Experimental Thermal and Fluid Science 77 (2016) 226–233

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Measuring heat transfer performance of viscoelastic fluid flow in curved microchannel using Ti–Pt film temperature sensor

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ARTICLE INFO

Article history:
Received 7 January 2016
Received in revised form 25 April 2016
Accepted 2 May 2016
Available online 10 May 2016

Keywords:
Ti–Pt film
Viscoelastic fluid
Microchannel
Heat transfer
Microfluidics

ABSTRACT

Temperature measurement is the core technique for investigating heat transfer in microfluidics. In this paper, the resistance thermometry of Titanium–Platinum (Ti–Pt) films is manufactured by microelectronic manufacturing technology and used for the micro-scaled temperature measurement. In order to obtain the accurate temperature on the bottom wall of microchannel, the Ti–Pt films are embedded on the bottom wall. With standardized calibration and error analysis, the experimental system is proven to be reliable and stable for flow and temperature measurement. The experiments of viscoelastic fluid with heat transfer at very-low-*Re* flow in the curved microchannel are conducted. Both viscoelastic fluid (polymeric solution) and Newtonian fluid (sucrose solution) are used as working fluids, and the corresponding heat transfer performances are obtained. Comparing with Newtonian fluid flow, higher heat transfer rate of viscoelastic fluid flow is achieved due to the irregular motion induced by the fluid viscoelasticity in the curved microchannel.

1. Introduction

With the increasing level of microelectronic techniques, typical MEMS devices structures become more complicated. Due to the complexities of multilayer type structure at micro- or nano-scale, the demand of heat removal from each component increases dramatically. As a result, effective heat transfer performance is crucial to meet the elevated heat removal requirement therein. In other words, the thermal design with high performance is a primary challenge of MEMS development nowadays.

So far, an increasing effort has been made in order to develop techniques to improve the heat transfer. Generally, the flow in microelectronic devices behaves laminar nature because of the extremely low Reynolds number (*Re*), which leads to very low heat transfer efficiency. And a disturbed flow can enhance the heat transfer. Therefore, a great number of efforts have been paid to perturb the low-*Re* flows by adopting the approaches developed in the conventional macroscale. Experimental studies have been carried out in many aspects including forced convective heat transfer issues [1–4], boiling heat transfer issues [5–9], adding perturbation by external force [10], using specially designed microchannel [11–14] and introducing nanofluids as working fluid [15,16]. However, these approaches have some limitations more or less for the micro-scale application. For instance, boiling heat transfer only occurs under high heat flux, and it is hard to control in practical microfluidics [5–9]. Adding external force and micro-structures usually make the system more complicated in applications and manufacture process [10–14]. As for the nanofluids, although the existence of nanoparticles can increase thermal conductivity of working fluid and consequently enhance heat transfer performance [15,16], the nanoparticles are also easy to adhere to the surface of the microchannel causing flow blockage problem. Therefore, there is still an urgent requirement of seeking efficient and proper method to promote the heat transfer at micro scale.

Following the idea of inducing flow instability or turbulence to improve heat transfer, the intriguing phenomena occurring in viscoelastic fluid flow at micro scale becomes an efficient alternative. The viscoelastic fluid, a kind of non-Newtonian fluid, shows nontrivial flow behaviors such as die swell effect, rod climbing effect, Kaye effect, and tubeless siphon effect [17]. Recently, it has been proven that the irregular or turbulent motion is possible to be excited in viscoelastic fluid flow at high Weissenberg number (*Wi*) even under inertialess or creeping flow conditions, i.e., purely elastic instability or elastic turbulence [17–24]. This provides another efficient way to promote heat transfer performance at micro scale by introducing viscoelastic fluids. The researches done by Steinberg et al. [20,21], Li et al. [22,23] and Tatsumi et al. [24]

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http://dx.doi.org/10.1016/j.expthermflusci.2016.05.001
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Nomenclature

A	Ti–Pt films area (m^2)
c_p	heat capacity at constant pressure (J/(kg K))
f	friction factor
h	convective heat transfer coefficient (W/(m^2 K))
k	thermal conductivity (W/(m K))
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
p	pressure (Pa)
Δp	pressure drop of flow (Pa)
Q	total heat (W)
R_i	inner ring radii of channel (μm)
R_o	outer ring radii of channel (μm)
R	resistance value (Ω) or result
Re	Reynold number
T	temperatures (K)
t	time (s)
Wi	Weissenberg number
U	velocity in the x-direction (m/s)
X	variable
x, y, z	coordinate directions (m)

Greek symbol

$\dot{\gamma}$	shear rate (1/s)
Δ	difference
δ	error of variable
η	dynamic viscosity (Pa s)
θ	circumferential direction
ρ	destiny (kg/m^3)
λ	relaxation time (s)
υ	kinematic viscosity (m^2/s)

Subscripts

i	microchannel inlet or radial direction sequence number
j	spanwise direction sequence number
N	variable sequence
o	microchannel outlet
w	wall of microchannel

have verified the significant mixing enhancement by purely elastic instabilities and turbulence in curved microchannel. However, few studies on heat transfer performance with viscoelastic flow under this condition have been conducted yet, which is an emphasis of the present work.

On the other hand, to evaluate the heat transfer performance in microchannel and get insight into its mechanism, it is of primary importance to employ proper temperature measurement method with high accuracy and stability in the experiments. Therefore, establishing the reliable temperature measurement method which is accurate and suitable for microchannel is the main focus of this work at the current stage. Generally, available techniques for temperature measurement can be classified into two categories, i.e., intrusive methods and nonintrusive methods. The intrusive instruments such as thermocouple and resistance thermometry are usually put in contact with specific measured point. While nonintrusive measurement techniques including thermo liquid crystal (TLC) [25], laser induced fluorescence (LIF) [26] and infrared thermography (IR) [1,27], etc. can cover the whole measurement field, and don't influence the fluid flow itself [28].

In the following, these two types of temperature measurement approaches are analyzed according to their cost and adaptability at micro scale. For the non-intrusive techniques, they are usually used for macroscaled flow and heat transfer, and have some disadvantages when applying in microchannels. TLC technique is easy to use, but it has low spatial resolution and measurement accuracy is about one degree in temperature. LIF technique is complicated since we need to construct a relevant laser generator and fluorescence microscope system. Moreover, its measurement accuracy is also about one degree. IR instrument could detect the whole temperature field at micro scale, though it costs too much to gain high resolution. As for intrusive methods, thermocouples are the most common sensor covering a wide range of temperature. However, it is arduous to place them inside the microchannel and meanwhile assure they do not affect the flow field. Recently, this intrusive method is also used in a nonintrusive way to measure the wall temperature in some microchannel experiments [6–10]. Therein, they are distributed along the flow direction under the channel wall. However, limited by the fabrication techniques, they are usually embedded under the chips with a certain distance off the working fluid. When experimental condition reaches the steady state, the measured temperature of thermocouple is treated as wall temperature. According to Fourier's Law, the thermal conductivity between thermocouples and wall will bring extra error. Resistance thermometry is another traditional intrusive method, and based on the linear relationship between resistance and temperature of thermometers [5]. Comparing with thermocouples, it is relatively inexpensive and can be fabricated into various forms according to the requirements, especially it can be as close to the fluid inside the channel as possible. Therefore, this technique becomes a promising option for temperature measurement at micro scale.

However, so far most of the resistance thermometers subject to the problem of inaccuracy and instability because the electric current passes through the resistances making them self-heated due to the material properties. Therefore, it is necessary to search a suitable material which is stable for temperature measurement. In this respect, Platinum (Pt) film with excellent steady properties and linearity resistance versus temperature has great potential not only for heating [11] and also for temperature measurement [12–15]. However, because Pt films directly contact with the working fluid, in some cases, it brings in ionization effect for some ionic liquids. Moreover, it also needs further consideration on manufacture procedures before using in microfluidic applications since Pt films are difficult to deposit on glass and polydimethylsiloxane (PDMS) during the fabrication process.

The present paper aims at establishing a reliable temperature measurement method which is accurate and suitable for the viscoelastic fluid flow through curvilinear micro channel. Considering the above-mentioned issues about the temperature measurement techniques, the resistance thermometry is adopted. In order to solve the fabrication problem of Pt films, the Titanium–Platinum (Ti–Pt) film is fabricated in the microchannel for wall temperature measurement, since Titanium makes Pt adhere to substrate well and steady. To avoid ionization effect from the Ti–Pt films, we add extremely thin passivation layer between working fluid and films. The present work focuses on design and fabrication of temperature sensor on the wall of microchannel, then investigates the heat transfer characteristics of viscoelastic fluids through the curved microchannel. For the further research, measuring the local temperature is the major point for us by using Ti–Pt films in order to get the insight into the local heat transfer performance of viscoelastic fluids flow through microchannel, especially the