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U.K. Zhapbasbayev[1], D.Zh. Bossinov[1], M.A. Pahomov[2], Z. Sattinova[3]✉

[1]*Satbayev University, Almaty, Kazakhstan;*
[2]*Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia;*
[3]*L.N. Gumilyov Eurasian National University, Astana, Kazakhstan*

Modeling of Turbulent Non-Isothermal Flow in a Heating Network Pipe

The article presents a mathematical model of turbulent non-isothermal flow of viscoplastic fluid in a pipe with a sudden expansion of the heat network. Heat exchange of non-isothermal flow of viscoplastic fluid with cold environment leads to an increase in its viscosity and yield strength. Shvedov-Bingham rheological model represents the viscoplastic state of fluid. The Reynolds Stress Model (RSM) turbulence model describes the properties of anisotropy of the velocity components of pulsating motion in a pipe with a sudden expansion. In addition, the ability to predict turbulence anisotropy of the RSM model is used to construct a linear model of turbulent viscosity. Calculation data are obtained for different values of Reynolds and Bingham numbers. The calculation results show that with an increase in the Bingham number, the circulation zone decreases behind the section of the sudden expansion of the pipe. The results of the comparison of the radial profiles of the normalized axial mean and fluctuation velocity with the experimental data along the pipe with sudden expansion are given. The results show the anisotropic property of the axial and radial profiles of the velocity of fluctuation movement, which are in agreement with the data of the DNS (Direct Numerical Simulation) model.

Keywords: sudden expansion pipe, non-isothermal turbulent flow, viscoplastic fluid, RSM model of turbulence, yield strength, heat transfer, recirculation region, fluctuation velocity

✉*Corresponding author*: Sattinova Zamira, sattinova.kz@gmail.com

Introduction

Sudden expansion of flow is widely used to intensify transfer processes in Newtonian flows (NF) and is encountered in many technical devices, for example, when connecting pipes of different diameters. Knowledge of the flow and heat transfer characteristics in separated flows is important from both fundamental and practical points of view. The flow in a sudden expansion pipe has been frequently used by several authors to test and evaluate turbulence models. Such a flow combines a region of strong nonequilibrium, a recirculation region, after which the flow returns to equilibrium. The sudden expansion pipe has also been the subject of many experimental studies, providing useful information and improving our understanding of turbulence. Of industrial interest is the application in flows associated with turbulence, such as corrosion in the heating network [1]. The separation and reattachment of flows in a sudden expansion pipe were studied experimentally in [2–6]. A numerical study was carried out in [7], where the (k-e) and algebraic stress models and their modifications to account for the curvature of streamlines were considered. As a result, it was shown that the modified algebraic stress model gives a better agreement with the experimental data [8].

It should be noted that we have not found any experimental or numerical works devoted to heat transfer in turbulent separated non-Newtonian flows, with the exception of [9]. The aim of this work is a numerical study of the flow structure, kinetic energy of turbulence and heat transfer of a non-Newtonian fluid in a pipe with sudden expansion. The novelty of this work is also the consideration of the dependence of viscosity and yield strength on temperature.

1. Mathematical model

1.1 Statement of the Problem

The pipe diameter at the inlet $D_1 = 2R_1 = 0.2\ m$, and after a sharp expansion $D_2 = 2R_2 = 0.3\ m$, the step height $H = 0.05\ m$, $\frac{H}{(2R_1)} = 0.25$, the expansion coefficient $ER = ER = \left(\frac{R_2}{R_1}\right)^2 = 2.25$. The pipe length

$L = 12\ m\left(\dfrac{x}{D_2} = 40\right)$. The average axial velocity and average temperature at the inlet $U_{m1} = 0.2 - 0.8\dfrac{m}{s}$, $T_1 = 303\ K$, respectively. The wall temperature is constant and varies within the range $T_w = 273 - 293\ K$. The Reynolds number $Re = \dfrac{U_{m1}D_1}{v_{w1}} = (0.7-3)\cdot 10^4$, where $v_{w1} = \mu_{w1}/\rho$. The Prandtl number of paraffinic oils at the inlet is $Pr = \mu_{w1}C_{p1}/\lambda_{w1} = 42$.

1.2 Basic equations

The basic equations of non-isothermal turbulent motion of a viscoplastic fluid are given in [10, 11]:

$$\nabla \cdot U = 0 \tag{1}$$

$$\nabla\cdot(\rho UU) = -\nabla P + \nabla\cdot\left(2\mu_{eff}S\right) + \nabla\cdot\left(-\rho u'u'\right) + \nabla\cdot 2\mu'_{eff}S' \tag{2}$$

$$\nabla\cdot\left(\rho C_p TU\right) = \nabla\cdot(\lambda\nabla T) + \nabla\cdot\left(-\rho C_p u't'\right) + \tau:\nabla U \tag{3}$$

The coefficient of effective molecular viscosity μ_{eff} is found from the expression [12–15]:

$$\mu_{eff} = \begin{cases} \mu_p + \tau_0\left|\dot{\gamma}\right|^{-1}, & |\tau| > \tau_0 \\ \infty, & |\tau| \le \tau_0 \end{cases} \tag{4}$$

The singular property $|\tau| \le \tau_0$ of formula (4) can be regularized using the approach [14, 15] and written as:

$$\mu_{eff} = \mu_p + \frac{\tau_0\left[1 - \exp\left(-m|\dot{\gamma}|\right)\right]}{|\dot{\gamma}|}, \tag{5}$$

where the regularization parameter is $m = 1000\,s$ [16].

The system of basic equations (1–5) is considered together with the RSM model of turbulent stresses, which is written in the form [17, 18]:

$$\frac{\partial}{\partial x_j}\left(\rho U_j u'_i u'_j\right) = \rho\left(P_{ij} + \phi_{ij} - \varepsilon_{ij}\right) + \frac{\partial}{\partial x_l}\left[\rho v_{eff}\delta_{lm} + \rho\frac{C_\mu T_T}{\sigma_k}u'_l u'_m\right]\frac{\partial}{\partial x_m}u'_i u'_j + D_{NNF}$$

$$\frac{\partial}{\partial x_j}\left(\rho U_j \varepsilon\right) = \frac{1}{T_T}\left(C_{\varepsilon 1}\tilde{P} - C_{\varepsilon 2}\varepsilon\right) + \frac{\partial}{\partial x_l}\left[\rho v_{eff}\delta_{lm} + \rho\frac{C_\mu T_T}{\sigma_\varepsilon}u'_l u'_m\right]\frac{\partial \varepsilon}{\partial x_m} + \varepsilon_{NNF}$$

$$\chi - L_T^2\nabla^2\chi = 1 \tag{6}$$

here, P_{ij} and $\tilde{P} = 0.5\tilde{P}_{kk}$ are stress production terms, ϕ_{ij} is redistribution term [17], $L_T = m\left(\dfrac{k^{3/2}}{\varepsilon}, C_\eta\dfrac{v^{3/4}}{\varepsilon^{1/4}}\right)$ and $T_T = \max\left(\dfrac{k}{\varepsilon}, C_T\sqrt{\dfrac{v}{\varepsilon}}\right)$ are turbulent time and length macroscales, where $2k = u'_i u'_j$ is the turbulent kinetic energy, ε_{ij} is viscous dissipation rate tensor of turbulent stresses, $\varepsilon = 0.5\varepsilon_{kk}$, and χ is a blending coefficient, and it changes from zero at the wall to unity far from the wall [17]. The constants and model functions of the system of equations (8) are given in [17].

1.3 Boundary conditions

The flow diagram is shown in Figure 1. On the pipe wall before and after expansion:

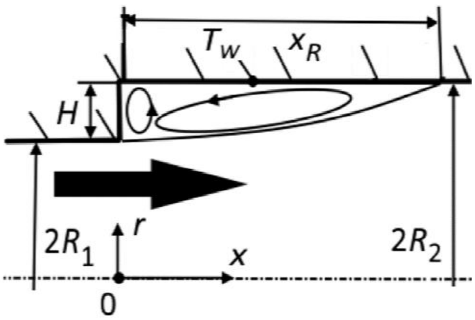


Figure 1. Flow diagram in a pipe with a sudden expansion

$$U = V = u'u' = 0;\ T = T_w = \text{const};\ \varepsilon = 2\nu_W \frac{k}{y^2};\chi = 0 \tag{7}$$

on the pipe axis:

$$\frac{\partial U}{\partial r} = V = \frac{\partial T}{\partial r} = \frac{\partial u'u'}{\partial r} = \frac{\partial \varepsilon}{\partial r} = \frac{\partial \chi}{\partial r} = 0 \tag{8}$$

Constant values of variables are set at the pipe inlet, and soft boundary conditions are set at the outlet.

2. Numerical realization

The numerical solution is obtained using a control volume method on a staggered grid. The algorithm for solving the system of equations (1)–(6) in the variables “velocity — pressure components” is described in detail in the work [10, 19]. All numerical predictions are performed using the “in-house” code.

The numerical method was verified by comparison with the experimental results [19] of isothermal flow in a pipe with a sharp expansion (Fig. 2). It is known [20] that the generalized model of a Newtonian fluid can describe non-Newtonian flows that thin under shear. The regime parameters, properties of Newtonian and non-Newtonian fluids with xanthan gum (XG) are given in Table. The power-law fluid was an aqueous solution with 0.2 % XG with an index n = 0.34 by weight [21] and 0.1 % XG with n = 0.43 [19]. The difference in the average axial velocity profiles between the results for NF and NNF is insignificant (Fig. 2*a*). The average axial velocity profiles for NF and NNF are similar in the experiments [19] and the authors’ calculations. The recirculation length in NNF is 20 % shorter than in NF (Table). The radial velocity profiles of axial pulsations show agreement between the measurements [19] and the authors’ calculations (Fig. 2*b*).

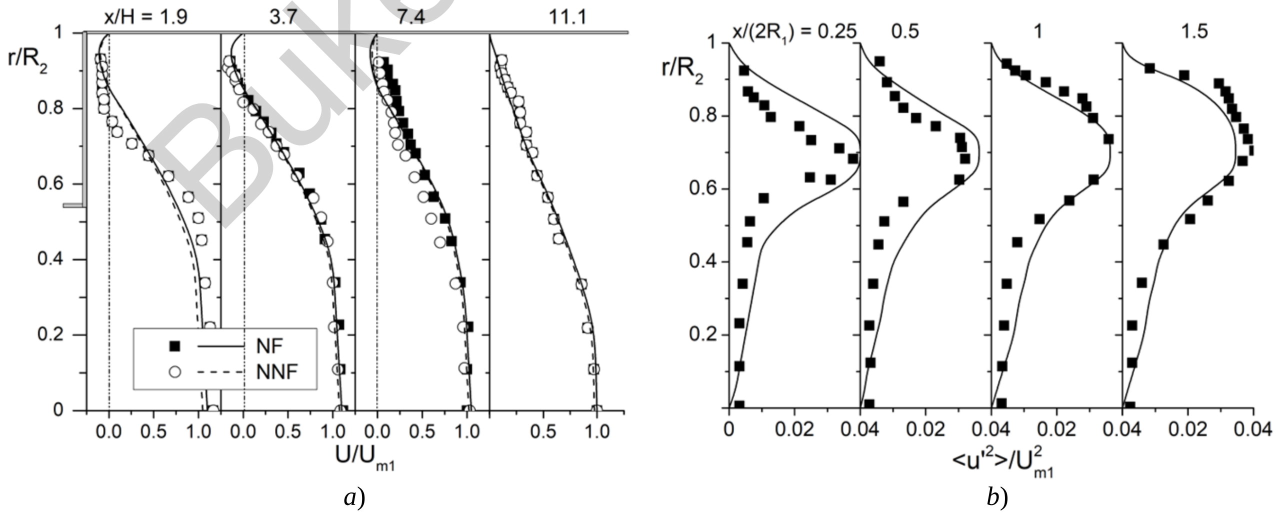


Figure 2. Radial profiles of axial average (*a*) and fluctuation (*b*) velocity along a pipe with sudden expansion. Symbols are measurements [18, 20], lines are authors’ calculations

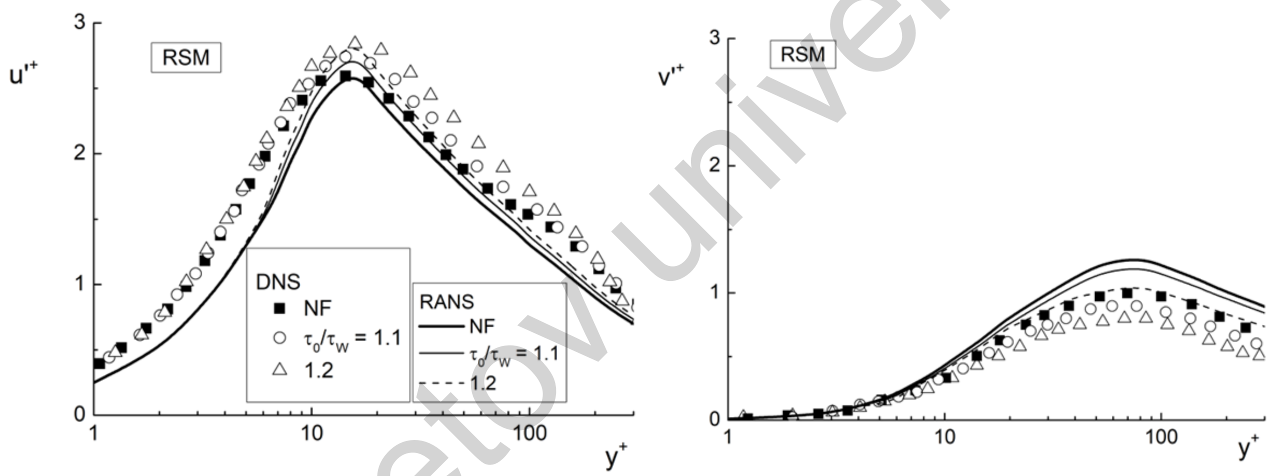
T a b l e

The length of recirculation region. Comparisons with measurements of [18]

Fluid	U_{m1}, m/s	Re_W	x_R/H [14]	Authors' simulations
Water	4.61	1.35×10^5	8.43	9
Water	1.73	5.03×10^4	8.71	9
0.1 % XG	3.04	1.96×10^4	6.93	7.5
0.2 % XG	4.05	1.94×10^4	7.14	7.4
0.2 % XG	5.01	2.72×10^4	6.78	7.3

3. Discussion of calculated data.
Viscoplastic turbulent flow in a pipe without sudden expansion

Figure 3 shows comparisons of the pulsating velocity in the axial and radial directions with the DNS data [22]. The RSM model qualitatively describes the anisotropy of the axial and radial velocity pulsation profiles well (Figs. 3*a* and 3*b*). The maximum discrepancy between DNS and RANS of the authors is up to 20 %. The positions of the maximum values and practically coincide with the DNS data [22]. The predictions obtained confirm the possibility of successfully using the RSM model to describe the non-isothermal turbulent flow of a viscoplastic fluid without additional terms in the RSM transfer equations.



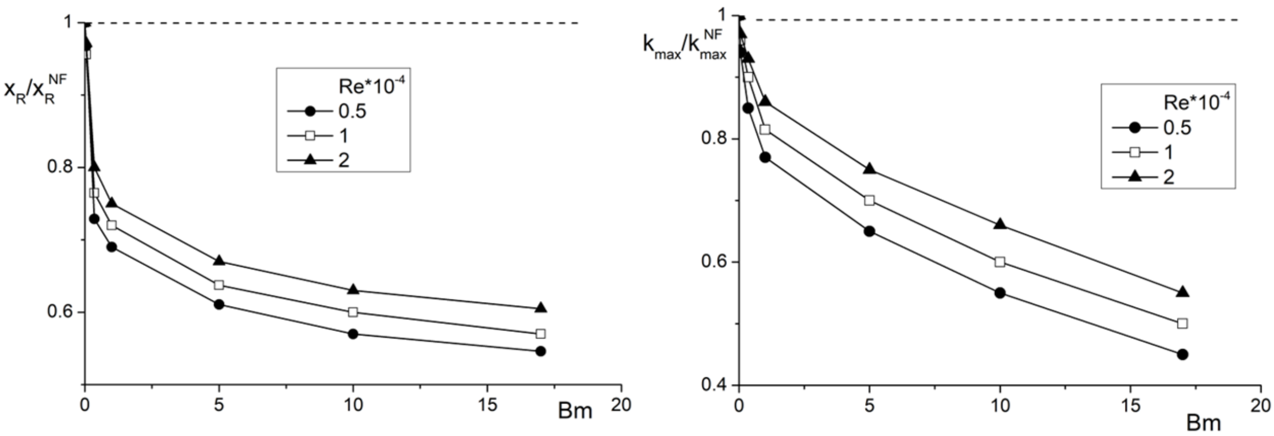
a) *b*)

Figure 3. Comparison of the results of calculations of the RSM model of axial (*a*) and radial (*b*) velocity fluctuations with the results of DNS [21]

4. Calculated data of turbulent flow of viscoplastic fluid.
Structure of viscoplastic fluid flow

Figure 4 shows the distributions of the recirculation length (a) and maximum values of turbulent kinetic energy (b) of isothermal viscoplastic fluid from Bingham numbers Bm. Here x_R^{NF} and $k_{\max}^{NF}$ are the recirculation length of the flow and the maximum value of turbulent kinetic energy Newtonian fluid (NF), respectively.

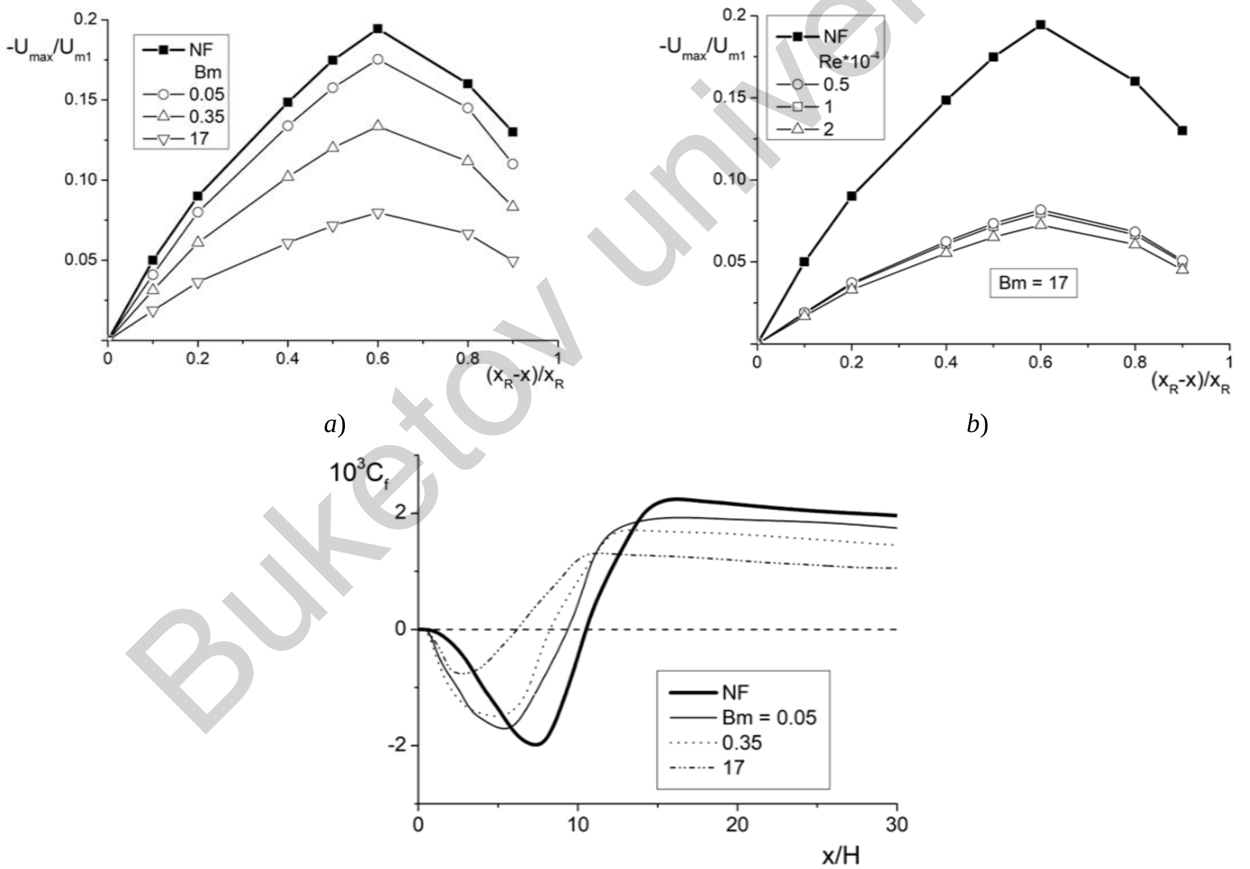
The non-Newtonian fluid causes a significant decrease in the length of the recirculation flow zone and the turbulence level (Figs. 4*a* and 4*b*). An almost twofold decrease in the length of the recirculation region is shown at Bm = 17 compared to the flow of a Newtonian fluid (Bm = 0) (Fig. 4*a*). The decrease in turbulent kinetic energy reaches 60 % at Bm = 17 (Fig. 4*b*). The Reynolds numbers $Re = 0.5\cdot10^4$ and $2.0\cdot10^4$ do not have a large effect on the length of the recirculation zone, the difference is up to 10 % at Bm = 17.



a) *b*)

Figure 4. The effect of flow Reynolds and Bingham numbers on distributions of recirculation length (*a*) and maximal values of turbulent kinetic energy (*b*)

Figure 5 shows the influence of the Bingham (a) and Reynolds (b) numbers on the maximum average axial value of the reverse flow of an isothermal viscoplastic fluid.



c)

Figure 5. The effect of Bingham (*a*) and Reynolds (*b*) numbers on the maximal mean axial magnitude of reverse flow, and wall friction (*c*) of isothermal SB fluid. (*a* and *c*): Re = 10^4; (*b*): Bm = 17

For a Newtonian fluid (Bm = 0), the maximum negative values of the reverse flow $-U_{max}/U_{m1}$ reach 20 % (Fig. 5*a*) and correspond to the known data for flow in a pipe with sudden expansion [23, 24]. The calculated data for different Bingham numbers are also presented here, and a sharp decrease in the maximum negative velocity ($-U_{max}/U_{m1} \approx 0.075$) is obtained for Bm = 17 (Fig. 5*a*). It can be noted that for non-isothermal flows of viscoplastic fluid, the recirculation zone does not have a significant effect on the processes of turbulent transfer of momentum and energy compared to the Newtonian one. Similarly, an increase in the Reynolds number of the flow does not have a significant effect on the dynamics of the reverse flow (Fig. 5*b*).

The distribution of the wall friction coefficient $C_f / 2 = \tau_W / \left(\rho U_{m1}^2\right)$ along the flow is shown in Figure 5*c* for different Bingham numbers Bm. The flow reattachment point for NF and NNF is located at $C_f = 0$. The value of the wall friction coefficient is negative in the recirculation region for NF and NNF due to the reverse flow (Fig. 5*c*). Downstream of the reattachment point, an increase in the wall friction coefficient is observed and the values become positive. The wall friction in isothermal flow is greater than for viscoplastic fluid. The location of the minimum point of C_f for NNF shifts upstream by almost 2 times compared to NF due to the manifestation of non-Newtonian behavior.

A comparison of non- and isothermal viscoplastic flow following sudden expansion of a pipe is shown in Figure 6.

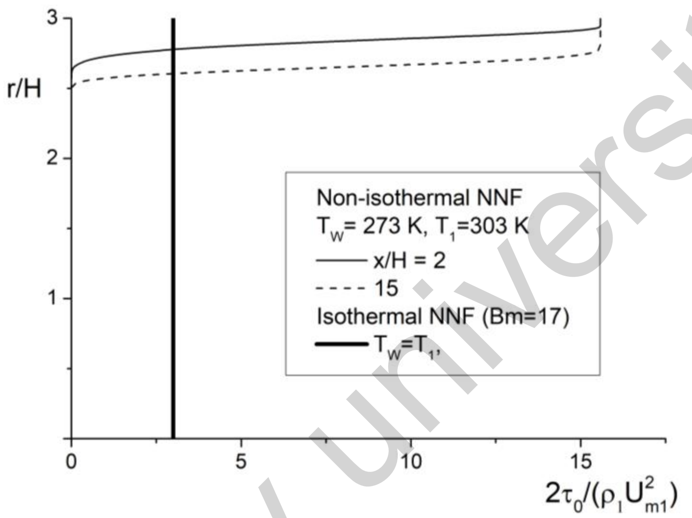


Figure 6. Distributions of yield shear stress τ_0 over the pipe radius for non- (solid and dashed lines) and isothermal (bold line) NNF behind the pipe sudden expansion

Calculation of isothermal flow NNF with a constant value of the Bingham number Bm = 17 shows a constant value of the yield strength along the pipe radius (Fig. 6). Calculations of the transition of non-isothermal turbulent flow of paraffinic crude oil show a more complex flow behavior. In the flow core, the yield strength value becomes zero ($\tau_0 \approx 0$) and in this zone the flow is Newtonian (Fig. 6). In the recirculation zone (x/H = 2) and near the pipe wall at (x/H = 15), the yield strength $\tau_0 \approx 16$ (Fig. 6). Viscoplastic flow of the liquid takes place in this region.

Conclusion

The results of modeling non-isothermal turbulent flow in a pipe with expansion show the correctness of the developed mathematical model. In particular, a comparison of the radial profiles of the normalized axial average and fluctuation velocity with experimental data along a pipe with sudden expansion is carried out. The calculations show the anisotropic property of the axial and radial profiles of the fluctuation motion velocity, which is in agreement with the data of the exact DNS model. Viscoplasticity of a turbulent fluid leads to the following effects: 1) reduction of the length of the recirculation zone and reduction of the kinetic energy of the fluctuation motion; 2) reduction of the maximum negative velocity ($-U_{max}/U_{m1} \approx 0.075$) and reduction of the friction coefficient $C_f / 2 = \tau_W / \left(\rho U_{m1}^2\right)$ in the recirculation zone. In general, the recirculation zone of a viscoplastic fluid does not have a significant effect on the processes of turbulent momentum and energy transfer compared to the Newtonian one.

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У.К. Жапбасбаев, Д.Ж. Босинов, М.А. Пахомов, З.К. Саттинова

Жылу желісі кенеттен кеңейгенде құбырдағы тұтқырпластикалы сұйықтықтың турбулентті ағынын модельдеу

Мақалада жылу желісінің кенеттен кеңеюі бар құбырдағы тұтқырпластикалы сұйықтықтың турбулентті изотермиялық емес ағынының математикалық моделі келтірілген. Тұтқырпластикалы сұйықтықтың изотермиялық емес ағынының суық ортамен жылу алмасуы оның тұтқырлығы мен аққыштығының жоғарылауына әкеледі. Шведов-Бингем реологиялық моделі сұйықтықтың тұтқыр-пластикалық күйін көрсетеді. RSM турбуленттік моделі кенет кеңеюі бар құбырдағы пульсациялы қозғалыстың жылдамдық компоненттерінің анизотропиясының қасиеттерін сипаттайды, сонымен қатар турбуленттілік анизотропиясын болжау мүмкіндігі турбуленттік тұтқырлықтың сызықтық моделін құру үшін қолданылады. Есептелген деректер Рейнольдс және Бингам сандарының әртүрлі мәндері үшін алынды. Есептеу нәтижелері Бингам санының ұлғаюымен құбырдың кенеттен кеңею қимасының артында циркуляциялық аймақтың кішірейетіндігін көрсетеді. Нормаланған осьтік орташа және флуктуация жылдамдығының радиалды профильдерін кенет кеңеюі бар құбыр бойындағы тәжірибелік мәліметтермен салыстыру нәтижелері берілген. Нәтижелер DNS (Direct Numerical Simulation) моделінің деректерімен сәйкес келетін тербелмелі қозғалыстың осьтік және радиалды жылдамдық профильдерінің анизотропты қасиеттерін көрсетеді.

Кілт сөздер: кенеттен кеңею құбыры, изотермиялық емес турбулентті ағын, тұтқырпластикалы сұйық, RSM турбуленттік моделі, аққыштық шегі, жылу тасымалдау, рециркуляция аймағы, флуктуация жылдамдығы

У.К. Жапбасбаев, Д.Ж. Босинов, М.А. Пахомов, З.К. Саттинова

Моделирование турбулентного течения вязкопластичной жидкости в трубе тепловой сети с резким расширением

В статье приводится математическая модель турбулентного неизотермического течения вязкопластичной жидкости в трубе с резким расширением. Теплообмен неизотермического потока вязкопластичной жидкости с холодной окружающей средой приводит к повышению ее вязкости и предела текучести. Реологическая модель Шведова-Бингама представляет вязкопластичное состояние жидкости. RSM модель турбулентности описывает свойства анизотропности компонент скорости пульсационного движения в трубе с резким расширением. Расчетные данные получены при различных значениях числа Рейнольдса и Бингама. Результаты расчетов показывают, что с ростом числа Бингама циркуляционная зона сокращается за сечением резкого расширения трубы. Приведены результаты сравнения радиальных профилей нормализованной осевой средней и флуктуационной скорости с опытными данными вдоль трубы с внезапным расширением. Результаты показывают анизотропное свойство осевых и радиальных профилей скорости флуктуационного движения, которые находятся в согласии с данными DNS (Direct Numerical Simulation) модели.

Ключевые слова: труба внезапного расширения, неизотермическое турбулентное течение, вязкопластичная жидкость, модель турбулентности RSM, предел текучести, теплопередача, область рециркуляции, скорость флуктуации

Information about the authors

Zhapbasbayev, Uzak — Doctor of Technical Sciences, Professor, Head of the Research and Production Laboratory “Modeling in Energy”, Satbayev University, 22 Satpaev Street, 050013 Almaty, Kazakhstan; e-mail: uzak.zh@mail.ru; ORCID ID: https://orcid.org/0000-0001-5973-5149

Bossinov, Daniyar — Master of Science, Research Worker, Satbayev University, 22 Satpaev Street, 050013 Almaty, Kazakhstan; e-mail: dansho.91@mail.ru; ORCID ID: https://orcid.org/0000-0003-3757-6460

Pahomov, Maksim — Doctor of Physical and Mathematical Sciences, Major Research Worker, Kutateladze Institute of Thermophysics SB RAS, Novosibirsk, Russia; e-mail: Pakhomov@itp.nsc.ru; ORCID ID: https://orcid.org/0000-0002-8127-3638

Sattinova, Zamira (*corresponding author)* — Candidate of Physical and Mathematical Sciences, Associated Professor, L.N. Gumilyov Eurasian National University, 2 Satpayev str., 010008 Astana, Kazakhstan; e-mail: sattinova.kz@gmail.com; ORCID ID: https://orcid.org/0000-0002-2990-6581