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An efficient micro-mixer by elastic instabilities of viscoelastic fluids: Mixing performance and mechanistic analysis

Cai Wei-Hua[1,*], Li Yong-Yao[1], Zhang Hong-Na[*], Li Yu-Ke, Cheng Jian-Ping, Li Xiao-Bin, Li Feng-Chen

School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, China

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ABSTRACT

Efficient mixing is one of the keen interest of many bioengineering and chemical engineering processes. In this work, we designed an efficient micro-mixer with viscoelastic fluid which can induce both strong shear and strong extension by being embedded several rhombic blocks to destabilize the viscoelastic fluid flow and can be also easily integrated. Experimental visualization and direct numerical simulation (DNS) of mixing process were conducted to evaluate the mixing performance. By adding green fluorescent particles into the fluids, apparent mixing enhancement was observed for viscoelastic fluid flow when the flow rate exceeded a threshold. The efficient micro mixing progress also shows great potential for bioengineering application with the biocompatible working fluids. Through DNS, we discussed the flow patterns and the role of polymers playing in viscoelastic fluid flow to respectively figure out the underlying mechanism of efficient mixing and the occurrence of unstable flow motions. The results show that when the elasticity is strong enough, the viscoelastic fluid flow is irregularly twisting and swinging in the channel, and as a result enhances the mixing by increasing the intersecting frequency of fluids of different concentrations. Moreover, owing to the special designed geometry, the polymers act as the energy supplier of unstable flow motions, which keeps the fluctuations from decaying towards the laminar regime.

1. Introduction

Recently, lab-on-a-chip (LOC) devices become an efficient and revolutionary solution to develop personal pharmacy, rapid diagnose of illness and materials synthesis (Ottino and Wiggins, 2004) and so forth. However, it faces a problem of poor mixing because of the encountered tiny dimension which confines the flow always being in laminar regime. In fact, efficient mixing is of great importance in many industrial processes, such as chemical engineering, biotechnology, *etc*. (Ng et al., 2015, Bhagat et al., 2005), that great mixing performance is beneficial to reduce the analysis time and the footprint of a lab-on-a-chip system. At macro scale, making flows to be chaotic and turbulent is one of the most effective manners to achieve an efficient mixing (Gan et al., 2007a), and the nonlinear inertia is the key to drive the flow to be turbulent when the Reynolds number ($\mathrm{Re} = UD/\nu$, U: the characteristic velocity, D: the characteristic length, ν: the kinematic viscosity of solution) is large enough. However, at micro scale, the nonlinear inertia is always too weak to induce the chaotic flow motions and only the molecular diffusion, which plays only at the interfaces between two different fluids, contributes to the mixing. Therefore, the mixing performance is often limited at this scale.

Seeking an efficient mixing manner at micro scale now attracts an increasing interest from lots of researchers working on microfluidics (Ammar et al., 2014; Li and Kim, 2017; Affanni and Chiorboli, 2010; McGovern et al., 2018; Ta et al., 2015; Stroock et al., 2002; Engler et al., 2003; Kockmann and Woias, 2003; Chen and Zhao, 2017; Akgönül et al., 2017; Mengeaud et al., 2002; Chen and Li, 2017; Mouheb et al., 2012; Haward et al., 2016a). With their efforts, various micro-mixers working either actively or passively have been designed. The common target of the existing micro-mixers is to induce unstable and chaotic flow motions no matter by active method or by passive method. In the active manner, some kinds of extra driving forces, typically pulsating pressure (Li and Kim, 2017), magnetohydrodynamic (MHD) (Affanni and Chiorboli, 2010) and ultrasonic (McGovern et al., 2018) forces *etc*., are introduced to disturb the flow. However, since the active ways often require the extra equipment and components, the

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[*] Corresponding authors.

E-mail addresses: caiwh@hit.edu.cn (W.-H. Cai), yy-li@stu.hit.edu.cn (Y.-Y. Li), zhanghn@hit.edu.cn (H.-N. Zhang), liyuke_lyric@hotmail.com (Y.-K. Li), chjp@hit.edu.cn (J.-P. Cheng), lixb@hit.edu.cn (X.-B. Li), lifch@hit.edu.cn (F.-C. Li).

[1] The authors contributed equally to this paper.

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Nomenclature

c	concentration
$\mathbf{C}$	conformation tensor
D	characteristic length
D_d	diffusion coefficient of the fluids
De	Deborah number
D_k	generalized diffusion term of the instantaneous kinetic energy
E_r	relative error between the numerical results and experimental ones
E_a	absolute error between the numerical results and experimental ones
E_k	instantaneous kinetic energy
E_{kf}	turbulent kinetic energy
E_p	instantaneous elastic energy
F_k	energy input by the external force
G_p	energy exchange between the flow motion and the polymers
G_p'	elastic contribution to the turbulent fluctuations
h	channel height
p	fluid pressure
Q_{in}	flow rate of the middle inlet
Re	Reynolds number
Sc	Schmidt number
t	time
U	characteristic velocity
$\mathbf{u}$	velocity field
u_{in}	velocity at the middle inlet
w	width of the inlet channel
Wi	Weissenberg number
ν	kinematic viscosity
μ	dynamic viscosity
λ	relaxation time of viscoelastic fluid
ρ	density of fluid
η_o	total viscosity
η_s	solvent dynamic viscosity
η_p	solute dynamic viscosity
η_{EM}	mixing efficiency
η_{Num}	efficiency of numerical results
η_{Exp}	efficiency of experimetal results
$\boldsymbol{\tau}$	stress tensor
$\boldsymbol{\tau}_s$	solvent contribution to the stress tensor
$\boldsymbol{\tau}_p$	solute contribution to the stress tensor
β	ratio of solvent viscosity to total viscosity
ε_v	viscous dissipation of the mean kinetic energy

mixing system of this kind is expensive and difficult to be integrated. On the other hand, the passive method enhances the mixing through modifying the geometrical configurations, such as embedding T-shaped structures, complex three-dimensional (3D) structures and two-dimensional (2D) or planar structures *etc*., into the micro-mixers to excite unstable and chaotic flows (Ta et al., 2015). Comparing with the active way, the method of this kind is easier and cheaper for system integration in the diagnose devices and micro reaction devices. Among them, complex 3D micro-mixers, which are made up of channels layer-by-layer, can work efficiently at relatively lower *Re* (Stroock et al., 2002) but at the cost of fabrication manipulate. Comparing with 3D micro-mixers, planar micro-mixers, such as T-shaped micro-mixers (Engler et al., 2003; Kockmann and Woias, 2003; Chen and Zhao, 2017), curved microchannel (Akgönül et al., 2017), zig-zag micro-mixers (Mengeaud et al., 2002; Chen and Li, 2017), cross-slot geometry (Mouheb et al., 2012; Haward et al., 2016a) and rhombic micro-mixer (Chung and Shih, 2008), are much simpler for fabrication, but usually require high-Re operating conditions, namely high-pressure drop. As aforementioned, the key of the micro-mixers is to induce unstable and chaotic flow motions at low Re. Changing the working medium, such as adopting non-Newtonian fluid, is an efficient way to reach this target.

Viscoelastic fluids, a typical type of non-Newtonian fluids, *e.g.*, solutions of some flexible high-molecular-weight polymers or surfactants, widely exists in nature. Different from Newtonian fluid flow, an additional nonlinear elastic effect, originating from long-chain polymers or flexible microstructures, exist besides the nonlinear inertial effect. The strength of elastic nonlinearity is often described by Weissenberg number ($\text{Wi} = \lambda U/D$, λ: the relaxation time of fluids) or Deborah number ($\text{De} = \lambda/\tau$, τ: the characteristic time of flow). Since Wi is inversely proportional to the channel dimension, the existence of elastic nonlinearity in viscoelastic fluid flow provides us another chance to excite chaotic flow motions at micro scale where inertia nonlinearity can be ignored but the elastic nonlinearity can solely dominate the flow. When Wi is above a critical value, the nonlinear elasticity can solely induce the flow transition from a laminar regime to a turbulent status which is the so-called elastic turbulence. The flow of this regime has been experimentally observed in several geometries, such as parallel-disk (Groisman and Steinberg, 2000; Burghelea et al., 2007), cone-and-disk (Groisman and Steinberg, 2004), Taylor-Couette (Akgönül et al., 2017), serpentine microchannels (Burghelea et al., 2004; Jun and Steinberg, 2011; Li et al., 2016b; Feng-Chen et al., 2012b; Li et al., 2016a), channel with cylindrical obstacles (Li et al., 2010), *etc*. Therein, the flow shows some features of developed inertial turbulence, *e.g.*, an abrupt increase of flow resistance, turbulent fluctuations of a wide range of temporal and spatial scales, turbulent structures of intermittency, and so forth. Recalling the common target of micro-mixers, this phenomenon shows a great potential to enhance mixing and heat transfer at micro scale. Currently, the mixing enhancement by this flow motion has been demonstrated by Groisman and Steinber (2001), Pathak et al. (2004) and Haward et al. (2016a) in a curvy microchannel. In their studies, the geometrical curvature plays as a trigger of elastic instabilities and elastic turbulence. Haward et al. (2016a) and Li et al. (2014) made an in-depth discussion on the mechanism of mixing enhancement by elastic instabilities from viewpoints of vortex structures and scalar transports. In addition to the above curvy microchannels, recently, both numerical and experimental measurements showed the occurrence of purely elastic instabilities in straight microchannels (Zhang et al., 2013; Pan et al., 2013; Bonn et al., 2011). Therein, the microchannels are specially designed either with large perturbation generator such as placing several cylinder obstacles at inlet or with nontrivial structures such as symmetrically and staggeredly adding 'well' structures to the sidewall of straight channel. However, without the initial or instantly generated perturbations, the straight wall tends to stabilize the elastic turbulent flow (Zhang et al., 2016; Hong et al., 2016; Julius et al., 2016). It is notable that in above microchannels, the key to induce the elastic instabilities lies in the shear flows. In fact, except the shear flows, the extension-dominated flow including flows through contractions and expansions and intersections (like cross slot, T- or Y-shaped junctions) can also trigger the elastic instabilities, *i.e.*, the so-called extensional elastic instabilities. In contraction-expansion geometry, the flow experiences a positive streamwise velocity gradient as it entering the contraction and a negative streamwise velocity gradient through the expansion (Groisman and Steinberg, 2004; Burghelea et al., 2004; Jun and Steinberg, 2011; Li et al., 2016b; Feng-Chen et al., 2012b). When the viscoelastic fluid passing a channel of this type, the recirculating vortices in the abrupt contraction/expansion microchannels appear asymmetrically when De exceeds a threshold. The unstable flow motions in this channel have