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Investigating the pressure loss associated with two-phase flow in a rectangular microchannel suddenly expanding into a manifold

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ABSTRACT

This study focuses on the experimental investigation of the two-phase pressure loss occurring as air-water flow exits a microchannel to a larger manifold. The microchannel has dimensions of 3.23 mm wide by 0.304 mm high by 164 mm long and expands into an exit manifold of 1.4 cm diameter oriented 90° relative to the flow direction. The expansion results in an additional 150–400 Pa pressure loss. Visualization of the flow illustrates water accumulation at the channel exit with varying behavior, resulting in the range of the pressure loss. Using the sudden expansion model of Abdelall et al. resulted in a mean absolute percent error of 96%. Treating the pressure loss as a result of the 90° bend, the model of Paliwoda produced a mean absolute percent error of 81%. The combined influence of the models of Abdelall et al. and Paliwoda predicted the experimental measurement with a mean absolute percent error of 78%.

Introduction

Pipe systems inevitably include bends, area contractions/expansions, or other geometric features that produce minor pressure losses in addition to the major frictional pressure drop. The prediction of the frictional pressure drop of two-phase flows in microchannels has received significant attention in the form of homogeneous [1–6], separated [7–18], and two-fluid models [4,19–24]. However, the minor pressure losses associated with two-phase flow have received less attention. The prevalence of micro-scale devices utilizing two-phase flow and experimental constraints to investigate two-phase frictional pressure loss necessitates an investigation of minor pressure losses.

Micro-heat exchangers present one such micro-scale device. Typically micro-heat exchangers consist of multiple parallel micro-scale channels terminating in an exit manifold of larger scale [25,26]. The coolant flowing through the microchannels undergoes a phase change and thus increases the heat transfer due to the laten heat of vaporization [15,27]. However, the full conversion of the coolant to vapor leads to a condition of dry-out, decreasing the overall heat transfer coefficient [28]. Therefore, designs will seek to maintain two-phase flow throughout the channel. A minor two-phase pressure loss occurs for each channel as the flow suddenly expands into the exit manifold. While decreasing the channel dimensions improves heat transfer, the total pressure drop of the system increases [15]; additional pressure losses may

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Nomenclature

Acronyms

FFT	Fast-Fourier transform
PEM	Polymer-Electrolyte Membrane

Greek Symbols

α	Void fraction [–]
α^*	Aspect ratio (smallest dimension/largest dimension) [–]
α_E	Mean volumetric liquid entrainment for Schmidt & Friedel (1996)
β	Homogeneous void fraction [–]
χ	Gas quality [–]
Δ	Difference between points
δ^*P	Percent error [–]
γ	Contact angle [deg.]
Γ_e	Downstream pressure correction term of Schmidt & Friedel (1996)
κ	Resistance coefficient [–]
μ	Dynamic viscosity [kg/m·s]
ϕ^2	Two-phase flow multiplier [–]
ρ	Density [kg/m^3]
ρ'	Density function (Eq. (36)) of Abdelall et al. (2005)
ρ''	Second density function (Eq. (37)) of Abdelall et al. (2005)
σ	Surface tension [N/m]
σ_A	Area-ratio= A_1/A_2 [–]
Υ	Correlation (Eq. (19)) of Attou & Bolle (1997)
ϑ	Correlation (Eq. (18)) of Attou & Bolle (1997)
X_h	Lockhart-Martinelli parameter [–]

Roman Symbols

$\dot{m}$	Mass flow rate per unit area [kg/m^2·s]
$\frac{R}{D}$	Ratio of bend radius to channel diameter [–]
$\mathbf{n}$	Unit normal [–]
$\mathbf{u}$	Velocity vector [m/s]
$\overline{C}$	Friction correlation constant [–]
$\overline{e}_{\%}$	Mean percent error [–]
A	Area [m^2]
B	Bend Coefficient of Chisholm (1980) [–]
C_h	Chisholm parameter [–]
d	Diameter [m]
D_H	Hydraulic diameter [m]
f	Frication factor [–]
f_m	Syringe pump frequency [Hz]
G	Total mass flux [kg/m^2·s]
g	Acceleration due to gravity [m/S^2]
h	Height [m]
K^*	Correction factor (0.83) of Wadle (1989)
L	Length [m]
n	Number of samples [–]
P	Pressure [Pa]
Q	Volumetric flow rate [m^3/s]
Re	Reynolds number [–]
S	Slip ratio [–]
s	Saturation [–]
U	Superficial velocity [m/s]
u	Axial velocity [m/s]
w	Width [m]
W_{rel}	Relation in the void fraction of Rouhani (1969)
We	Weber number [–]
z	Downstream distance [m]

Superscripts

r	Correlation exponent (1.4) of Attou & Bolle (1997)

Subscripts

0	Flange location
1	Upstream location
2	Downstream location
3	Exit tap location
b	Bend
c	Cross-sectional
e	Effective condition for Schmidt & Friedel (1996)
exit	Exit
expected	Expected
G	Gas
I	Irreversible
L	Liquid
lo	Liquid-only
R	Reversible
sp	Single-phase
tp	Two-phase

Operators

$\langle\,\rangle$	Area-averaged quantity
$\sum$	Summation

make the specific design inefficient or impractical. Consequently, optimal heat-exchanger design requires an understanding of all possible pressure loss mechanisms.

Polymer-electrolyte membrane (PEM) fuel cells represent another example. The gas-supply channels serve to supply the PEM fuel cell with reactants and to remove excess water produced by the hydrogen-oxygen reaction. Similar to micro-heat exchangers, PEM fuel cells consist of several parallel channels in various configurations [29], which terminate at a manifold. A minor pressure loss will occur as a result. Additionally, the geometric change from a small channel to a large channel can result in the local accumulation of water [30–32]. Water accumulation will influence the distribution of reactants and minor pressure losses will influence the scale of pumps necessary to supply the reactants. As designers continue to seek improved PEM fuel cell performance [33], understanding different loss mechanisms can aid in achieving this goal.

However, understanding two-phase flow itself introduces enough complexity that researchers focus on characterizing the two-phase flow independent of any exit influences. For example, English & Kandlikar [11] designed the exit of the microchannel specifically to mitigate its influence on the results and Grimm et al. [34] used rolled up paper at the exit to prevent water accumulation near the channel exit. At times, however, experimental measurements require placing

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