Some Aspects of Design and Modelling of Multi-phase Separation Process in Complex Channels Under Magnetic Fields

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Abstract Multiphase fluids within separated flows in complex channels were described by Navier-Stokes and Reynolds full equations for the case of complex wall configuration. Heat transfer, turbulence, presence of mass inertial forces were taken into account from multi-physics approach perspective. Modelling of separation flows was carried out using the algorithms of SIMPLE and L.M. Simuni's approach with generalization for the case with variable radius of a longitudinal gradient of pressure. Experimental validation of the modelling approach has proven to be effective for the optimisation of separators design and fluids engineering.

1 Introduction

Industrial metalworking technology requires clean and efficient processing of cutting fluids that can be contaminated by various particles both metallic and non-metallic. Separation process of working industrial fluids, often complex mixture of water-, oil-based solutions, can be described using the principles of fluids dynamics and multi-physics modelling with non-linear multi-parametric algorithms.

Separation technology for complex industrial fluids, often consisting of water-, oil-based mixture with particles produced by a working process, such as metals-cutting, can be challenging due to the several factors. First, from its physical nature a range of solid and fluid materials in separation flows can influence fluid dynamics through change of particles size and concentration, which influence fluid viscosity and flow rate. Second, size and concentration of particles in fluids affect the efficiency of separation technology in terms of both number and size of particles removed from working fluid. Third, the processing parameters of working fluids such as temperature, flow velocity, viscosity, and others can influence non-linear behaviour of fluids and result in turbulences, vortex rings and other phenomena

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reducing the operational performance of separation technology. As a result predictive modelling of separation non-linear dynamics in multi-phase fluids are commonly unknown due to multi-parametric and multi-physics aspects of this process.

Multi-phase flows and configurations of convective heat transfer in channels were consistently studied [1] by mathematical and numerical modelling of complex shear internal flows. Computational models [2, 3] were improved with the development of complex multi-parametric turbulent model of the second order for a component of full tensor of Reynolds stresses and specific scalar fluxes with original basic bases from the transport equations for scales of dissipative dynamic and thermal stress. However, these models have certain limitations. First, calculated time of these models is for simple one-parametrical models. Secondly, there is no satisfactory consent in the description of essentially anisotropic movement. In order to combine the theory and experiment the modelling was not updated with experiments.

On another side RSAM-turbulent models have been developed in order to reduce calculations of the differential equations in RANS-models. In some cases RANS-models are expressed as algebraic relationships for stresses through introduction of simplifying assumptions for convective and diffusive terms in the transport equations for Reynolds stresses. RSAM-models are used together with $k\varepsilon$—kL—or kω-equations in the form expanding two-parametrical model. Additional effects (curvature of streamlines, rotation, buoyancy etc.) can be added to governing equations through additional terms.

In the past two decades a progress in turbulence modelling was primarily focused on the possibility of complex flows analysis using RANS-models. However RANS-models do not describe effects of molecular viscosity that present significant limitations concerning modelling in terms of redistribution, diffusion, dissipation. High-Reynolds models, the study of low-Reynolds closing was not completed enough to account for the complex flows. And it is a subject of intensive research on turbulent modelling conducted by Launder, Hanjalic, Gibson, Najot [6–8]. These RANS-ε-models have provided a comprehensive modelling of flow parameters such as velocity fields, shear components of Reynolds stresses full tensor. However, these versions of RANS-models with base in the form of ε-equation cannot predict autocorrelations of pulsations of axial velocity component $\overline{u'^2}$ and a positive value of normal pressure at a wall.

The analysis of RANS-models in [6] B.E. Launder underlines, that preservation of terms to the third order in a fast part of a redistributing term appears sufficient for modelling of near-wall behaviour of turbulence. In addition research on diffusive modelling for $\overline{u_i'u_j'}$-equations has demonstrated the use of simpler form of gradient type for D_{ij}. Therefore this research and testing of these models will provide both accurate yet multi-physics approach accounting for the complexity of engineering physical and mathematical models of flow and heat transfer.

In this part developed turbulent fluids flow and heat transfer in cylindrical pipes and channels with constant and weak-changeable cross-section section is considered. It is supposed that a flow is one-component chemically inert media but consisting of multi-phase fluids such as water or oil-based solutions. Movement is axisymmetrical and carried out in the absence of external forces, gravity and volumetric sources of heat. Temperature drops can be considerable so that it is necessary to account for variability of thermos-physics characteristics of a working fluid from temperature.

The system of the equations defining a flow and heat transfer includes the equation of continuity, movement (Reynolds full equations), energy and a condition and looks like, which is presented in tensor form:

$$\frac{\partial(\rho U_j)}{\partial x_j} = 0; \tag{1}$$

$$\frac{\partial(\rho U_i U_j)}{\partial x_j} = -\frac{\partial p_1}{\partial x_i} + \frac{\partial}{\partial x_j}(\mu \frac{\partial U_i}{\partial x_j} - \rho \overline{u_i^{'} u_j^{'}}) + \frac{\partial}{\partial x_j}[\mu(\frac{\partial U_j}{\partial x_i} - \frac{2}{3}\frac{\partial U_i}{\partial x_i}\delta_{ij})]; \tag{2}$$

$$c_p \frac{\partial(\rho U_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}(\lambda \frac{\partial T}{\partial x_i} - \rho c_p \overline{u_i^{'} t^{'}}); \tag{3}$$

$$p_0 = \rho R_0 T; \tag{4}$$

The used designations in these (1)–(4) are standard, all values are averaged ones (Reynolds averaging). For closing of the defining equations the model of turbulence with the equations of balance of the one-point correlation moments of the second order of pulsations of velocity field $(\overline{u_i^{'} u_j^{'}})$ and temperatures $(\overline{u_i^{'} t^{'}})$ is involved.

The (4)–(6) are integrated at the input (X = 0)—homogeneous profiles of averaged and fluctuated values, at the exit (X = XK)—so-called “soft” boundary conditions. At the wall (r = R)—absence of flow for hydrodynamic values and thermal stability for averaged temperatures (T = Tw or qw = const), the turbulent heat flux is neglected due to small value. At the axis (r = 0)—a condition of symmetry for all values, except shear stresses and a radial heat flux.

$$\frac{D}{Dt} = U\frac{\partial}{\partial x} + V\frac{\partial}{\partial r}; \quad a = \frac{\nu}{\mathrm{Pr}}; \quad P_{ij} = -\overline{u_i^{'} u_\alpha^{'}}\frac{\partial U_j}{\partial x_\alpha} - \frac{\partial U_i}{\partial x_\alpha}; \tag{4}$$

$$\begin{aligned} &f_\mu = (1 + 3.45/\sqrt{\mathrm{Re}_t})[1 - \exp(-y^+/85)]; \ f_{\mu\theta} = f_\mu f(\mathrm{Pr}); \\ &f(\mathrm{Pr}) = 0.5 \cdot \left(1 + 0.871/\sqrt{\mathrm{Pr}}\right); \end{aligned} \tag{5}$$

$$f_2 = \left[1 - \exp\left(\frac{-y^+}{4.9}\right)\right]^2; \ \mathrm{Re}_t = k\tau/\nu \ l_{\overline{u_i^{'} t^{'}}} = f(\mathrm{Pr})\tau\sqrt{k}; \tag{6}$$

$c_{k1} = 0.9$; $c_{d1} = 1.853$; $c_{d2} = 0.83$; $c_{d3} = 1.7$; $c_{d4} = 1.44$; $d_2 = 1.4$; $d_3 = 140$; $d_4 = 0.7$; $c_{\mu\theta} = 0.15$; $c_\mu = 0.09$; $c_{\mu1} = 0.225$; $c_{\mu2} = 0.066$; $c_{\varepsilon1} = 1.44$; $c_{\varepsilon2} = 1.7$.

2 Results

The modelling and experiments are validated for the cases of turbulent convective swirled and direct-flows. Computational modelling and experimental validation of mechanical design for separation equipment resulted in the following findings.

The multiphase flows in complex channels were described by Navier-Stokes and Reynolds full equations for the cases of complex wall configuration (sudden expansion, narrowing, condenser-diffuser sections) and accounted for heat transfer, turbulence, presence of mass inertial forces (i.e. swirling was carried out by a method of local swirling in the field of an input and method of a rotating wall of a pipe round the longitudinal axis). Modelling of stationary laminar and turbulent subsonic, chemically inert, not isothermal axisymmetric flows was carried out finite elements technique using the joined algorithms of SIMPLE and L.M. Simuni's approach with generalization for a case variable radius of a longitudinal gradient of pressure.

The modelling approach with the SIMPLE algorithm can be applied to strong swirled laminar and turbulent flows observed in the studies system with magnetic fields (Ro > 4, h/d = 0.5—flows in pipes with local swirling in the field of an input; Ro > 2, h/d = 0.5—a rotating wall) and with L.M. Simuni's generalised algorithm for other cases of isothermal and not isothermal, laminar and turbulent axisymmetric flows in cylindrical pipes with complex surface (condenser-diffuser sections, sections of expansion—narrowing). Calculations were well supported and correlated with experimental results. For swirled isothermal and not isothermal turbulent flows the modelling approach included the transport equations for a component of full tensor of Reynolds stresses, specific turbulent thermal fluxes and basic bases from two-parametrical kL, k_ dynamic and thermal models with the equations for dissipative times of scalar and dynamic fields, integrated scale of turbulence presented in Figs. 1, 2, and 3. In Fig. 1 calculation is solid line, symbols lines are experimental data [4, 5]: Ro = 0 (1, ■), 0.5—(2, ▲), 1—(3, ●).

Hydrodynamics and heat transfer modelling was completed for the case of a flow laminarisation. Results of modelling have good correlation of calculations of local

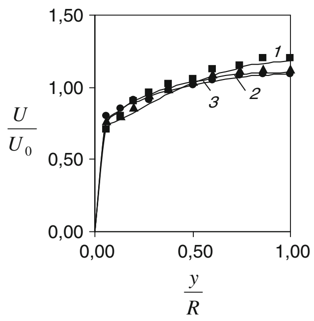

Fig. 1 Radial distribution of U/U_0 axial velocity in section $x/D = 4$ at various swirling parameter Ro

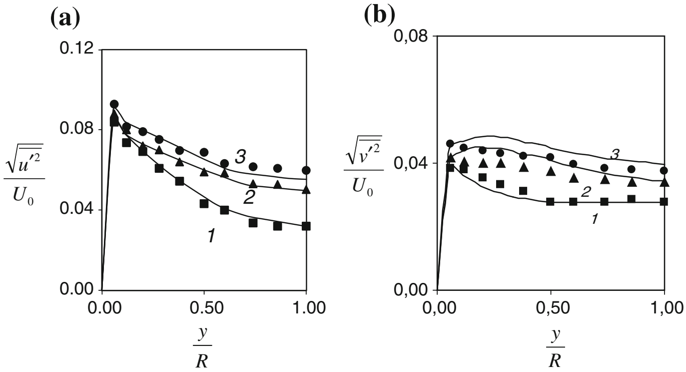

Fig. 2 Radial distributions of correlations of velocity pulsations $\overline{u_i^{'} u_j^{'}}$ in channel section x/D = 4 at various parameters Ro

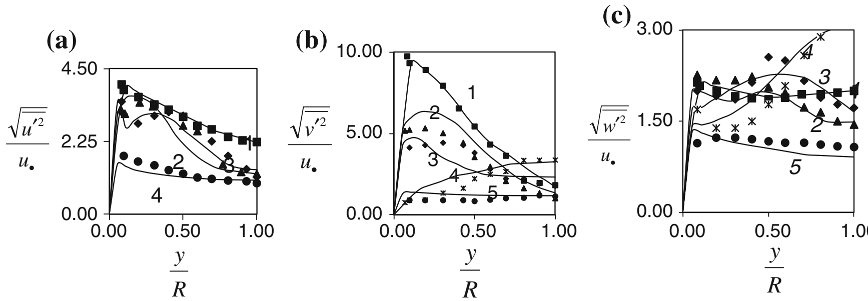

Fig. 3 Radial distributions of pulsated intensity of normal velocity components (axial—**a**, radial—**b**, tangential—**c**) at Ro = 3 in an entrance site. Line is calculation, symbols are experimental data [6]: ■—x/D = 0.35, ▲—5.1, ♦—10, *—50, ●—100

anisotropic turbulence on RANS-, RSAM-models. Modelling results could be used for the general theory of rotating turbulent flows and universal statistical models for turbulent momentum and heat transfer in internal systems, in Figs. 4, 5 and 6.

3 Discussion

This research presented the preliminary results of MAGFIS project that aims to provide the technology advancements and innovation in separation magnetic equipment design. This research contributed to the development of Navier-Stokes and Reynolds equations for the cases of complex wall configuration and includes the algorithms of SIMPLE and L.M. Simuni's approach with generalization for a variable gradient of pressure. The experiments with fluids and modeling approach

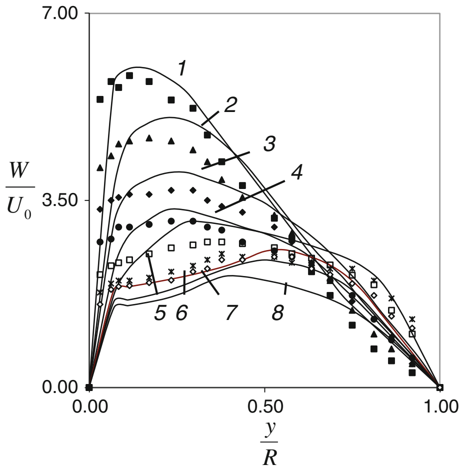

Fig. 4 Radial profiles of tangential velocity at K = 6. *Solid line* is calculation, symbols are experiments—x/D = 0 (■), 2–2 (▲), 3–4.5 (♦), 4–7.05 (●), 5–10.6 (○), 6–14.1 (*), 7–16

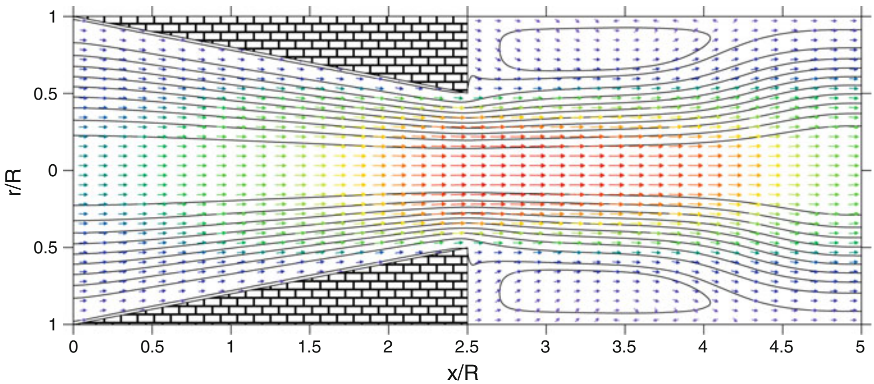

Fig. 5 Streamlines and a vector field in the channel flow with gradual narrowing to the channel middle (Re = 20, hR/R = 0.5, hx/L = 0.5)

was effective in optimising operational regimes and design approach to complex channels with magnetic fields, affecting transport of industrial fluids. A range of benefits also include (a) the ability to optimize performance and efficiency of equipment, (b) understanding of multi-phase flow allowing savings of processing materials and (c) the ability to reduce the environmental impact of fluids by materials recycling and removal.

The novelty of the works lies in the systematic approach to design, modelling and experimental validation of industrial magnetic separator with innovative design

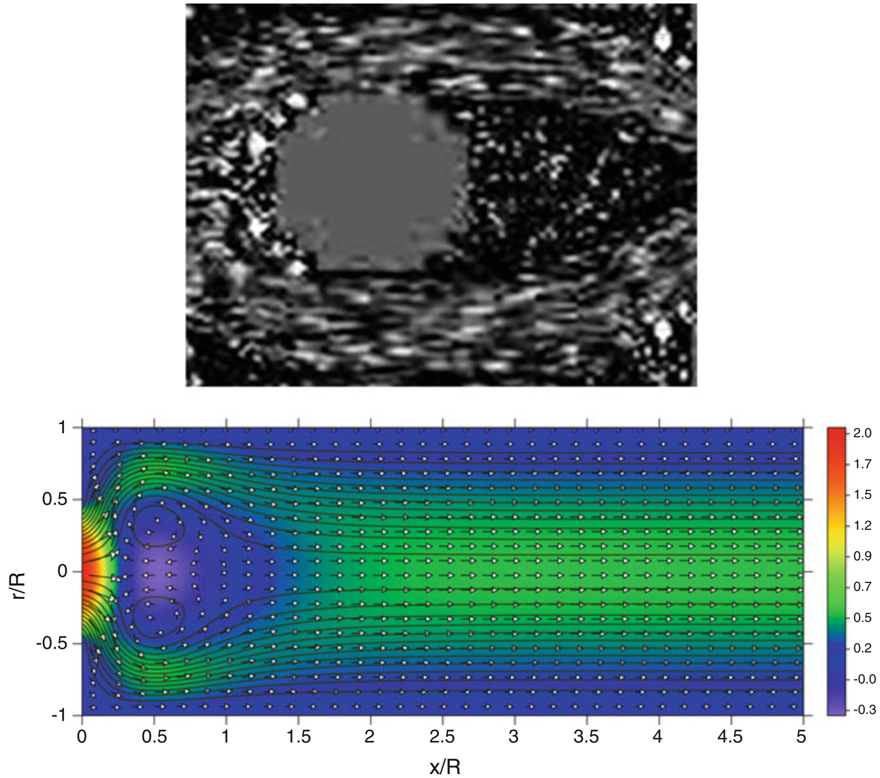

Fig. 6 Experimental streamlines and modelled vector fields of swirled flow at the input in conditions of suddenly extended chamber of separation channel (Re = 20, h/R = 0.5, Ro = 6)

and engineering concepts. Ideas presented here also enabled wider application of magnetic separators in the metals-working industry.

In conclusion it might worth mentioning the application and benefits of this research. Application of these modelling results include the following: (a) the ability to optimize performance and efficiency of separation technology, (b) the fundamental understanding of multi-phase flow of industrial fluids with particles affecting dynamic behaviour of process flows and stability of equipment and (c) the ability to improve both the economy of industrial process and environmental efficiency arising from recycling of extracted materials from contaminated fluids. The main scientific contributions of this research lies in the combination of the following: (I) the development of computational methods and tools to predict performance of the separation systems, (II) the development of some aspects for design of next generation separators with magnetic elements and (III) multi-physics modelling tools for experimental validation and practical assessment of separators performance. Modelling in its way can provide the foundation for design and development of separation technology and innovative equipment, which uses for example magnetic columns and pipes in order to separate magnetic materials from industrial fluids, thereby assisting to achieve longer fluids life, environmental and economic benefits yet the quality of surface engineering.

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