Euler-Euler model can be used for adiabatic multi-phase flow, in which Euler's approach is used for each phase of the mixture. Euler multi-phase mixture models include the volumetric model (VOF), the mixture model and the Euler model. The volumetric VOF model may be used in simulations of the flow of mixtures where a 10% dispersed fraction in the carrier liquid is not exceeded, as well as in cases of stratified or plug flow. The other two models allows for an analysis of the impact of the physical properties of the components of the mixture, the size of solid particles and their mass share. Those models also can take into consideration the creation of flow structures or phase segregation. The Mixture model and the Euler model are therefore dedicated to modelling the flow of the mixture in elbows, bends, collector tubes and valves.

When the relationships used in the models are analysed, it becomes clear that the Euler model is the most complex multi-phase model and the Mixture model is a simplification of the Euler model. The simplification is due to fact that in the Euler model, the mass and momentum conservation equations are solved for each phase of the mixture, while in the Mixture model, the continuity and motion equations are solved for the entire mixture. Nevertheless, the Mixture model for 'granular' flow makes it possible to take into consideration the physical properties of the dispersed phase, where the share of the dispersed phase in the carrier liquid may range from 0% to 100%. The model also makes it possible to take into account various velocities of particular phases or, if the velocity of the phases is identical, the model is reduced to a homogenous multi-phase flow.

The choice between the Mixture and Euler models is not completely straightforward. The Euler model, being the more complex one, requires more time-consuming calculations but allows for a greater accuracy of the results. The Mixture model also makes it possible to obtain the same level of accuracy in some cases but in a shorter time. Considering the presented objective of performing the numerical simulations of slurry ice flow, the authors decided to use the Mixture model.

2. Equations describing slurry ice flow

Slurry ice is a mixture of two phases: the carrier (liquid) phase, i.e. an aquatic solution of ethyl alcohol and ice particles (the dispersed phase) with a particular mass (volumetric) share. In the Mixture model, for an adiabatic two-phase flow, the mass conservation and momentum equations are used for the mixture and may be complemented with equations specifying the mass and momentum transfer processes between the phases [2]. In the mass conservation equation for the mixture (m), the mean mass velocity of the mixture is described by the equation:

$$\vec{v}_m = \frac{\sum_{k=1}^{n} \alpha_k \rho_k \cdot \vec{v}_k}{\rho_m} \tag{1}$$

In equation (1) k is the subsequent phase of the mixture, and ρ_m is the density of the mixture described as:

$$\rho_m = \sum_{k=1}^{n} \alpha_k \rho_k \tag{2}$$

The equation of motion for the mixture is the sum of two equations of motion for particular phases of the mixture:

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot [\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m T)] + + \rho_m \cdot \vec{g} + \vec{F} + \nabla \cdot \left(\sum_{k=1}^{n} \alpha_k \rho_k \vec{v}_{dr,k} \vec{v}_{dr,k} \right) \tag{3}$$

where:

n – describes the number of phases of the mixture,

$\vec{F}$ – body force,

μ_m – viscosity of the mixture, defined as:

$$\mu_m = \sum_{k=1}^{n} \alpha_k \mu_k \tag{4}$$

$\vec{v}_{dr,k}$ – rubbing speed of the dispersed phases of the mixture:

$$\vec{v}_{dr,k} = \vec{v}_k - \vec{v}_m \tag{5}$$

In the case of the flow of slurry ice through a valve, homogenous slurry ice flow was assumed as $\vec{v}_s = \vec{v}_a$ therefore, equation (5) adopts a null value for each of the phases, i.e. the equation of motion of the mixture (3) is simplified to the following form:

$$\frac{\partial}{\partial t}(\rho_m \vec{v}_m) + \nabla \cdot (\rho_m \vec{v}_m \vec{v}_m) = -\nabla p + \nabla \cdot [\mu_m (\nabla \vec{v}_m + \nabla \vec{v}_m T)] + \rho_m \cdot \vec{g} + \vec{F} \tag{6}$$

The volume share of the dispersed phase (ice) s is obtained from the mass conservation equation for the dispersed phase:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s) + \nabla \cdot (\alpha_s \rho_s \vec{v}_m) = -\nabla \cdot (\alpha_s \rho_s \vec{v}_s) + \sum_{p=1}^{n} \dot{m}_{ps} \tag{7}$$

The Mixture model makes it possible to calculate the dynamic viscosity coefficient of solid particles μ_s, as the sum of:

$$\mu_s = \mu_{col} + \mu_{s,kin} + \mu_{s,fr} \tag{8}$$

where $\mu_{s,fr}$ amounts to the effect of mutual friction of particles in the event of their maximum density [8]. Viscosity μ_{col} and $\mu_{s,kin}$ is related to the transfer of momentum caused by the movement of solid particles and their mutual collisions. The viscosity is described by equations (9), (10) [3]:

$$\mu_{col} = 0.8\alpha_s \rho_s d_s g_{0,ss} (1 + e_{ss}) \left(\frac{\Theta_s}{\pi} \right)^{0.5} \tag{9}$$

$$\mu_{s,km} = \frac{10\rho_s d_s (\Theta_s \cdot \pi)^{0.5}}{96\alpha_s (1 + e_{ss}) \cdot g_{0,m}} (1 + 0.8 g_{0,ss} \alpha_s (1 + e_{ss}))^2 \tag{10}$$

where:

- e_{ss} – coefficient compensating for particle collisions, $e_{ss} = 0.9$ [7],
- $g_{0,ss}$ – coefficient correcting the probability of solid particle collisions – for a single solid phase, it is described by formula [9]:

$$g_{0,ss} = \left[1 - \left(\frac{\alpha_s}{\alpha_{s,\max}} \right)^{1/3} \right]^{-1} \tag{11}$$

The equation of motion (3) refers to the laminar flow of the slurry. In the case of modelling the turbulent flow of the mixture, the aforementioned equations should be complemented with a turbulence model (dispersed or turbulence for each phase). For a multi-phase flow, with minor differences in phase densities, the recommended model is a mixture turbulence model. The concept of this model is based on the description of the turbulence model k–ε for the mixture. The equations of kinetic energy of turbulence k and dissipation of the kinetic energy of the turbulence ε for the mixture are determined by formula [2, 7]:

$$\frac{\partial}{\partial t}(\rho_m k) + \nabla \cdot (\rho_m \vec{v}_m k) = \nabla \cdot \left(\frac{\mu_{t,m}}{\delta_k} \nabla k \right) + G_{k,m} - (\rho_m \varepsilon) \tag{12}$$

$$\frac{\partial}{\partial t}(\rho_m \varepsilon) + \nabla \cdot (\rho_m \vec{v}_m \varepsilon) = \nabla \cdot \left(\frac{\mu_{t,m}}{\delta_\varepsilon} \nabla \varepsilon \right) + \frac{\varepsilon}{k}(C_{1\varepsilon} G_{k,m} - C_{2\varepsilon} \rho_m \varepsilon) \tag{13}$$

In the simulation calculations, the adopted turbulence model was RNG k–ε [1, 4, 10]. A full description of Euler's model in reference to the flow of slurry ice is included in [7].

The modelling of flow processes required the physical properties of the mixture to be determined. The adopted method of specifying the physical properties of an aquatic solution of ethyl alcohol and slurry ice is shown in [6].

A HERZ Strömax-M DN20 straight-run control valve was chosen for numerical studies of the slurry ice flow in valves. For the purposes of simulation calculations, a geometrical model of the valve was constructed on the basis of the valve previously used in experimental studies. This allowed for the elimination of the possible impact of workmanship accuracy of particular valves on the numerical calculations. The results obtained from the simulation numerical calculations were compared with the results obtained from experimental studies.

3. Simulation of the flow of slurry ice through a control valve

The simulation of slurry ice flow through a control valve was presented within the largest range of the revolution angle of the valve stem for slurries with ice contents of: 5%; 10%; 15%; 20%.

The grid of the geometrical model adopted in the calculations is shown in Fig. 1.

Various values of the mass flux of the liquid were assumed at the valve inlet, depending on the rotation angle of the valve stem. In the calculations the atmospheric pressure at the outlet of the valve was assumed. The valve inlet and outlet were extended by a section equal to double the diameter of the tube on which the valve was installed. At the remaining outer walls of the model, a constant temperature value was assumed as a boundary condition (adiabatic flow of the slurry ice through the valve).

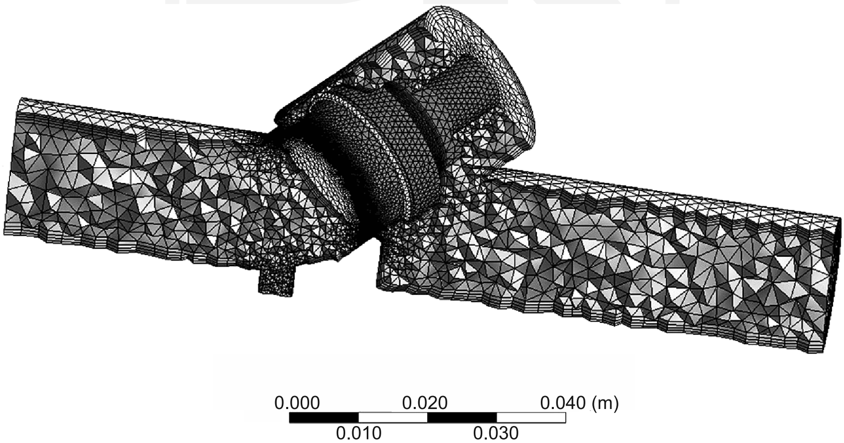

Fig. 1. Geometric model grid for slurry ice flow through a valve, multi-phase model, 3D [5]

Moreover, the model took into account locations adapted to measuring pressure drops at the valve provided by the valve manufacturer. For turbulent flow, the boundary conditions need to be complemented with the turbulence parameter (turbulence intensity). Turbulence intensity may be determined using formula [7]:

$$I_t = 0.16 \cdot \mathrm{Re}_B^{-1/8} \tag{14}$$

The simulation of slurry ice flow through the valve was performed using the Mixture model in ANSYS FLUENT. The results of numerical and experimental calculations for slurry ice flow through the valve are presented in Fig. 2 for ice contents of 5% and 10% and in Fig. 3 for ice contents of 15% and 20%. The physical properties of the slurry ice have been determined in line with the recommendations included in [6, 7].

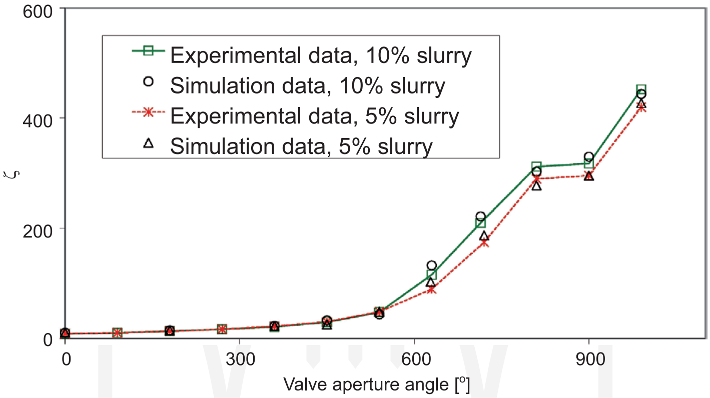

Fig. 2. A comparison of the calculated and experimental values of the local loss coefficient in the valve during the flow of ice slurry with a 5% and 10% content of ice, depending on the valve aperture angle

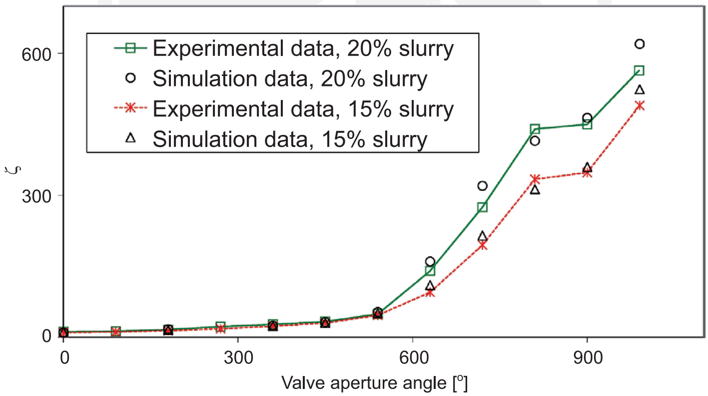

Fig. 3. A comparison of the calculated and experimental values of the local loss coefficient in the valve during the flow of ice slurry with a 15% and 20% content of ice, depending on the valve aperture angle

During comparative experimental studies of the flow of ice slurry through a control valve, flow resistances at the valve Δp_{meas} were measured. It was measured simultaneously as a sum of local resistances at the valve together with friction resistances in straight-line sections with the distance L_1 and L_2, as well as friction resistances Δp_L within a straight-line section with the length of L. Later, local resistances at the valve were determined on the basis of formula (15) [6]:

$$\Delta p_z = \Delta p_{\mathrm{meas}} - \Delta p_L \frac{L_1 + L_2}{L} \tag{15}$$

The studies relied on pressure measurement stubs installed at a distance of 80D and 50D upstream of the valve and 95D and 65D downstream of the valve.

The results of simulation calculations and experimental studies indicated a point of inflection in the characteristics of the local loss coefficient (ζ) at the valve aperture angle of ca. 800° (the moment when the poppet enters the valve socket).

4. Conclusions

On the basis of the results of experimental studies and simulation calculations, it was determined that the existing CFD modelling software can effectively be used to optimise the structure of a valve in terms of controlling ice slurry flow. Up to the aperture angle of ca. 500º there are no differences in the values of the local loss coefficients for slurry ice with various proportions of ice flowing through the valve. After that limit value of the valve aperture angle, the values of local resistance coefficients are heavily dependent on the content of ice particles in the slurry (the higher the ice content, the higher their values). The higher the content of ice particles in the slurry, the steeper the characteristics of the valve through which the slurry ice flows. The point of inflection of the characteristics of the local loss coefficient at the valve aperture angle of ca. 800° represents the moment when the poppet enters the valve socket (within a certain range, the free cross-section area in the valve through which the slurry ice flows is constant).

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