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The Effect of Hydrophobicity on Hydraulic Resistance during Transportation of Fluid Media

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ABSTRACT

This work discusses the influence of hydrophobization of functional surfaces on hydraulic resistance during transportation of fluid media. It has been mentioned that the decrease in hydrodynamic loss is stipulated by slip occurring mainly for superhydrophobic surfaces with steady heterogeneous wetting mode.
Pipe samples were made of brass (L63) for experimental studies, their surfaces were modified by various methods: by application of surfactants (contact angle: 111.4°) and by formation of micro/nanoscale relief using laser equipment (contact angle: ~156°).
Analysis of the experimental data demonstrated that decrease in hydraulic resistance for surfaces modified by surfactants was 5.2%, and for superhydrophobic surfaces modified by laser equipment the hydraulic resistance increased by 8.9%..

Key words: drag reduction, hydrophobicity, surface, relief, slip, surfactants, laser textured surface.

1. INTRODUCTION

The most common method of long-distance transportation of fluid media is pipeline transport based on conveyance of fluid medium from source to consumer under the action of pressure difference in pipeline cross section created by compressors.
Russia occupies one of the leading positions in the field of pipeline transportation of hydrocarbons, heat carriers, aqueous and other working fluids. For instance, pipeline systems of public heating, water supply, and sewage are inherent features for cities and apartment buildings. The length of pipeline networks in internal utility systems reaches 3–5 million km [1]. Herewith, total length of pipelines of Russian heating system, one of the most extensive and extended networks in the world, according to various estimations, equals from 20 to 350 thousand km [2, 3]. Such significant scopes of supplying systems are stipulated by huge area of the country, its main portion is located in climatic zine with dominating low temperatures for sufficiently long time.
The state of such systems is characterized by high wear, low efficiency and reliability resulting from such negative factors as corrosion and erosion, sediment accumulation on functional surfaces. In the course of routine operation, these processes run simultaneously, which increases their influence. Thus, corrosion on functional pipe surfaces, on the one hand, increases roughness increasing the coefficient of hydraulic friction, and on the other hand, accelerates sediment accumulation narrowing pipeline flow area. This leads to increase in hydraulic loss and necessity of regular increase in input pressure of conveyed medium in order to maintain design flow rate, which increases power consumption for transportation and pipe breakages at high working pressure.
While analyzing up-to-date publications, it has been revealed that a challenging approach to improve efficiency of metal pipelines for transportation of aqueous media is based on hydrophobization of functional surfaces. Hydrophobic metal surfaces are characterized by a set of unique properties, including self-cleaning [4], higher corrosion resistance [5], and their application in various fields promotes decrease in hydraulic resistance for transportation of fluid media [6–7], reduced rate of ice formation [8-10], intensification of heat exchange [11] and others.

2. SLIP OVER HYDROPHOBIC SURFACES

Increasing number of studies in recent decades devoted to the essence of hydrophobic properties, development of methods of achievement of hydrophobic state of various surfaces, determination of efficiency of hydrophobic surfaces in various scopes demonstrated that the most promising were superhydrophobic surfaces with contact angle higher than 150°.

2.1 Wetting of hydrophobic surfaces

It has been mentioned in the previous work [12] that the maximum contact angle upon hydrophobization of smooth surface by modification of chemical composition of surface layer does not exceed 120°. Achievement of higher values is provided by roughness which also exerts significant influence on thermal and hydrodynamic state of fluid droplet on surface. Superhydrophobic surfaces are characterized by homogeneous (the Wenzel state [13]) and heterogeneous (the Cassie–Baxter state [14, 15]) wetting modes. Herewith, wetting mode on superhydrophobic surface will be determined by surface relief geometry [16].

The homogeneous wetting, when fluid contacts with overall surface filling all cavities, is characterized by high adhesion at fluid/solid interface. Despite high contact angle, a water droplet adheres to superhydrophobic surface and does not evacuate at any tilt angles. Such surfaces can be exemplified well by rose petal surfaces and gecko adherence system [17, 18]. Such surfaces are widely applied, for instance, upon transportation of microdroplets of supermagnetic fluid using magnetic fields [19, 20].

However, the heterogeneous wetting is characterized by low adhesion at fluid/solid interface resulting in low angle of fluid droplet roll-off from surface. In this case the fluid contacts only with protrusions on surface, whereas pores and cavities contain air presenting contact with aqueous medium. This can be exemplified well by such surface as lotus leaf characterized by self-cleaning due to water droplet roll-off from surface [19, 21]. In addition, numerous insects and animals are characterized both by superhydrophobic and self-cleaning properties and by decrease in resistance in fluid flows [22].

Analysis of various states of superhydrophobic surfaces has demonstrated that, aiming at efficiency improvement of pipelines for transportation of aqueous medium, the optimum results will be obtained on the basis of superhydrophobic surfaces with heterogeneous wetting.

2.2 Reduction of hydraulic resistance

The slip distance b is equivalent to the distance where the velocity profile is extrapolated to zero (Fig. 1, b) and is determined by the ratio of fluid slip velocity on surface u_s to the respective shear rate on surface $\frac{\partial u}{\partial z}$:

$$b = \frac{u_s}{\partial u / \partial z}. \quad (1)$$

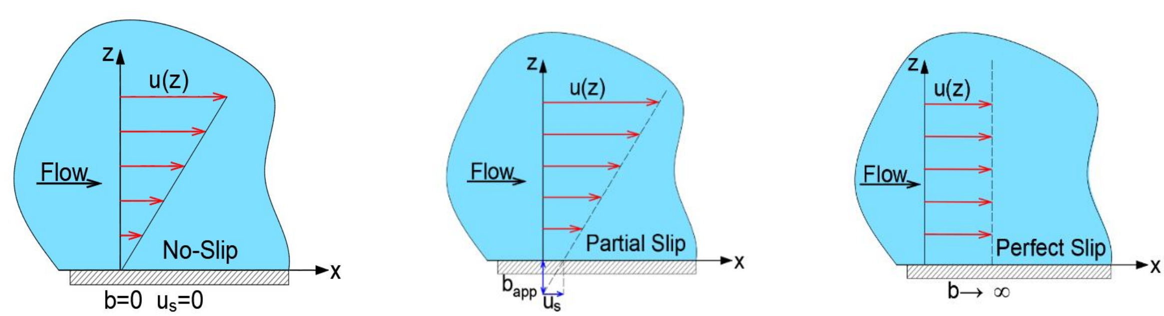
The shear stress on solid surface σ_s is proportional to the slip velocity u_s, and the proportionality factor is the friction coefficient ε:

$$\sigma_s = \varepsilon u_s = \eta \frac{\partial u}{\partial z}, \quad (2)$$

where η is the viscosity of fluid. Based on Eqs. (1) and (2), for the slip length b it is possible to write as follows:

$$b = \frac{\eta}{\varepsilon}. \quad (3)$$

At the slip distance $b = 0$ (Fig. 1, a), the boundary condition is reduced to classical condition of no-slip (adherence) of fluid on surface and corresponds to the velocity $u_s = 0$. The slip length $b \to \infty$ is determined by no-friction $\varepsilon \to 0$ and takes place in the case of ideal slip characteristic for plug flow at zero velocity gradient $\frac{\partial u}{\partial z} = 0$ (Fig. 1, c) [24]. In addition, the slip length b, as illustrated by Eqs. (1) and (3), depends on the parameters determining properties of surface (friction coefficient ε) and fluid (viscosity η).



(a) (b) (c)

Figure 1: Schematic view of velocity profile and slip distance upon fluid flow over solid surface under the following boundary conditions: (a) no-slip (adherence); (b) partial slip; and (c) perfect slip (no-friction).

In recent years it has been recognized that unique properties of superhydrophobic surfaces caused by relief geometry can influence significantly fluid dynamics near solid surface and, as a consequence, promote decrease in hydraulic resistance upon transportation of fluid media. This is stipulated by fluid hydrodynamic slip near solid superhydrophobic surface [25, 26].

At present the following slip models are determined:
- real (molecular) slip (Fig. 2, a);
- apparent (observed) slip (Fig. 2, b);
- effective slip (Fig. 2, c).

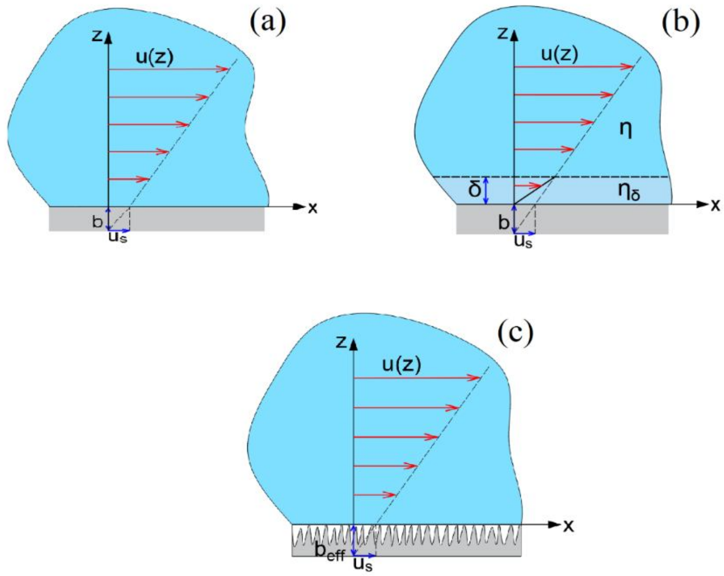


Figure 2: Schematic view of models of (a) real, (b) apparent, and (c) effective slip.

Computer molecular dynamic simulations have demonstrated that slipping of molecules directly above solid surface can be caused by the fact that cohesion of fluid molecules exceeds adhesion at solid/fluid interface, that is, on hydrophobic surface [27-29]. However, the simulated slip distances b were low (not more than 10 nm) [30, 31].

In some tests with hydrophobic surfaces the slip distance reached up to ~100 nm [30, 32], which exceeded significantly the simulated results of molecular slip. In this regard the model of apparent (observed) slip was developed which assumed formation of thin lubricating layer on surface (gaseous or liquid film with significantly lower viscosity in comparison with that in bulk $\eta_\delta \ll \eta$) with the thickness δ (Fig. 2, b) [24, 32]. The apparent slip is provided due to higher shear rate $\partial u/\partial z$ in low viscosity δ layer in comparison with bulk shear rate. The distance of apparent slip is determined as follows [24]:

$$b_{app} = \delta(\frac{\eta}{\eta_\delta} - 1) \approx \delta\frac{\eta}{\eta_\delta}. \qquad (4)$$

Despite its seeming simplicity, this slip model reflects formation of low viscosity layer near hydrophobic wall and allows to understand the influence of interface structure on interfacial transportation phenomena.

In the case of slip over heterogeneous surface, it would be reasonable to consider the effective slip distance b_{eff} (Fig. 2, c) instead of local system description, that is, averaged with respect to characteristic scale of heterogeneity [33–35]. Such approach allows to determine solutions to the problems and to analyze complex systems without cumbersome computations of local field of fluid velocity. Herewith, the effective slip distance b_{eff} is determined by the ratio of average slip velocity $\langle u_s \rangle$ to average shear rate near wall:

$$b_{eff} = \frac{\langle u_s \rangle}{\langle \partial u/\partial z \rangle}. \qquad (5)$$

The use of effective slip distance b_{eff} makes it possible to substitute actual heterogeneous surface with smooth plane with the same observed properties as the actual surface.

It has been demonstrated in [7, 36] that superhydrophobic surfaces allow to increase the slip distance by several hundred of microns by means of steady gaseous phase constrained in the cavities of microrelief. Therefore, they are highly attractive for reduction of hydrodynamic resistance.

3. EXPERIMENTAL

3.1 Test rig

Aiming at determination of the influence of superhydrophobic surfaces on hydraulic resistance upon transportation of aqueous medium, the test rig was developed (Fig. 3).

Water circulates over closed circuit comprised of the test section, the tank, the water flow meter, and the circulation pump. The tank is preliminary filled with cold tap water. The pressure drop at the test section is detected using liquid U-shaped differential pressure meter.

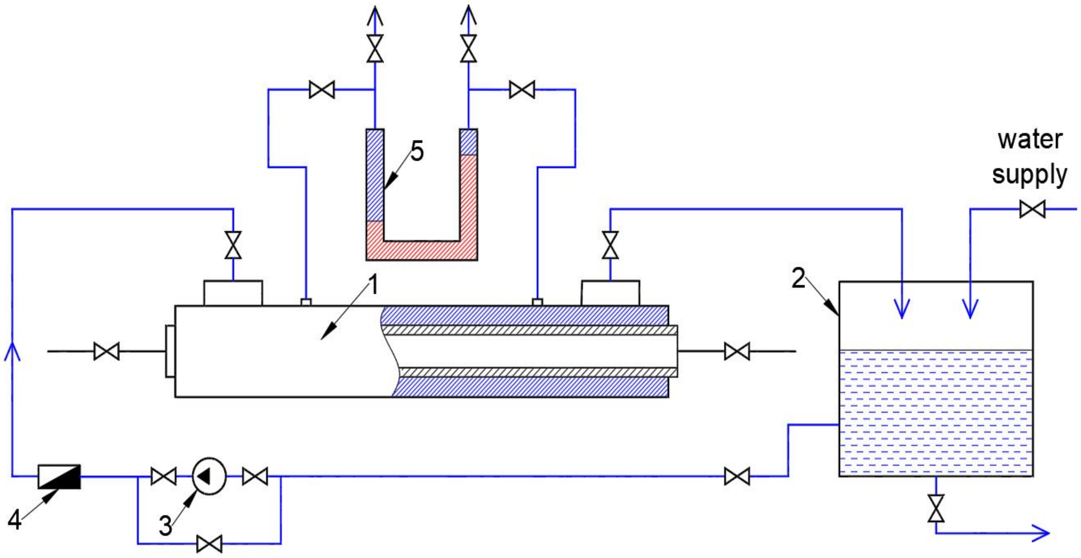


Figure 3: Schematic view of test rig: 1 – test section, 2 – tank, 3 – circulation pump, 4 - water flow meter, 5 - U-shaped pressure meter.

The test section (Fig. 4) for water flow is comprised of annular space arranged by external pipe with the outer diameter of 90 mm with the wall thickness of 3 mm and internal pipe with the outer diameter of 30 mm and the wall thickness of 1 mm. The internal pipe is made of brass, grade L63, and the external pipe is made of steel, grade St20. The overall section distance is 2,000 mm.

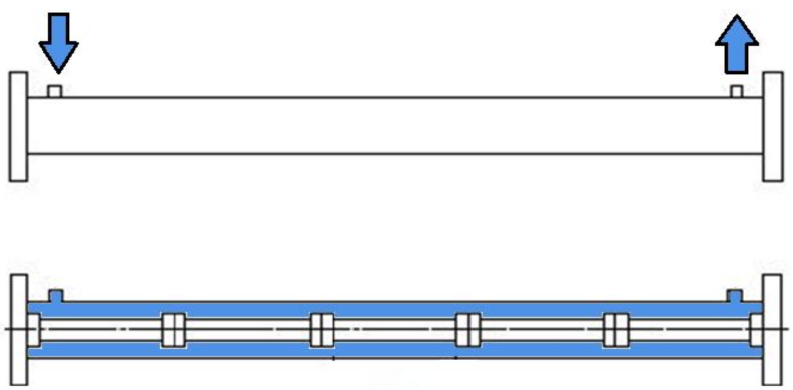


Figure 4: Schematic view of test section.

Due to restrictions related with the maximum allowable length of a sample which can be installed into the rotational unit upon laser modification of surface, the internal pipe is subdivided into five elements, the length of each is 400 mm. It should be mentioned that treatment of internal pipe surfaces attracts great attention for reduction of hydraulic resistance. In this work the internal pipe surface could not be treated, and only external pipe surface was treated.

3.2 *Production and modification of surface of test samples*

In the course of tests, the samples with various surfaces were used including:

- initial surfaces;
- surfaces modified by surfactants;
- surfaces modified by laser equipment.

As-delivered pipes were used as samples with initial surfaces. The measured contact angle on such surfaces was 78.3°.

3.3 *Surface modification by surfactants*

The functional surface of pipe samples was modified by the following surfactant: octadecylamine, a film forming aliphatic amine (ODA).

The ODA molecular layers were formed on external surfaces of test samples by means of special separate circuit comprised of the process tank, the circulation pump, and the ejecting unit including the metering tank for surfactants, the shut-off adjusting valves, the connecting pipelines and the ejector. This circuit provides preparation, circulation, heating and maintaining preset temperature of emulsion or solution to which samples are immersed during the required time of formation of molecular layers on the treated surfaces.

The contact angle measured after the described modification of brass surfaces was 111.4°.

3.3 *Surface modification by laser*

The modification of surfaces by laser equipment was based on formation of micro/nanoscale relief using laser pulse impact applied to the surface. Similar studies aimed at achievement of hydrophobic state of brass surfaces were described in [12, 37].

The relief was formed during passing of laser beam over surface of rotating pipe so that the increment between two generated spiral turns was 100 µm. The parameters of laser radiation upon the modification were as follows:

- laser radiation power: 20 W;
- laser radiation frequency: 20 kHz;
- linear velocity of beam travel along pipe surface: 100 mm/s.

After holding the test samples with laser modified surfaces in air under standard ambient conditions in 14 days, the wetting parameters were analyzed. The contact angles were measured by placing droplets of various volumes onto the surface: 2, 4, and 5 µl. Different droplet volumes were stipulated by complicated studies caused by sufficiently low roll-off angle and surface curvature of samples.

It has been determined that the droplet volume effects the contact angle of surfaces. Herewith, the contact angle decreases with the increase in droplet volume (Fig. 5).

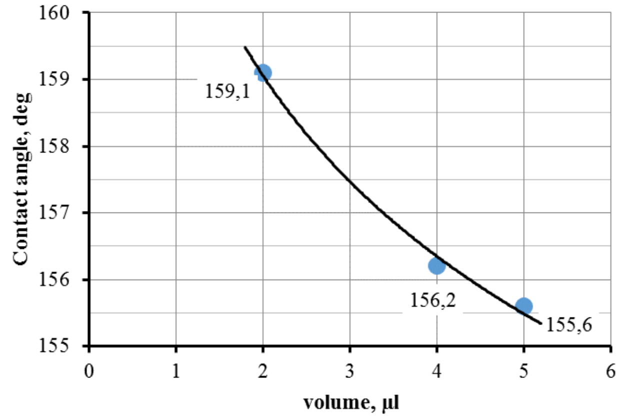


Figure 5: Contact angle on hydrophobic surface as a function of droplet volume

As can be seen in Fig. 6, where droplets of various volume (2, 4, and 5 µl) on surface modified by laser equipment are shown, heterogeneous wetting can be observed.

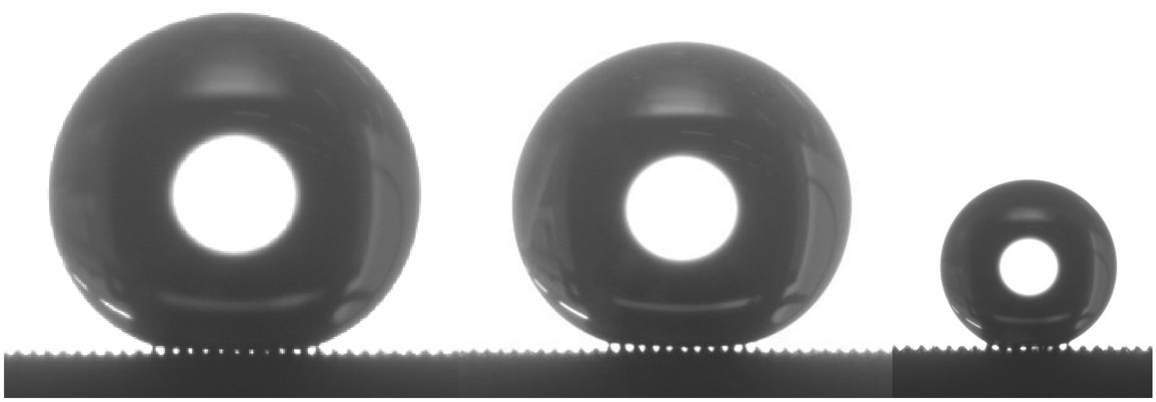


Figure 6: Photos of droplets with the volumes of 5, 4, and 2 µl (from left to right) on modified surface in equal scale.

4. RESULTS AND DISCUSSION

Based on experimental data, the hydraulic resistance along the test section was plotted as a function of Re number (Fig. 7); it can be seen that the loss was decreased only for experimental samples modified by surfactants. Herewith, the maximum effect is observed under conditions of turbulent flow of aqueous medium at Re>10,000 and the maximum relative decrease is 5.2% at Re=15,000.

For the test samples with surfaces modified by laser equipment, the hydraulic resistance increased by 8.9% at Re=15,000.

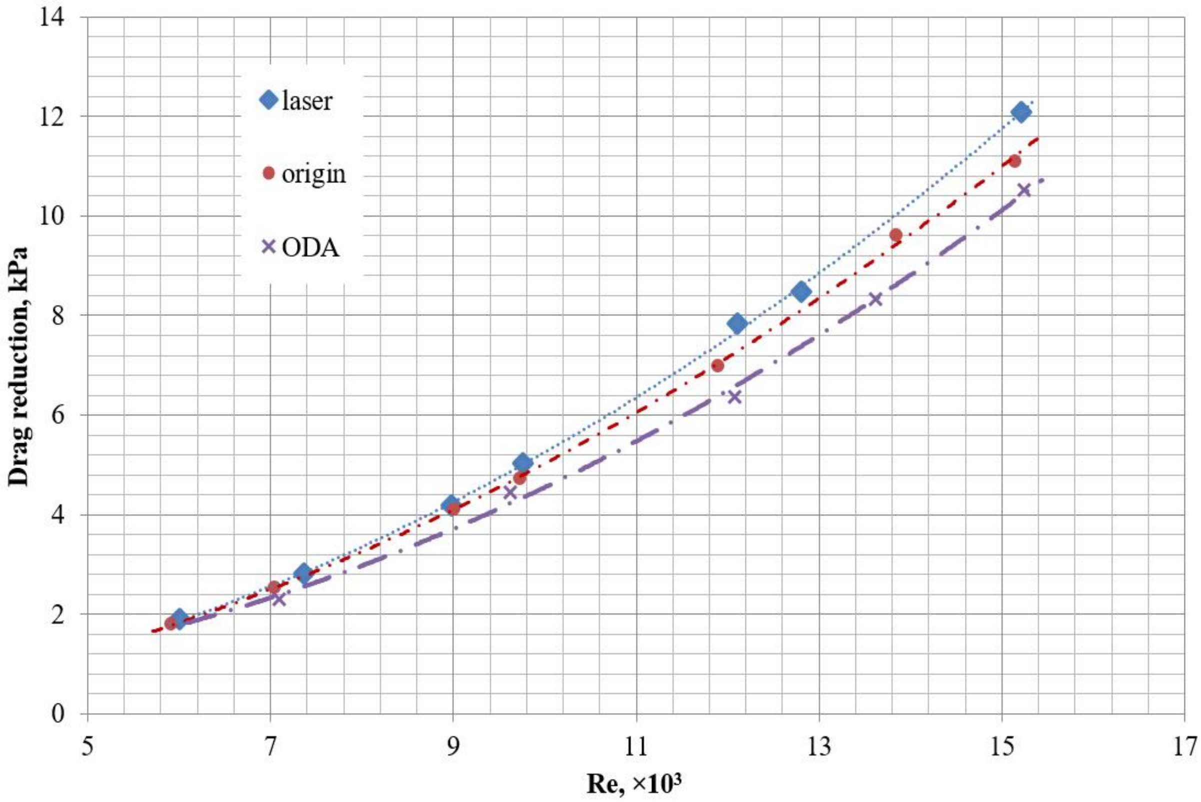


Figure 7: Hydraulic resistance as a function of Re number for test samples: 'laser' – surface modification by laser equipment, 'original' – initial surface, 'ODA' – surface modification by surfactants.

It should be mentioned that immediately after the tests, the internal pipe with laser modified surface was dismounted, its surface was wetted with water, i.e. was characterized by hydrophilic properties. This stipulates the increase in hydraulic loss and could be attributed to the following factors:

- superhydrophobic state was achieved as a consequence of relief formation on laser modified surface and decrease in surface energy due to physically adsorbed organic layer [12]. However, such layer can be easily removed from the surface as a consequence of interaction with fluid medium, which initiates uncontrolled loss of superhydrophobic state [38].
- in the case of complex reliefs, fluid can wet surface partially, which corresponds to metastable state under which a water droplet on surface is characterized by the state intermediate between heterogeneous and homogeneous wetting [39]. Transition from metastable heterogeneous wetting to steady homogeneous mode can be caused by the impact of various impacts, including vibration [40], evaporation [41, 42], air diffusion [43, 44], or droplet falling [45, 46].

5. CONCLUSION

It has been revealed that application of hydrophobic surfaces decreases hydraulic resistance upon transportation of fluid media.

It has been mentioned that the maximum decrease in hydraulic resistance for the surfaces modified by surfactants is observed upon turbulent flow of aqueous medium equaling to 5.2% at $Re = 15{,}000$. For superhydrophobic surfaces modified by laser equipment, the hydraulic resistance increased by 8.9% at $Re = 15{,}000$.

It is assumed that the decrease in hydraulic resistance is stipulated by loss of superhydrophobic properties of surfaces due to such factors as removal of organic layer upon contact with aqueous medium and/or as consequence of external factors, for instance, excessive pressure of aqueous medium. The latter factor leads to unsuitability of such coating for commercial application, especially externally. However, for instance, octadecylamine, would probably lead to formation of solid and chemically stable superhydrophobic coatings.

It should be mentioned that knowledge of transition from heterogeneous to homogeneous wetting and dynamics of metastable state is important for control and improvement of superhydrophobic surfaces.

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