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An experimental investigations of the single phase fluid flow through mini pipes with circular cross section

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Abstract. The experimental investigation that has been conducted on the fluid flow in mini pipes with circular cross-sections are presented in this paper. The working fluid is water and its main physical-chemical analysis (pH, total hardness, electrical conductivity) were carried out. The liquid flow through mini pipes of 1, 2 and 3 mm diameter with simulated pressure drops from 1.01 to 61 bar is investigated and the experimental results are presented. The laminar and turbulent friction factor *f* at different pressure drop values, the transition from the laminar to turbulent flow, the effect of relative roughness, and the boundary-layer thickness, *δ*, are computed and studied. The experimental results are presented, discussed and analysed, according to the theoretical principles.

Keywords: fluid flow, mini pipes, pressure drops, friction factor, relative roughness

1. Introduction

The experimental investigation is referring to the single phase fluid flow in mini pipes with circular cross-sections. The studied pipes are horizontal with a circular cross-section having the advantage of being axial-symmetrical and easier to be characterized. The fluid is assumed to be Newtonian, incompressible and the general continuum description is based on the incompressible continuity equation [1]:

$$\frac{\partial u_j}{\partial x_j} = 0,\ j = 1,2,3 \quad (1)$$

and the momentum equation [2]

$$\rho\left(\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j}\right) = \frac{\partial \tau_{ij}}{\partial x_j} + \rho f_i \quad (2)$$

The u_i is the i^{th} component of the velocity vector, ρ is the mass density [kg/m^3], f_i is the body force per unit mass [m/s^2], and τ_{ij} is the tensor of surface tensions that includes both normal and tangential forces and it is composed of the thermodynamic pressure, p, and the viscosity stress, which is dependent on the velocity gradient and the coefficient of viscosity η; although it is a matrix, qualitatively it can be described as:

$$\tau_{ij} = -p\delta_{ij} + \eta\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \quad (3)$$

where, δ_{ij} is the Kronecker delta.

The boundary condition is the no-slip condition, $u = 0$ on the boundary. The volumetric flow rate is given by the following expression [3]:

$$Q = \bar{u}A \quad (4)$$

The pressure drop between inlet and outlet of the pipe is given by the next relationship:

$$\Delta p = \rho g h_r = f\frac{l}{d}\rho\frac{\bar{u}^2}{2} \quad (5)$$

where, ρ is the mass density [kg/m^3], g is the local acceleration due to gravity [m/s^2], h_r is the head losses [m], f is the friction factor defined first time by Darcy and Weisbach, l is pipe length [m], d is the inner pipe diameter [m], $\bar{u}$ is the average velocity of the fluid [m/s].

The Reynolds number is defined by [4]:

$$Re = \frac{\rho\bar{u}l}{\eta} \quad (6)$$

For the laminar flow, this factor is calculated with the Hagen-Poiseuille relationship:

$$f = \frac{64}{Re} \quad (7)$$

The friction factor for laminar flow is only a function of Reynolds number and no dependence of surface roughness appeared [1].

In the turbulent flow, the size of the viscous layer near the wall decreases. This layer adjacent to the wall is called boundary-layer thickness and is noted with δ. As roughness elements begin to put in through this layer, they start to have an effect, and the friction factor becomes a function of both the Reynolds number and the relative roughness k/d.

For turbulent flow, the following empirical correlations describe the friction factor [2]:

- Blasius relationship for hydraulically smooth regime:

$$f = 0,3164Re^{-0.25} \quad (8)$$

- Prandtl-Karman correlation for hydraulically smooth regime :

$$\frac{1}{\sqrt{f}} = 2\,lg\left(Re\sqrt{f}\right) - 0,80 \quad (9)$$

- Nikuradse relationship [2] for hydraulically transitional regime:

$$f = 0.0032 + \frac{0.221}{Re^{0,237}} \quad (10)$$

- Filonenko correlation for hydraulically transitional regime:

$$f = (1,82\,lg\,Re - 1,64)^{-2} \quad (11)$$

- Colebrook-White correlation for hydraulically fully rough regime:

$$\frac{1}{\sqrt{f}} = -2\,lg\frac{k_e}{3,72d} + \frac{2,51}{Re\sqrt{f}} \quad (12)$$

The boundary-layer thickness in circular pipe for turbulent flow is calculated with the following expression:

$$\delta = \frac{30d}{Re\sqrt{\frac{f}{8}}} \quad (13)$$

The flow is considered "hydraulically smooth" when the roughness of the pipe wall is smaller than the following value:

$$\delta_{LM} = \frac{30\nu}{\sqrt{\frac{\tau_0}{\rho}}} \qquad (14)$$

where, τ_0 is the tangential stress calculated with relationship:

$$\tau_0 = \frac{f \cdot \rho \cdot \overline{u}^2}{8} \qquad (15)$$

2. Materials and Experiment description

In order to study the fluid flow through mini pipes with inner diameters of 1 mm, 2 mm, and 3 mm, the test rig was designed and realized. The experimental installation consists of following devices: compression and control pressure board (TPCP), 2 high-pressure air compressed cylinders hydrostatic simulator (SH), recipient with a level gouge (RIN), measuring recipient (RG), pipes to be studied with an inner diameter of 1 mm, 2 mm, and 3mm, and high pressure connecting hoses.

Fig. 1: Test rig

TPCP is feeding with high pressured air (p = 200 bar) from 2 high-pressure air compressed cylinders 2 x 12 L, by a high-pressure connecting hose with a nominal diameter of ½ inch. The air inlet is controlled by a valve and the TPCP inlet pressure by a manometer and a pressure regulator.

The working pressure is monitored by 2 serial coupled manometers, one with the range from 0 to 250 MSW and one with the range from 0 to 25 MSW. Both manometers are attached to the TPCP by a Hansen coupling system that allows an easier coupling.

Using the pressure regulated, the working pressure is adjusted, controlled and sent to SH. The connection between TPCP and SH is realized by the hose with a nominal diameter of ½ inch. The pressure from the TPCP exit to SH is controlled by a high pressure valve that has working pressure range from 0 to 300 MSW.

SH is designed for a working pressure up to 300 MSW, is made of stainless steel having a 107 mm diameter, 500 mm height. SH is provided with an air feeding system with a non – return valve, water feeding system and joint reduction system for coupling of different sizes of pipes.

RIN is made of duralumin having 140 mm diameter, 400 mm height. This is provided with exhaust valve and liquid levelling measuring set.

The feed water was analysed in terms of a physical-chemical point of view. Therefore, the analysis of the main physical-chemical characteristics (pH, turbidity, electrical conductivity, and total hardness) was carried out that could influence the quality of the feed water. This quality monitoring of the feed water is necessary because poor standard water could become a corrosive and aggressive agent for the transport pipes. In order to measure pH and electrical conductivity of the water samples, a Hanna Combo HI98129 multiparameter was used, turbidity was analysed with a TSS portable hand-held instrument (Hach) and the total hardness analysis was carried out by titration with EDTA solutions.

3. Results and significances

The characteristics of fluid flow will be analysed for all 3 pipes. The volume flow rate is computed with the following relationship:

$$\dot{V} = \frac{\pi D_i^2 h}{4\tau} \qquad (16)$$

where, $\dot{V}$ is volume flow rate [m^3/s], D_i^2 is RIN inner diameter [m], h is fluid column height [m] and τ is the time [s].

Knowing the volume flow rate, the average velocity of the fluid flow is calculated:

$$\bar{u} = \frac{4\dot{V}}{\pi d^2} \qquad (17)$$

where, $\bar{u}$ is average velocity of the fluid flow [m/s] and d is inner diameter of the pipe [m]. Then the Reynolds number is computed:

$$Re = \frac{\bar{u} d}{\upsilon} \qquad (18)$$

where, υ– kinematic viscosity [m^2/s].

Based on these calculated values, the dimensionless coefficient called the Darcy friction factor is computing with the following relationship:

$$f = \frac{2 \cdot g \cdot h_r \cdot d}{l \cdot \bar{u}^2} \qquad (19)$$

where, g is local acceleration due to gravity [m/s^2] and l is pipe length [m], d is the inner pipe diameter.

To complete the flow profile, the main physical – chemical characteristics of the feed water were analysed, and the results are found in Table 1. The values obtained for pH, turbidity, total hardness, and electrical conductivity showed that the feed water is quality water, according to [5], and which could not be a chemical corrosion medium (at pH less than 6.5) for the transport pipes.

Table 1 Physical – chemical analysis of water feed

No.	Physical-chemical indicators	Unit	Obtained values	Maximum admitted values (according to [5])
1	pH (t= 20°C)	pH units	7.52	6.5-9.5
2	Turbidity	NTU	0.300	≤ 5.0
3	Electrical conductivity (t= 20°C)	μS/cm	425	2500
4	Total Hardness	°dH	8.24	≥ 5.0

Using the SH there are generated pressure drops from 0.04 bar to 5.53 bar, corresponding to head losses from 0.41 m to 56.36 m for the cooper pipe of 1 mm inner diameter and 0.003 m outer diameter and 1.3 m length. The values of the volume flow rates are from 0.05 and 0.24 l/min, and the average velocities of the fluid flow are from 0.1 to 5.13 m/s.

For generated head losses from 0.4 m up to 10.25 m, the flow is laminar with values of Reynolds number from 95 to 2000. The maximum Re value obtained is 5076 for a produced head loss of 56.36 m. The flow is turbulent, and because of Re<105 and obtained values of the boundary-layer thickness, δ are upper than the values of the roughness of the wall, k, the flow is hydraulically smooth.

The value of the Darcy friction factor has a pronounced falling with mean velocity increasing for Re values from 95 and 700, and up to Re values of 5076, the value of Darcy friction factor presents a smoothly decreasing. In Figure 2 there are showing the friction factor values experimentally obtained versus the values obtained with formulas (7) Hagen – Poiseuille, (8) – Blasius and (9) - Prandtl – Karman.

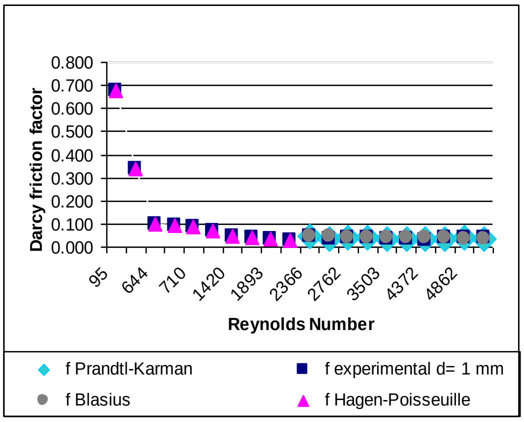

Fig. 2. The value of Darcy friction factor obtained experimental compared with Hagen-Poiseuille, Blasius and Prandtl –Karman reported values (pipe with 1 mm inner diameter)

The value of the boundary-layer thickness, δ, δ_{LM}, and the roughness of the wall, k is representing in the Fig. 3, where it could be observed that boundary-layer thickness is thicker than the roughness of the pipe wall that means that flow is "hydraulically smooth" in the circular pipe.

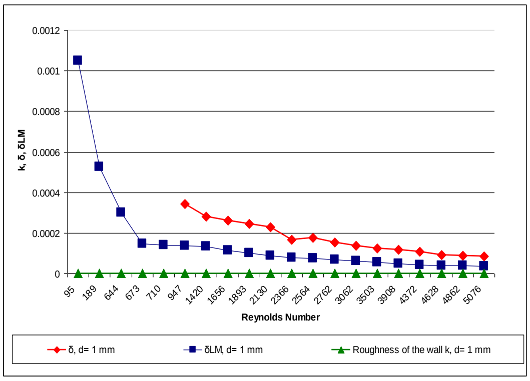

Fig.3. Representation of boundary-layer thickness, δ, δ_{LM} and the roughness of the wall, k (pipe with 1 mm inner diameter)

Experimental tests have been conducted on high density polypropylene pipe of 2 mm inner diameter and 0.006 m outer diameter, 1.2 m length, using the SH there are generated pressure drops from 0.01 bar to 5.33 bar, corresponding to head losses from 0.1 m to 54.31 m. The test results reported values of the volume flow rates from 0.02 and 1.52 L/min, the means velocities of the fluid flow from 0.1 to 8.08m/s with pronounced increasing beyond head losses of 3 m. The laminar flow was obtained for generated head losses from 0.1 to 2 m, Reynolds number ranging from 205 to 2360. Above two up to 54.31 meters head losses the flow become turbulent, the maximum Reynolds number obtained being 16008. When the experimental tests were plotted on the Moody diagram, the plotted points generally conformed to the curve for laminar flow for Re <2300 and hydraulically smooth pipes for Re>2300.

As it could be seen from Fig. 4, the roughness of the wall is slighter then δ_{LM} and δ values, so the pipe behaviour is hydraulically smooth.

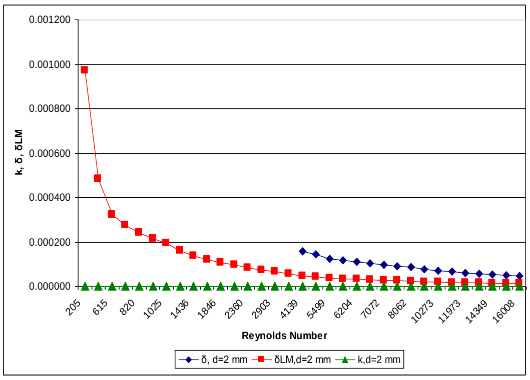

Fig. 4. Representation of boundary-layer thickness, δ, δ_{LM} and the roughness of the wall, *k* (pipe with 2 mm inner diameter)

Experimentally investigations have been performed on stainless steel pipe of 3 mm inner diameter and 0.006 m outer diameter, 0.92 m length. There were created pressure drops from 0.01 bar to 3.62 bar, corresponding to head losses from 0.1 m to 36.89 m. The test results reported values of the volume flow rates are from 0.1 and 4.2 L/min, the mean velocities of the fluid flow from 0.3 to 10.09 m/s. The laminar flow was gained for caused head losses from 0.1 to 0.5 m, Reynolds number ranging from 903 to 2300. The flow becomes turbulent over 0.5 meters head losses, the maximum Reynolds number obtained is 29975. In Fig. 5, the Darcy friction factor values obtained experimentally is represented versus theoretical values.

The experimental results matched with the Moody diagram, the plotted points generally conformed to the curve for laminar flow for Re <2300 and hydraulically smooth pipes for Re>2300. Based on the experimental results, the values of the boundary-layer thickness, δ was calculated obtaining upper values of the roughness of the wall, *k*, that it means that the pipe is also, hydraulically smooth.

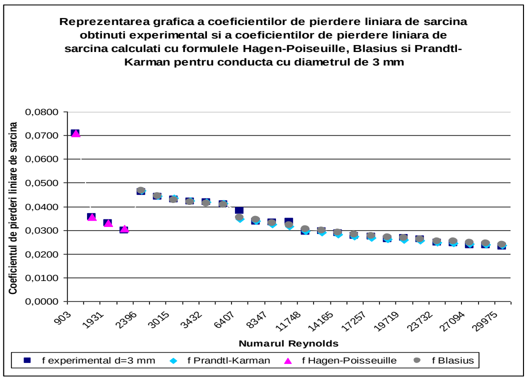

Fig. 5. The values of Darcy friction factor obtained experimental compared with reported values k (pipe with 3 mm inner diameter)

4. Conclusions

For all 3 pipes, the friction factor is in the range of accepted laminar flow behaviour agreed with classical hydrodynamic theory with negligible differences. Below Re = 2320 the values are in agreement with Hagen – Poiseuille correlation and experimental results matched with the Moody diagram.

For Re<4000 the friction factor value is in conformity with Blasius and Prandtl – Karman relationships.

In all cases, for Re>4000 the value of the boundary-layer thickness, δ, is higher than the roughness of the wall, *k*, and these let conclude that the flow in all pipes is in the hydraulically smooth regime.

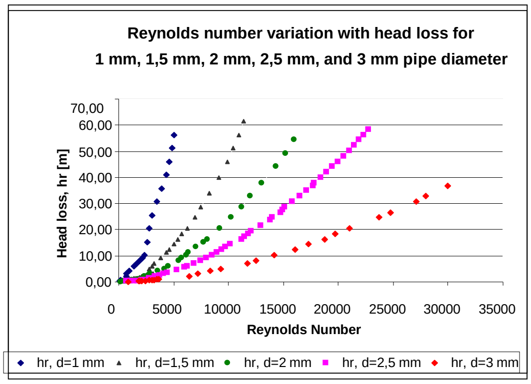

Fig. 6. Reynolds number versus head loss for 1mm, 2 mm and 3 mm inner diameter pipes

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