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Investigation of the roughness effect on flow behavior and heat transfer characteristics in microchannels

Yangpeng Liu, Guoqiang Xu, Jining Sun, Haiwang Li *

National Key Lab. of Science and Technology on Aero-Engines, Beijing University of Aeronautics and Astronautics, Beijing 100191, China

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ABSTRACT

Experiments were conducted to investigate the flow behavior and heat transfer characteristics in microchannels with various surface roughnesses. In the experiments, six test pieces with various roughnesses were fabricated in the stainless steel panel and divided into three groups. Each panel includes 30 microchannels in parallel with uniform geometrical parameters. Both width and depth of microchannels are 0.4 mm. The relative roughness of surface in the microchannel is from 0.58% to 1.26%. All tests were performed with air. The experiments were completed with the Reynolds number in the ranges of 200–2100. The friction factor, heat transfer coefficient, Nusselt number and thermal performance were analyzed based on the experimental results. Results of experiments showed that the surface roughness in microchannel has a remarkable effect on the performance of flow behavior and heat transfer. Based on the experimental data, the friction factor and the Nusselt number increase with the increasing of the surface relative roughness. At the same time, the effect of roughness in the thermal performances is small within the range of experimental parameters. The results also indicate that the heat flux rarely affects the Nusselt number. In this paper, the corresponding empiric equations for flow resistance and heat transfer characteristics in microchannels were developed.

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1. Introduction

With the development of electronic instrument industry, microchannels which have the superior heat transfer characteristics with higher ratio between surface and volume are widely used [1]. In the research field of aero-engine, the temperature before the turbine inlet becomes higher and higher in order to improve the performance of aero-engine. However, higher inlet temperature leads the turbine components, such as blades, to suffer more and more thermal stress and heat loads which sharply degrade the reliability and operation life of the turbine components. Generally, the turbine inlet temperature reaches up to 1950 K [2], which is higher than the blade material melting temperature at around 1150 K [3]. It means that the cooling method must be applied to protect the blade [4]. So far, the major cooling techniques include internal cooling passage, impinging cooling, film cooling and so on [5]. The advanced cooling method with higher cooling efficiency is the popular research topic for the researchers and designer of aero-engine.

For the past decades, many researchers are studying the application of microchannels in the turbine blade [6]. There are many publications to investigate the characteristics of fluid flow and heat transfer in the microchannel [6–16]. However, some of the existing experimental results show that there are some discrepancies between conventional values and the experimental data.

The flow resistance is one of the main factors to be investigated. Wu and Little [7] indicated that the friction factor of gas laminar flow in the microchannels was higher than the value calculated from the classical formula under the fully developed laminar flow, the critical Reynolds which represent transition from laminar to turbulent flow decreased significantly from $Re_c = 2300$ for the traditional macrochannel to $Re_c = 400–900$ for the microchannel. The Reynolds analogy was not suitable for the microchannels. Pfund [8] used water as the working medium. It was found that the friction factor was higher than the conventional value significantly. Qu et al. [9] investigated the pressure drop of water flow in trapezoidal silicon microchannels. They found the pressure drop was higher than the conventional value. Wu and Cheng [10] experimentally investigated the flow in different trapezoidal silicon microchannels. The experimental data showed that the laminar friction factor was different from the conventional values. These discrepancies became more obvious at large Reynolds number. Li et al. [11] studied the flow in a stainless steel microtube with diameter of 128.76–179.8 μm. The Poiseuille number for tubes exceed the

* Corresponding author.
E-mail address: 09620@buaa.edu.cn (H. Li).

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Nomenclature

c_p	specific heat capacity [kJ/(kg K]
d_h	hydraulic diameter [m]
L	channel length [m]
H	height of the water inside the measuring cylinder [m]
m	mass flow rate [kg/s]
V	volume of the air [m^3]
t	collection time [s]
g	acceleration of gravity [m/s^2]
N_f	total number of microchannels
A_c	cross-sectional area of microchannel [m^2]
A_h	contact area between test pieces and copper plate [m^2]
A_T	contact area between copper plate and nylon plate [m^2]
f	friction factor
q	heat flux [W/m^2]
Q	heating power [W]
Po	Poiseuille number
h	heat transfer coefficient [$W/(m^2 K)$]
$\bar{h}$	averaged heat transfer coefficient [$W/(m^2 K)$]
Nu	Nusselt number
$\overline{Nu}$	averaged Nusselt number
P	pressure [Pa]
ΔP	pressure drop [Pa]
Re	Reynolds number
Pr	Prandtl number
T	temperature [K]
u	velocity [m/s]

Greek symbols

η	thermal performance
μ	dynamic viscosity [Pa s]
λ	thermal conductivity [$W/(m^2 K)$]
ρ	density [kg/m^3]
ε	roughness height [μm]
$\|\varepsilon\|$	relative roughness height
δ	thickness of nylon plates [m]

Subscripts

water	water
w	wall
f	characteristic value
loss	heat loss
in	inlet
out	outlet
x	number
air	working medium
min	minimum value
nl	nylon plates

value corresponding to conventional theory and the critical value of the Reynolds number was about 1700 for micro-tube with diameter 128.76 μm. Sepideh et al. [12] used micro particle shadow velocimetry to study the flow of water through micro circular sudden expansions. The measured pressure drop in the geometry for the range of Reynolds numbers did not match the predictions of the available empirical correlations. Zhang et al. [13] investigated the flow characteristics of a flat aluminum extruded multiport tube using water as working fluid. The test was performed covering the laminar, critical and early transition zone. The experimental data showed the transition occured at $Re = 1200–1600$ for different samples. The friction factor was affected by entrance effect significantly and aspect ratio did not influence the early transition.

The heat transfer characteristic is another main factor to be investigated. Qu et al. [14] found that Nusselt numbers were lower than the conventional values, which was contradictory to the other published experimental results. Rahman [15] adopted a new measurement for pressure drop and heat transfer coefficient in microchannel heat sinks, the experimental data showed a larger average Nusselt numbers than those predicted for larger size channels. Wu and Cheng [10] also experimentally investigated the heat transfer characteristics in different trapezoidal silicon microchannels. The experimental data showed that the Nusselt number increased almost linearly with the Reynolds number at low Reynolds number ($Re < 100$), but increased slowly when the Reynolds number was greater than 100. Hung et al. [16] investigated the effect of streamwise conduction on the thermal characteristics of forced convection for flow in rectangular microchannel heat sinks under isothermal wall and developed models with and without streamwise conduction term in the energy equation for hydrodynamically and thermally fully-developed flow. The study revealed the effect of streamwise conduction could not be neglected in the forced convective heat transfer analysis of microchannel heat sinks. Zhang et al. [13] showed that the Nusselt number was enhanced in convective heat transfer process and the entrance effect was more effective in the laminar region.

As showed above, some of existing experimental results of friction factors and Nusselt numbers in microchannels are different from the conventional values. Meanwhile it seems that the experimental results of different researches are different. Maybe these phenomena are due to neglecting significant scaling effect or experimental inaccuracy. However, some researchers identify the surface roughness as an important parameter among numerous reasons about the characteristics of microchannels which are contrary to the traditional theories [17]. Many studies of the roughness effects on flow behavior and heat transfer characteristics in microchannels have been carried on during the past decades.

The main amplitude of the roughness wall studied by Pfund [8] was ±1.9 μm with the maximum peak value height of approximately 14.67 μm. The data showed the friction factor was higher than the conventional value significantly. Qu et al. [9,14] attributed both the higher pressure drop and lower Nusselt numbers to the wall roughness and proposed a roughness-viscosity model to interpret their experimental data. However, it should be noted that the increase in wall roughness would cause the decrease in Nusselt number according to their model. Kandlikar et al. [18] studied the effect of surface roughness on pressure drop and heat transfer in two circular tubes with three different roughness values. The results showed that the effect of surface roughness was significant for tubes with small diameter. High surface roughness led to high heat transfer and pressure drop values. The relative surface roughness of different trapezoidal silicon microchannels according to Wu and Cheng [10] was from 3.26×10^{-5} to 1.09×10^{-2}. The experimental data showed that the laminar friction factor and Nusselt number increased as the surface roughness increased. These increases became more obvious at large Reynolds number. In the investigation by Li et al. [11], the relative roughness of stainless steel microtube was about 3–4%. As stated before, the Poiseuille number exceeded the value corresponding to conventional theory and the critical value of the Reynolds number decreased. Zhou and Yao [19] studied the effect of roughness on pressure drop and transition based on experimental data from the open literature and found all the normalized data could be predicted within error of 15% using the original constricted flow model. Lin et al. [20] investigated flow behavior and heat transfer

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