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Micro-orifice single-phase flow at very high Reynolds number

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ABSTRACT

Micro-orifice discharge with single-phase liquid flow was experimentally investigated with six circular micro-orifices with diameters of 300 µm and 600 µm. The experiments were carried out with water at high pressure (12 MPa) and high temperature (503 K), such that the Reynolds number varied between 28,000 and 220,000, a range significantly wider than inspected during previous researches on turbulent flow conditions in micro-orifices. The dimensionless pressure drop slightly decreased with increasing Reynolds number, with no apparent influence of the micro-orifice diameter ratio or aspect ratio. Using the newly generated data presented here, the validity of an existing micro-orifice discharge prediction method for turbulent flow conditions was extended to microfluidics applications with very high Reynolds numbers.

1. Introduction

The progress achieved over the last decades in micro-fabrication techniques has promoted the flourishing of microfluidics, a subject dealing with the manipulation, the analysis and the modeling of fluid flow when geometrically constrained in the sub-millimeter scale. Microfluidics is now a very active research area within modern fluid mechanics: systems such as micro evaporators, micro condensers, micro heat sinks, micro pumps and micro valves are critical in several industrial applications including, but not limited to, micro thermal technologies, micro propulsion and micro machines [1–8], and lab-on-chip micro devices capable of real-time analysis of microscopic biological fluid samples. Some of these approaches are revolutionizing the early diagnosis of diseases [9], or transforming molecular biology procedures for proteomics and DNA analysis [10].

Micro-orifices, in particular, are key components of several microfluidics systems that include micro cooling systems, micro evaporators, micro pumps, micro valves and micro injectors. For example, in multi microchannel evaporators, micro-orifices are normally used at the inlet of the channels to promote a uniform flow distribution and suppress backflow and instabilities [11]. Micro-orifices are also employed as expansion and flow control devices in vapor compression refrigeration systems for automotive and residential air conditioning [12–19]. Due to their practical relevance, micro-orifices have been investigated quite extensively [20–34], both for single-phase liquid flow and two-phase cavitating flow. The present study, in particular, is restricted to single-phase liquid flow conditions and it is focused on the discharge at high Reynolds number, when the flow through the micro-orifice is turbulent. In single-phase liquid flow conditions, the parameter that characterizes the flow through an orifice is the dimensionless pressure drop K defined as follows:

$$K = \frac{2\Delta P}{\rho V^2} \tag{1}$$

where ρ is the fluid density, V is the average flow velocity through the orifice and ΔP is the pressure drop across the orifice. With circular orifices, in particular, the dimensionless pressure drop K is typically a function of the orifice Reynolds number Re and of the diameter ratio d/D and thickness ratio t/d of the orifice, so that:

$$K = K\left(Re, \frac{d}{D}, \frac{t}{d}\right) \tag{2}$$

where d and t are the orifice diameter and thickness, respectively, while D is the diameter of the tube where the orifice is located. The orifice Reynolds number is defined as:

$$Re = \frac{\rho V d}{\mu} \tag{3}$$

where μ is the fluid viscosity. If the orifice is not circular, then the hydraulic diameter ($4\ A_{flow}/P_{wet}$, i.e. four times the orifice flow area divided by the orifice wetted perimeter) is used in place of the orifice diameter in the equations above. If the diameter ratio d/D is small (d/D lower than about ≈ 0.2), which is the case for the available micro-orifice data [30], its influence on the dimensionless pressure drop is

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Nomenclature

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 ($kg\,m^{-3}$)

negligible or absent and, consequently, Eq. (2) simplifies as follows:

$$K = K\left(Re,\frac{t}{d}\right) \quad (4)$$

As discussed by Cioncolini et al. [30], in laminar flow conditions at low Reynolds number, the dimensionless pressure drop K depends on both the orifice Reynolds number Re and the orifice thickness to diameter ratio t/d, and in particular K decreases with increasing Reynolds number and increases with the thickness to diameter ratio. On the other hand, for Reynolds number values above about $Re \approx 1000$ the influence of the orifice thickness ratio becomes negligible, and the dimensionless pressure drop becomes a function of the Reynolds number alone:

$$K = K(Re) \text{ for } Re \geqslant 1000 \quad (5)$$

Using available micro-orifice discharge data at high Reynolds number, Cioncolini et al. [30] proposed the following micro-orifice discharge prediction method:

$$K = 3.137\, Re^{-0.0737} \quad \text{for } 1000 \leqslant Re \leqslant 25{,}000 \quad (6)$$

In particular, Eq. (6) fits its underlying databank (188 data points collected from 4 different studies for water and refrigerants R113 and R134a, and both circular and square micro-orifices with diameter from 31.0 μm to 2.0 mm) with a mean absolute percentage error of 8.1%. As can be seen, Eq. (6) is applicable for orifice Reynolds numbers as large as $Re \approx 25{,}000$, which is the upper limit of the experimental data currently available.

Relatively speaking, a micro-orifice Reynolds number of $Re \approx 25{,}000$ is quite large for single-phase microfluidics flows, so that Eq. (6) actually covers a wide range of practical applications. Notably, however, there are emerging microfluidics applications that require the knowledge of micro-orifice discharge at Reynolds number values much higher than those covered by existing studies and prediction methods such as Eq. (6). The application that motivates the present study, in particular, is corrosion in pressurized water nuclear power stations [35–39]. If the water chemistry conditions are favorable, the steam generator tubes in nuclear power stations can undergo oxide formation preferentially localized at the inlet of the tube bundle. This has an adverse effect on the heat transfer process, as the oxide layer acts as an additional thermal resistance and can reduce the coolant flow area. The mechanisms behind the oxide formation are associated with an electrokinetic related process, and to corroborate this hypothesis micro-orifices are used in reduced scale experiments to reproduce the fluid conditions encountered at the inlet of steam generators tube bundles. Since the oxide build up restricts the net cross section and reduces the micro-orifice discharge, the measurement of the pressure drop across the micro-orifice and the measurement of the mass flow rate through the micro-orifice can be used to monitor remotely and in real time the oxide build up rate, provided that an accurate micro-orifice discharge prediction method is available [40,41]. The micro-orifice Reynolds number values of interest for oxide build up studies for commercial

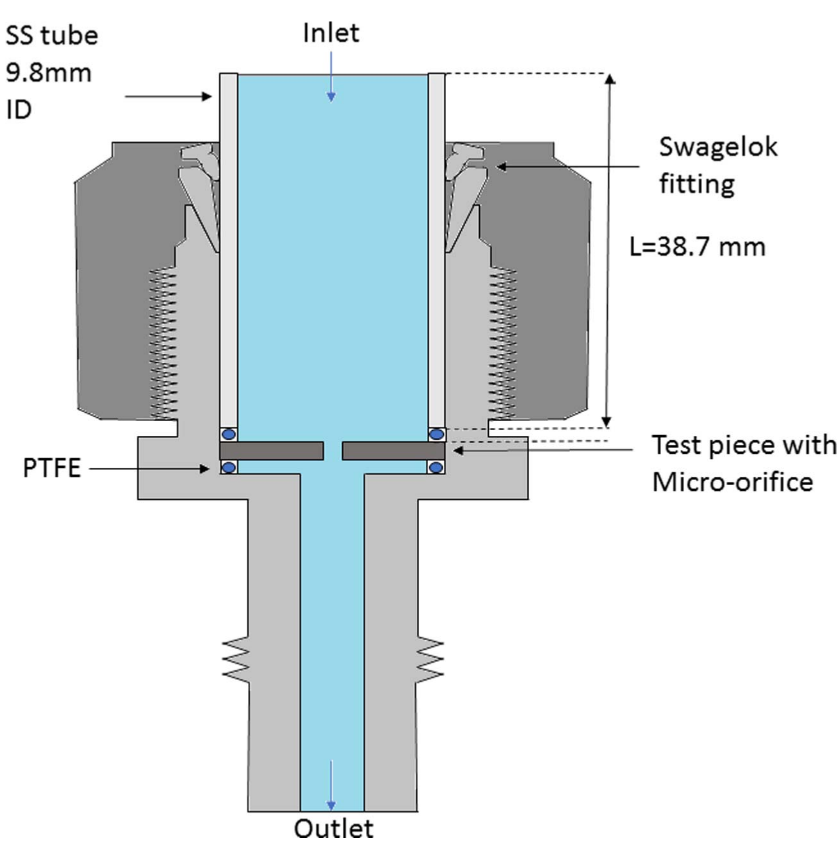

Fig. 1. Schematic view of the test section (not to scale).