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FULL LENGTH ARTICLE

Experimental investigation of surface roughness effects on flow behavior and heat transfer characteristics for circular microchannels

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Abstract This paper experimentally investigates the effect of surface roughness on flow and heat transfer characteristics in circular microchannels. All test pieces include 44 identical, parallel circular microchannels with diameters of 0.4 mm and 10 mm in length. The surface roughness of the microchannels is R_a = 0.86, 0.92, 1.02 μm, and the Reynolds number ranges from 150 to 2800. Results show that the surface roughness of the circular microchannels has remarkable effects on the performance of flow behavior and heat transfer. It is found that the Poiseuille and Nusselt numbers are higher when the relative surface roughness is larger. For flow behavior, the friction factor increases consistently with the increasing Reynolds number, and it is larger than the constant theoretical value for macrochannels. The Reynolds number for the transition from laminar to turbulent flow is about 1500, which is lower than the value for macrochannels. For the heat transfer property, Nusselt number also increases with increasing Reynolds number, and larger roughness contributes to higher Nusselt number.

1. Introduction

With continuing development of aircraft engines, turbine inlet temperatures become increasingly higher, often far exceeding the melting point of turbine blade materials. Efficient cooling techniques are among the most important methods to ensure safe operation of turbines. Many cooling techniques, e.g. film cooling and impingement cooling, have been applied to aero engines. Microchannels, which have superior heat transfer characteristics with higher surface to volume ratios, are attracting more and more attention for application in cooling techniques. After the landmark work of Tuckerman and

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Pease,[1] many researchers in the last decade have investigated the flow and heat transfer behavior of microchannels (< 1 mm), which differ from those in the macro-scale.

Early in their investigation, Peng et al.[2,3] experimented with the behaviors of flowing fluid and heat transfer in rectangular microchannels with diameters ranging from 0.1 mm to 0.3 mm. Water was used as the working fluid. It was noted that the overall hydrodynamic performance of microchannels was different from conventional theories. Based on their experimental results, the friction factor in laminar and turbulence flow regimes was inversely proportional to $Re^{1.98}$ and to $Re^{1.72}$, respectively. This is in stark contrast to what is expected from the conventional theories on laminar and turbulent regimes according to Filonenko.[4] What's more, the authors found a transition occurred at Reynolds numbers 300–700, which was considered smaller than the transitional critical Reynolds number 2300.

Mala and Li[5] completed experiments in microtubes with diameters ranging from 50 μm to 254 μm. The results also indicated departure of flow characteristics from conventional theory of microtubes. In their experiment, the friction factor in laminar regime is higher than that predicted by conventional theory. The experimental results indicated the transition from laminar to turbulent flow mode at Reynolds numbers between 300 and 900. Yang and Lin[6] investigated the heat transfer and friction characteristics of water flow in microtubes. Experimental results reveal that there is no significant size effect for water flow in tubes with diameters ranging from 123 μm to 962 μm. Zhao et al.[7] investigated the characteristics of nitrogen flow in microtubes with diameters of 2.05, 5.03, and 10.10 μm. The results indicated that the flow characteristics had significant discrepancies between the experimental data and predictions from the classical Poiseuille's theory. Lelea et al.[8] found that the conventional theories were applicable in laminar flow regimes. Hasan et al.[9] employed numerical simulation and concluded that Reynolds number, thermal conductivity ratio and hydraulic diameter all affect the behavior of axial heat conduction. The authors explained that porous fin enhanced heat transfer performance along with the mechanism of water in microchannels reducing the pressure drop it affects.

As indicated above, most investigations show that thermal and hydrodynamic performance in microchannels is different from that of macrochannels. However, researchers have reached various conclusions about the cause of this divergence. Some investigators consider that the discrepancies might be caused by factors that are ignored in macrochannels. One of the most important of these, surface roughness, has attracted more and more attention. Tang et al.[10] investigated flow characteristics for nitrogen and helium in stainless steel microtubes, fused silica microtubes and fused silica square microchannels. The data in fused silica microtubes (D_h range: 50–201 μm, D_h is hydraulic diameter) are consistent with conventional predictions; however, the friction factors in stainless steel tubes (D_h range: 119–300 μm) are much higher than theoretical values. The authors believed that such significant deviations can be attributed to large surface relative roughness. Yang et al.[11] investigated the pressure drop and heat transfer performance of air flow in microtubes with inner diameters of 86, 308, and 920 μm. The surface roughness of the microtubes is R_a = 0.704, 0.685, 0.135 μm, respectively, and are all less than 1.5% of the diameter. The experimental friction factor shows a good agreement with the conventional theory. Lorenzini et al.[12] later conducted an investigation about compressible flow of nitrogen through circular microchannels from 26 μm to 508 μm with different surface roughness parameters. They found that, for both smooth and rough microtubes, the friction factor agrees well with conventional theory. It should be noted that when the Reynolds number was larger than 1300, the friction factor of smaller microchannels (< 100 μm) varies from the Poiseuille law. Liu et al.[13] studied the flow behaviors for air flow in rectangular microchannels with relative roughness of R_a = 0.58, 0.82, 1.26. The experimental results indicated that a larger roughness tends toward larger Poiseuille numbers; thus, the effect of roughness cannot be ignored in experiments. Kharati-Koopaee and Zare[14] numerically studied the flow and heat transfer characteristics of air and water with aligned and offset roughness patterns in rectangular microchannels. The results indicated that the offset arrangement leads to lower pressure loss for both fluids and also a lower heat transfer rate for water than the aligned pattern. It should be noted that both roughness patterns contribute to better thermal performance. Zhang et al.[15] numerically investigated gas slip flow characteristics affected by rough surfaces. The results revealed that gas flow behavior in rough microchannels is affected by the statistical roughness height and rarefaction. Kandlikar et al.[16] investigated heat transfer behaviors for microtubes of different diameters, 0.62 mm and 1.032 mm, and roughness ranging from R_a = 1.0 μm to R_a = 3.0 μm. This study finds that relative surface roughness bears no or little effect on the heat transfer characteristics for larger-diameter cases. However, the roughness effect is significant for the smaller diameters. Lin et al.[17] studied the effect of roughness on flowing fluid and heat transfer performance of air and CO_2 for microtubes with a 1 mm diameter. In the experiment, four different roughness features were generated. The results showed that the effect of roughness is different in laminar and turbulence flow regimes: in laminar flow, there was no difference of heat transfer between smooth and rough channels. However, in turbulent flow, rough channels have better thermal behavior. Koo and Kleinstreuer[18] numerically investigated the effect of surface roughness on heat transfer in micro-channels. They concluded that the Nusselt number increases with the increase in relative surface roughness in laminar flow. For turbulent flow, the Nusselt number becomes higher when the relative surface roughness of the tubes was larger. Guo et al.[19] built a model to investigate the influence of wall roughness on fluid flow and heat transfer in microchannels. The results showed that roughness plays a positive role in thermal performance as well as flow resistance.

Although the effects of roughness on flow and heat transfer behavior of microchannels have been studied by some, there is a lack of research on the behavior of roughness in undeveloped sections with air. What's more, owing to the difficulties in measuring pressure, temperature and roughness, data about flow and heat transfer behavior in circular microchannels are lacking. Thus, considering the applications for turbine blades, heat transfer and flow behavior of air flow affected by surface roughness in circular microchannels are examined in this paper.

Experimental and theoretical investigation of the flow and heat transfer behavior in circular microchannels of 0.4 mm diameter and 10 mm length with various surface roughness follows. Based on experimental data, the corresponding empiric equations for Poiseuille and Nusselt numbers were developed.

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