International Journal of Heat and Mass Transfer 102 (2016) 360–368

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental study on functionality of surfactant solution in turbulent heat transfer by varying local shear rate

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ARTICLE INFO

Article history:
Received 30 November 2015
Received in revised form 7 April 2016
Accepted 8 June 2016
Available online 29 June 2016

Keywords:
Viscoelasticity
Drag reduction
Turbulent flow
Heat transfer
Surfactant solution

ABSTRACT

Inhibiting turbulence by adding a surfactant may simultaneously induce a heat-transfer reduction as well as a drag reduction. Those reductions are attributed to micellar network structures (MNS) that form in the surfactant solution under suitable conditions in terms of temperature, concentration, and shear rate. Fluid functionalities of such a fluid with respect to mass and heat transfers are still unclear, in particular, for complex geometries accompanied by locally-enhanced shear rates. We carried out experiments under various conditions of fluid flow and liquid states in terms of temperatures and concentrations of the solution with a view to identify the factors affecting surfactant solution flow. To estimate the influence of a local shear rate on relevant bulk flow of a surfactant solution, we installed an orifice in a two-dimensional channel and measured the variations of the local heat-transfer coefficient downstream of the orifice. When passed through the orifice, the flow should be accompanied by strong shear layers separating from the orifice edges. Hence, the orifice associated with locally-enhanced shear rate gave rise to a degradation of the heat transfer reducing effect at lower Reynolds numbers because of catastrophic destruction of the large-scale micellar network. This degradation was limited just behind orifice maybe due to the ability of the micellar network to self-repair. The effective structural number, representing the amount of networking micelles, was introduced to describe the relationship between the magnitude of the heat transfer reductions and the fluid flow conditions including the local shear rate, the surfactant concentration, and the temperature. We interpreted the catastrophic destruction of the large-scale micellar network structure from the aspect of the percolation theory. The orifice installation provided the possibility of controlling fluid functionality by the adoption of the combined effect of the concentration or temperature of the solution.

1. Introduction

Many researchers have demonstrated that dilute surfactant solutions reduce frictional drag and heat transfer coefficients in turbulent flows when compared to a Newtonian fluid. In such a drag-reducing fluid, surfactant molecules form aggregates called micelles. The micelles organize into micellar-network structures (MNS) if the surfactant concentration and the fluid temperature are in a suitable range. We believe MNS plays a key role in the turbulence suppression of fluid flows on smooth walls. Fundamental studies into this phenomenon of a surfactant/polymer solution have shed light on the drag-reduction (DR) mechanism as summarized by several review papers [1–4]. Many application investigations were carried out to realize the energy saving in fluid transportation [5–7]. However, there still remain open questions regarding the fluid functionalities of surfactant solutions in terms of mass and heat transfers in relation to more complex geometries with non-passive scalar fields rather than smooth pipes or channels. Regarding the case of a polymer solution, its functionality is rather weak with respect to engineering applications because the polymer cannot repair itself once it is broken by excessive shear stress.

The surfactant molecule composes an aggregate form in its solution flow. The surfactant solution is similar to a Newtonian fluid if the globular/rod-like micelles are predominant in the liquid. Although there exist reports that even such a solution with isolated globular micelles affect flow [8,9], the viscoelastic character emerges after a transformation from the isolated rod-like micelles to the MNS. The DR and heat-transfer reduction (HTR) abilities are due to this structure. The main factors for this transformation are the concentration, the temperature of solution, and the shear rate of flow [10,11]. There should be a critical value for each main factor to provide MNS. Once a factor exceeds its critical value, the MNS

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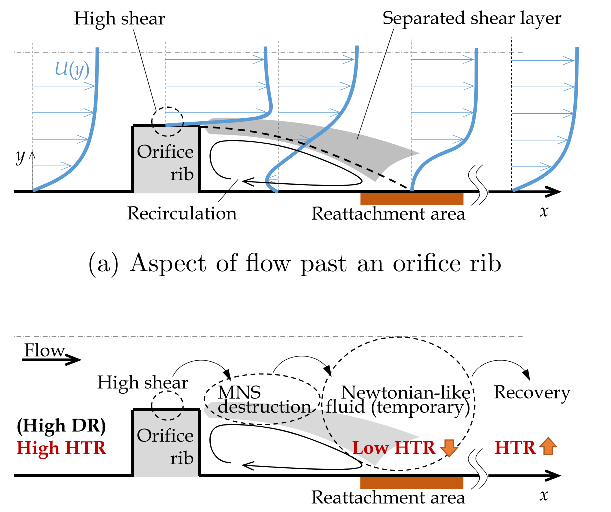
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.024
0017-9310/

should be degraded to isolated micelles that give less viscoelasticity. The combined effects of those factors on the heat transfer behavior of a surfactant solution were also found in a channel turbulence situation [12,13]. As mentioned above, the MNS may be broken by strong shear or heating but it would be possible to restructure itself after once being free from the stress or by being cooled, which is dissimilar to the polymer solution flow. This emphasizes rich functionalities of surfactant fluid.

A strong shear that causes a MNS destruction may be encountered in flows around a bluff body. In addition to the onset of wake turbulence, the bluff body may change locally the fluid rheology of surfactant solution by the MNS destruction. The surfactant solution exhibits also elasticity with a specific relaxation time, and therefore, non-equilibrium state of flows through or over a bluff body would be complicated to predict. We should account for the loss of fluid functionality due to the MNS destruction in a locally-enhanced shear rate around the bluff body. The turbulence-suppression effect of the MNS may diminish in a region where the shear stress exceeds the critical level that will disrupt the network. The micelles that are freed by a high shear rate can reform networks after a certain period. The spatial and temporal changes of the MNS produce a transient change in the characteristics of turbulence and the fluid itself. In addition to the bluff-body influence, the temperature dependency of the micellar structure should also be addressed, since both the structure formation and the drag-reducing effect would be degraded under high temperature conditions [10]. Rose and Foster [11] demonstrated that a critical parameter for the effectiveness of surfactant drag reducers is the shear stress in addition to the concentration and temperature rather than the Reynolds number. The mechanical degradation as well as the high temperature loss of DR are reversible due to the ability of the MNS to conduct self-repairs. Further studies are needed into the effectiveness of surfactant drag reducers and turbulent heat transfer of a non-equilibrium, viscoelastic-fluid flow that is dependent on the local shear rate and temperature.

Tsukahara et al. [14–16] numerically studied the turbulent orifice flows and heat transfer of drag-reducing viscoelastic fluids mimicked by the Giesekus viscoelastic constitutive equation. They found differences in the characteristics of the turbulence and the bulk flow properties from those of the Newtonian flow. The degradation of DR and MNS itself cannot be demonstrated yet by viscoelastic model simulations. Hence, we have not discussed any influence of the break or repair of the MNS based on local shear, temperature, or concentration. As already reported in the literature regarding *smooth*-wall turbulence [17], the HTR-to-DR ratio was found to depend weakly on the Reynolds number and be approximately 1 for an orifice flow except for the transitional regime [16]. In those studies, experiments were conducted under the conditions that allowed for consideration of temperature as a passive scalar quantity. There are several numerical and experimental works on turbulent sudden-expansion flows [18–21] including a backward-facing step flow [22], and a cavity flow [23]. However, the heat transfer in such complicated geometries was less investigated [24] while [25–27] discuss the case of smooth walls. There are several experimental studies regarding the non-equilibrium states of DR and HTR, which targeted an enhancement of the heat transfer process in drag-reducing turbulent flows [28–31].

In the present study, which follows on from our previous work [32], we focused on the transient momentum and heat transfer of a surfactant solution downstream of a rectangular orifice installed in a plane turbulent channel flow. Based on the variations of the local heat transfer coefficient over a flat-plate heater, we investigated the influences of the orifice installation and the fluid temperature on augmentation and degradation of the fluid functionality with respect to turbulence suppression and HTR, as depicted in Fig. 1. We discussed a local degradation of the viscoelastic-fluid functionality in the downstream region of the orifice, in which the dependencies of the fluid (or flow) on the Reynolds number and temperature are rather prominent.



(a) Aspect of flow past an orifice rib

(b) Rib-induced MNS destruction and HTR degradation

Fig. 1. Schematic diagram of the present orifice flow and an expected functionality variation.

2. Experimental set-up and conditions

The closed-circuit water loop used for this study consists of a water storage tank and a plane channel with a gap width of $2h = 40$ mm as the test section, as shown in Fig. 2(a). This channel is made of transparent acrylic resin with wall thickness of 20 mm. A transverse rectangular orifice with a thickness of 20 mm and height of 10 mm was installed 4230 mm (211.5h) downstream from the channel inlet, where a fully-developed velocity profile of the flow approaching the orifice was ensured. The working fluid temperature at the inlet was maintained constant at either $T_{\rm in} = 298$ K or 308 K by heater and cooling coils, with a pump providing the motive force for the fluid. The mass flow rate was adjusted using an electro-magnetic flowmeter (with uncertainty of ±0.01 m^3/min) to a value which would produce a desired bulk Reynolds number in the test section. The Reynolds number considered for this study varied between Re = 10,000 and 37,000 based on the bulk mean velocity $U_{\rm b}$ of the approaching flow; the channel width 2h; and the fluid kinematic viscosity ν. In this study, ν was assumed constant throughout the channel at each $T_{\rm in}$, even in the heating section.

The configuration of the heating plate installed on the bottom channel wall is shown with the coordinate system in Fig. 2(b). The heated surface of a metal plate spanned from the orifice location to 1540 mm (=77h) downstream. This heating wall boundary was adopted only on one side of the channel, while the opposite wall was treated as an adiabatic boundary. The temperature of the heating plate was kept constant at $T_{\rm wall} = 323$ K; that is the heating plate was hotter than the approaching fluid by 15–25 K.

We measured streamwise variations of the local heat transfer coefficient using a power meter and T-type thermocouples connected to each individual heater unit of the flat rubber heater attached to the back side of a thin copper plate (of 3-mm thickness) facing the fluid flow. As illustrated in Fig. 2(b), the streamwise size of each unit was not uniform since gradual expansion