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# FLOW IN CIRCULAR CROSS SECTION TUBE USING THE PARTIAL SURFACE WETTING CONDITIONS

# PROUDĚNÍ V POTRUBÍ KRUHOVÉHO PRŮŘEZU ZA POUŽITÍ PODMÍNKY ČÁSTEČNĚ SMÁČIVÉHO POVRCHU

## Abstract

This contribution deals with the possibility of numerical modeling of fluid flow in horizontal pipes of circular cross section with boundary condition including the effect of wall partial wetting. ANSYS Fluent software was used for numerical modeling. Boundary condition including the effect of wall partial wetting is based on a theory where the adhesive coefficient *k* determines the wettability of the wall, defined by prof. Pochylý [1-5]. User defined function (UDF) was created for this boundary condition and it was verified in both 2D and 3D geometry. The results of numerical modeling have been verified by theoretical assumptions. Furthermore, the article presents the physical experiment results of pressure losses measuring in pipes of circular cross section of different materials in laminar flow. Subsequently, the experiment results are compared with the theory of fully wettable and partially wettable walls to determine the adhesive coefficient *k* for the material of used pipes.

## Abstrakt

Článek pojednává o možnosti numerického modelování proudění kapaliny ve vodorovném potrubí kruhového průřezu s využitím okrajové podmínky zahrnující vliv částečné smáčivosti stěn. Pro numerické modelování bylo využito programu ANSYS Fluent. Okrajová podmínka zahrnující vliv částečné smáčivosti stěn vychází z teorie, kde smáčivost povrchu stěny určuje adhesní součinitel *k*, který definoval prof. Pochylý [1-5]. Pro tuto podmínku byla vytvořena uživatelsky definovaná funkce (UDF), která byla ověřena ve 2D i 3D geometrii. Výsledky z numerického modelování byly ověřeny dle teoretických předpokladů. Dále článek představuje výsledky z provedeného fyzikálního experimentu měření tlakových ztrát v potrubí kruhového průřezu z různých materiálů při laminárním proudění. Následně jsou výsledky experimentu srovnány s teorií smáčivých i částečně smáčivých stěn s cílem stanovit adhezní součinitel *k* pro použité materiály potrubí.

## 1 INTRODUCTION

Flow in pipe is affected by physical properties of liquids or surface treatment of material in which a liquid flows around. Suitable choice of material or its surface treatment on the parts of hydraulic machines and equipment can decrease hydraulic losses and thus increase their efficiency. In piping systems the hydraulic losses can be divided into friction losses and local losses; in a straight

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pipe friction losses just play a big role. Friction losses of the liquid caused by device surface may to some extent be influenced by roughness and material treatment, but also its hydrophobicity, whereas the use of hydrophobic materials can significantly reduce friction losses. It is therefore appropriate to investigate how the change in pipe surface wettability changes the value of friction losses. The device was constructed to measure the friction losses in laminar flow in pipes of circular cross section, where the plastic pipes PVC-U, PVC-C, ABS and PVDF were tested. For standard wettable materials (glass, steel) is velocity on the wall equal to zero, ANSYS Fluent software includes this condition as "no slip" in boundary conditions setting for a wall. At hydrophobic material the liquid slips along the surface and fluid velocity on the wall is not equal to zero. For this case the UDF function was defined calculating the shear stress on the wall according to (1). Partial wetting is thus given by the adhesive coefficient *k*.

## 2 PHYSICAL EXPERIMENT – PRESSURE LOSSES MEASURING IN PIPES OF CIRCULAR CROSS SECTION FROM DIFFERENT MATERIALS

### 2.1 Equipment description

The equipment for measuring pressure losses in pipes of circular cross section from different materials was designed and implemented, see Fig. 1.

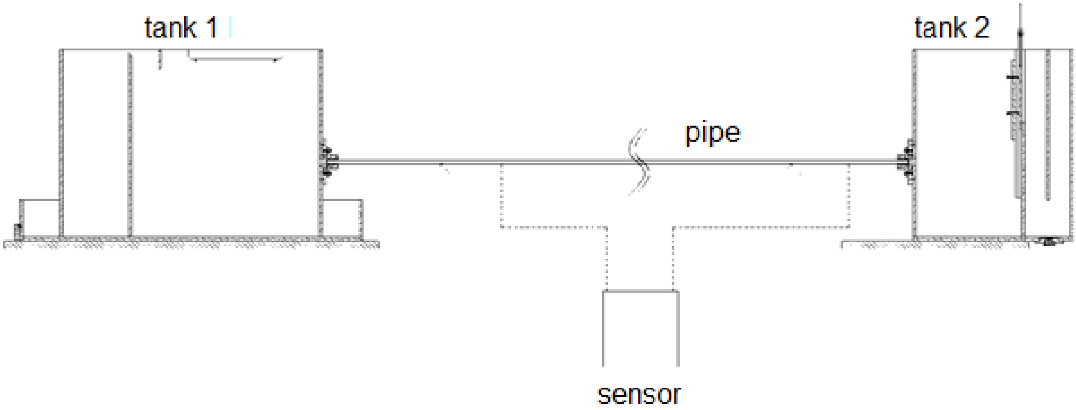

**Fig. 1** Scheme of equipment for measuring the friction losses in pipes in laminar flow regime.

The pressure drop required for the laminar movement of fluid in pipe at total length of 5 m is ensured by changing the height of the overflow in the tanks. Also, condition of low flow velocity is achieved just by overflows. An overflow in the tank 1 is fixed and used for steadying of the level of the transported liquid after its entry into the tank. The overflow in the tank2 is movable, which is pushed to the wall of the tank with bolts and sealed by sealing cord. Transported liquid flows into a measuring container through this overflow. It can be set to different heights using the threaded rod with nut. Flow rate measurement is performed using either a branded orifice, when the water level in the measuring container gives the value of volumetric flow rates according to the calibration curve of orifice or into measuring container, where we measure the volume of fluid drained at the time.

For these small flow velocities and for measured length of the pipe 4 m the sensor for measuring the pressure difference between the sampling places – Honeywell ST 3000 Smart Transmitter Draft with an optional range of pressure measurements at two scales of 0 to 1/25 mbar was chosen. The sensor ensures measurement accuracy of 0,1 %, which is required in the low pressure measurement. Differential pressure transmitter is connected to the pipe via two sampling places, one of which is located 1 m behind the pipe inlet because of start-up length consideration. Second sampling place is at the end of the pipe outlet. All pipes had a length of 5 m, external diameter 16 mm, inner diameter was slightly different as suppliers possible – PVC-C, PVC-U, and ABS tubes 12.4 mm, PVDF pipe 12.2 mm.

One of the goals of the measurement was to assign a value of the adhesive coefficient to various partially wettable materials; therefore the pipes from various materials were selected for the physical experiment. The examined plastics were assumed partial wetting, especially PVDF material, which is similar to Teflon with its polymeric chain.

## 2.2 The results of pressure losses measurement in pipes of different materials

Hydraulic losses are divided into friction and local losses. Given that there are no fittings in pipe system, pressure drop can be considered as a friction loss. Local losses could be considered such as the pipes inlet and outlet. However, it was assumed that these places are situated outside the sampling places of pressure. Pipes inlet and outlet would not affect the pressure loss due to sufficient start-up length of 1 m for velocity profile steadying.

For other local loss the air bubbles could be considered, which are deposited in pipe during the measurement. The measuring device is designed as an open-ended circuit, where the flowing liquid was water from water tap. Venting of pipes was carried out so that when the pipe was installed, the greatest pressure drop has created, thus the maximum of bubbles tore in a stream of water. Furthermore, before each measurement of pressure loss the each pipe was percussed for venting the pipe and it was possible to observe the departure of the bubbles in pipes output. The measured values of pressure losses for each of the tubes are in the following Fig. 2.

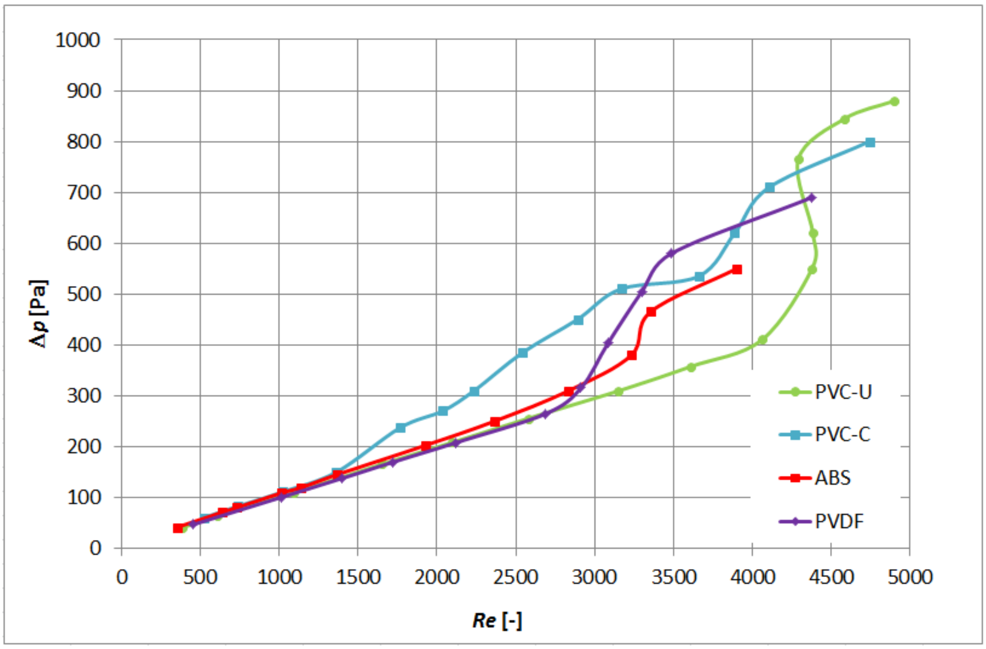

**Fig. 2** Measured values of pressure loss in pipes of various materials depending on the Reynolds number.

Each pipe had air intake in a different extent. In pipe made from PVDF material could be observed a lot of small bubbles adhere to the walls, so the length of pipe was covered by “air film” in some places. This tube has a minimum value of pressure drop, so that could be considered as partially wettable. It is possible that partial wetting of the material is caused by the amount of air which adheres to this material.

In Fig. 2, which contains the entire range of measured Reynolds numbers, it is possible to notice where the regime of flow passed from laminar area characterized by a linear dependence of $\Delta p$ on $Re$, to transition and turbulent area. The theory for flow in smooth circular pipes (“no slip”) prescribes the critical value of Reynolds number $Re_k = 2\ 320$, but it is generally considered that laminar flow may occur between $Re_k = 2\ 000 \div 4\ 000$.

But it was possible to observe the transition from laminar to turbulent flow regime even earlier than at this critical value of *Re*. This transition at lower values of *Re* can be explained by comparing the theoretical calculations of the critical Reynolds number for a given pipe diameter, where the flowing medium is water in one case and mixture of water and air in second case. Kinematic viscosity will change depending on what volume fraction of air in the mixture is expected. At the same pipe diameter, the same velocity and different kinematic viscosity, the value of $Re_k$ for mixture will be more than two times lower than for water, if we consider a mixture consisting of 90 % water and 10 % air.

## 3 APPLICATION OF PARTIAL WETTABILITY BOUNDARY TO THE CALCULATIONS AT NUMERICAL MODELING

### 3.1 Partial wettability theory

Prof. Pochylý derived formula (1) for general curved surfaces in contact with the liquid, where it is assumed that if the liquid slips on the surface by the velocity $\vec{v}$, shear stress vector $\vec{\sigma}$ lies in the plane defined by the outer normal vector to the surface $\vec{n}$ and the velocity vector $\vec{v}$, and vector of adhesive shear stress at the wall is $\vec{\sigma}_A$. Based on this idea it can be assumed that the shear stress vector on a partially wettable surface is proportional to the velocity of the fluid:

$$\vec{\sigma}_A = (\vec{\sigma} \times \vec{n}) \times \vec{n} = -k\,\vec{v} \tag{1}$$

where *k* is adhesive coefficient [Pa.s.m$^{-1}$].

We consider laminar, isothermal, steady flow of incompressible fluid in pipes of circular cross section for which the theory of fully wettable walls is well known. Theory from prof. Pochylý [1-5], taking into account partially wettable walls, is also derived for laminar flow. Velocity profile in pipes of circular cross section is parabolic for wettable wall [9]. For partially wettable walls velocity profile is not only composed of paraboloid, but is divided into a cylindrical part and the parabolic part, it is therefore modified by the adhesion coefficient *k* [9]. The following equations are the basic equations for calculation of pressure losses in wettable and partially wettable pipe, which then served to compare the results of numerical modeling.

Equation of dependence of pressure drop $\Delta p$ in wettable pipe on flow rate based on the formula for calculation the velocity profile in pipe of circular cross section in cylindrical coordinates is:

$$\Delta p = \frac{8\eta l Q}{\pi R^4} \qquad \Delta p = \frac{8 l \eta Q}{\pi R^4\left(1 + \frac{4\eta}{Rk}\right)} \tag{2}$$

When considering partially wettable pipe wall there is an essential difference of non zero velocity on the wall of pipe, which becomes significant decreasing of pressure loss in pipe. In the numerical testing good agreement of numerical results with analytical relations has been found, see [9], so for further evaluation the theoretical calculations will be used.

By the physical experiment the bubbles adhering to the pipe wall was found, the numerical experiment was performed on this theme, where it was examined how the value of pressure drop varies with the increasing the content of air in liquid. It was found that the more air is delivered into the pipe, the smaller value of pressure drop can be observed. The result corresponds to the mentioned assumption that hydrophobicity of materials may be caused by air that adheres to the wall of such material. This conclusion can be explained by comparing the values of critical Reynolds number for flowing water and mixture of water and air.

## 4 COMPARISON OF THE RESULTS ACHIEVED IN THE PHYSICAL EXPERIMENT WITH THE FULL AND PARTIAL WETTABILITY THEORY

The graphs in this chapter are arranged by two groups of material according to pipes inner diameter – PVDF plastic pipe with a diameter of 12.2 mm, PVC-U, PVC-C and ABS plastic pipes with a diameter of 12.4 mm.

An analysis is now limited only on laminar flow. First, the measured values of pressure loss in a wider range of Reynolds numbers are compared with the theory. Of course, it is necessary to take into account the fact that the theory can´t cover the entire contexts that occur in real measurements. Plastics can have such a different coefficient of friction than other materials like steel [11], thus the theoretical pressure drop for wettable wall would be changed.

The measured curve of pressure drop for pipe made from PVDF is shown in Fig. 3. Pressure drop for lower Reynolds numbers is lower than the pressure drop for theoretical no slipping condition. PVDF pipe in which the highest hydrophobicity was expected, fulfilled this assumption and the values of pressure drop across the laminar area are still below the theoretical value for the wettable wall. A slight transition over the theoretical value comes to around $Re_k = 1\ 800$, where the values of the pressure drop still hold close to theoretical values for no slip condition. Up to about $Re = 2\ 750$ the measured curve enters the transition area of flow and pressure drop values sharply increase.

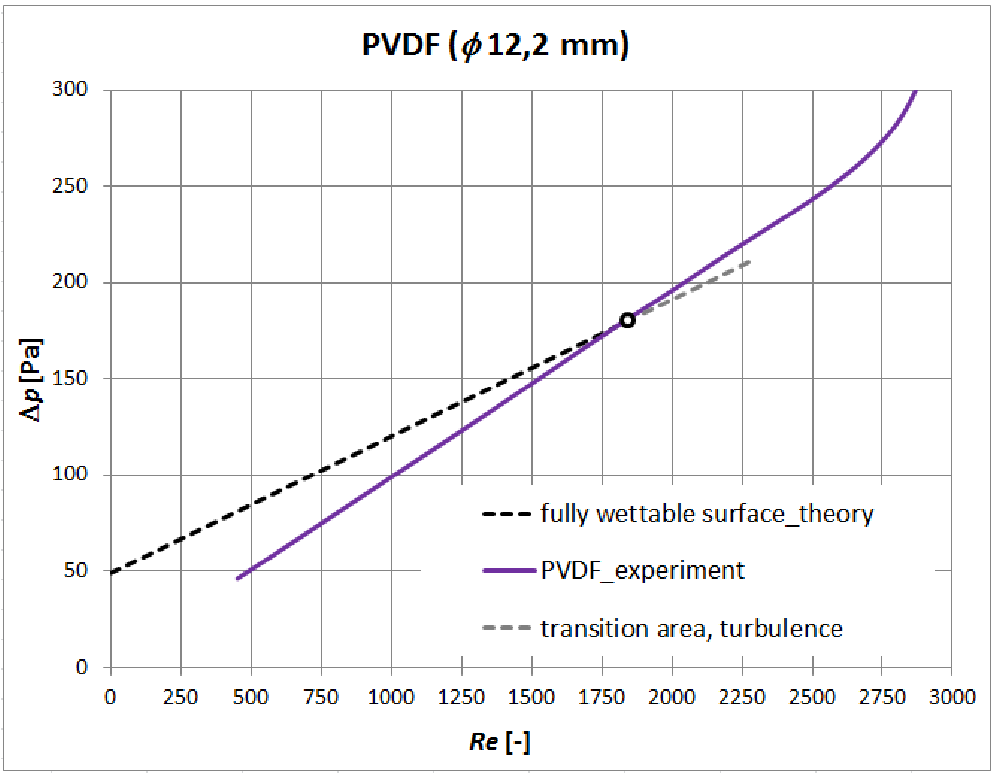

**Fig. 3** Comparison of measured values of pressure loss for PVDF pipe with no slip theory.

In following Fig. 4 there are all other plastic pipes compared with the corresponding theoretical value of no slip condition. We can see the graphs of measured values where the values of pressure drop are under the theoretical value of no slip condition at lower values of *Re*. At higher value of *Re* the measured values exceed the theoretical pressure drop for no slip condition. Crossing the theoretical no slip value occurs at $Re_k = 1\ 250 \div 1\ 500$.

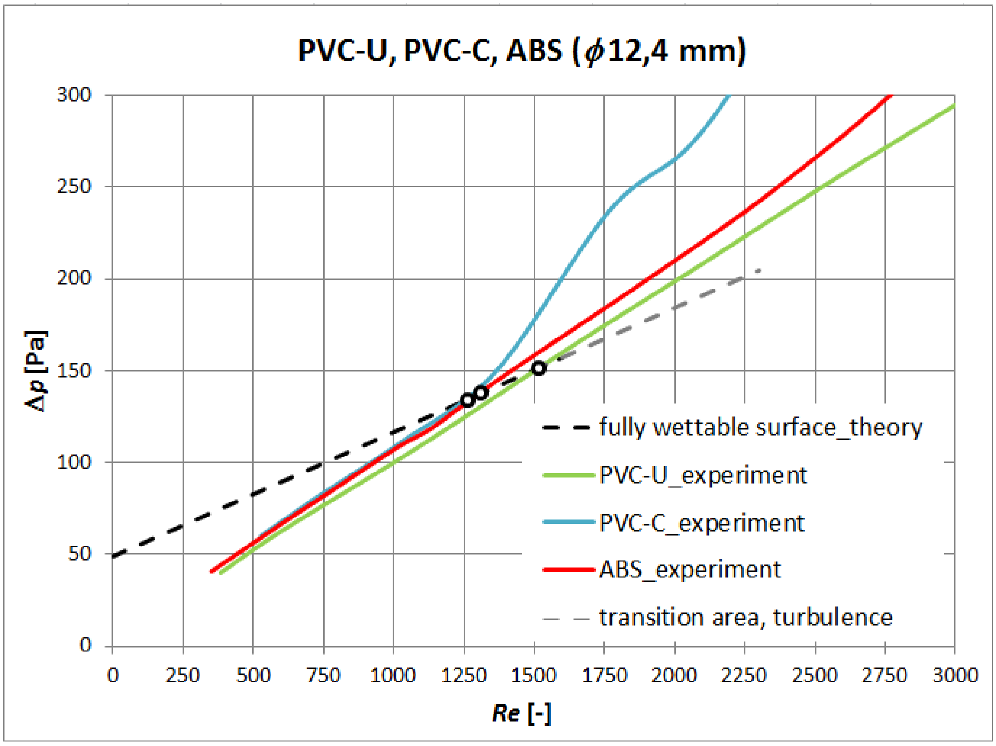

**Fig. 4** Comparison of measured pressure loss values for other plastic pipes with no slip theory.

The increase of pressure drop can be explained by the presence of air in the pipes. For smaller *Re*, which is a laminar flow, more air bubbles adhere to the surface of the pipe and the pressure drop decreases. At higher values of *Re* the bubbles are carried by a stream, they adhere less on the wall and the pressure drop increases.

All measurements showed a fluctuation of the measured values of pressure drop over the area of specified $Re_k$. Oscillation of pressure drop values indicates that the regime of flow changes from laminar area to transition area. Oscillation of pressure drop can be observed by eye in transition area of flow, the frequency of oscillation is lower than the turbulence frequency. Following assumption can be deduced: laminar flow is observed only in the values under $Re_k$, when *Re* is higher then $Re_k$ the flow is the transition flow and after that turbulence, where the theory for laminar flow regime doesn´t valid. Why the critical Reynolds numbers for plastics are lower than mentioned in literature can be explained again by above-mentioned difference in the critical Reynolds number for flowing water and a mixture of water and air. All pipes contained a mixture of water and air in the measurement, which changes the viscosity and density and the critical Reynolds number moves to lower values.

To determine the adhesion coefficient of partial wetting, it is appropriate to limit research only to the values measured in the laminar flow regime, i.e. below the critical values of $Re_k$. To assign a value of the adhesive coefficient to given materials, it is necessary construct a graph of dependence of pressure drop $\Delta p$ vs. adhesive coefficient *k*, see Fig. 5. For selected Reynolds number is possible to assign the measured value of pressure drop to the value on the curve according to the theory of partially wettable walls. The value of adhesive coefficient $k = 1.6$ Pa·s·m$^{-1}$ was assigned to PVDF pipe for $Re = 1\ 000$. The same procedure was applied for assigning adhesion coefficient to other plastic pipes, see Fig. 6. The value of adhesive coefficient $k = 2$ Pa·s·m$^{-1}$ was assigned to PVC-U pipe, the value of $k = 5.3$ Pa·s·m$^{-1}$ was assigned to PVC-C pipe and the value of $k = 4.1$ Pa·s·m$^{-1}$ was assigned to ABS pipe, all for $Re = 1\ 000$.

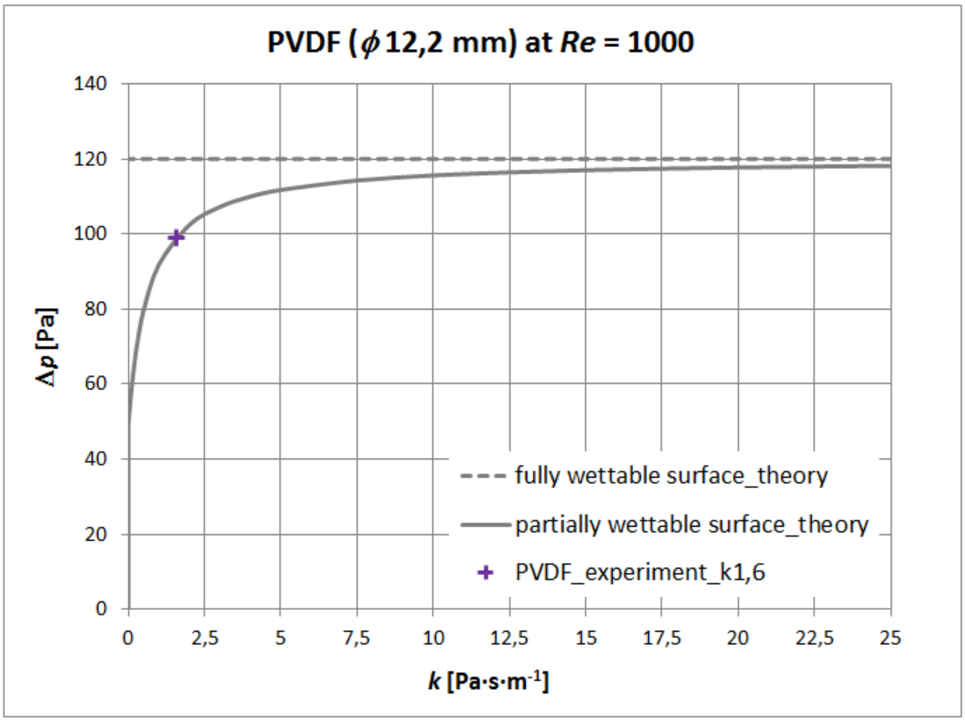

**Fig. 5** Assigning value of the adhesive coefficient *k* to the pipe from PVDF material.

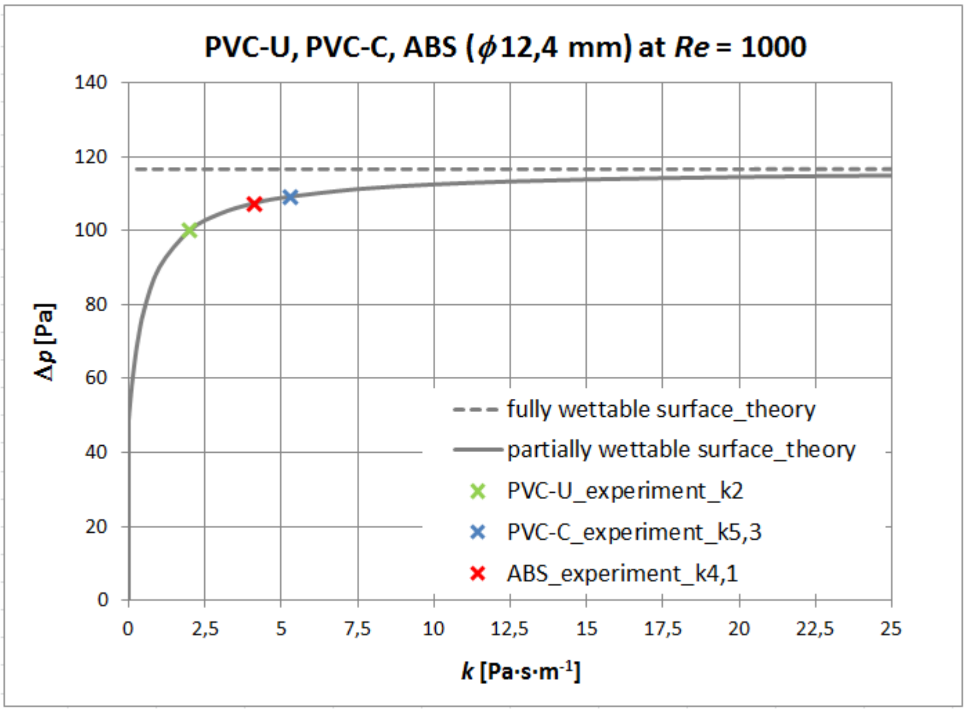

**Fig. 6** Assigning values of the adhesive coefficient *k* to the pipes
from PVC-U, PVC-C and ABS materials.

From Fig. 5 and Fig. 6 it is obvious that the pipe will be less wettable, the less pressure drop across it can be measured and vice versa. The question might sound, how much partial wetting is property of the material and how much partial wetting is the phenomenon resulting from the air, which more adhere on these partially wettable materials and which decreases the pressure drop value. These two options are closely linked, because when the material is hydrophobic, it more keep away the liquid and the air bubbles more adhere on it. This air is the cause of lower pressure drop.

Already commented graph of pressure drop $\Delta p$ vs. *Re* can be added of the theoretical values of the pressure drop for partially wettable walls, see Fig. 7 for PVDF pipe showing the graphs of pressure drop depending on Reynolds number in a wettable and partially wettable pipe at $k = 1.6\ \mathrm{Pa{\cdot}s{\cdot}m^{-1}}$. These two lines are crossed by the line of experimentally measured values for PVDF pipe. For this material at the $Re = 1\,000$ the value of adhesive coefficient $k = 1.6\ \mathrm{Pa{\cdot}s{\cdot}m^{-1}}$ was assigned. However, if we move in the graph to the lower values of *Re*, we would get a lower values of adhesive coefficient *k* and therefore a greater hydrophobicity. Conversely, at higher values of *Re*, the higher values of adhesive coefficient *k* will belong to experimentally measured line for PVDF material and the more we approach to the wettability. The explanation can be found again in the air contained in flowing water, where for smaller *Re* the liquid flows slowly and the more air bubbles adhere on the wall, which decrease the pressure drop and vice versa.

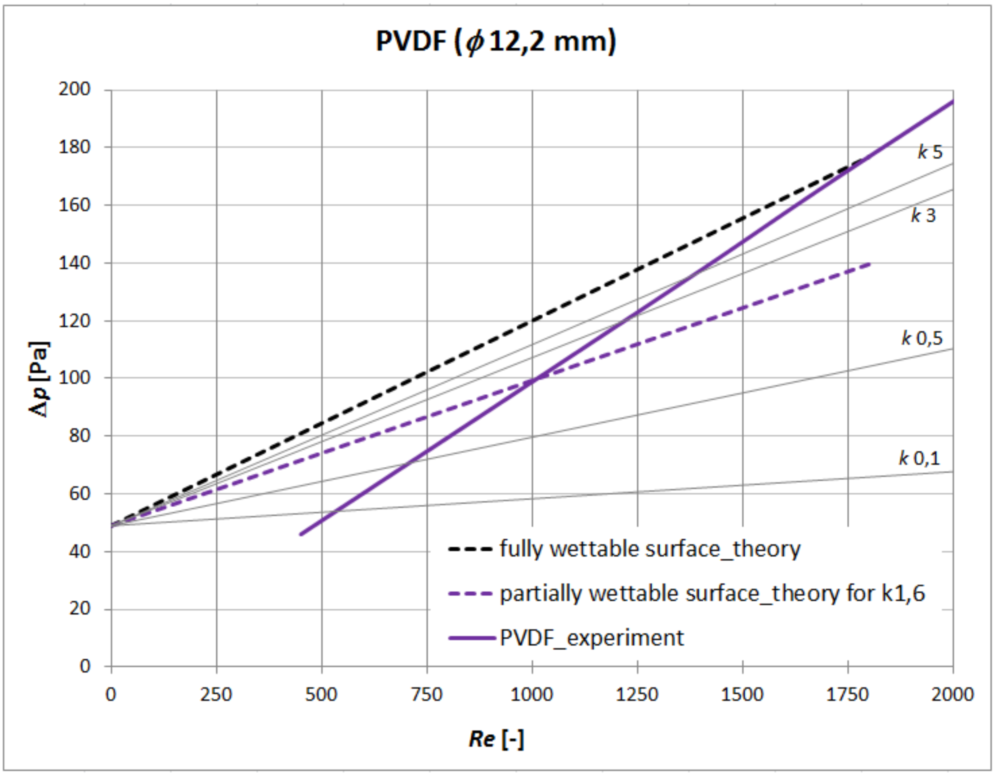

**Fig. 7** Measured values of pressure loss for PVDF pipe in comparison with the no slip theory and theory for partially wettable walls.

According to the measured values, adhesive coefficient isn´t a constant for certain material, so its value may change at different velocity of flowing liquid and thus at a different Reynolds number. Creating this graph with the theoretical values of the pressure drop for various values of the adhesive coefficient is required for each of the measured materials. If we wanted to work with these partially wettable materials, this graph will serve as the basis for numerical simulations. For given Reynolds number and the value of the adhesive coefficient, we can pre-estimate a relevant value of the pressure drop. Graph for other plastic pipes (PVC-U, PVC-C, ABS) would be analogous to the graph in Fig. 7.

Measurement showed that in the laminar range of Reynolds numbers the most hydrophobic pipe is PVDF pipe, followed by PVC-U pipe, classic polyvinyl chloride, and then ABS and PVC-C pipes.

## 5 CONCLUSION

In order to investigate the partial wettability of different materials the equipment for measuring the friction losses in the pipe has been designed. Pipes from various materials was tested - PVDF, PVC-U, PVC-C, ABS. Physical measurement showed that all plastic pipes can be considered partially wettable in laminar flow regime. It also was illustrated by the fact, that the phenomenon of wall partial wetting is closely connected with air content in water. Air adheres to these materials and that causes their partial wetting.

Flow in the pipe of circular cross section was tested using numerical modeling and during this the created UDF function including the partial wetting condition was verified. It allows modifying the wall stress according to (1). Results of numerical experiment showed good agreement with results from empirical assumptions. The theory of partial wettability could therefore be used in the evaluation of the measured values from the physical experiment.

It was demonstrated that the flow in plastic pipes has a lower critical Reynolds number at which the laminar flow regime changes to turbulent. Furthermore, it was found that all plastic pipes can be considered as partially wettable, because the values of pressure drop in the laminar area were always below the values, which belong to theory of fully wettable walls. Measurement showed that the most hydrophobic pipe is PVDF pipe, followed by PVC-U pipe, and then ABS and PVC-C pipes in the laminar range of Reynolds numbers. Values of the adhesive coefficient *k* were assigned to all used pipes. This value *k*, however, is valid for the material only under certain conditions. Adhesive coefficient *k* is not constant for partially wettable material, but is variable according to the velocity.

The results obtained from physical and numerical experiment represent a comprehensive view on the issue of partial wetting, and can serve as a basis for more demanding jobs, whether in the form physical or numerical experiments.

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