Conference materials
UDC 532.517.2 ,532.133
DOI: https://doi.org/10.18721/JPM.161.145

Influence of variable thermophysical properties on the flow of fluids in an annular channel under intensive heat exchange

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Abstract. This paper considers the flow of viscous incompressible fluids in an annular channel, on the inner and outer surfaces of which intensive heat exchange conditions are set, mathematical formulation of which is reduced to boundary conditions of the first kind. Different temperature dependencies of liquid viscosity are considered: monotonic (liquid viscosity decreases monotonously as the temperature rises) and anomalous (liquid viscosity depends on the temperature in a non-monotonic way). Mathematical model comprises continuity, Navier-Stokes and energy conservation equations written in cylindrical coordinate system with axial symmetry considered in dimensionless form. The equations of the mathematical model were solved numerically using the method of control volume. Because of numerical simulation, velocity diagrams in various sections of the annular channel, as well as distributions of temperature and viscosity fields in the flow area, have been plotted. The influence of geometric parameters of the annular channel, heat exchange conditions on its walls and rheological parameters of the fluid on the flow pattern has been determined. It is shown that in a liquid with a non-monotone dependence of viscosity on temperature, the hydrodynamic parameters of the flow significantly depend on the location of the high-viscosity flow region (the "viscous barrier").

Keywords: annular channel, thermophysical properties, monotonic viscosity temperature dependence, non-monotonic viscosity temperature dependence

Funding: The research was supported by the Russian Science Foundation (Project "Experimental and theoretical investigation of the stability of fluid flow with variable viscosity in flat and annular channels" No. 22-21-00915).

Citation: Mukhutdinova A.A., Kireev V.N., Urmancheev S.F., Influence of variable thermophysical properties on the flow of fluids in an annular channel under intensive heat exchange, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.1) (2023) 269–274. DOI: https://doi.org/10.18721/JPM.161.145

Материалы конференции
УДК 532.517.2 ,532.133
DOI: https://doi.org/10.18721/JPM.161.145

Влияние переменных теплофизических свойств на течение жидкостей в кольцевом канале при интенсивном теплообмене

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Аннотация. В настоящей работе рассматривается течение вязких несжимаемых жидкостей в кольцевом канале, на внутренней и внешней поверхностях которого задаются

условия интенсивного теплообмена. Учитываются различные виды температурных зависимостей вязкости жидкости: монотонная и аномальная. В результате численного моделирования были построены эпюры скоростей в различных сечениях кольцевого канала, а также распределения полей температуры и вязкости в области течения. Показано, что в жидкости с немонотонной зависимостью вязкости от температуры гидродинамические параметры течения существенно зависят от расположения высоковязкой области течения – «вязкого барьера».

Ключевые слова: кольцевой канал, теплофизические свойства, монотонная температурная зависимость вязкости, немонотонная температурная зависимость вязкости

Финансирование: Исследование выполнено при поддержке Российского научного фонда (проект «Экспериментальное и теоретическое исследование устойчивости течения жидкости с переменной вязкостью в плоских и кольцевых каналах» № 22-21-00915).

Ссылка при цитировании: Мухутдинова А.А., Киреев В.Н., Урманчеев С.Ф. Влияние переменных теплофизических свойств на течение жидкостей в кольцевом канале при интенсивном теплообмене // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.1. С. 269–274. DOI: https://doi.org/10.18721/JPM.161.145

Introduction

Variations in the thermal properties of fluids can significantly affect the flow pattern and determine the performance of technical systems. In various devices for the heating or cooling of working liquid, shell-and-tube heat exchangers are widely used, in which the coolant flows in an annular channel (gap) formed by two coaxial circular cylinders of different radii. Calculation of thermal and hydraulic parameters of such heat exchangers involves considering the dependence of viscosity, thermal conductivity and heat capacity on temperature. For example, viscosity of formate based coolant Nordway-FORM 60 (Roshal Chemical Plant) in a working temperature range from –50 °C to +40 °C decreases 45 times from 108.3 mPa·s to 2.34 mPa·s [1–3]. The fuel assemblies of nuclear reactors can serve as an example of such structures. Thus, a theoretical investigation of the hydrodynamic and heat exchange processes at the coolant flow seems to be important.

Statement of the problem

To study features of distribution of hydrodynamic parameters in the flow of thermally incompressible fluid a model problem of the flow of thermally incompressible fluid in an annular channel, formed by two coaxial circular cylinders with the same constant temperatures on internal and external surfaces has been considered. The temperature at which the liquid flows into the channel is denoted by T_w, and the temperature of the channel walls by T_0, and it is assumed that $T_w > T_0$. The flow of liquid is conditioned by a pressure drop (Fig. 1).

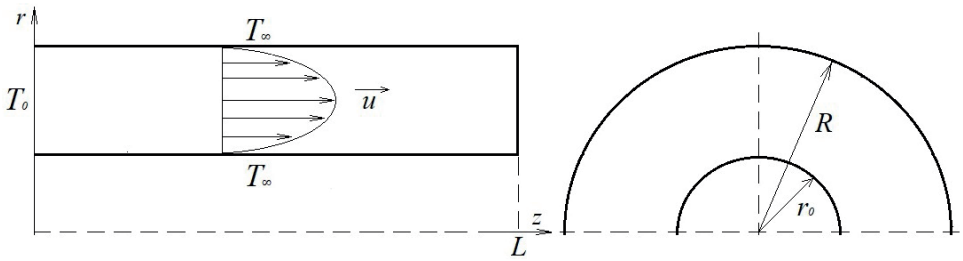

Fig. 1. Channel geometry

Mathematical model of the thermoviscous fluid flow in the annular channel comprises the equations of continuity, Navier-Stokes and energy conservation written in the cylindrical coordinate system with axial symmetry in dimensionless form [4]. Let's denote the dimensionless value of radius by $\tilde{r} = (r - r_0)/(R - r_0)$ and thus $0 \le \tilde{r} \le 1$. Further, the value of the dimensionless radius is used without the tilde.

$$\frac{\partial u_r}{\partial r} + \frac{\partial u_z}{\partial z} + \frac{u_r}{r} = 0, \tag{1}$$

$$\frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + u_z \frac{\partial u_r}{\partial z} = -\frac{\partial P}{\partial r} + \frac{1}{\mathrm{Re}}\left(\begin{array}{l} \frac{\partial}{\partial r}\left(\mu(T)\frac{\partial u_r}{\partial r}\right) + \frac{\partial}{\partial z}\left(\mu(T)\frac{\partial u_r}{\partial z}\right) + \mu(T)\frac{1}{r}\frac{\partial u_r}{\partial r} \\ -\mu(T)\frac{u_r}{r^2} \end{array}\right), \tag{2}$$

$$\frac{\partial u_z}{\partial t} + u_r \frac{\partial u_z}{\partial r} + u_z \frac{\partial u_z}{\partial z} = -\frac{\partial P}{\partial z} + \frac{1}{\mathrm{Re}}\left(\frac{\partial}{\partial r}\left(\mu(T)\frac{\partial u_z}{\partial r}\right) + \frac{\partial}{\partial z}\left(\mu(T)\frac{\partial u_z}{\partial z}\right) + \mu(T)\frac{1}{r}\frac{\partial u_z}{\partial r}\right), \tag{3}$$

$$\frac{\partial T}{\partial t} + u_r \frac{\partial T}{\partial r} + u_z \frac{\partial T}{\partial z} = \frac{1}{\mathrm{Pe}}\left(\frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right), \tag{4}$$

where u_z, u_r are velocity components; μ is fluid viscosity; P is pressure; T is temperature; Re, Pe are Reynolds and Peclet numbers.

The fluid flow is conditioned by a pressure drop. Two types of temperature dependences of viscosity of liquid are considered: exponential monotonically decreasing dependence [6]

$$\mu = \mu_0 \cdot \exp\left(-\alpha \cdot (T - T_0)\right), \tag{5}$$

and anomalous one (viscosity of liquid depends on temperature in a non-monotonous way) [7] (Fig. 2),

$$\mu = \mu_{\min}\left(1 + A \cdot \exp\left(-B \cdot (T - T_*)^2\right)\right), \tag{6}$$

where μ_0 is viscosity at temperature T_0, $\alpha > 0$ is parameter characterizing viscosity change, $A = \mu_{\max}/\mu_{\min} - 1$ and $B > 0$ are parameters characterizing anomalous viscosity dependence on temperature, $T^* = (T_w + T_0)/2$.

Numerical results

The equations of mathematical model are implemented by computer code based on control volume method using SIMPLE (Semi-Implicit Method for Pressure-Linked Equation) algorithm [5] changed to include variable viscosity coefficient and written program in C++ in the cross-platform development environment Qt Creator.

Monotonic viscosity temperature dependence

The longitudinal velocity and viscosity isolines of the thermoviscous liquid flow in the axial section of the annular channel are shown in Fig. 3. Under the problem statement, hot liquid was

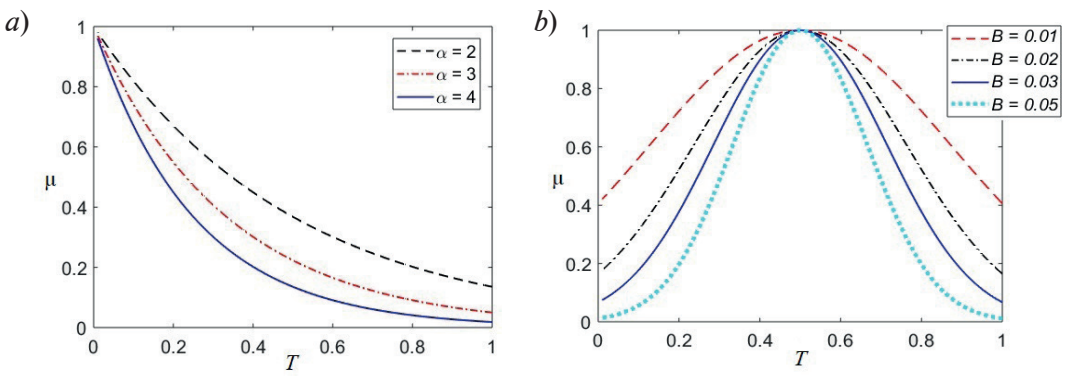

Fig. 2. Monotonic (*a*) and anomalous (*b*) viscosity dependence on temperature

supplied to the inlet section and the channel walls were kept cold. A pronounced inhomogeneity of distribution of these parameters seems to be clear. In Fig. 3, *a*, near the inlet section, an area with increased velocity values is detected, which can be interpreted as a zone of flooded jet flow formation associated with viscosity value distribution (Fig. 3, *b*) in the considered flow area.

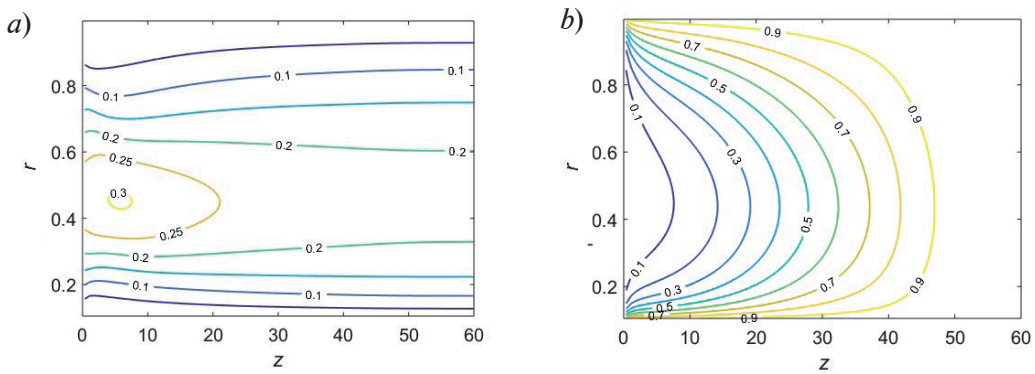

Fig. 3. Steady-state distributions of longitudinal velocity (*a*), viscosity (*b*) in the cooled channel (monotone dependence at α = 3)

The effect of the thermal viscosity parameter α on the temperature distribution at $r = 0.5$ is shown in Fig. 4. An increase in this parameter leads to a flatter temperature distribution along the channel axis. Obviously, at α = 0, the monotonic decrease in temperature is due to heat transfer at the channel walls.

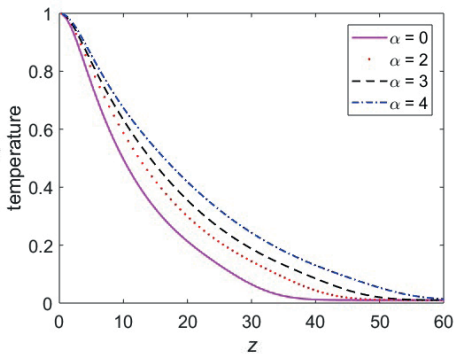

Fig. 4. Steady-state temperature distribution along the channel axis at different thermal viscosity parameters

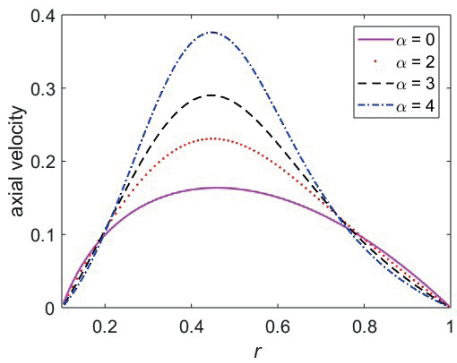

Fig. 5. Longitudinal velocity diagrams of the thermoviscous fluid across the cross section of the annulus at different α thermoviscosity parameters ($z = 10$)

The longitudinal velocity diagrams across the annulus cross section at $z = 10$, depending on the value of parameter α are of considerable interest. The velocity distribution curve at α = 0 characterises the Poiseuille flow in the isothermal case. Thus, increasing α leads to increasing maximum value of longitudinal velocity in the flooded jet flow zone.

Non-monotonic viscosity temperature dependence

For the anomalously thermally viscous fluid, the longitudinal velocity and viscosity isolines in the channel axial section are shown in Fig. 6 and Fig. 7 for the values of the anomalous thermal viscosity parameter $B = 0.02$ and $B = 0.05$, respectively. Compared to the monotonic dependence of viscosity change on temperature, in this case, the parameter distributions are more complex. It should be noted only that here, too, the formation of zones of flooded jet flow is observed (Fig. 6, *a* and 7, *a*). At that, for higher value of parameter B in Fig. 7, a we have more extended jet with higher value of maximum longitudinal velocity. Peculiarities of flow velocity distribution are directly connected to viscosity field distribution, which in this case leads to formation of a highly viscous region in liquid flow - viscous barrier. At $B = 0.02$, the high-viscosity zone is entirely in considered flow area and its isolines are closed. Whereas at $B = 0.05$ (Fig. 7, *b*) the viscous barrier isolines are open at the same pressure drop value.

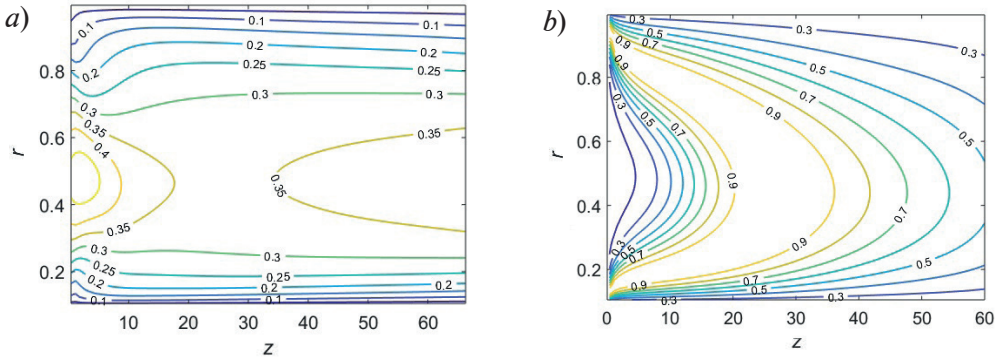

Fig. 6. Steady-state distributions of longitudinal velocity (*a*), viscosity (*b*) in the cooled channel (non-monotone dependence at $B = 0.02$)

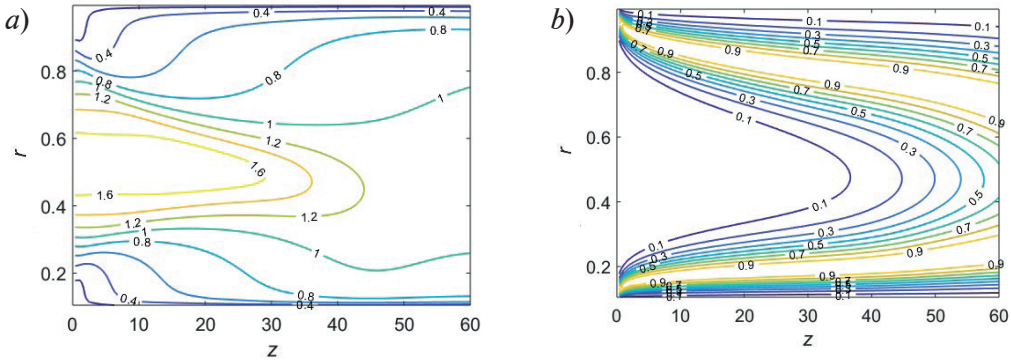

Fig. 7. Steady-state distributions of longitudinal velocity (*a*), viscosity (*b*) in the cooled channel (non-monotone dependence at $B = 0.05$)

Fig. 8 and Fig. 9 show plots of temperature change along the channel axis ($r = 0.5$) and longitudinal velocity diagrams ($z = 10$), respectively, for different values of parameter B. At $B = 0$, as in case of monotonic dependence, we deal with fluid having constant viscosity, which does not depend on temperature. At values of $B < 0.05$, the nature of temperature changes qualitatively repeats the dependence for fluids with monotonically decreasing viscosity. However, at $B = 0.05$, the temperature change curve turns from concave to convex, which shows a change in heat transfer along the channel axis. The longitudinal velocity diagrams show an increasing trend in the intensity of the flooded jet stream as the anomalous thermal viscosity parameter increases. At $B = 0.05$, a significant increase not only in maximum velocity value but also in the area covered by the jet flow is noticeable. If we pay attention to Fig. 7, *b*, we can conclude that

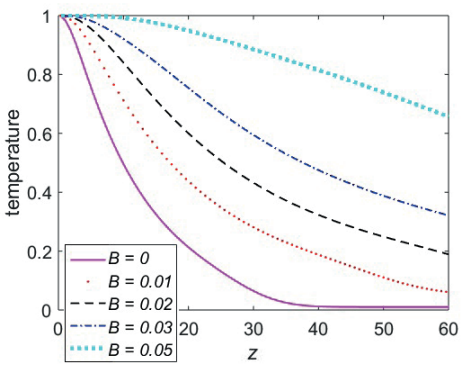

Fig. 8. The steady-state temperature distribution along the channel axis at various anomalous thermal viscosity parameters

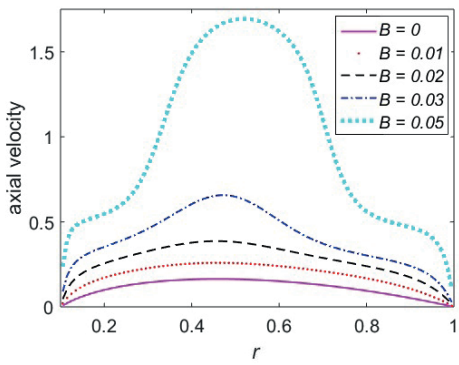

Fig. 9. Longitudinal velocity diagrams of thermoviscous fluid across the cross section of the annulus at different parameters of anomalous thermal B ($z = 10$)

at a ratio of pressure drop, geometrical parameters and heat exchange conditions on the channel walls, the viscous barrier isolines within the channel area appeared to be open, which resulted in an increase of flow velocity and fluid flow rate. Thus, the formation of a viscous barrier in inhomogeneous temperature field leads to a local increase of hydraulic resistance to abnormally thermoviscous liquid flow.

Conclusion

Due to the numerical simulation, the hydrodynamic parameters in the axial and various cross sections of the annular channel have been constructed. The patterns of longitudinal flow velocity, temperature and viscosity field changes depending on the rheological parameters of the fluid characterized by thermoviscous parameters are determined. The essential influence of heat exchange on the hydrodynamic behavior of various thermoviscous liquids has been established.

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Received 24.10.2022. Approved after reviewing 09.11.2022. Accepted 11.11.2022.