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Heat transfer coefficient measurement of LN_2 and GN_2 in a microchannel at low Reynolds flow ☆

Seungwhan Baek *, Peter E. Bradley, Ray Radebaugh

Material Measurement Laboratory, National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305, USA

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ABSTRACT

The heat transfer coefficients of single-phase fluids in the laminar flow regime have been studied for decades. However, inconsistent results are found in the literature. The common finding is that the Nusselt number is dependent on the Reynolds number in the laminar flow regime, which is contrary to laminar flow heat transfer theory. Recently, researchers indicated that axial conduction in the wall of the microchannel can affect the measurement. However, there have not been thorough studies that demonstrate consistency or lack thereof between experiment and theory. This study provides an experimental investigation on heat transfer performance of gaseous and liquid nitrogen flow through microchannels with hydraulic diameters of 110 μm and 180 μm. A model has been developed to investigate heat transfer in a microchannel from which analysis shows that the temperature profile of the fluid and wall change non-linearly along the length of the microchannel when the flow rate is low (e.g., $Re < 1000$). The non-linear temperature profile conflicts with the assumption of a linear temperature profile commensurate with the traditional Nusselt number estimation method, which leads to dependency on the Reynolds number. Comparison between the experiment and numerical model of the present work validates the conclusion that the heat transfer coefficient is uniform within the laminar flow regime ($Re < 2000$) for microchannels.

1. Introduction

As microscale cooling devices are developed, the heat transfer characteristics of the fluid in the microchannels become important, with typical dimensions from 10 μm to 1 mm [1]. Microscale heat exchangers can be developed with micro-fabrication processes, which can have an extremely high heat transfer surface area per unit volume, a higher heat transfer coefficient, and a low thermal resistance. Heat transfer correlations are required to design such a heat exchanger; however, conventional forced convection heat transfer correlations were based on tubes with macro-scale dimensions. The development of heat transfer coefficient correlation for microchannels is still on-going, and has become more important due to the rapid growth in microscale cooling technology applications [2–4]. However, a heat transfer coefficient correlation for single-phase fluid flow in the laminar regime has not been developed.

Various groups have performed experimental and theoretical studies of single-phase fluid heat transfer in microchannels [5–7], but discrepancies exist among measurement results and various correlation approaches. Wu and Little [8] first measured the heat transfer coefficients of nitrogen gas flowing through micro-heat exchangers. The microchannels were prepared on silicon substrates by photolithographic technique. The hydraulic diameters of the trapezoidal microchannels were from 134 μm to 165 μm. In the laminar regime the Nusselt numbers decreased as Reynolds numbers decreased to lower values ($Re < 1000$). Later, Choi et al. [9] presented experimental data correlating Nusselt numbers with Reynolds number ranging from 50 to 10,000 in microchannels (D_h = 9.7 μm, 53 μm, and 81.2 μm). The microchannels were silica tubes with a thin polymide coating over the outer surface of the tube. They found the Nusselt numbers to be lower than theoretical values at low Reynolds flow ($Re < 2000$), and they proposed new correlations for the average Nusselt number for laminar flow. The correlation proposed by Choi et al. [9] did not agree with the experimental data by Wu and Little [8], however.

Peng and Peterson [10] measured heat transfer coefficients for water flow in microchannels. The rectangular microchannels were

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* Corresponding author at: Launcher Propulsion System Team, KSLV-II R&D Head Office, Korea Aerospace Research Institute, 169-84 Gwahak-ro, Yuseong-gu, Daejeon 34133, Republic of Korea.

E-mail addresses: sbaek@kari.re.kr (S. Baek), pbradley@nist.gov (P.E. Bradley), radebaugh@nist.gov (R. Radebaugh).

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Nomenclature

A	heat transfer area (m^2)
A_c	cross sectional area of fluid flow (m^2)
B	total bias error
c_p	heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
D_h	hydraulic diameter (m)
D_i	tube inside diameter (m)
f	friction factor
G	mass flux ($kg \cdot s^{-1} \cdot m^{-2}$)
h	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
i	enthalpy ($J \cdot kg^{-1}$)
k	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
K	loss coefficient
L	length (m)
$\dot{m}$	mass flow rate ($kg \cdot s^{-1}$)
N	number of data
Nu	Nusselt number
p	pressure (Pa)
q	heat rate (W)
q''	heat flux ($W \cdot m^{-2}$)
Re	Reynolds number
S	standard deviation
T	temperature (K)
$t_{95\%}$	T-distribution for a confidence level
th	thickness (m)
U	uncertainty
x	length of certain point (m)

Subscripts

a	acceleration
app	apparent
exp	experimental
f	fluid, frictional
h	heating length
in	inlet
out	outlet
t	total
w	wall
x	position

Greek letters

λ	axial conduction parameter
μ	viscosity ($Pa \cdot s$)
ρ	density ($kg \cdot m^{-3}$)
σ	contraction ratio

machined into a stainless steel plate with hydraulic diameters ranging from 150 μm to 343 μm. The dependency of the Nusselt number on the Reynolds number was found for Reynolds numbers less than 2000. They proposed an empirical correlation based on the geometric shape of the rectangular microchannel. Qu et al. [11] measured heat transfer characteristics of laminar water flow in microchannels composed of Pyrex and silicon. The experimentally derived Nusselt numbers were lower than the theoretical values, from which they concluded that the Nusselt number was related to the surface roughness. Celata et al. [12] estimated Nusselt numbers for R114 flowing in stainless steel microchannels, and also observed a reduction of the Nusselt number for the laminar flow regime. While Nusselt number appears to depend on Reynolds number for Reynolds flow less than 2000 in microchannels, none of the studies provided a clear explanation of the factors contributing to the observed reduction, and a general correlation has not been developed.

In a later work, Maranzana et al. [13] proposed an analytical heat transfer model to include the effect of axial conduction along the microchannel, and were able to describe temperature profiles that change non-linearly along the channels. This non-linearity led to a very large bias in the experimental estimation of the heat transfer coefficients, especially for low Reynolds numbers. However, precise experimental verification did not accompany the model simulations. Hetsroni et al. [14] noted that axial conduction in the wall can be significant for laminar flow. Morini et al. [15] compared Nusselt values from a thick wall microchannel to a thin wall microchannel to explain the axial conduction effect on the measurement, but the experimental data were insufficient to explain the reduction of the Nusselt number. Lin and Kandlikar [16] derived an equation to investigate the reduction of the Nusselt number by the 1st law of thermodynamics. The proposed equation was compared to available experimental data, and it was concluded that the reduction of the Nusselt number is related to the axial conduction effect.

In summary most recent studies showed significant discrepancies among experimental results and theoretical predictions. Based on recent work, consideration of the effect of axial conduction in microchannels appears to be important, but to the knowledge of the authors, direct comparisons between simulation and experimental work are not available. In the previously discussed work, the traditional Nusselt number estimation method was adopted. The traditional method measures the wall temperature at the middle of the heating section, and the inlet and outlet fluid temperatures. The fluid temperature at the middle of the heating section is calculated from the inlet and outlet fluid temperatures. It is interesting that such discrepancies are generated within similar experiments.

The purpose of this study is to highlight the discrepancies of the traditional heat transfer coefficient measurement of laminar flow in microchannels with the linear fluid temperature profile assumption. In this paper, the heat transfer coefficients of liquid and gaseous nitrogen are measured with the linear fluid temperature profile assumption. Those experimental data will be compared to the heat transfer model including the axial conduction effect. The comparison will provide a clear explanation of how the reduction of the Nusselt number is derived. In the end, the evidence of a constant Nusselt number in the laminar flow for microchannels will be provided.

2. Experimental method

The heat transfer characteristics of the gas and liquid nitrogen are examined in the microchannel. The closed-loop experimental setup enabled steady flow rate, continuous temperature and pressure measurement across the microchannel. The GM-cryocooler produced the lower temperature, which liquefies gaseous nitrogen in the closed-loop setup. The most complicated part was winding the heater and attaching thermometers on the microchannel. The following section describes the experimental setup and data reduction method.

2.1. Experiment setup

Fig. 1 displays a schematic of the experimental setup for the heat transfer coefficient measurement of a fluid in a microchannel. The closed-loop setup including a compressor, a microchannel test section, the GM-cryocooler, and a vacuum chamber is utilized for