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Experimental and numerical investigation of forced convection of subsonic gas flows in microtubes

Yahui Yang [a], Chungpyo Hong [b], Gian Luca Morini [a,*], Yutaka Asako [c]

[a] DIN, Alma Mater Studiorum, Università di Bologna, Bologna, Italy
[b] Dept. of Mechanical Engineering, Kagoshima University, Kagoshima, Japan
[c] Dept. of Mechanical Engineering, Tokyo University of Science, Tokyo, Japan

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ABSTRACT

The aim of this paper is to investigate the impact of gas compressibility on forced convection through commercial stainless steel microtubes with an inner diameter of 750 μm, 510 μm and 170 μm by combining experimental data with numerical simulations. The analysis covers both transitional and turbulent flow regimes ($3000 < Re < 12{,}000$). The results have evidenced that compressibility effects can significantly enhance convective heat transfer when the gas flow is heated by the walls (H boundary condition). This enhancement turns out to be more remarkable for microtubes with smaller inner diameter (lower than 200 μm). In order to explore in-depth the heat transfer mechanism along the microtube in presence of non negligible compressibility effects, the experimental data have been integrated with the numerical results obtained by modeling the fluid flow through the microtube with the adoption of the Arbitrary–Lagrangian–Eulerian (ALE) method and the Lam–Bremhorst Low–Reynolds number turbulence model in order to evaluate eddy viscosity coefficient and turbulence energy within the gas flow. The results presented in this work put in evidence that the integration of the experimental data with the numerical results is strongly beneficial in order to obtain a deep investigation of the physics of micro convection for compressible flows. The experimental values of the Nusselt numbers obtained for three different microtubes have been compared with both classical correlations validated for conventional pipes and specific correlations proposed for microtubes. This comparison highlights that the conventional correlations still holds for gas flow convection through microtubes when the compressibility effect is not significant. On the contrary, when compressibility is no longer negligible, the conventional correlations tend to underestimate the value of the Nusselt number. It is also demonstrated that the specific correlations proposed for the prediction of the Nusselt number in microtubes fail in presence of strong compressibility effects.

1. Introduction

During the last decades a rapid progress there has been in the technology of miniaturization, with devices and systems being scaled down from macro-metric sizes to micro-metric dimensions. This trend was not only driven by extensive engineering and industrial applications with promising market potential but also stimulated by multidisciplinary research intersecting chemistry, physics, biology, life science, pharmaceutics and engineering, etc. The analysis of flow and heat transfer mechanisms at microscale level is an interesting topic not completely investigated up to now as remarked in a recent review by Kandlikar et al. [1]. One of the main questions remaining unanswered is in which conditions the macroscale rules for single-phase flow heat transfer are still valid for microscale phenomena. For this reason, in the last years a large amount of experimental analyses has been addressed to the analysis of fluid-dynamics and heat transfer characteristics of single- and two-phase flows in microchannels [1]; however, the results are not always univocal as evidenced by Morini [2] and Hetsroni et al. [3].

As underlined in [1], forced convection of single-phase liquid flows in microchannels has been extensively investigated in the past and now it is possible to conclude that the conventional theory developed at macroscale is able to predict the convective

* Corresponding author. Address: Department of Industrial Engineering (DIN), School of Engineering and Architecture, Alma Mater Studiorum, University of Bologna, viale del Risorgimento 2, 40136 Bologna, Italy. Tel.: +39 051 2093381; fax: +39 051 2093296.

E-mail address: gianluca.morini3@unibo.it (G.L. Morini).

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Nomenclature

Br	Brinkman number (–)
c_p	specific heat at constant pressure (J/kg K)
d	inner diameter (m)
D	external diameter (m)
d_h	hydraulic diameter (m)
h	heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	microtube total length (m)
L_h	microtube heated length (m)
L_{th}	microtube thermal entrance length (m)
$\dot{m}$	mass flow rate (kg/s)
M	wall axial conduction parameter (–)
Ma	Mach number (–)
Nu	Nusselt number (–)
P	heating power (W)
Pr	Prandtl number (–)
q	heat flux (W/m^2)
R	specific gas constant (J/kg K)
r	radius (m)
Re	Reynolds number (–)
T	temperature (K)
u	velocity (m/s)

Greek symbols

γ	specific heat ratio (c_p/c_v) (–)
ε	absolute roughness (m)
μ	dynamic viscosity (kg/ms)
ρ	density (kg/m^3)

Subscript

ad	adiabatic
b	bulk value
e	external surface
f	fluid
i	internal surface
in	inlet value
m	mean value
out	outlet value
T	total
w	wall
*w*6	wall value measured by the thermocouple close to the outlet

heat transfer coefficient for liquid flows in microchannels, with minor deviations caused by experimental errors [4] and/or by the presence of non negligible scaling effects [5–7]. On the contrary, in the case of gas micro convection very few experiments support the theoretical models and a significant effort is still needed in this direction [1]; this fact has been also stressed by Colin [8] in a recent review focused on gas micro convection.

The first experimental investigation devoted to the analysis of gas micro convection can be traced back to the work by Wu and Little [9] in the 1980s, who explored the flow and heat transfer characteristics of N_2, H_2 and Ar through miniaturized rectangular channels with hydraulic diameter from 40 to 80 μm. The comparison of their experimental Nusselt numbers with the predictions of the classical correlations (i.e. Sieder and Tate [10], Hausen [11] and Dittus and Boelter [12]) evidenced a strong disagreement in laminar, transitional and turbulent regimes.

The experimental data published by Choi et al. [13] successively, obtained with nitrogen flow, confirmed that the Nusselt number in turbulent regime was larger than the prediction of the Dittus–Boelter correlation [12] but their data were not in agreement with the correlation proposed previously by Wu and Little [9]. In laminar regime Choi et al. [13] obtained very low values of Nusselt number compared to the predictions of the conventional correlations. The authors gave no justification to this trend, both in laminar and turbulent regime, and proposed two new correlations for the prediction of the Nusselt number in microtubes by fitting their own experimental data.

Yu et al. [14] investigated the convective heat transfer of nitrogen flow in turbulent regime through microtubes with inner diameters between 19 μm and 102 μm. Also in this case, the Nusselt numbers obtained in turbulent regime were larger than those predicted by means of conventional correlations but the authors avoided any physical explanation of their results and proposed a new correlation for the prediction of the Nusselt number in microtubes, not in agreement with the previous correlations of Wu and Little [9] and Choi et al. [13].

Hara et al. [15] experimentally investigated the convective heat transfer of air flows through square minichannels with hydraulic diameters between 0.3 mm and 2 mm. Unlike the other researchers, they found that the deviation of Nusselt number from conventional theory may depend on the hydraulic diameter and length of the tested minichannels.

A possible physical explanation of the large Nusselt numbers evidenced by the experimental runs in [9,13–15] is linked to the significant role played by gas compressibility in microtubes. When the inner dimensions of a tube are reduced, for a fixed mass flow rate, the fluid velocity increases and the local Mach number can reach large values (larger than 0.3) even for Reynolds numbers less than 5000–10,000, especially close to the tube exit. In this case the gas compressibility cannot be ignored inducing conversion from thermal energy to kinetic energy when the flow accelerates along the microtube and this can justify an augmentation of the Nusselt number. However, this effect has been ignored in [9,13–15] and for this reason in the proposed correlations the Mach number is never involved. The beneficial effect of gas compressibility on the Nusselt number has been also demonstrated numerically for very large values of the Mach number (up to $Ma > 1$) by Hong et al. [16] and Lijo et al. [17].

More recently, Chen et al. [18] and Yang et al. [19] conducted experimental research on forced convection of air and carbon dioxide through microtubes with an inner diameter from 86 μm to 920 μm. The trend of the Nusselt number in both laminar and turbulent regime was found in agreement with the classical correlation proposed by Gnielinski [20], which was validated for incompressible flow at macro scale. These experimental results seem to indicate that the heat transfer coefficient is not influenced by the flow compressibility effect even at very large Reynolds numbers ($Re \sim 20\,000$), if the Mach number at the outlet is lower than 0.3.

It is possible to conclude that the experimental results obtained recently by Chen et al. [18] and Yang et al. [19] and the numerical results of Hong et al. [16] and Lijo et al. [17] are in disagreement with the results of the previous works due to Wu and Little [9] and Choi et al. [13] Yu et al. [14] and Hara et al. [15] and these last works are not in agreement each to other.

For these reasons, the main objective of the present work is to investigate the limits of validity of the conventional correlations for the prediction of Nusselt numbers in microtubes having an inner diameter down to 170 μm by using nitrogen as working gas. The experimental investigation is made with the aim to quantify