ISSN 2518-1483 (Online),
ISSN 2224-5227 (Print)

2025 • 1

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ
АКАДЕМИЯСЫ» РҚБ

«ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ» РҚБ

БАЯНДАМАЛАРЫ

ДОКЛАДЫ

РОО «НАЦИОНАЛЬНОЙ
АКАДЕМИИ НАУК РЕСПУБЛИКИ КАЗАХСТАН»

REPORTS

OF THE ACADEMY OF SCIENCES
OF THE REPUBLIC OF KAZAKHSTAN

PUBLISHED SINCE JANUARY 1944

ALMATY, NAS RK

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫНЫҢ
БАЯНДАМАЛАРЫ **2025 • 1**

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ISSN 2518-1483 (Online), ISSN 2224-5227 (Print)

Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» Республикалық қоғамдық бірлестігі (Алматы қ.).

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Тақырыптық бағыты: *физика, химия.*

Мерзімділігі: жылына 4 рет.

http://reports-science.kz/index.php/en/archive

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Доклады Национальной академии наук Республики Казахстан»
ISSN 2518-1483 (Online), ISSN 2224-5227 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы).

Свидетельство **N°KZ31VPY00111215** о повторной регистрации периодического печатного издания информационного агентства, информационного агентства и сетевого издания, выданное Республиканским государственным учреждением «Комитет информации» Министерства культуры и информации Республики Казахстан **31.01.2025**

Тематическая направленность: *физика, химия.*

Периодичность: 4 раза в год.

http://reports-science.kz/index.php/en/archive

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Reports of the National Academy of Sciences of the Republic of Kazakhstan.
ISSN 2518-1483 (Online), ISSN 2224-5227 (Print)
Owner: RPA «National Academy of Sciences of the Republic of Kazakhstan» (Almaty).
The certificate of registration of a periodical printed publication in the Committee of Information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No.KZ31VPY00111215** issued **31. 01. 2025**
Thematic scope: *physics and chemistry.*
Periodicity: 4 times a year.
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REPORTS OF THE NATIONAL ACADEMY OF SCIENCES OF THE REPUBLIC OF KAZAKHSTAN
ISSN 2224-5227
Volume 1. Number 353 (2025), 64–77

https://doi.org/10.32014/2025.2518-1483.324

UDC 532.542, 532.135

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TURBULENT FLOW OF VISCOPLASTIC FLUID IN A PIPE WITH SUDDEN EXPANSION

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Abstract. The article examines the non-isothermal turbulent flow of a yield-stress viscoplastic fluid in a pipe with a sudden expansion. The effective molecular viscosity approach is employed to represent the rheological model of the yield-stress viscoplastic fluid. To perform a thorough calculation of the undeformed region of the viscoplastic fluid, the Papanastasiou regularization method for the effective molecular viscosity formula is applied.

Numerical simulations are conducted to analyze the velocity, temperature, and turbulent kinetic energy distributions. The results indicate significant differences in the flow structure between Newtonian and non-Newtonian fluids. In the case of Newtonian fluids, a recirculation region with negative velocities is observed downstream of the sudden pipe expansion, forming a characteristic end vortex. However, for viscoplastic fluids, this vortex structure is absent due to the yield stress effects, which suppress secondary flow formation.

The heat transfer characteristics along the pipe surface are also investigated. It is found that the distributions of heat flux for turbulent Newtonian and non-Newtonian fluids exhibit qualitative similarities, although quantitative differences arise due to the fluid’s rheological properties. The study provides insight into the complex behavior of viscoplastic fluids under turbulent conditions and can be beneficial for engineering applications involving pipeline systems, heat exchangers, and energy transport processes.

Keywords: non-isothermal turbulent flow, viscoplastic fluid, yield stress, RANS, sudden expansion

Acknowledgments

This work was supported by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant number AP23486543 for 2024-2026)

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КЕНЕТТЕН КЕҢЕЮІ БАР ҚҰБЫРДАҒЫ ТҰТҚЫР-ПЛАСТИКАЛЫҚ СҰЙЫҚТЫҚТЫҢ ТУРБУЛЕНТТІК АҒЫНЫ

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Аннотация. Мақалада кенеттен кеңеюі бар құбырдағы тұтқыр-пластикалық сұйықтықтың изотермиялық емес турбуленттік ағыны қарастырылады. Тұтқырлық шегі бар тұтқыр-пластикалық сұйықтықтың реологиялық моделін сипаттау үшін эффективті молекулалық тұтқырлық әдісі қолданылады. Тұтқыр-пластикалық сұйықтықтың деформацияланбайтын аймағын түпкілікті есептеу үшін эффективті молекулалық тұтқырлық формуласы үшін Папанастасиудың регуляризация әдісі қолданылады.

Жылдамдық, температура және турбуленттіліктің кинетикалық энергиясының таралуын талдау үшін сандық модельдеу жүргізілді. Ньютондық және Ньютондық емес сұйықтықтардың ағын құрылымында айтарлықтай айырмашылықтар бар екені анықталды. Ньютондық сұйықтық жағдайында құбырдың кенеттен кеңею аймағынан кейін соңғы құйынды құрайтын теріс жылдамдықты рециркуляция аймағы байқалады. Алайда тұтқыр-пластикалық сұйықтықтарда ағымдық шектің әсерінен мұндай құйын құрылымы пайда болмайды, себебі ол екінші реттік ағынның түзілуін тежейді.

Сонымен қатар, құбырдың беті бойынша жылу алмасу сипаттамалары зерттелді.

Турбулентті Ньютондық және Ньютондық емес сұйықтықтар үшін құбырдың беті бойынша жылу ағынының таралуы сапалы түрде ұқсастық көрсетті. Зерттеу турбулентті жағдайда тұтқыр-пластикалық сұйықтықтардың күрделі әрекетін сипаттауға мүмкіндік береді және құбыр жүйелері, жылу алмастырғыштар мен энергия тасымалдау процестеріне байланысты инженерлік қолданбалар үшін пайдалы болуы мүмкін.

Түйін сөздер: изотермиялық емес турбулентті ағын, тұтқыр-пластикалық сұйықтық, аққыштық шегі, Рейнольдс бойынша орташаланған Навье-Стокс теңдеулері, кенеттен кеңею.

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ТУРБУЛЕНТНОЕ ТЕЧЕНИЕ ВЯЗКОПЛАСТИЧНОЙ ЖИДКОСТИ В ТРУБЕ С РЕЗКИМ РАСШИРЕНИЕМ

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Аннотация. В статье рассматривается неизотермическое турбулентное течение вязкопластичной жидкости в трубе с резким расширением. Для представления реологической модели вязкопластичной жидкости с пределом текучести используется метод эффективной молекулярной вязкости. Для выполнения сквозного расчёта недеформируемой области вязкопластичной жидкости применяется метод регуляризации Папанастасиу в сочетании с формулой эффективной молекулярной вязкости.

Численные моделирования проведены для анализа распределений скорости, температуры и кинетической энергии турбулентности. Результаты показывают значительные различия в структуре течения ньютоновских и неньютоновских жидкостей. В случае ньютоновских жидкостей за участком резкого расширения трубы наблюдается зона рециркуляции с отрицательными скоростями, формирующая характерный концевой вихрь. Однако у вязкопластичных жидкостей такая вихревая структура отсутствует из-за влияния предела текучести, который подавляет формирование вторичного течения. Дополнительно исследованы характеристики теплообмена вдоль поверхности трубы. Установлено, что распределения теплового потока для турбулентных ньютоновских и неньютоновских жидкостей имеют качественные сходства, однако количественные различия обусловлены реологическими свойствами жидкости.

Исследование даёт представление о сложном поведении вязкопластичных жидкостей в турбулентных условиях и может быть полезным для инженерных приложений, связанных с трубопроводными системами, теплообменниками и процессами транспортировки энергии.

Ключевые слова: неизотермическое турбулентное течение, вязкопластичная жидкость, предел текучести, уравнения Навье-Стокса, осреднённые по Рейнольдсу, резкое расширение.

Introduction

The turbulent flow of non-Newtonian fluids in pipes or planar channels, accompanied by flow separation followed by reattachment, is one of the most common cases of shear flow. The study of such separated flows is of interest both from a fundamental perspective, as it provides new insights into the turbulent structure of flows, and from a practical standpoint, particularly in applications involving the flow around sharp-edged bodies. These flows are among the most important and complex cases of wall-bounded shear flows, characterized by elevated levels of turbulence.

In the flow separation region, significant changes in velocity, pressure, and heat transfer fields are observed, along with an intensification of turbulent wall-boundary transport processes (see monographs (Chang, 1970; Alemasov, et al., 1990; Terekhov, et al., 2021) and review papers (Eaton, et al., 1981; Simpson, 1989; Polyakov, et al., 1996; Ota, 2000; Chen, et al., 2018)). Sudden flow expansion is widely used to enhance transport processes in Newtonian flows and is encountered in many technical devices, such as when connecting pipes of different diameters. Understanding the characteristics of flow and heat transfer under such conditions is crucial from both fundamental and practical perspectives.

It should be noted that despite decades of intensive research and the involvement of numerous scientific groups, a comprehensive theory of momentum and heat transfer for turbulent flows of Newtonian fluids has yet to be developed.

To date, studies on the turbulent flow and heat transfer of viscoplastic fluids in a pipe following a sudden expansion have not been well-documented in the available literature.

The aim of this work is the numerical study of flow structure and heat transfer in a turbulent flow of an incompressible non-Newtonian fluid in a pipe with sudden expansion.

Materials and Methods

Mathematical model

Rheology of a viscoplastic fluid

According to the rheology of viscoplastic fluids, the effective molecular viscosity can be expressed as follows (Schwedoff, 1981; Bingham, 1922; Wilkinson, 1960; Pakhomov, et al., 2023):

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

here τ_0 represents the yield stress and μ_p denotes the plastic viscosity. The other expressions in formula (1) are provided in (Pakhomov, et al., 2023).

However, because of mathematical complexities, expression (1) cannot be utilized without regularization. For this purpose, the formula presented in (Papanastasiou, 1987) is employed. In this case, the effective molecular viscosity has a limitation as the shear rate tends to zero $|\dot{\gamma}| \to 0$:

$$\mu_{eff} = \mu_p + \tau_0 \frac{[1 - exp(-10^3 |\dot{\gamma}|)]}{|\dot{\gamma}|} \tag{2}$$

The effect of carrier fluid temperature has a strong effect on rheological properties (Zhapbasbayev, et al., 2021; Pakhomov, et al., 2024) is taken into account by dependence of plastic viscosity $\mu_P(T)$, yield stress $\tau_0(T)$, and Bingham numbers on $\mathrm{Bm} = \tau_0 R/(\mu_P U_{m1})$ fluid temperature (waxy crude oil) (Pakhomov, et al., 2023; Pakhomov, et al., 2024) (see Table 1). These dependencies rely on the experimental data (Pakhomov, et al., 2024).

Table 1 – Values of yield shear stress, plastic viscosity and Bingham numbers vs fluid temperature of NNF

t, °C	T, K	τ_0, Pa	μ_p, Pa·s	Bm
0	273	589.6	0.36	822.32
10	283	2.03	0.06	17.01
20	293	7.01E-03	0.01	0.35
25	298	4.12E-04	0.004	0.05
30	303	2.42E-05	0.002	0.007

Governing equations

The equation system for the turbulent non-isothermal flow of viscoplastic NNF fluid is written in (Pakhomov, et al., 2023; Pakhomov, et al., 2024):

$$\nabla \cdot U = 0 \tag{3}$$

$$\nabla \cdot (\rho \mathrm{UU}) = -\nabla P + \nabla \cdot (2\mu_{eff} S) + \nabla \cdot \left(-\rho \langle u^/ u^/ \rangle\right) + \nabla \cdot \left\langle 2\mu_{eff}^/ S^/ \right\rangle \tag{4}$$

$$\nabla \cdot (\rho C_p T U) = \nabla \cdot (\lambda \nabla T) + \nabla \cdot \left(-\rho C_p \langle u^/ t^/ \rangle\right) + \tau{:}\mathrm{S} \tag{5}$$

The turbulent Reynolds stress $-\rho\langle u^/ u^/ \rangle$ are modeled using k–$\tilde{\varepsilon}$ turbulence isotropic model and RSM approach. Turbulent heat flux $\rho C_p \langle u^/ t^/ \rangle$ is given in (Pakhomov, et al., 2023). The expression $\nabla \cdot \left\langle 2\mu_{eff}^/ S^/ \right\rangle$ in equation (4) is found according to representation of (Pakhomov, et al., 2023; Pakhomov, et al., 2024). The term $\tau{:}S$ considers the dissipation of kinetic energy and has the form as in (Pakhomov, et al., 2023). Formula for the averaged shear rate can be written as (Gavrilov, et al., 2016):

$$\langle\dot{\gamma}\rangle^2 = 2\langle S_{ij}\rangle\langle S_{ij}\rangle + (\rho\varepsilon)/\langle\mu\rangle, \text{ where } \langle\mu\rangle = \frac{\tau_0}{\langle\dot{\gamma}\rangle} + k_v\langle\dot{\gamma}\rangle^{n-1}.$$

The elliptical relaxation Reynolds stress model (Fadai-Ghotbi, et al., 2008) partially considers anisotropy of complicated turbulent flows and is computationally more complicated than the isotropic two-equation *k–ε* turbulence model:

$$\nabla\cdot\left(\rho U\langle u'u'\rangle\right) = \rho\left(P_{ij} + \phi - \varepsilon\right) + \nabla\cdot\left[\rho\frac{C_\mu T_T}{\sigma_k}\langle u'u'\rangle\nabla\left(\langle u'u'\rangle\right)\right]$$

$$\nabla\cdot(\rho U\varepsilon) = \frac{1}{T_t}\left(C_{\varepsilon1}P_2 - C_{\varepsilon2}\varepsilon\right) + \nabla\cdot\left[\rho\frac{C_\mu T_T}{\sigma_\varepsilon}\left\langle u^{-}u^{-}\right\rangle\nabla\varepsilon\right] + \tag{6}$$

$$+\nabla\cdot(\mu\nabla\varepsilon) + C_{\varepsilon3}\frac{\mu k}{\varepsilon}\left\langle u'u'\right\rangle\cdot\nabla^2U\cdot\nabla^2U$$

$$\chi - L_T^2\nabla^2\chi = 1/(\varepsilon T_T).$$

Here, P_{ij} is the intensity of the energy transfer from the average velocity to the pulsating one, T_T is the turbulent time macroscale; φ is the redistribution term, ε is the dissipation rate. The constants and functions of (6) for Newtonian turbulent fluid are taken from (Fadai-Ghotbi, et al., 2008). The RSM models do not consider the effect of non-Newtonian fluid on fluid turbulence. The same assumption was used in our previous papers (Pakhomov, et al., 2023; Pakhomov, et al., 2024).

Boundary conditions

The flow schematic is shown in Fig. 1a. The boundary conditions on the wall surface ($r = R_2$), pipe axis ($r = 0$), in the inlet section ($x = 0$), and at the outlet edge ($x = L$) are stated in the paper Waxy crude oil in the inlet cross-section is considered as a NF, then the behavior of a non-Newtonian SB fluid with yield stress appears.

On the inner surface wall ($r = R_2$):

$$U = V = \left\langle u'u'\right\rangle = 0;\ T = T_w = const;\ \varepsilon = 2\nu\frac{k}{y^2};\ \chi = 0 \tag{7}$$

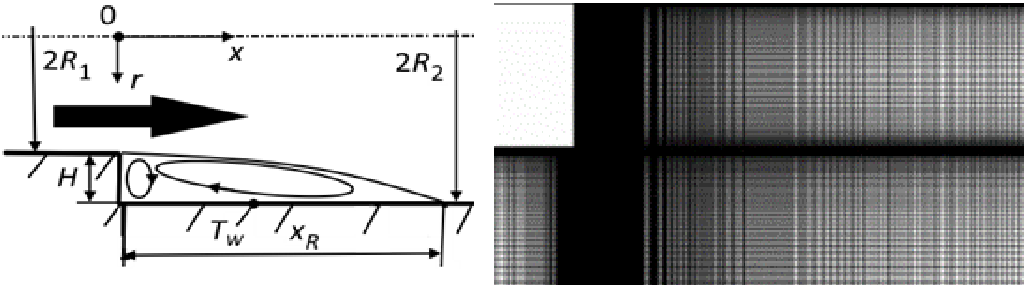
On the pipe axis ($r = 0$):

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

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

Numerical realization

All numerical predictions are performed using "in-house" code (Pakhomov, et al., 2023; Pakhomov, et al., 2024a; Pakhomov, et al., 2024b). The set of Eqs. (1–5) with boundary conditions (7–9) is solved numerically using the finite control volume method, QUICK, and SIMPLEC algorithms. The simulations use a non-uniform mesh (in axial and radial directions) with refinement close to the pipe wall and in the entrance zone (see Fig. 1b). The numerical realization is described in detail in (Pakhomov, et al., 2023; Pakhomov, et al., 2024a; Pakhomov, et al., 2024b). The grid convergence test for the local Nusselt numbers $\mathrm{Nu} = -(\partial T/\partial y)_W H/(T_W - T_m)$ along the streamwise coordinate is performed on the grids: 250×100 ("coarse"), 500×150 ("basic") and 750×250 ("fine") (see Fig. 2), where $y = R - \mathrm{r}$ is a distance normal to a wall, H is step height, and T_m is a mean-mass fluid temperature. The difference between "basic" and "fine" grids is very small (up to 0.1%) and the "basic" grid is used in authors' simulations.



a) b)

Figure 1. Schematic view of the flow behind pipe with sudden expansion (a) and the computational grid (not in the scale) (b). Arrow is a turbulent flow of a waxy crude oil.

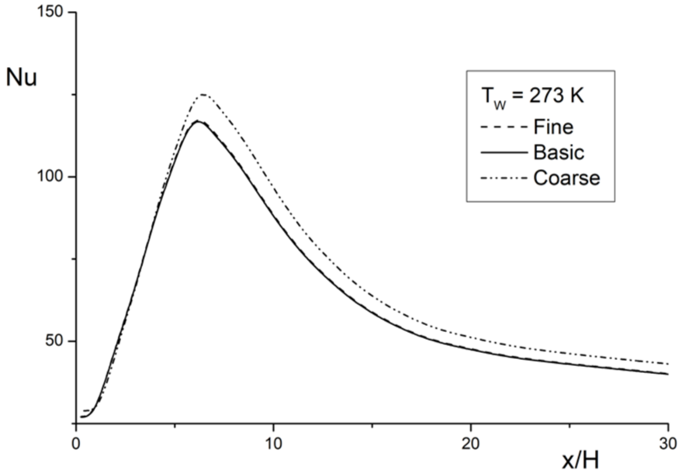
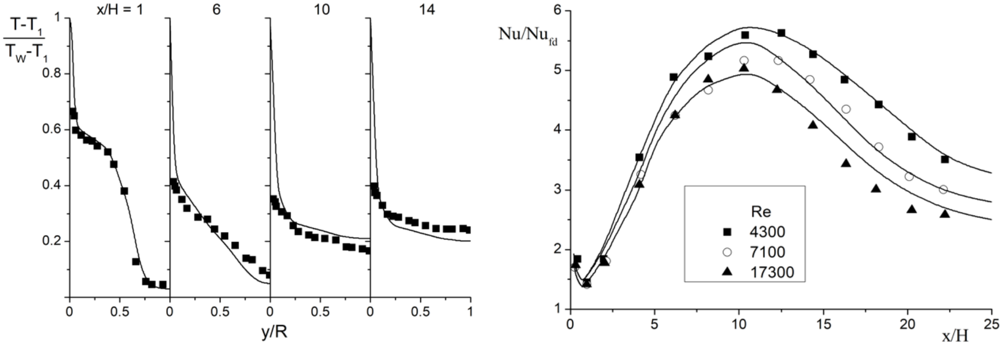


Figure 2. Grid independence test for T_W = 273 K. "Fine" grid has 750×250 control volumes (CVs), "basic" has grid 500×150 CVs and "coarse" grid has 250×100 CVs.

Validation and verification for the Newtonian turbulent fluid in a pipe with sudden expansion

For validation and verification, a comparison was conducted with experimental data (Baughn, et al., 1984) on heat transfer in the turbulent flow of a Newtonian fluid (air) downstream of a sudden pipe expansion (see Fig. 3). The first two cross-sections are located within the recirculation zone, the third approximately corresponds to the reattachment point of the flow, and the fourth is situated in the relaxation zone downstream of the reattachment (see Fig. 3a).

In the first cross-section, an increase in the thermal mixing layer is observed behind the sudden pipe expansion. Intense turbulent mixing in the separation zone results in the majority of the temperature difference between the wall and the axis being concentrated in a thin near-wall layer at $r/R \geq 0.95$. Thus, mixing processes in this near-wall layer play a dominant role in the heat transfer between the pipe wall and the turbulent fluid flow.



a) b)

Figure 3. Radial temperature profiles along the pipe length (a) and effect of the Reynolds numbers on heat transfer enhancement ratio Nu/Nu_{fd} in the pipe sudden expansion (b). Points are measurements of Baughn et al., 1984 at T_W = const; solid lines are authors' computations. $Re_2 = U_{m2}2R_2/\nu = 1.73\times10^4$.

Figure 3b presents the distributions of local heat transfer downstream of the sudden pipe expansion along the longitudinal coordinate. Here, Nu_{fd} represents the Nusselt number for a fully developed flow in a pipe without sudden expansion. It can be seen that as the Reynolds number (flow velocity) increases, the intensity of heat transfer significantly rises, which is expected.

Notably, the location of the maximum heat transfer approximately coincides with the reattachment point for Newtonian fluids. This finding is consistent with both the experimental measurements (Baughn, et al., 1984) and our calculations. Overall, the analysis of the data presented in Fig. 3 demonstrates good agreement between the measurements (Fadai-Ghotbi, et al., 2008) and the results of our calculations.

Results and Discussion

Numerical results for the non-Newtonian turbulent flow behind pipe sudden expansion and discussion

A non-isothermal viscoplastic non-Newtonian fluid (waxy crude oil) flows along a pipe with sudden expansion. Pipe I.D. Diameter before sudden expansion is $D_1 = 2R_1 = 0.2$ m, pipe diameter behind the sudden expansion is $D_2 = 2R_2 = 0.3$ m, step height is $H = 0.05$ m, $H/(2R_1) = 0.25$, expansion ratio $ER = (R_2/R_1)2 = 2.25$. Pipe length is $L = 20$ m $(x/D = 100)$. The temperature profile is uniform at the pipe inlet. Mean axial velocity and mean temperature at the inlet $U_{m1} = 0.25$ m/s, $T_1 = 303$ K respectively. The wall temperature is uniform along the pipe length after sudden expansion and it varies $T_w = const = 273–293\ K$. Reynolds number based on pipe diameter $Re = U_{m1}2R_1/\nu_{W1} = (0.7–3)\times10^4$, Reynolds number based on step height $Re_H = U_{m1}H/\nu_{W1} = (1.7–7.5)\times10^3$. The Prandl number of the Newtonian fluid is $Pr = \mu_{W1}C_{P1}/\lambda_{W1} = 42$. The Kolmogorov geometric scale η_K and time scale τ_K were determined using the following formulas of (Baughn, et al., 1984):

$$\eta_K = 2R_1\, Re_{c1}^{-3/4},\ \tau_K = \eta_K^2/\nu,$$

where $Re_{c1} = 2R_1 < u'_{c1} >/\nu$ is the Reynolds number, and $< u'_{c1} >$ represents the root-mean-square velocity fluctuations of the gas at the pipe axis before the separation section of the flow.

For the conditions of this study, $\eta_K = 0.002$ m and $\tau_K = 0.82$ s (at $Re = 10^4$).

All predictions are carried out in the region of hydrodynamic and thermal stabilization in a steady-state fluid flow in a pipe with sudden expansion. Waxy crude oil in the inlet cross-section is considered as a Newtonian turbulent fluid. Then, the process of heat transfer through a cold pipe wall starts with fluid movement through a pipe. A fluid temperature decreases by heat transfer with cold surrounding soil through a pipe wall. This leads to a sharp increase in viscosity and the appearance of yield shear stress τ_0 (Zhapbasbayev, et al., 2021; Pakhomov, et al., 2024).

Local flow structure and turbulent characteristics

Figure 4 shows the streamlines for Newtonian (a) and non-Newtonian SB (b) fluids downstream of a sudden expansion in a pipe. After the separation section, the streamlines undergo significant changes compared to the flow in the pipe prior to the sudden expansion. Due to flow separation, a recirculating flow zone is formed, and for the Newtonian fluid, a small end vortex is observed immediately downstream of the step. This is consistent with the conclusions for separated flows of Newtonian fluids (Chang, 1970; Alemasov, et al., 1990; Terekhov, et al., 2021). The flow attachment point is located at for the flow and for the non-Newtonian fluid.

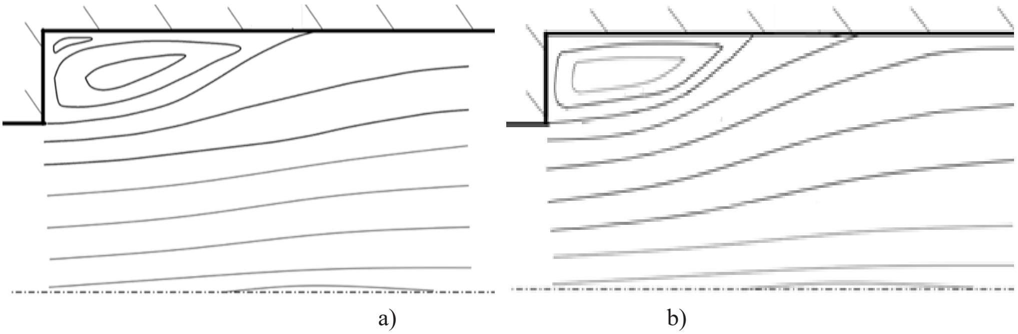
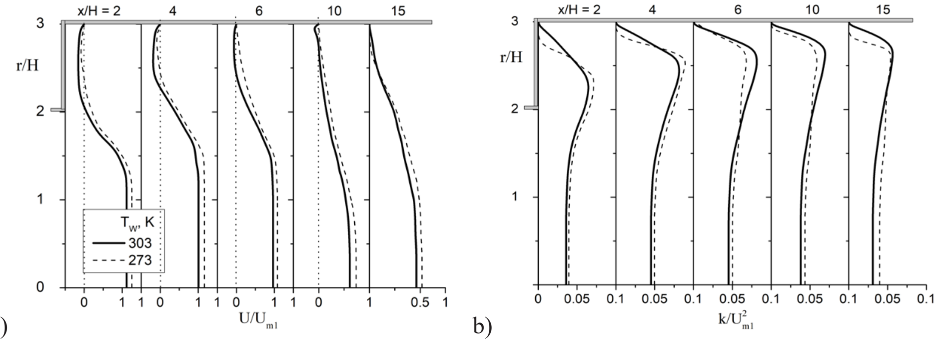

a) b)

Figure. 4. Streamlines of Newtonian ($T_1 = T_W$=303 K) (a) and non-Newtonian SB (b) (T_1 = 303 K, T_W = 273 K) fluids behind pipe sudden expansion.

The center of the main recirculating eddy is located around $x/H = 5$ and $y/H = 0.5$. The small corner eddy takes place around $x/H = 1$, and the mean flow velocity in this area is very small. The lengths of recirculation zones are determined from the zero value of mean axial flow velocity ($U = 0$) for the NF and NNF. The direction of rotation in this vortex coincides with the direction of the main flow. As the Newtonian flow cools, the non-Newtonian properties of the fluid begin to manifest (a significant increase in plastic viscosity μ_P and yield stress τ_0), and the flow takes on the characteristics of a turbulent viscoplastic Schwedoff-Bingham fluid. Flow attachment occurs at =6.2. Thus, it can be said that the length of the flow separation region is significantly reduced (by approximately 40%). It is noteworthy that the end vortex region disappears for the non-Newtonian SB fluid. Qualitatively, this agrees with the experimental data for turbulent non-Newtonian fluids in the absence of heat exchange (Pereira, et al., 2000); Pereira, et al., 2002). It should be noted that qualitatively, the flow of non-Newtonian Schwedoff-Bingham fluid after the sudden expansion of the pipe is similar to that of Newtonian fluid.

Figures 5 show the profiles of the axially averaged velocity for Newtonian (bold lines) and non-Newtonian Schwedoff-Bingham (dashed curves) fluids downstream of the sudden expansion in the pipe. The first two cross-sections are located in the flow separation region for both fluids. The $x/H = 15$ cross-section is in the recirculation region (for the Newtonian fluid) and in the flow attachment region (for the non-Newtonian fluid). The fourth cross-section is located in the flow attachment zone for the Newtonian fluid. The $x/H = 15$ cross-section corresponds to the flow relaxation zone after the flow attachment point for both fluids.

It should be noted that downstream from the flow separation cross-section, a sharp change in the flow structure is observed. For the velocity profiles of the fluid (see Fig. 5a), a region of negative velocities appears, corresponding to the flow recirculation zone. After the flow attachment point, the flow begins to recover, and dynamic and thermal boundary layers develop. The flow starts to exhibit the characteristics of hydrodynamically stabilized flow in a circular pipe. Complete hydrodynamic stabilization of the Newtonian turbulent flow downstream of the sudden expansion in the pipe occurs at distances x/H>40 (Terekhov et al., 2021). For the non-Newtonian viscoplastic turbulent fluid flow after the sudden expansion, the presence of a flow separation region is also observed. The intensity of such a flow is lower (approximately by 25%) compared to the corresponding Newtonian flow. The flow velocity in the core of the flow for the SB fluid slightly exceeds the corresponding value for the Newtonian turbulent flow. In the immediate vicinity of the wall, at r/R>0.9, the flow nearly stagnates due to yield stresses and plastic viscosity.



a) b)

Figure. 5. Radial profiles of dimensionless distributions of mean axial velocity U (a), turbulent kinetic energy k (b).

In Figure 5b, the distributions of kinetic energy of turbulence (KET) across the radius of the pipe downstream of its sudden expansion are shown. Turbulence was determined using the Reynolds stress transport model (Fadai-Ghotbi, et al., 2008), and for axisymmetric NF and NNF, it was calculated using the relation: $2k = \langle u'^2 \rangle + \langle v'^2 \rangle + \langle w'^2 \rangle \approx \langle u'^2 \rangle + 2\langle v'^2 \rangle$. The maximum value of the KET for both types of fluids studied in the work is observed in the shear mixing layer. As the flow progresses downstream, the magnitude of the turbulence energy maximum decreases and shifts toward the pipe wall. The profile of the averaged longitudinal velocity component for both Newtonian and non-Newtonian fluids becomes more gradual. The turbulence level in the recirculation zone for the SB fluid is noticeably lower than for the Newtonian flow due to the manifestation of the non-Newtonian properties of waxy crude oil as it cools (approximately up to 30%). In the immediate vicinity of the wall, at $r/R > 0.9$, where the fluid nearly stagnates (see Fig. 5a), the KET level k approaches zero.

Profiles of the averaged effective dynamic viscosity $\mu_{eff} = \mu_T + \mu + \mu_P$ at a few stations behind the sudden pipe expansion for various wall temperatures are presented in Fig. 6, where μ is the molecular (laminar) viscosity.

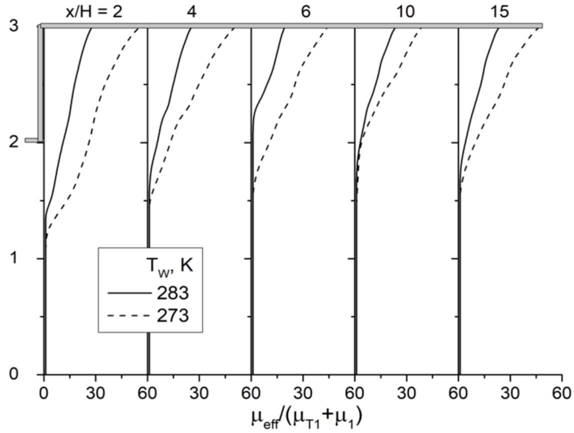


Figure 6. Radial dimensionless profiles of averaged effective dynamic viscosity μ_{eff}. Re = 10^4, Re_H =2600, Pr = 42, Bm = 0.007.

With this form of writing the expression, it is easy to analyze the influence of non-Newtonian properties of the turbulent fluid on viscosity. It can be seen that the greatest manifestation of the viscoplastic behavior of turbulent fluid is revealed at T_W = 273 K. The flow shows the properties of a Newtonian fluid and the value of apparent viscosity $\mu_{eff} / (\mu_T + \mu) \rightarrow 1$ at T_W = 303 K. The main zone of manifestation of non-Newtonian behavior of turbulent fluid is limited to the recirculating region at $r/R > 2$. As we showed earlier (Zhapbasbayev, et al., 2021; Pakhomov, et al., 2023) for a turbulent flow of waxy crude oil in a pipe without sudden expansion, the properties of SB fluid appear at $T_W \leq$ 293 K. Qualitatively similar behavior of turbulent non-isothermal fluid is obtained for the flow in a pipe with sudden expansion.

Conclusion

The transition of a Newtonian turbulent fluid into a viscoplastic non-Newtonian Schewedoff-Bingham fluid in a pipe with a sudden expansion is numerically studied. The kinetic energy of turbulence of a fluid flow is predicted using the elliptic relaxation Reynolds stress model.

For the velocity profiles of the fluid (see Fig. 5a), a region of negative velocities corresponding to the flow recirculation zone is observed. For the turbulent flow of non-Newtonian viscoplastic fluid after the sudden expansion, the presence of a flow separation region is also identified.

For the Schwedoff-Bingham viscoplastic fluid, it is characteristic that there is no local minimum in heat transfer in the angular part of the step. The turbulence level in the flow recirculation zone for the SB fluid is significantly lower than for the Newtonian flow, which is explained by the manifestation of non-Newtonian properties of waxy crude oil as it cools (approximately up to 30%). Near the wall, at r/R>0.9, where the fluid nearly stagnates, the turbulence level tends to zero.

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www:nauka-nanrk.kz
ISSN 2518-1483 (Online), ISSN 2224-5227 (Print)
http://reports-science.kz/index.php/en/archive

Директор отдела издания научных журналов НАН РК *А. Ботанқызы*
Редакторы: *Д.С. Аленов, Ж.Ш. Әден*
Верстка на компьютере *Г.Д. Жадырановой*

Подписано в печать 31.03.2025.
Формат 60x88$^{1}/_{8}$.
18,0 п.л. Заказ 1.

РОО «Национальная академия наук РК» 050010,
Алматы, ул. Шевченко, 28, т. 272-13-19