Experimental Thermal and Fluid Science 75 (2016) 118–128

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Measuring elasticity-induced unstable flow structures in a curved microchannel using confocal micro particle image velocimetry

Xiao-Bin Li [a,b,c,d,*], Masamichi Oishi [b], Marie Oshima [b], Feng-Chen Li [a,*], Song-Jing Li [c]

[a] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China
[b] Institute of Industrial Science, The University of Tokyo, Tokyo 153-8505, Japan
[c] School of Mechatronics Engineering, Harbin Institute of Technology, Harbin 150001, China
[d] Key Laboratory of Efficient Utilization of Low and Medium Grade Energy (Tianjin University), Ministry of Education of China, Tianjin 300072, China

ARTICLE INFO

Article history:
Received 23 July 2015
Received in revised form 6 February 2016
Accepted 6 February 2016
Available online 11 February 2016

Keywords:
Curved microchannel
Flow structure
Confocal micro particle image velocimetry
Viscoelastic fluid
Elastic instability

ABSTRACT

This paper presents a measurement of the three-dimensional structures of a micellar solution flow in a curvilinear microchannel using confocal micro particle image velocimetry. An aqueous solution of cetyltrimethylammonium chloride/sodium salicylate was used as the working fluid, and fluorescent beads were added as tracer particles. With the aid of a fast-moving piezo stage, the three-dimensional flow structure was measured by scanning the flow layer by layer in the depth direction. It was found that the internal flow oscillates, and is typically twisted. In addition, the flow direction changes according to geometric curvature. Based on the statistics of velocity features, the viscoelastic flow field inside the curved microchannel shares the main features of elastic turbulence.

1. Introduction

Elasticity-induced unstable flow usually occurs in geometries with curved streamlines even at trivially small Reynolds numbers (*Re*). These geometries facilitate the coupling between elastic stress and strain in viscoelastic fluid flow, and lead to nontrivial three-dimensional (3D) flow structures [1]. Depending on the geometries, the flow shows diverse patterns of motion when the elastic effect exceeds a critical Weissenberg number *Wi* (or Deborah number *De*, both *Wi* and *De* are non-dimensional numbers representing the measure of elasticity). For conventional viscometric devices, disordered Taylor vortices are the typical patterns in Taylor–Couette (TC) geometries, Archimedean spirals occur in cone-and-disk geometries, and Bernoulli spirals are generated in disk-and-disk geometries [2]. Also, for geometrically simple lid-driven cavity flow, 3D spiral vortices will arise in the direction along the motion of the lid. Moreover, as the elasticity of flow grows, elastic turbulent flow will be induced [3,4]. Groisman and Steinberg have reported experimental observations on the viscoelastic fluid flow in a series of geometries with curvilinear streamlines, and suggested the elastic turbulence is random in time and smooth in space [5].

Newtonian fluids in a microchannel are characterized by laminar flow. However, Bonn et al. (2011) injected a viscoelastic polymer solution into a millimetric cylindrical tube, and a turbulent-like flow at very low *Re* was generated, with a velocity fluctuation level of around 30% [6]. In addition, by modifying the flow boundaries with continuous curvature, instabilities and elastic turbulence could be readily generated for viscoelastic fluids [7,8]. Because of the irregular flow in the cross-section, efficient mixing was achieved in the curvilinear microchannel [9]. The power spectrum of injected energy fluctuations, P, decays in frequency, f, with $P \sim f^{\delta}$, where $\delta < -3$; the elastic turbulence proved to be analogous to the Batchelor regime of high-*Re* hydrodynamic turbulence [7]. Later, Jun and Steinberg showed that for low-*Re* Kármán swirling flow, the power spectra of both injected energy fluctuation, P, and pressure fluctuation, p, have similar power-law decays in the frequency domain [10]. Nevertheless, the geometric curvature is not a prerequisite to the flow instabilities at microscale due to the particular properties of fluids. For a class of complex fluids whose underlying constitutive relation between shear stress and shear rate is non-monotonic, for instance allowing multiple strain rate values at a given stress or vice versa, shear banding instability emerges even for a homogeneous flow [11,12]. These complex fluids include the shear-banded wormlike micellar solutions, polymer solutions and melts, and the non-monotonic part (or the plateau regime) of constitutive curve is in the middle shear range [13]. Nghe et al. has experimentally verified the interfacial instabilities

---

[*] Corresponding authors at: School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China (X.-B. Li). Tel.: +86 451 86403254.
E-mail addresses: lixb@hit.edu.cn (X.-B. Li), lifch@hit.edu.cn (F.-C. Li).

http://dx.doi.org/10.1016/j.expthermflusci.2016.02.005
0894-1777/

Nomenclature

d	height of measured plane
De	Deborah number
E_{vv}	power spectra based on velocity component v
f	frequency
F	Fourier transformation
h	depth
$N1$	primary normal stress difference
p	pressure
P	injected energy
Q	flow rate
r	radius of the microchannel
R	correlation function
R_i	inner radius
R_o	outer radius
Re	Reynolds number
RMS	root mean squared values
U	absolute velocity
u, v	components of the absolute velocity
w	width
Wi	Weissenberg number
x, y	in-plane directions in Cartesian coordinates
z	depth direction (off the bottom wall of the microchannel)
δ	exponent

using a shear-banded micellar surfactant solution in a straight microchannel. The spatial features of interfacial modulations that develop in shear-banded flow, and the high-shear rheology were also quantified [14,15]. It showed that the banding instability induced circulation flow is quite weak. Fardin et al. found another interfacial instability in the form of cellular structures in the conventional TC device at the middle shear range [16]. Similar structures was also clarified in other rotational rheometric devices at the similar range of shear [17,18]. At the high shear rate branch of the flow curve, Fardin et al. [19] found that the shear banding instability in the TC device would tend to a bulk turbulent state. Thus the shear-banding in the plateau regime is due to the interfacial mechanism, differing from the curvature-elasticity coupling mechanism which drives classical elastic turbulence. This was also theoretically clarified by Fielding [20]. Using TC flow, Fielding tested the effect of curvature on the interfacial mechanism. It is suggested that both interfacial and bulk elastic mechanisms could be observed for different values of streamlines curvature and normal stresses. Moreover, it predicted that in a curved geometry, the interfacial mechanism is less favorable.

It is worth noting that the shear-banding instability is driven by a jump in second normal stress across the interface, and this is in consistence with the origin of secondary flow of viscoelastic fluid in the straight channel [21,22]. In contrast, the bulk viscoelastic instability or elastic turbulence at high shear regime is driven by a large first normal stress in the flow. Hence, the flow fields in the latter case should greatly differ from the former. Especially, the bulk elastic turbulent flow in the continuous curved microchannel is of our great interest.

Through careful measurements of Kármán swirling flow of polymer solutions using particle image velocimetry (PIV), Burghelea et al. have shown that the azimuthal velocities oscillate strongly and the varying vortex has a size comparable to the geometry dimensions [4]. While the fluctuation of vorticity and velocity gradients is saturated in the bulk of the elastic turbulence, the elastic stresses also saturate [4]. As for the viscoelastic flow measurement in the curved channel, Jun and Steinberg have measured the polymeric solution flow in a curved mini-channel with inner and outer radii of $R_i = 1$ mm and $R_o = 2$ mm respectively. With the aid of conventional PIV, the velocity profile and velocity gradient variation were given, exhibiting a clear difference between laminar flow and hydrodynamic turbulence [23]. In a curved microchannel with a 3/4-circle unit, Li et al. made a preliminary measurement of the 3D structure of the surfactant solution using confocal micro-PIV, and showed that the flow profile was changing from the lower plane to the top plane along the depth direction [24]. However, to date, the detailed flow structures of viscoelastic fluid flow in the curved microchannel have not been provided. In the present study, we used confocal micro-PIV to investigate viscoelastic surfactant solution flow in a curved microchannel, aiming to reveal the detailed flow structures and the flow evolution.

2. Experimental process

2.1. Microchannel

The microchannels used in the experiments were made of polydimethylsiloxane (PDMS, Sylgard 184, Dow Corning, Michigan, USA) by means of standard lithography fabrication. Fig. 1 shows the schematic of the microchannel design. The channel contains 32 pairs of identical 1/2-circle units, with inner and outer radii of $R_i = 50\ \mu\text{m}$ and $R_o = 150\ \mu\text{m}$, respectively. The cross-section of the channel is rectangular, so the channel width reads $w = R_o - R_i = 100\ \mu\text{m}$, while the depth is $h = 60\ \mu\text{m}$. After calibration using an objective micrometer (Olympus, C1, 0.01 mm, Japan) and Color 3D Laser Microscope (Keyence, VK-8710, Japan), the precise dimensions of the microchannel were found to be $w = 110\ \mu\text{m}$ and $h = 68\ \mu\text{m}$. The microchannel has two access ports of 3 mm in diameter, which are for fluid inflow and outflow, respectively. The fluid was driven into the microchannel using a syringe pump (KDS100, KD Scientific, Massachusetts, USA), through a stiff Teflon tube which was connected to the inlet port and the syringe.

2.2. Test fluid

The viscoelastic fluid used in the current experiments was an aqueous solution of surfactant cetyltrimethylammonium chloride (CTAC, analytical grade, Wako, Tokyo, Japan), with the addition of salt sodium salicylate (NaSal, analytical grade, Wako, Tokyo, Japan). Both CTAC and NaSal in the solution were at the same mass concentration, 1000 ppm. The rheological parameters of CTAC/NaSal solution were measured using cone-and-disk geometry (Kinexus Pro, Malvern, UK), as shown in Fig. 2. The fluid shows shear-thinning behavior and remarkable elastic effect (with growing primary normal stress difference, N1). Therein, the stress variation under the steady shear was also presented.

2.3. Experimental apparatus

The confocal micro-PIV used an inverted-type microscope (DMIRE2, Leica, Germany) combined with a dual Nipkow disk-type confocal scanner unit (CSU22, Yokogawa, Japan) and an air-cooled blue argon ion laser (543-BS-A03, CW, Melles Groit, USA)