Practical aspects of the wettability

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Abstract. A new knowledge of fluid flow on hydrophobic surface will be presented. The boundary condition will be refined considering the effects of air adhering to the rough, hydrophilic surface. Possibilities of turbulent viscosity effects as a result of liquid slippage on the hydrophobic surface will also be considered. These effects will be demonstrated on the basis of performed experiments. The experimental study will be focused on the determination of the pressure difference in the tube, whose surface is provided with an ultrahydrophobic coating with a contact angle higher than 140 °. Results will be reported based on Reynolds number. In addition to the results of the experiment, the thesis will also include a theoretical study aimed at refining the boundary condition, expressing the interaction of the liquid with the hydrophobic surface. In conclusion, the dissipation function will be derived, expressing the effects of liquid slippage on the hydrophobic surface and compared with its value taking into account the hydrophilic properties of the surface.

1 Introduction

Various mathematical models of fluid flow on a hydrophobic surface have been demonstrated in previous works [1], [7]. In these models, Navier's hypothesis of the dependence of shear stress vs. slip velocity was taken as the basis. This condition has been enhanced for the liquid motion on a general curvilinear surface [4]. Another upgrade of the mathematical model was made by Tesca [8], who assumed that the movement of the liquid on the hydrophobic surface would not occur until a certain value of shear stress was overcome. These models put the size of the contact angle in correlation with the angle of the inclined plane, when the droplet detaches from the surface and moves. The adhesion coefficient k [7] was then determined according to the droplet velocity. Since the value of k is not dimensionless, a more accurate coefficient of adhesion κ is introduced as a function of the velocity of the droplet movement on the inclined plane v_t.

Using this defined mathematical model, computational modelling of both laminar and turbulent flow was performed. As a result of the analysis it was obtained, that the hydrophilic surfaces characterized by a coefficient $\kappa > 10$ behave as hydrophilic [2]. Furthermore, it has been shown that the fluid slip increases the cavitation zone width and reduces the number of Taylor vortices. Hydraulic losses are also reduced at $\kappa < 10$. These mathematical models were verified by experiments in both laminar and turbulent flow. Experiments have shown that the hydrophobic surface has the ability to bind air molecules to one another. The result is a thin air layer adjacent to the surface. Its stability is dependent on the value of the adhesion coefficient κ. The thickness of the air layer decreases as the adhesion coefficient increases. Experiments carried out on tubes of the size close to capillaries have shown that in the laminar flow, as the pressure drop increases, the air layer is compressed. While the pressure drop is lowered, the air layer increases again, so that the air layer restores.

In the turbulent flow, part of the air layer is washed away because the thickness of the air layer is not restored when the pressure drop is reduced back. These statements will be demonstrated in details using examples.

2 Analysis of mathematical model - velocity profiles

The flow in a rigid tube of circular cross-section is considered. Turbulent flow is solved using the power model for incompressible liquid.

Hydrophilic surface - laminar flow

$$v = \Delta p \frac{R^2}{4L\eta}\left[1-\left(\frac{r}{R}\right)^2\right]; \quad v_s = 0 \qquad (1)$$

Hydrophobic surface - laminar flow

$$v = \Delta p \frac{R^2}{4L\eta}\left\{\frac{2\eta}{R\kappa} + \left[1 - \left(\frac{r}{R}\right)^2\right]\right\}; \quad v_s = \Delta p \frac{R}{2L}\frac{1}{\kappa} \tag{2}$$

Hydrophilic surface - turbulent flow

$$v = \Delta p \frac{R^2}{2L\eta}\frac{n}{n+1}\left[1 - \left(\frac{r}{R}\right)^{\frac{n+1}{n}}\right]; \quad v_s = 0 \tag{3}$$

Hydrophobic surface - turbulent flow

$$v = \Delta p \frac{R^2}{2L\eta_s(R)}\frac{n}{n+1}\left\{\frac{\eta_s(R)}{R\kappa}\frac{n+1}{n} + \left[1 - \left(\frac{r}{R}\right)^{\frac{n+1}{n}}\right]\right\}; \tag{4}$$

$$v_s = \Delta p \frac{R}{2L}\frac{1}{\kappa} \tag{5}$$

From these terms it is clear that they do not consider the effect of the air layer near the surface. In the case of turbulent flow, it is assumed that near the surface due to the slip of the liquid on the surface, a turbulent viscosity develops. This contains the expression (4). However, it is clear from (5) that the turbulent viscosity value does not affect the slip velocity in this model. However, this does not correspond to the experiment, as it will be shown in the next chapter. In [4] this model is refined by the effect of turbulent viscosity on κ. This stems from the fact that after the air layer is washed away, the liquid must slip on the surface. However, slippage will cause turbulent viscosity, which will affect liquid slippage due to turbulent fluctuations. This may reduce the slip of the drop across the surface. This, however, contradicts the equation (5).

3 New mathematical model

In a mathematical model describing the flow between two parallel walls, a layer of air near the hydrophobic surface [1], [8] was considered. Both laminar and turbulent models were derived.

3.1 Laminar flow

The boundary condition was defined by [4]:

$$\tau = \eta_B \frac{\partial u}{\partial y} = \kappa u_s \quad , \quad \text{where} \quad \eta_B = \frac{\eta}{1 + c\eta u_0} \quad \text{and} \quad \kappa = \rho v_t \alpha \tag{6}$$

From this it is obvious that at $\kappa = 0$ is $\tau = 0$ which indicates the correct physical sense, since in the intact air layer the air adheres to the hydrophobic surface, so it holds that $u_s = 0$. The slip velocity [1], [4] corresponds to the value of the viscosity η_B:

$$v_s = \Delta p \frac{(4Hc\eta u_0^3 - c\eta u_0^3 + 6H^2)}{12LH(c\eta u_0^2 + 1)\kappa + 12L\eta} \tag{7}$$

For $\kappa = 0$ the velocity $v_s \neq 0$, which is contrary to the physical reality. Therefore, we propose a new mathematical model that is in accordance with the definition of κ. Since dimension κ is equal to the dimension of the viscosity gradient, we propose the following mathematical model to formulate the boundary conditions:

$$\boldsymbol{\tau} = \eta_B \frac{\partial \mathbf{u}}{\partial y} = \left(\kappa + \frac{\partial \eta_B}{\partial y}\right)\mathbf{v} \tag{8}$$

This model is generic enough to describe different flow variants considering the small air layer near the surface. The following viscosity model was proposed in [1] for the air layer:

$$\eta_B = \frac{\eta}{1 + c\eta(u_0 - u)^2} \tag{9}$$

This model well describes the behavior of the fluid in the air layer.

$$\left.\frac{\partial \eta_B}{\partial y}\right]_{y=0} = 2\frac{\eta}{u_0}\frac{\alpha}{(1+\beta)^2} \ , \quad \beta = c\eta u_0^2 \tag{10}$$

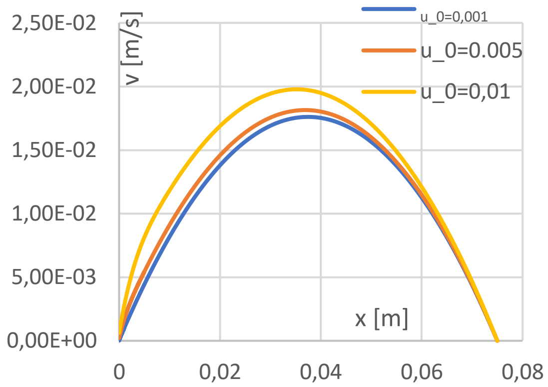

Fig. 1 Examples of the velocity profiles

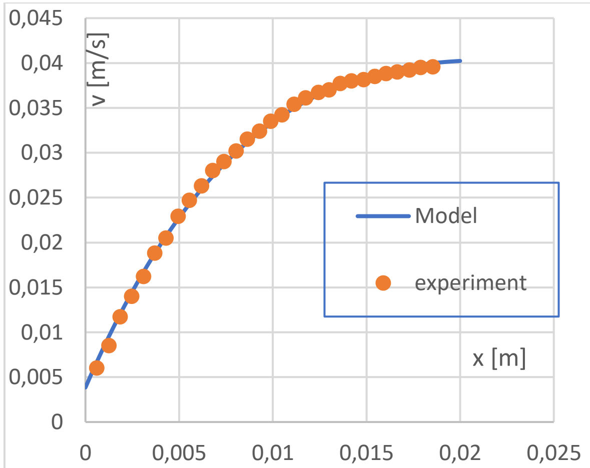

Fig. 2 Model comparison with the experiment

3.2 Turbulent flow

In the case of turbulent flow, two variants can be considered:

- Assuming that the air layer is washed away, it can be assumed that turbulent fluctuations in velocity and pressure will occur on and near the surface, causing turbulent viscosity on the surface. At the same time, due to the turbulent viscosity, the slip of the liquid on the hydrophobic surface decreases. In this case, the boundary condition will depend on the turbulent viscosity and its gradient so that the shear stress can be assumed to depend on the slip rate in the form:

$$\boldsymbol{\tau} = \underbrace{\hat{\eta}}_{\hat{\eta}=\eta+\eta_t} \frac{\partial \mathbf{v}}{\partial r} = \frac{\partial \eta_t}{\partial r}\mathbf{v} \qquad (11)$$

- Assuming that the hydrophilic surface is not completely smooth, it is either coarse due to corrosion or artificially created with the surface uneven with the holes or grooves. In such a case, the surface is partially hydrophobic and partly formed by holes filled with the air. In this case, the boundary condition for shear stress can be written in the form:

$$\boldsymbol{\tau} = \eta_B \frac{\partial \mathbf{v}}{\partial r} = \left(\kappa + \frac{\partial \eta_t}{\partial r}\right)\mathbf{v} \qquad (12)$$

These mathematical models are based on the following experimental results.

4 Experiments

Figures 3, 4 show the flow in a minichannel with parallel walls. There is an apparent thickness of the air layer in laminar flow compared to the liquid layer. The following figure 5 shows the change in air layer thickness as a function of the Reynolds number and the degree of hydrophobia expressed by the contact angle Θ [3].

From this view, the influence of the air layer and its compression up to the value of Re 5000 is evident. In the mathematical model (11) this effect can be easily understood.

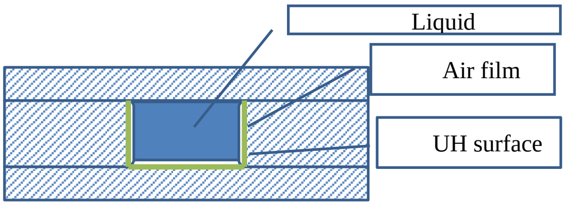

Fig 3. The geometry of the air film formation in the mini-channel. [3]

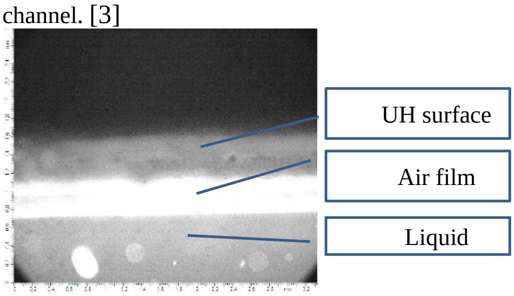

Fig.4 The visualization of the air film with the microscope magnification 10x. [3]

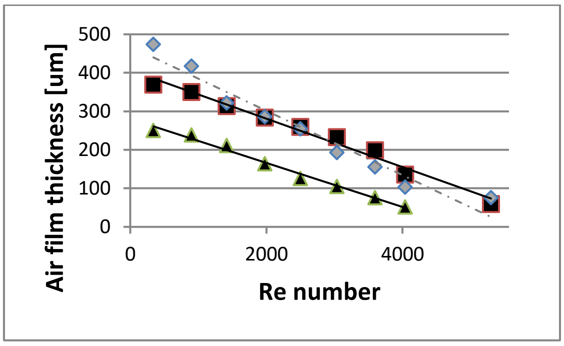

Fig. 5 The graph: air film thickness dependant on Re number. [3]

4.1 Smooth hydrophobic surface

Further experiments were carried out again in a channel with parallel walls, one of which was provided with a hydrophobic surface. The profile dimensions were 75x80mm [2]. Figures 6, 7, 8 show the measured velocity profiles for Re 2000, Re 9000, Re 13000.

The wall provided with a hydrophobic surface had a contact angle of 150 °. It is apparent from Figures 6,7 that the velocity profile near the surface is influenced by the air layer bound to the hydrophobic surface, which results in a relatively high velocity near the surface.

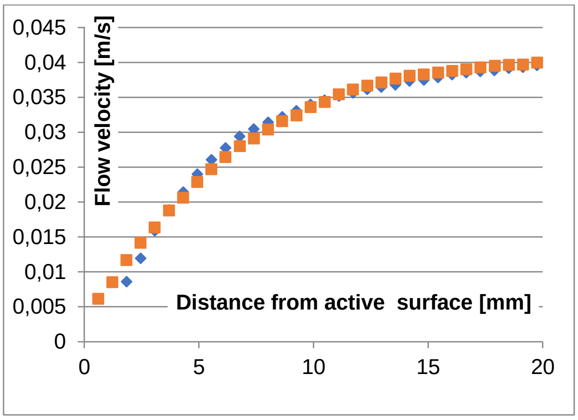

Fig. 6 Re=2000; Dependence of Velocity on the distance from active surface, which is on the position 0

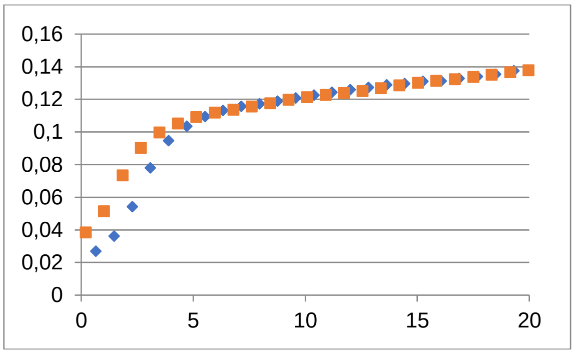

Fig. 7 Re=9000; Dependence of Velocity on the distance from active surface, which is on the position 0

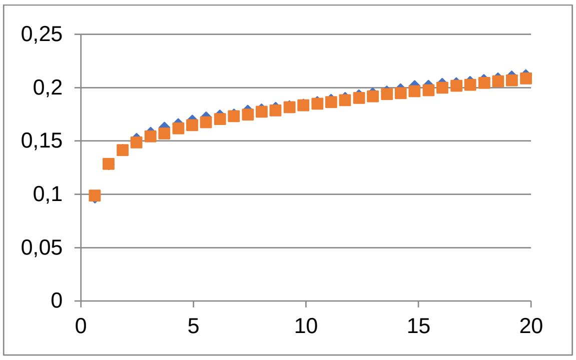

Fig. 8 Re=13000; Dependence of Velocity on the distance from active surface, which is on the position 0

Another situation occurs at higher Reynolds numbers. Even at Re 13000, some of the air layer residues are partially washed away and compressed, so that the wall behaves as wettable.

To verify this, another experiment is performed, this time with a tube of circular cross-section whose inner surface has been treated with three types of hydrophobic coatings with the following parameters:

$$D = 0{,}042m \text{ a } L = 6m$$

a) Stainless steel $\Theta = 80°$
b) Stainless steel + UED $\Theta = 158°$
c) Ceramics + UED $\Theta = 157°$

The measured section is shown in Fig. 9.

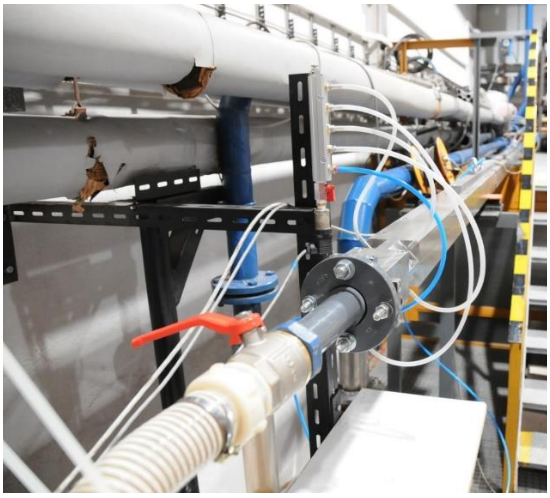
Fig. 9 Experimental stand

The dependence of specific energy on Reynolds number is shown in Fig. 7. Stainless steel has a contact angle of only 80 °, which is at the edge of hydrophilia. It can therefore be assumed that liquid adheres to this surface.

The other two surfaces are ultrahydrophobic, so they can be assumed to be aerophillic. However, it is apparent from the value of the measured pressure difference that the air layer has already been washed away or so compressed when the turbulent flow is developed that the surface already behaves as wettable as the liquid adheres to the surface.

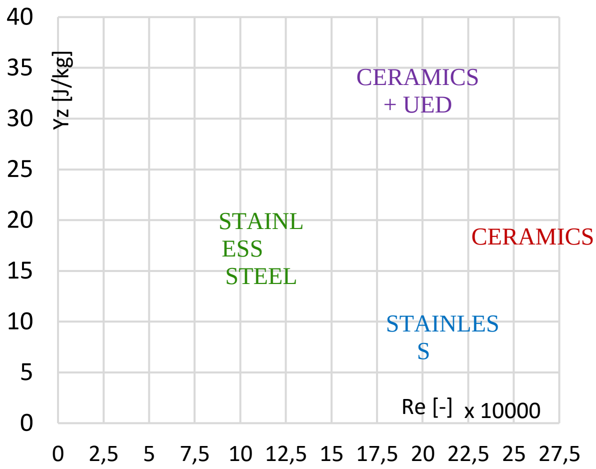

Fig. 10 The dependence of specific energy on Reynolds number

If the air layer is washed away and the liquid slips, the conditions for turbulent viscosity are created directly on the surface and the pressure difference may increase. From the measured values shown in Fig. 10, it is evident that the ultrahydrophobic smooth surface is characterized by a higher pressure difference than the smooth hydrophilic surface corresponding to the stainless steel material. This result is very surprising and will be verified by further experiments.

4.2 Coarse-textured surfaces

A surface with a rough structure is shown schematically in Figure 11. It is characterized by the air filled in the holes (grooves) of the hydrophobic coarse textured surface. This type of surface is characteristic for surfaces affected by corrosion. Experiments carried out on this type of surfaces draw a very important conclusion on hydraulic losses [5].

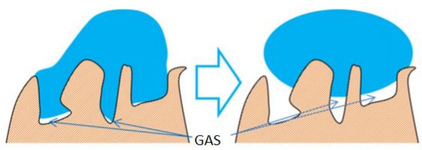

Fig. 11 Surface with a rough structure [5]

Figure 12 shows the pressure difference for a surface affected by corrosion. Its profile is shown in Fig. 13.

Different types of hydrophobia were considered in the experiments depending on the contact angle Θ and the angle of the inclined plane at which the drop motion occurs.

The experiments show that the pressure difference is lower for hydrophobic surfaces, compared to the original surface variant affected by corrosion. The cause is an air layer that adheres to the superhydrophobic surface and is not washed away by the liquid stream. For this type of surfaces, boundary conditions (12) can be used in computational modeling.

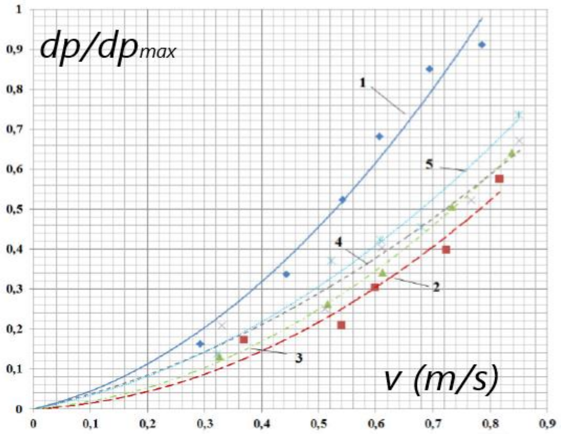

Fig. 12 Pressure difference ratio for different types of contact angles (1-78°, 2-110°, 3-128°, 4-130°, 5-133°)

Fig. 13 Coarse-textured surface [5]

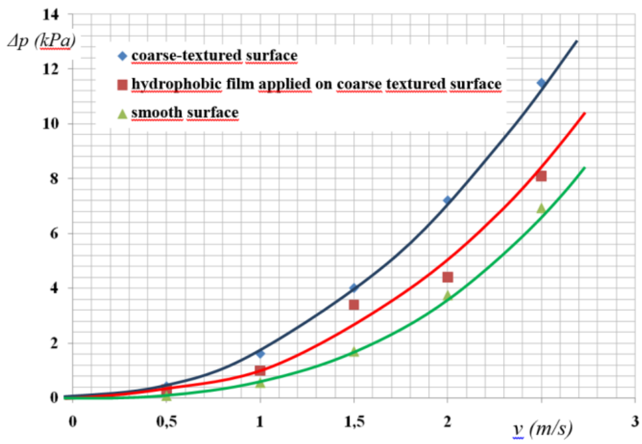

Fig. 14 **P**ressure difference versus the velocity of the liquid for different quality of surfaces [6]

In addition to these experiments, another [6], taking into account the flow of oil, was also performed in a circular-section tube with a rough structure. The results are analogous to the previous study. Figure 14 shows three curves of the pressure difference versus the velocity of the liquid.

Based on these experiments, it can be concluded that hydrophobic technology applied to surfaces with high roughness reduces hydraulic losses when fluid flows through a pipe.

The energy dissipation characterizing the power input to cover hydraulic losses in a constant cross section tube is determined from:

$$p = \int_V \hat{\eta} v_{ij} v_{ij} dV = \Delta p Q - |\boldsymbol{\sigma}||\mathbf{v}_s|\Gamma \qquad (13)$$

$$\text{ale } \boldsymbol{Q} = \hat{\mathbf{v}} S, |\boldsymbol{\sigma}|\Gamma = \Delta p \mathbf{S}, \text{ takže} \qquad (14)$$

$$p = \Delta p \mathbf{S}(\hat{\mathbf{v}} - |\mathbf{v}_s|) \qquad (15)$$

$\hat{\mathbf{v}}$ mean velocity of liquid in section S

$\mathbf{v}_s$ slip speed, or velocity at the boundary of the air layer.

5 Conclusion

The detailed analysis of the mathematical model of the boundary condition for the liquid in contact with the hydrophobic surface was performed. This analysis was based on a new knowledge gained from experiments of incompressible fluid flow in tubes of constant cross-section. The experiments showed a strong dependence of the velocity of the liquid near the hydrophobic surface on the thickness of the air layer during both laminar and turbulent flow. Based on these findings from the experiment, a mathematical model of the boundary condition for shear stresses on the wall of the hydrophobic surface was formulated. This was included in the $k - \varepsilon$ turbulence model.

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