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Experimental investigation of pressure drop and friction factor for water flow in microtubes

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ABSTRACT

The pressure drop and friction factor for the flow distilled water in microtubes with the diameters ranging from 0.20 mm to 0.589 mm were investigated experimentally. The experiments were carried out in the Reynolds number range of approximately 100–10000 and the length-to-diameter ratios (L/d) in the range of 16–265. It was observed that two different mechanisms of transition from laminar to turbulent flow occurred as smooth and abrupt. The pressure drop and friction factor values agreed with the values of classical channel flow theory. The L/d ratio had an important effect on the apparent friction factor in case of $L/d < 100$. It was found that the critical Reynolds number for the transition was between 2000 and 2500.

1. Introduction

With development of the microsystem technology, the investigation of the flow phenomena in microtube and channels has been one of the most important subjects. There are several studies, experimental or theoretical, on the heat transfer and the pressure drop for laminar and turbulent liquid or gas flow in microchannels. The reviews of these studies are given by several researchers [1–5]. The effects of the surface roughness, geometry of channel, type of fluid (gas or liquid, single or two phase), flow rate, surface fluid interaction, have been the major parameters, which were considered in the studies on the fluid flow in the microchannel. In general, the experimental data have been compared with the conventional theories, and in many cases contradictory results have been reported. The first diversity between studies is that the fact that there are three different results of the friction factor values; that is, the results smaller than, higher than and similar to the friction factor values predicted by classical theory. These results have been reviewed by several researchers [1–4,6]. The second is related to the critical value of Reynolds number at which the flow regime changes from laminar-to-turbulent. For the transition from the laminar to turbulent flow, different Reynolds numbers have been reported for very similar conditions. It was also reported very early transition Reynolds numbers such as, in the range of 200–700 for water flowing through rectangular channels having hydraulic diameters of 0.133–0.367 mm [7], and of 300–900 for water flowing in microtubes with the diameters ranging from 0.050 to 0.245 mm [8], and 240 for water flowing through a rectangular channel with the hydraulic diameter of 0.146 mm [9].

Vijayalakshmi et al. [10] investigated the effect of compressibility, and the transition to turbulence flow through microchannels of hydraulic diameter ranging from 0.0605 mm to 0.211 mm, employing nitrogen as the working fluid. They reported that the transition to turbulent occurred in the Reynolds number range of 1600–2300. They claimed that the slight decrease in the transition range may be due to the relative roughness or the edge effects of the trapezoidal channel geometry. Morini et al. [11] studied the laminar to turbulent transition in the fused silica and stainless steel microtubes having the diameters ranging from 0.125 to 0.180 mm, using nitrogen as working fluid. They reported that the transitional regime started at the Reynolds numbers around 1800–2000, and the surface roughness had no effect on the hydraulic resistance in the laminar region for a relative roughness lower than 4.4%, taking compressibility into account. Lorenzini et al. [12] investigated the flow of nitrogen inside circular microchannels having the diameters ranging from 26 μm to 508 μm with different surface roughness values and L/d ratios in the range of 591–1689.

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Nomenclature

d	tube diameter (m)
f	friction factor (−)
K	loss coefficient
L	tube length (m)
ΔP	pressure drop (Pa)
Re	Reynolds number (−)
u	mean velocity (m s^{-1})
ρ	density (kg m^{-3})
μ	viscosity (kg m^{-1} s^{-1})

Subscripts

app	apparent
d	developing
e	exit
i	inlet
m	miscellaneous
net	net
o	outlet
t	total

In macro channel flow, the effect of inlet configuration, namely squared-edged, re-entrant and bell-mouth, of the circular straight horizontal tube on the transition to turbulence was investigated by Ghajar and Madon [13] under isothermal flow conditions, by Tam and Ghajar [14] for non-isothermal flow conditions. They used 316 stainless steel tubes with an inside diameter of 1.58 cm and length-to-diameter ratio (L/d) of 386 to provide fully developed flow condition. It is reported that the transition occurred in the Reynolds number range of 1980–2600 for the re-entrant inlet, 2070–2800 for the square-edged inlet and 2125–3200 for the bell-mouth inlet for isothermal conditions, and it changed depending on heat flux in the case of non-isothermal flow. On the other hand, several investigators remarked the dependence of critical Reynolds number on the surface roughness and geometry [11,15,16].

In microchannel flow, the flow regime is often in laminar or transition region, especially, in the case of liquid flow. Therefore, the pressure drop and friction factor characteristic of fluid flow under transition condition is important. Recently, Ghajar et al. [17] performed an experimental investigation for friction factor in the transition region for water flow in stainless steel minitubes and microtubes with the diameters in the range of 337 μm–2083 μm. They reported that the decrease in the tube diameter and increase in the relative roughness affected friction factor, even in the laminar flow, and that the Reynolds number range for the transition flow became narrower with decreasing tube diameter. It was also reported that when the diameter of the tube changed from 2083 μm to 667 μm, the onset of transition region delayed at Reynolds number from 1500 to 2200.

Although there are several studies on pressure drop and friction factor characteristics of the microchannel, because of the diversities between results, it can be said that further investigation is required in order to verify if the classical correlations can predict friction factor in laminar, transition and turbulent regimes. Moreover, in many of the studies, the length-to-diameter ratio of the channel has been selected higher than 100 to provide fully developed condition [11,12]. However, in some practical applications such as micro-exchangers, micro-reactors etc, it can be difficult to establish a flow length for hydrodynamically fully developed flow. Therefore, the entrance effect, L/d ratio should be taken into account for pressure drop and friction factor characteristics of the fluid flow in micro-tubes. In this study, it was aimed to investigate the pressure drop and friction factor of water flowing through microtubes with different diameters and L/d ratios for the cases of laminar, transition and turbulent flow conditions.

2. Experimental set up and data reduction

Experimental set up adapted from our previous study [18,19] is shown schematically in Fig. 1. It consists of mainly a high-pressure nitrogen gas tube, a micro filter, a digital balance, a circulated water bath and the test section including micro-tube. The flow to the test section was provided by high-pressure nitrogen gas and the flow rates were adjusted by a two-stage gas regulator. The fluid passed through a micro filter before entering test section and was collected after the test section to be weighed. Distilled water was used as working fluid and its temperature was kept at 25 ± 0.2 °C by circulated bath. Five stainless steal tubes, produced for the purpose of the medical treatment, with diameter in range of 0.200 mm–0.589 mm were used as test channel. The geometrical dimensions of the channels used in the experiments are given in Table 1. The dimension of the tubes was measured by NİKON MM 400 L video measuring microscope. The pressure difference in the test section was measured by pressure transmitter (KELLER) in range 0–6 bar ± 0.5% FS.

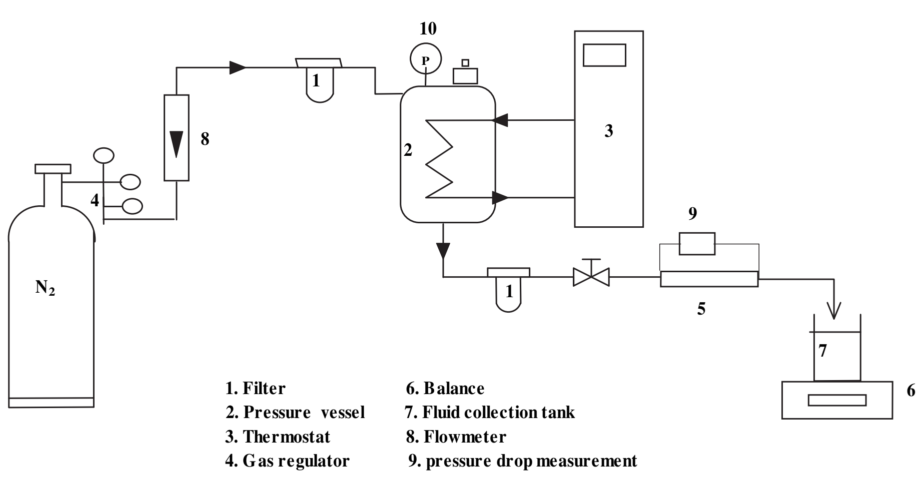

Fig. 1. Experimental set up.