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An experimental investigation on forced convection heat transfer performance in micro tubes by the method of liquid crystal thermography

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Abstract

This study proposed a non-contacted liquid crystal thermography (LCT) method for micro tube surface temperature measurement. It avoids the thermal shunt error caused while using the direct contact thermocouples. Two stainless steel tubes with inside diameter of 123 μm and 962 μm were tested. The test results agree very well with those predicted by the conventional correlations. It successfully extends the validity of conventional single-phase heat transfer correlations to the tube with inside diameter of 123 μm. This method can be further applied for measuring smaller tube surface temperature that the thermal shunt may be more significant by using direct contact temperature measurements methods.

Keywords: Liquid crystal thermography (LCT); Micro tube; Forced convection heat transfer; Thermal shunt

1. Introduction

The study on heat transfer performance in micro tubes has become more important due to the rapid growth of the application for high heat flux electronic devices cooling. However, definitive information on heat transfer coefficient of such small channels is not available in the published literatures. The traditional forced convection heat transfer correlations were derived from tubes with diameter much larger than those used in micro-channels. They have not been verified to work well for predicting the heat transfer coefficient inside small hydraulic diameter tubes. Several researches dealing with the single-phase forced convection heat transfer in micro tubes have been published in the past years. Most of their tests results are significantly departed from those of the traditional forced convection heat transfer coefficients in larger tubes. Guo and Li [1] proposed that the measurement accuracy is one of the most important factors that may cause this discrepancy. Since the diameter of the sensor for measuring micro tubes surface temperature is comparable to the size of the micro tubes, the tube surface temperature cannot be accurately measured due to the effect of sensor wire thermal shunt. A non-contacted temperature measurement method must be developed for precisely measuring the micro tube surface temperature without thermal shunt effect.

Attributed to the dramatic progressive of image processing technologies, liquid crystal thermography (LCT) has been widely used for qualitatively and quantitatively surface temperature measurement in the past decade. The surface which to be measured was coated with thermochromic liquid crystal (TLC). By illuminating white light, TLC reacts to change color continuously by changing its temperature. Color of liquid crystal at working range may be defined as a property of light and represented by three characteristics, i.e. hue, saturation and intensity. Camci et al. [2] indicated that a direct relation between the local temperature and the locally measured hue value could be experimentally established. The change of hue value with

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Nomenclature

A	heat transfer area (m^2)	Nu_d	Nusselt number (dimensionless)
A_c	tube cross section area (m^2)	q	heat transfer rate (W)
c_p	specific heat (J/kg K)	Re_d	Reynolds number (dimensionless)
d_i	tube inside diameter (m)	T_i	inlet water temperature (°C)
f	friction factor (dimensionless)	T_x	local water temperature (°C)
G	mass velocity (kg/m^2 s)	T_{wx}	local tube inside wall temperature (°C)
h	heat transfer coefficient (W/m^2 °C)	TLC	thermochromic liquid crystal
H	hue value (dimensionless)	x	axial position of tubes (m)
k	water conductivity (W/m °C)		
L	tube heating length (m)	*Greek symbol*	
LCT	liquid crystal thermography	μ	viscosity (N/m^2 s)
$\dot{m}$	mass flow rate (kg/s)		

temperature is reversible and repeatable. Their data showed that the variation of local light intensity did not strongly alter the hue value and the influence of illumination angle bellows 40° is negligible. The present study applies the above stated non-contacted liquid crystal thermography method for micro tube surface temperature measurement. It avoids the thermal shunt error caused while using the direct contact thermocouples.

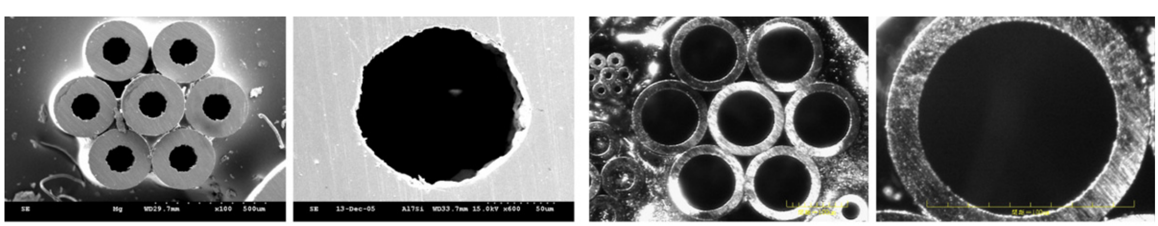
2. Experimental method

2.1. Tubes dimensions

Two smooth stainless steel tubes with inside diameter of 123 μm and 962 μm were tested in this study. The tubes diameters were measured from the enlarged photographs taken by scanning electron microscope (SEM) and optical microscope (OM) for 123 μm and 962 μm tubes, respectively. Fig. 1 shows the sample enlarged photographs of the cross section view of the tubes. For reducing the measurement uncertainties, several tubes were bundled together, cut and polished to have smooth cross section surface. For each size of tube, each tube was measured and all tubes' diameters were averaged to obtain the average tube diameter. Table 1 gives the detail dimensions of these tubes. The surface roughness for both tubes was also measured as 1.4 μm.

2.2. Experimental system setup

Fig. 2 shows the schematic diagrams of the test facilities. A pressure vessel connected to high-pressure nitrogen was used to push the water through test tubes. The inlet water temperature was measured by a resistance temperature



(a) d_i = 123 μm (by SEM) (b) d_i = 962 μm (by OM)

Fig. 1. Enlarged photographs of the micro tubes.

Table 1
Detail dimensions of the tubes tested

Tube notation	Tube length (mm)	Number of tubes measured	Average outside diameter, d_o (μm)	Average inside diameter, d_i (μm)	Standard deviation (μm)	Wall temperature measuring position (mm)	Heating length, L (mm)
123 μm (L)	140	15	250	123	1.00	75	120
123 μm (S)	64					29	34
962 μm	356	14	1260	962	1.28	287	327