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Short communication

Prediction of two-phase mass split in mini tubes

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ABSTRACT

Two-phase flow in single mini tubes and parallel mini channels find a lot of practical applications. Although it is possible to measure pressure drop and void fraction, using methods like visualization, quantifying the mass split of the two phases is a hard task. This is especially the case when dealing with parallel channels where there is a need to correct the maldistribution between the channels, which is a common issue. In the present study, a semi-analytical model based on the separated flow model is proposed to estimate the mass split between air and water, one of the most commonly handled situations, for slug flow regime in horizontal mini channels, with diameters ranging from 1.0 to 2.0 mm, where the competing magnitudes of inertia and surface forces makes the flow distribution complicated.

1. Introduction

A careful enhancement in heat transfer without a severe hike in the pressure drop can be achieved by using mini channels (200 μm ≤ D_h ≥ 3 mm, according to Kandlikar and Grande [1]). Compact heat exchangers, used in aircrafts, air separation plants and small sized refrigeration systems, employ flow channels of dimension 1–2 mm. Parallel channels, with inherent unequal distribution (flow maldistribution) of even a single-phase fluid into various channels from the header [2], is utilized to improve the cooling performance in such applications. The performance reduction by flow maldistribution can be significant [3]. When compared to single-phase flow, introducing two-phase flow into the parallel channels (Fig. 1) can ensure larger heat removal, albeit at the cost of an increased pressure drop, which is more desirable. The distribution of two-phases is often even more non-uniform, with conspicuous variations between channels.

Most of the experimental studies make use of the pressure drop across the parallel channels to analyze the situation. Further, it is not uncommon to have the void fraction estimated using methods like visualization or some other means like using a combination of neutron radiography and image processing [4]. Slug flow regime in horizontal mini tubes is one of the very commonly observed regimes and can be confirmed to exist in a two-phase flow situation by visualization, as shown in Fig. 2. Furthermore, it is evident from the superficial velocities shown in Fig. 3 that for slug flow in mini tubes, of diameters ranging from 0.6 to 2.6 mm, the flow is laminar for both the air and water phases when one of the phases is flowing at a time. When the two-phase flow is confirmed to be in the slug regime, the present note helps to estimate the mass split between the individual phases. This can help to correct any possible cooling issues due to maldistribution.

2. Estimation of mass split in each channel

Since the slug flow regime falls under the separated flow category, a separated flow model is used as the first step. According to Lockhart and Martinelli [6],

$$\left.\frac{\Delta P}{L}\right|_{2\phi} = \phi_l^2 \left.\frac{\Delta P}{L}\right|_l \tag{1}$$

$$\phi_l^2 = 1 + \frac{C}{X} + \frac{1}{X^2} \tag{2}$$

$$\left.\frac{\Delta P}{L}\right|_l = 4f_l \frac{1}{d_c} G^2 (1-x)^2 \frac{1}{2\rho_l} \tag{3}$$

Here, since the acceleration component is negligible in adiabatic flows and the gravity component is zero for horizontal tubes, the two-phase pressure drop is only due to friction.

From Venkatesan et al. [5], the two-phase phase flow is concluded to be laminar for the slug regime. This conclusion is reached because the Reynolds number, estimated by using only air/water superficial velocity, is found to be less than 2000. This is even true for the highest diameter used by Venkatesan et al. [5], i.e., 2.6 mm. This is a vital information when dealing with the separated flow models.

Kreutzer et al. [7], by performing experiments in a vertical tube of diameter 2.3 mm, underscores the effect of interfacial effects in capil-

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English Symbols

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Bo	Bond number ($Bo = (\rho_l - \rho_g)gd^2/\sigma$)
C	Chisholm's parameter
Ca	capillary number ($Ca = \mu U/\sigma$)
d	diameter (m)
f	Fanning friction factor
g	acceleration due to gravity (m/s^2)
G	mass flux (kg/m^2 s)
L	distance between pressure taps (mm)
ΔP	pressure drop (Pa)
Re	superficial Reynolds number ($Re = \rho U\ d/\mu$)
S	slip ratio
U	superficial velocity (m/s)
x	gas mass fraction
X	Martinelli parameter

Greek Symbols

α	void fraction
ρ	density (kg/m^3)
σ	surface tension (N/m)
ϕ_l^2	two-phase frictional multiplier for liquid flowing alone

Subscripts

c	channel
h	header
g	gas
l	liquid
2ϕ	two-phase

lary tube slug flows. They propose a correction for the friction factor calculation based on the slug length, *Ca* and *Re*, which is significant when the slug length is smaller (typically less than 10 times the tube diameter). This effect is primarily due to difference in curvature at the front and back end of the bubble. When the slug is longer, say, greater than 10 times the tube diameter, this correction can be skipped and the conventional laminar correlation can be used to find the friction factor, as per Kreutzer et al. [7] (Fig. 4).

But Venkatesan et al. [8] shows that the slug lengths for mini tubes of diameter less than 2mm are more than 10 times the tube diameter, for the slug flow situations depicted in Fig. 3. Fig. 5 shows a representative plot for slug lengths when tube diameter is 1.7 and 2.6 mm. So, the friction factor is not corrected for this range of diameters (i.e., 1.0–2.0 mm). However, when the tube diameter is 2.6 mm, the slug length is found to be less than 10 times the tube diameter, similar to the observations of Kreutzer et al. [7]. Further, investigators like Kawahara et al. [9] observed that the single phase friction factor, from experiments with nitrogen-water two-phase flow in micro channels, agreed very well with that predicted by using the conventional laminar correlation. Thus, it gives:

$$X^2 = \left(\frac{\rho_g}{\rho_l}\right)\left(\frac{\mu_l}{\mu_g}\right)\left(\frac{1-x}{x}\right) \tag{4}$$

$$f_l = \frac{16}{\mathrm{Re}_l} \tag{5}$$

Additionally, with the help of a slip ratio, gas mass fraction and void fraction can be related (Eq. (6)). Chisholm [10] gives a reasonably accurate correlation (Eq. (7)) to find the slip ratio. Void fraction can be measured from the experiments. Thus, Eqs. (6) and (7) result in a cubic equation in gas mass fraction which can be solved to get the gas mass fraction for a channel whose void fraction is used:

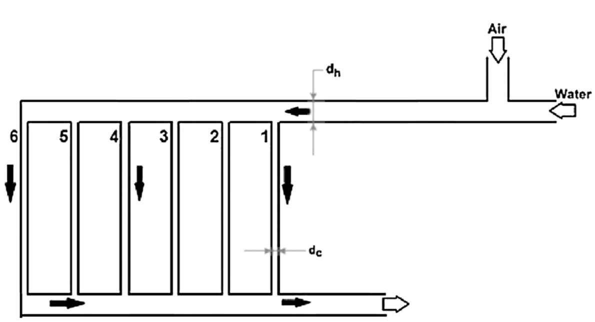

Fig. 1. Schematic of two-phase flow in parallel mini channels.

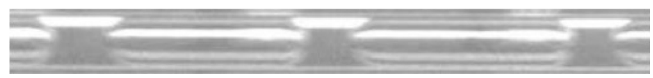

Fig. 2. Visualization of slug flow in a 1.7 mm diameter single horizontal mini tube [5].

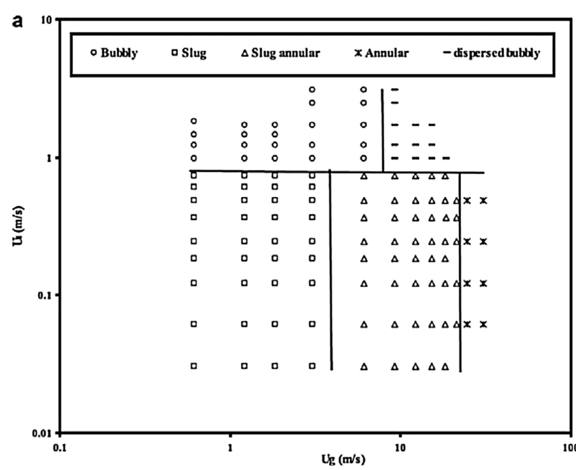

Fig. 3. Flow regimes predicted for a 1.7 mm mini tube [5].

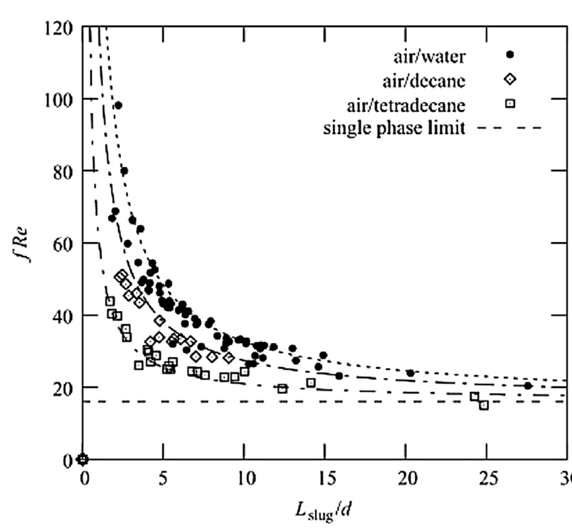

Fig. 4. (*fRe*) as a function of slug length, for a vertical tube of diameter 2.3 mm [7].