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Structural analysis of turbulent transport in a heated drag-reducing channel flow with surfactant additives

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Abstract

Turbulence transport features in a heated drag-reducing surfactant solution (CTAC, 30 wppm) channel flow was investigated by simultaneously measuring velocity and temperature fluctuations in the thermal boundary layer. Measurement was made at inlet fluid temperature of 304 K and at three Reynolds numbers (based on channel height, bulk velocity and solvent viscosity): 3.5×10^4, 2.5×10^4 and 1.5×10^4. Structural analysis showed that the drag-reducing additives inhibited the motions associated with ejections of low-momentum fluid away from the wall and sweeps of high-momentum fluid toward the wall (the second and fourth quadrant motion respectively) but had no obvious effect on the outward motion of high-momentum fluid and wall-ward motion of low-momentum fluid (the first and third quadrant motion respectively). The depression of wall-normal turbulent heat flux was due to the decreased contributions of the second and fourth quadrant motions.
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Keywords: Channel flow; Surfactant solution; Drag reduction; Heat transfer reduction; Quadrant analysis

1. Introduction

It is known for more than 50 years that small amounts of long-chain polymers or surfactants, when added to turbulent water flows, have a dramatically large macroscopic effect (the so-called Toms effect [1]) on reducing the pressure drop in a pipe flow. Although the drag-reducing polymeric additives and surfactant additives have similar ability to reduce frictional drag, causing drag-reduction (DR) of even more than 80%, polymeric additives are susceptible to an irreversible degradation of the drag-reducing ability in high shear flows (e.g., when driven by a pump) whereas surfactant additives are not. Therefore, surfactant additives are more appropriate for fluid circulating systems, such as hydronic district heating and cooling systems, in which pumping power is necessary. The microstructure in a carefully-made drag-reducing surfactant solution imparts viscoelasticity to the fluid, which is thought to cause DR. Such microstructure is mechanically degraded when it flows through a pump, but it recovers immediately after the high shear is released and this recovery procedure can be repeated any number of times after passing through the pump [2].

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Nomenclature

D	hydraulic diameter of flow channel (m)
H	channel height (m)
Pr	molecular Prandtl number
q	heat flux (K m/s)
Re	Reynolds number based on bulk velocity, channel height and water viscosity
Re_τ	Reynolds number based on friction velocity and half channel height
T	local fluid temperature (K)
T_b	bulk temperature (K)
T_{in}	inlet fluid temperature (K)
T_w	heated wall temperature (K)
T_τ	friction temperature (K)
U	the streamwise velocity (m/s)
u	the streamwise velocity fluctuation (m/s)
u_τ	friction velocity (m/s)
v	the wall-normal velocity fluctuation (m/s)
x	coordinate in the streamwise direction (m)
y	coordinate in the wall-normal direction (m)

Greek symbols

Θ	local mean temperature difference, $\equiv T_w - T$ (K)
θ	temperature difference fluctuation (K)
τ	shear stress (Pa)

Superscripts

$(\cdot)'$	root-mean-square value
$(\cdot)^+$	normalized with wall units

In a heated drag-reducing flow produced by additives, heat transfer reduction (HTR) of the same order of DR also occurs. The reduction of heat transfer in heat exchangers is an important issue in a hydronic heat transportation system. Hence, it is important to clarify the mechanism of HTR as well as DR in solving the conflicting problems between HTR and DR (DR is beneficial to save pumping energy whereas HTR reduces the efficiency of heat exchangers), so as to broaden the applications of drag-reducing additives.

In experimental studies of a cationic surfactant solution (aqueous solution of cetyltrimethyl ammonium chloride, CTAC) channel flow [3–5], the characteristics of DR and HTR, turbulence structures and turbulence transport for momentum have been investigated. From the previous experimental results, including those obtained with drag-reducing surfactant and polymeric flows by other researchers [6–10], a consensus understanding of the DR phenomena has been achieved, such as the extension of inner layer and upward shift of the mean velocity in the log-law layer of the velocity profile, increase in the streamwise velocity fluctuation intensity (normalized with the friction velocity) near the wall, decrease in the wall-normal velocity fluctuation intensity, depression in the Reynolds shear stress, decrease in turbulent kinetic energy production, decrease in frequency of occurrence of bursting events, enlargement of distance between the near-wall low-speed streaks, and variations on the power spectrum of the streamwise velocity fluctuations, i.e., the decrease at high frequencies and increase at low frequencies, compared with a Newtonian fluid flow.

Recently, the characteristics of thermal turbulence structures and turbulence transport for heat in a heated CTAC solution channel flow were also investigated [11–13]. The results will be summarized in Section 3. In this paper, we continue experimental investigation of the behaviors of HTR as well as DR in a heated drag-reducing surfactant solution flow, focusing on the structural analysis of the wall-normal turbulence transports for momentum and heat influenced by the drag-reducing surfactant additives.

2. Overview of the experiment

A closed-circuit water channel is used in the present study. The 10 m-long channel is made of transparent acrylic resin (except for the heating section), with a height (H) of 0.04 m and a width of 0.5 m. The heating section (consisting of backplate, heater and copper plate) is 0.9 m long, located at 8.2 m (measured from the front edge) downstream from the channel entrance, as shown in Fig. 1. The measurement station is in a central plane in the spanwise direction and is located at 0.8 m (20H) downstream from the front edge of the heating section, and thus 9.0 m (225H) downstream from the channel

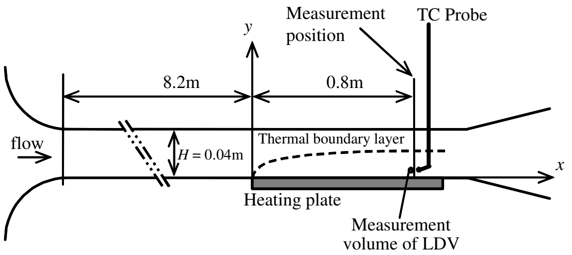

Fig. 1. Schematic diagram of the test section.

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