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Effect of thickness to diameter ratio on micro-orifice single-phase liquid flow at low Reynolds number

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ABSTRACT

Micro-orifice discharge with single-phase water flow was experimentally investigated with six multi-micro-orifice test pieces with orifice diameter of 200 μm and thickness to diameter ratio between 4.25 and 27.0. During the experiments the Reynolds number varied between 5 and 4500: a range that corresponds to creeping flow and laminar to turbulent transitional flow. The emergence of turbulence, as indirectly deduced from the change in slope of the pressure drop versus mass flow rate profiles, was found to be gradual and smooth. Using the newly generated data presented here, the validity of an existing micro-orifice discharge prediction method for creeping flow conditions was extended to microfluidics applications with thick micro-orifices.

1. Introduction

With advancements in micro-fabrication techniques [1,2], microfluidic devices now offer an increasingly effective alternative to conventional devices, such as micro cooling systems [3,4], micro evaporators [5], micro-pumps [6] and lab-on-chip devices [7,8]. Progress in microfluidics is also driving the development of novel applications in biology, engineering and industry [9], including drug delivery systems [10], microsatellites [11,12] and biosensors [13,14].

Notably, micro-orifices are key components in many microfluidic systems, including micro-pumps, injectors, cooling systems and heat sinks, and have therefore being investigated quite extensively [15–26]. Micro-orifices have also been successfully employed in miniature-scale corrosion studies relevant in steam generators and nuclear plant cooling loops [27]. Recent advances in the understanding of corrosion in these challenging environments have shown that corrosion deposition may be exacerbated by the acceleration of electrokinetic streaming current [28], which peaks around areas of flow constriction [29]. Local accumulation of deposits decreases the local heat transfer coefficient of the steam generator tubing, which degrades efficiency, and in severe cases can affect the availability and safety of nuclear plants.

A summary of data available from the literature concerning single-phase liquid flow through micro-orifices is provided in Table 1. Water, oil and refrigerants have been tested in square or circular, for the most part thick micro-orifices, *i.e.* micro-orifices characterized by orifice thickness to diameter ratio $t/d > 0.5$. In general, micro-orifice data from the literature show qualitatively similar trends to those observed with data generated with conventional macroscopic orifices.

Single-phase liquid flow through micro-orifices is completely characterized by the micro-orifice Reynolds number Re and dimensionless pressure drop K, which are defined respectively by:

$$Re = \frac{\rho V d}{\mu} \tag{1}$$

$$K = \frac{2\Delta P}{\rho V^2} \tag{2}$$

where ρ and μ are the fluid density and viscosity, V is the average flow velocity through the orifice, and ΔP is the pressure drop across the orifice. In the case of multi-micro-orifice samples that comprise multiple identical micro-orifices, as in the present study, the pressure drop across the sample is equivalent to the pressure drop across any individual orifice, and the average orifice flow velocity can be calculated from the total mass flow divided by the number of (identical) micro-orifices within the sample.

Existing prediction methods for micro-orifice single-phase flow include the analytical method developed by Dagan et al. [30] for creeping flows, which reads as follows:

$$K = \frac{12\pi}{Re}\left(1 + \frac{16}{3\pi}\frac{t}{d}\right) \cong \frac{37.7}{Re}\left(1 + 1.7\frac{t}{d}\right) \text{ for } Re \to 0^{+} \text{ and } 0 \leqslant \frac{t}{d} \leqslant 2 \tag{3}$$

In particular, Eq. (3) stems from an infinite-series analytical solution of the Navier-Stokes problem for single-phase flow through a finite

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Nomenclature

Symbol	Description
A_{flow}	orifice flow area (m^2)
d	orifice diameter (m)
D	tube diameter (m)
K	orifice dimensionless pressure drop (–)
P_{wet}	orifice wetted perimeter (m)
Re	orifice Reynolds number (–)
t	orifice thickness (m)
V	orifice average flow velocity ($m\,s^{-1}$)
ΔP	pressure drop across the orifice (Pa)
μ	liquid viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	liquid density ($kg\,m^{-3}$)

Table 1
Experimental data bank for micro-orifice liquid flow.

Reference	d (μm)	d/D	t/d	Fluid	Reynolds	Cross section
Johansen [18]	704; 1634	0.09; 0.209	0.083	Oil	0.1–150	Circular
Kojasoy et al. [20]	1000; 2000	0.057; 0.114	1.0; 2.0	R-113	560–14,000	Circular
Wang et al. [21]	150[a]; 370[a]	na	na	Water	800–4500	Square
Mishra and Peles [22]	11.5[a]	0.114	1.7	Water	160–550	Square
Phares et al. [23]	81.7; 99.6	0.008; 0.010	2.65; 3.23	Water	2.5–120	Circular
	130.7; 159.2	0.013; 0.016	4.24; 5.16			
Tu et al. [15]	31.0; 52.0	0.007; 0.012	2.5; 4.2	R134a	1600–6500	Circular
Ushida et al. [17]	100; 400	na	0.05; 0.2	Water	1.3–1300	Circular
Cioncolini et al. [25]	150; 300; 600	0.015; 0.03	1.87; 3.53	Water	6000–25,000	Circular
		0.06	3.70; 4.97			
			6.43; 6.93			
Cioncolini et al. [26]	300; 600	0.0306; 0.0612	1.67; 3.33	Water	18,000–220,000	Circular

[a] Hydraulic diameter ($4 A_{flow} {P_{wet}}^{-1}$, *i.e.* four times the flow area divided by the wetted perimeter).

aspect ratio pore in the creeping flow limit of small Reynolds number values, and is therefore applicable to the micro-orifices of interest here. On the other hand, for turbulent flow conditions at high orifice Reynolds numbers Cioncolini et al. [25,26] proposed the following empirical correlation:

$$K = 3.137Re^{-0.0737} \quad \text{for } 1000 \leqslant Re \leqslant 220{,}000 \text{ and } \frac{t}{d} \leqslant 7 \tag{4}$$

As shown in previous studies [25,26], the available creeping flow data agree well with the analytical prediction method by Dagan et al. [30]. In particular, the measurements provided by Phares et al. [23] suggest that this method is applicable to micro-orifices with thickness to diameter ratio t/d up to 4.24, which is slightly beyond the range of applicability $0 < t/d < 2$ originally proposed by Dagan et al. [30]. In turbulent flow conditions, on the other hand, the available data do not show any dependence on the orifice thickness to diameter ratio t/d and follow the empirical correlation proposed by Cioncolini et al. [25,26].

Notwithstanding the investigations carried out so far, as can be noticed from inspecting Table 1 only limited data are currently available in creeping flow and laminar to turbulent transitional flow. In particular, to the best of the authors' knowledge thick micro-orifices with thickness to diameter ratio t/d above 4.24 are presently not characterized at these flow conditions: this is the gap in the existing knowledge that motivated the present study. While in macroscale applications orifices are typically thin, in microfluidics systems thick orifices are much more common because thin micro-orifices would be difficult to manufacture and, more importantly, might suffer from excessive mechanical deformation during operation due to the differential pressure load. This partly explains the limitations of macroscale orifice prediction methods when extrapolated to micro-systems, and the need to develop design methods specifically intended for micro-orifices. The present study was therefore conducted in order to advance the knowledge of liquid flow through thick micro-orifices in creeping flow and laminar to turbulent transitional flow, by experimentally investigating six multi-micro-orifices having diameter of 200 μm and thickness to diameter ratio t/d in the range between 4.25 and 27.0.

2. Experiments

Multi-micro-orifice samples were fabricated from 12 mm diameter Rulon LR (reinforced Teflon) plate with 400 μm/200 μm outer diameter/inner diameter aluminium micro-pipes inserted into 7 pre-drilled

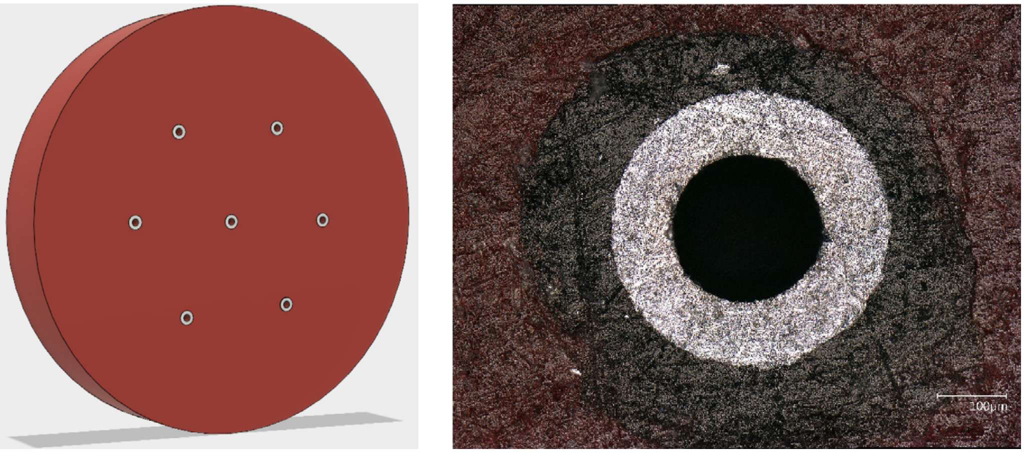

Fig. 1. Schematic diagram of a multi-micro-orifice test piece (left); and detailed image of a single micro-tube (right).