Suppression of flow pulsation activity by relaxation process of additive effect on viscous media transport

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Abstract. The article presents the analysis of the processes occurring together with the turbulent transfer of impulse in mixture of hydrocarbon fluid and polymer solutions (anti-turbulent additives). The study evaluates complex shear flows by popular theoretical and practical methods. Understanding of hydrodynamic and dissipative effects of laminar-turbulent transition tightening and turbulence suppression is provided. The peculiarities of "thin" flow structure in pipeline zones with complex shape walls are evaluated. Recommendations to forecast the local flow parameters, calculation of hydraulic resistance are given.

1. Introduction

Currently, oil and gas transporting companies face the challenges of effective development and application of technologies, which increase flow capability of pipeline systems [1, 2]. The application of antiturbulent additives (ATA) is valuable due to the effective raw hydrocarbons transportation management without influencing pipeline system structure.

Thus application of ATA looks promising, mostly because it enlarges pipeline transmission capacity. But numerous instabilities in technological processes, as well as changes in heat and vortical transfer significantly influence flow regimes. These range of questions, connected with the understanding of viscous media and polymer additive flow features, defines the relevance of the article and requires detailed analysis within physical, mathematical and chemical modeling. The study of heat, mass and impulse transfer in the above mentioned systems will allow to minimize energy loss and to make positive forecast of laminarized flow dynamics. The study will enlarge the analysis database of transition flows and create the basis for making integral linkage of hydraulic resistance.

The article aims to systematize the data concerning hydrodynamics of laminarized flows with ATA in nature and mechanics; to develop criteria linkages for monitoring and control of hydraulic resistance in complex shear flows with polymer additives; to develop mathematical model of steady and transition hydrocarbon flow regimes in pipelines.

2. Questions of inner flow modeling with inhomogeneous turbulence

It is known [8-10], that pipeline flow could be laminarized within approaches, which consider the specificity of viscous media flow: in the areas of variable cross-sections (the acceleration in joints of confusser and diffuser types) or by an inlet of special high-molecular polymer additives. Particularly, the Toms' effect [3], discovered at 1946, has found a broad application in various fields, such as pipeline oil transportation, mud injection into wells, fire safety. In spite of significant number of supplements, physical and mathematical essence of the effect is still having some questions to be considered. There is a need in detailed research of flows with inhomogeneous anisotropic turbulence in inner systems. The physical modeling is based on L. Prandtl and T. Karman's, studies about multiband structure of turbulent flow [4].

The analysis of data, which have been obtained in [5], makes it possible to state, that the injection of such additive polymer solutions leads to considerable energy economy, mostly caused by flow laminarization in viscous sublayer and buffer zone, at that, the core flow does not undergo any changes. Considering the physical description of mechanisms, it should be mentioned that the most widespread theory [1, 2, 6, 7] of such processes description, states that the long-length polymer molecule prevents the development of vortex by creating the "cocoon, coil" structure or "polymer solution – media". It has been discovered [1, 6, 7], that the efficiency of ATA depends on its concentration. A large number of ATA function in minor concentration zone ($10^{-3} \div 10^{-4}$%), but the growth of concentration leads to the decrease of laminarization rate. The bibliographic data shows there are no unified laws and mechanisms of turbulent flow generation in these areas. Thus, the detailed theoretical and experimental analysis of convection-diffusion processes in solutions at laminarization process within the models with anisotropic turbulence. In particular, the study of the hydrodynamic questions of disturbances relaxation in laminarazing flow, gives the results, which allow estimating Toms' effect [8] time initiation by criterion:

$$\frac{u_*^2 \theta}{\nu} \geq 1, \tag{1}$$

where u_* – dynamic velocity,

v – kinematic viscosity,

θ – perturbation relaxation time in polymer solution.

However the criterion (1) is inefficient for the description of complex shear flow evolution and imposed external forces. Certain problems have been studied in [2, 9], where conditions of process limits (flow laminarization) were formulated with the help of Lumley criterion and description of turbulent flow by Blasius's friction law. This approach is practically valuable for industrial testing and producing of ATA, but from the point of rigorous flow modeling, these criterions do not explain ATA interaction with pulsating flow parameters.

3. Integral parameters forecast

Among the number of mentioned questions, special attention should be paid to hydraulic friction coefficient modeling. There are many formulas that have been successfully applied for the calculation and construction of pipelines, as well as for the determination of the required number of pumping stations and their distribution. It is considered, that the equation (2) should be applied for calculating smooth pipes parameters, while equation (3) is applied for calculating rough inner surface parameters:

$$\frac{1}{\sqrt{\lambda}} = 2 \lg(\mathrm{Re}\sqrt{\lambda}) - 0,8 \tag{2}$$

$$3,75 + \frac{2\sqrt{2}}{\sqrt{\lambda}} - 5,75 \lg \frac{a}{k} = \Phi\left(\frac{k \cdot \upsilon_*}{\nu}\right) \tag{3}$$

It should be mentioned that the application of (2) and (3) relations for the description of viscous hydrocarbon flow (media and ATA) motion is inappropriate because these equations do not consider the effect of ATA on the wall friction. The article attempts to derive an appropriate formula for λ in flows with additives.

In particular, when describing the friction loss in flow media, it should be considered that ATA are unable to create chemical reaction of liquid and polymer solution and that the concentration of ATA is not enough to change the rheology of transported media. This allows basing only on concentration and ATA parameters during the modification of equation (2), but due to the lack of data of FLX-O additive testing, the concentration influence becomes the single parameter of modification. Modification of equation (2) is realized by introducing $\psi(C)$ dependence, where C is the concentration of the additive:

$$\frac{1}{\sqrt{\lambda}} = 2(\lg e) \cdot \psi(C) \ln(\mathrm{Re}\sqrt{\lambda}) - 0,8 \tag{4}$$

Industrial test data of FLO-X additive [10] allows calculating $\psi(C)$ (table 1).

Table 1. $\psi(C)$ values with different concentrations of FLO-X.

C, ml/m³	0	5,2	11,3	19	28,8	37,5	**50**
$\Psi(C)$	**0.979**	**1.018**	**1.140**	**1.32**	**1.49**	**1.64**	**1.84**

Due to the fact that the equation (4) is given implicitly, the calculation of function dependencies is performed with numerical methods. The mathematical processing of the calculation was performed by Mathcad and Maple 17 software programs. Obtained dependencies, calculated values of approximation accuracy and correlation coefficients are presented in table 2.

Table 2. Types of $\Psi(C)$ function and evaluation of the results reliability.

Function type	Formula description	Approximation accuracy R^2	Correlation coefficient
Linear	$\Psi(C) = 0.0184 \cdot C + 0.9429$	0.997	0.998
Exponential, 1st type	$\Psi(C) = 0.989 \cdot \exp(0.0131 \cdot C)$	0.978	0.989
Exponential, 2nd type	$\Psi(C) = 1 - \exp(-18.525 \cdot C^{-1})$	0.972	0.979
Logarithmic	$\Psi(C) = 0.357 \cdot \ln(C) + 0.343$	0.935	0.967
Degree	$\Psi(C) = 0.631 \cdot C^{0.262}$	0.969	0.985

It should be noted that the presented dependences of $\psi(C)$ are only practical particular equations and there is a need in further evaluations for the real pipeline transportation conditions.

4. Prospects of physical and mathematical modeling of complex shear flows
In case of complex shear flows with inhomogeneous turbulence in transition regimes there is a clear in creating connections between parameters of turbulent additives and "thin" parameters of pumped medium with its rheological properties. However the question about the types of such connections remains open. Modeling of such complex spatial flows is impossible without PC and the whole spectrum analysis of viscous media flows. It is well-known [11], that conservation laws of mass, momentum and energy are the ground of the researched phenomenon. These laws can be described by equations:

$$\frac{\partial \rho}{\partial t} + div(\rho \bar{v}) = 0 \tag{5}$$

$$\frac{D(\rho \vec{v})}{Dt} = DIV \ \vec{\bar{\tau}} + \vec{F} \tag{6}$$

$$\frac{D(\rho c_p T)}{Dt} = div(\lambda gradT) + S_T \tag{7}$$

$$\Phi(P, R,T) \equiv 0 \tag{8}$$

Symbols in the equations (5) – (8) are commonly accepted.

Bibliographic data analysis of complex shear stress flow modeling shows [11, 12] that applied engineer calculations are based on RANS method. Besides, interpretation of results requires validation and verification of chosen turbulence model. It should be noted that at "flexible" semi-empiric turbulent model application, the following aspects should be considered:

- ATA inlet does not cause chemical reaction of liquid and polymer solution;
- Use rate of ATA does not change the rheology of transported media;
- The temperatures of media and ATA are the same; there is no processes of interphase heat exchange.

On the ground of bibliographic data analysis [1 – 12] it is possible to make a conclusion that there are benefits of changes prediction in local structure of complex flow by two-parameter models ((k-ε), (k-ω), (k-L)). These models have the parameters which show changes in local properties of pulsating flow: here (k) is kinetic energy, (ε)-rate of dissipation, (ω)-pseudovorticity, (L)-integral scale of energy-vortex. However, it should be noted that attempts to make the analysis of flows with strong anisotropic structure on the basis of these models are unlikely to be correct. The reason is that all these models are based on the assumption that molar diffusion coefficients are scalar (viscosity, thermal conductivity). In such cases it will be particularly valuable to apply RSS (Reynolds Shear Stresses) models with transport equations for one-point correlation moments of second order velocity fields fluctuations with the support base of two-parameter turbulence models. For example, (RSS-L) [11, 12].

5. Discussion of the results

Despite the relative limits of presented relations of λ forecast, it is possible to draw the conclusion about ATA interaction with fluid. The highest rate of accuracy is obtained by linear and exponential (I type) dependencies application. This is proved by calculated coefficients of correlation (0.998 and 0.989) and approximation accuracy (0.997 and 0.978).

The obtained dependencies (figures 1 – 2) show satisfactory dynamics in smooth pipe, which was originally built into foundation as the result of choosing the equation (2) as a basic one. In the range of Re numbers higher than 30,000 it is necessary to take into account the relative roughness of pipe walls in order to obtain the correct flow description.
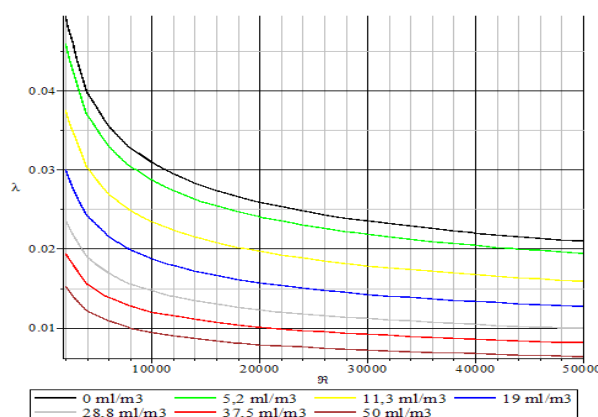

Figure 1. The dependence of hydraulic friction coefficient λ on Re number and concentrations of ATA (FLO-X) in case when $\psi(C)$ is described by linear dependence.
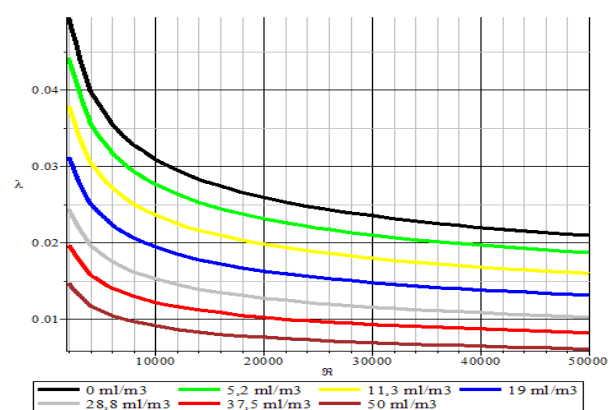

Figure 2. The dependence of hydraulic friction coefficient λ on Re number and concentrations of ATA (FLO-X) in case when $\psi(C)$ is described by exponential dependence.

In figures 3, 4 turbulent viscosity field changes (figure 3) and speed (figure 4) are given to show the dynamic parts of the averaged and pulsating flow structure, as well as the properties evolution of space vortex formations in pipelines with U-joints. Calculations of isothermal flow of homogeneous hydrocarbon droplet (low viscosity oil) are made with the introduction of RSS-kL-model. Features of the solution method and formulation of the model is described in details in [12]. It is evident that in areas with a curved boundary background. There is a field that results in both turbulence and laminarization, due to the acceleration and deceleration of flow. Localization of these areas is only possible on the basis of models with high-level circuits of constitutive equations. Moreover, the suppression of turbulence intensity by introducing polymer additives in these zones will effectively manage the process of natural resources transportation.
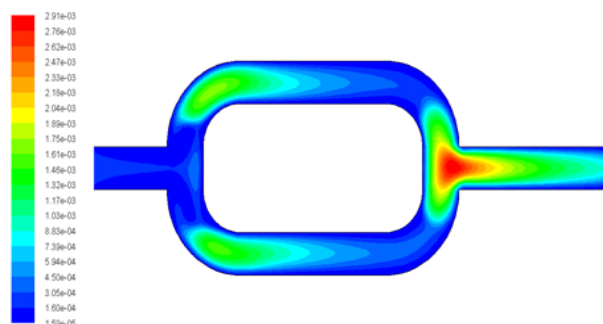

Figure 3. Molar dynamic viscosity field of Newtonian dropping fluid with low viscosity. Properties are similar to the oil in pipelines of complex shape (Re_{in}=8000, U- shaped junction of the constant diameter, calculation - RSS-*kL*- model [12])
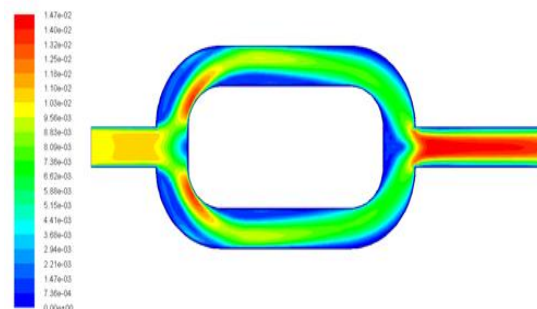
Figure 4. Velocity field distribution in pipelines with U-sections (D=0.5, m, Re_{in}=10000)

6. Conclusion

Despite significant progress in modeling of relaminarazing flows in complex pipelines there is still no clear understanding of processes, occurring in mixtures of viscous media with polymer solution of random concentration. The majority of experimental research is concentrated on integral parameters of flow without considering such characteristics as turbulent viscosity, frequencies of turbulent vortex pulsations and etc. It is obvious that experiments with fixation of abovementioned parameters should be held. On the other hand, the description of hydraulic resistance coefficient should be studied due to the prospect to get a distribution of velocity profile. Systematic investigations of flow dynamic structure should be carried out depending on ATA parameters changing: molecular weight of the polymer, the effective length of the polymer chain, elasticity of the molecule and its ability to dampen.

Calculations of the "thin" flow structure shows that the closure of the defining equation system (5)–(8) with RSS turbulence model, allows to formulate valuable practical conditions for pipeline optimal functioning with complex pipeline wall structure and connections. The turbulence model is justified by the class of laminirazing flows in pipes. Obtained results enable to enlarge the experimental database to derive new semi-empirical models which are necessary to study transportation of gas hydrates and liquefied natural gas. These issues could become subjects of further investigations.

References

[1]   Tarasov M Yu and Yuzhakov I S 2011 Field tests of anti-turbulence additive agents for increasingflow capacity of heavy oils pipelines *Oil Industry Journal* **10** 117–19

[2]   Rakhmatulin Sh I 2005 O turbulentnom techeniyi slaboconcentrirovannikh rastvorov polimerov v truboprovodakh *Neftegazovoye delo* – URL: http://www.ogbus.ru/authors/Rahmatullin/ Rahmatullin_1.pdf

[3]   Toms B A 1949 Some observations on the flow of linear polymer solutions through straight tubes at large Reynolds numbers *In Proceedings of the 1st International Congress on Rheology (North Holland, Scheveningen, 21–24 September 1948)* **2** 135–41

[4]   Laufer J 1954 The structure of turbulence in fully developed pipe flow *NACA Technical Report* (Washington, DC, USA) **1174** 1–18

[5]   Bogdevich V G et al 1980 Some problems of wall flows control *Journal of applied mechanics and technical physics* **5** 99–109

[6]   Voskoroboynic V A, Grinchenkov V T and Makarenko A P 2007 Snizhenie gidrodinamicheskikh shumov rastvorami visokopolimernikh polimerov *Acusticheskiy vestnik* **10** 33–42

[7]   Kornilov V I 2005 Problems of turbulent friction with active and passive methods *Thermal physics and aeromechanics* **2** 183–208

[8]   Lumley J F 1969 Drag reduction by additives *Fluid Mechanics* 367–84

[9]   Zaryankin A E and Baranovskiy B V 1975O svyazi stepeni turbulentnosti s chislom Reynoldtca. *IVUZ, seriya "Energetika"* **5** 144–47

[10]   Bogdevičius M et al 2013 Mathematical modeling of oil transportation by pipelines using anti-turbulent additives *Journal of Vibroengineering* **15** 419

[11]   Bubenchikov A M and Kharlamov S N 2001 Mathematical models of heterogeneous anisotropic turbulency in inner flows (Tomsk: TGU publishing) p 440

[12]   Kharlamov S N and Alginov R A 2014 Modelling of Complex Shear Flow Structure in Pipelines *International Journal of Engineering, Science and Innovative Technology* **3** 500–9