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Experimental investigation of polymer diffusion in the drag-reduced turbulent channel flow of inhomogeneous solution

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ABSTRACT

Spatial polymer diffusion in the drag-reduced turbulent channel flow of an inhomogeneous polymer solution was investigated by simultaneously measuring velocity and concentration fields using particle imaging velocimetry and planar laser-induced fluorescence techniques. The polymer solution was dosed into the turbulent channel flow from the surface of one-side of the channel wall. The Reynolds number (based on channel height, bulk velocity and solvent viscosity) was set as 4.0×10^4 and the weight concentrations of dosed polymer solution were set to 25, 50 and 100 ppm. The measurements were obtained in the streamwise wall-normal (x–y) plane at three streamwise positions along the dosing wall. The detailed statistical analyses consisting of concentration distribution, turbulence modification, turbulent mass flux, and eddy diffusivities of momentum and of mass are presented. The results show that the polymer diffusion, which has a close relationship with the local polymer concentration and drag reduction in the drag-reduced turbulent channel flow, is suppressed due to the inhibited turbulence other than the diffusion of passive scalar in ordinary turbulence. Two characteristic regions exist in the near-wall region according to the diffusion characteristics and altered motions in the wall-normal direction. The wall-normal turbulent fluxes that control the transport of mass are reduced significantly in the near-wall region for the drag-reduced flow when compared with the case of dosing water. With the increase of local polymer concentration in the "effective position", the corresponding drag reduction rate (DR) increases. The turbulent Schmidt number (Sc_T), which represents the relative intensities of the eddy diffusivities of momentum and of mass, is also found to increase with increasing DR. The mean value of Sc_T for the drag-reduced flow can rise to 2.9, while it is 1.2 for the case of dosing water in the present measurements.

1. Introduction

It has been known for more than 60 years that the addition of some kinds of high-molecular-weight polymer solution to turbulent water flow can reduce the skin frictional drag as the Toms effect [1]. This drag-reducing effect can be applied to crude oil pipelines, district heating and cooling (DHC) systems and ship hulls to produce a major benefit in terms of energy conservation [2–4]. To ascertain the mechanism of drag reduction in wall turbulence, many researchers have concentrated on the complicated effects of polymer on turbulence in the drag-reduced flow of homogeneous polymer solutions in which the polymer was considered to be uniformly mixed. Meanwhile, the drag reduction effect caused by inhomogeneous polymer solutions has gradually attracted more attention based on the increasing requirements of drag reduction for some external flows [5,6]. In this case, the polymer solution was added into the turbulent flow by injection as needed. Hence, the drag reduction effect was generated during the process of diffusion of the polymer additives [7,8].

At present, the most common and well-known method of polymer addition to achieve drag reduction for an external flow is to inject polymer solution into the bulk flow via a slot on the wall where the boundary layer forms [9–11]. On the basis of this slot-injection method, many researchers have investigated the turbulence characteristics modified by inhomogeneous polymer solutions using the particle imaging velocimetry (PIV) technique [9–14]. Some consensuses have been reached on some of the mechanisms including: the turbulent motion (e.g. Reynolds shear stress, bursting rate) is inhibited in the near-wall region, the mean

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Nomenclature

C	concentration
C_0	initial concentration
C_f	frictional coefficient
C_w	concentration at the internal surface of wall
c'	concentration fluctuation
H	height of channel
h	half height of channel
L	distance between fixed pressure taps
N_k	number of the frames
N_x	number of the points in one streamwise line
Pr_T	turbulent Prandtl number
Q	flow rate
Sc_T	turbulent Schmidt number
Sh	Sherwood number
t	time
U	mean streamwise velocity
u	streamwise velocity component
u'	streamwise velocity fluctuation
u_τ	frictional velocity
v	wall-normal velocity component
v'	wall-normal velocity fluctuation
x	streamwise coordinate
y	wall-normal coordinate
z	spanwise coordinate
δ	thickness of polymer-affecting region for mass eddy diffusivity
δc	thickness of concentration layer
Δp	static pressure difference
τ	wall shear stress
ε_t	eddy diffusivity of momentum
ε_m	eddy diffusivity of mass

Subscripts

bulk	bulk flow
dosing	with dosing of polymer solution
k	*k*th frame
max	maximum
p	dosing polymer solution
rms	root mean square
w	dosing water
water	water flow

Superscript

+	normalized quantity by inner variables

velocity profile of logarithmic layer is shifted upward compared with that of Newtonian fluid turbulent flow and the near-wall turbulence structures including low-speed streak and vortex are modified.

Beyond that, several researchers have also investigated polymer diffusion and concentration distribution in drag-reduced flow by sampling or the planar laser-induced fluorescence (PLIF) technique. Fruman et al. [15] investigated the concentration distribution of injected polymers along the plate and found it can be represented by two regions: one corresponding to a constant concentration and the other in which the concentration decreases as the inverse of the distance from the injection slot. Poreh et al. [16] measured the diffusion process in a turbulent boundary layer (TBL) and concluded that the diffusion rate of diluted polymers was reduced together with the skin frictional drag. Vdovin et al. [17] observed the differences between active admixtures of polymer solution in a drag-reduced TBL and passive admixtures of potassium chloride solution in a TBL. They also linked drag reduction to the polymer concentration. Walker et al. [18] measured the time-resolved polymer concentration in a drag-reduced channel flow with polymer injection from the spanwise slot on the wall and showed that high-concentration fluid moved from the near-wall region to the outer region in the form of long filaments lifted from the wall layer. Dimitropoulos et al. [19] investigated the drag-reduced flow of inhomogeneous polymer solutions by using direct numerical simulation (DNS). The results showed that the transport of polymer decreased drag reduction downstream compared with that in a homogeneous case and the polymer concentration fluctuations were anti-correlated with streamwise velocity fluctuations. Winkel et al. [7] investigated the relationship between concentration of polymer injected from a spanwise slot and the local drag reduction in a TBL at a high Reynolds number. Elbing et al. [20] obtained the divisional characteristics of polymer diffusion in the streamwise direction based on the measurements in a rough-walled TBL with polymer degradation.

These studies have clearly provided us with a basic and meaningful understanding of polymer diffusion in the near-wall region of drag-reduced flow with polymer injection. In more recent work, to link the diffusion process with the turbulent motion in drag-reduced flow by polymer additives, Somandepalli et al. [8] measured the concentration and velocity fields simultaneously and studied the spatial distribution and spread of the injected polymer solution in a drag-reduced flat-plate TBL. The results indicated that the action of polymer reduced the streamwise and wall-normal concentration fluxes in the boundary layer before the polymer lost its effectiveness. However, the intrinsic relationship between the concentration flux and turbulent momentum transfer has not been elucidated comprehensively for drag-reduced flow with inhomogeneous polymer solutions. On the other hand, these previous investigations of polymer diffusion have been conducted primarily in TBL, with polymer injection from a spanwise slot on the wall. The drag reduction rate (DR) obtained by this method cannot be sustained for long distances from the slot.

Recently, against the background of applying the Toms effect to ship hulls, a new method of developing novel antifouling paint, which can release a small amount of polymer while a ship is sailing, was proposed for reducing drag [21]. To simulate the release process and investigate the interaction of polymer with external flow during this process in lab experiments, a channel with a permeable wall was used to carry out the related research. The polymer solution was dosed into the turbulent channel flow from the surface of one-side of the channel wall due to the attached dosing wall having micro pores. Conspicuous drag reduction via this wall-blowing method was obtained [22–23]. Nevertheless, owing to the injection process differing from the case of slot-injection, clear differences of concentration distribution and spatial development of polymer solution, especially in the streamwise direction, were found to emerge in this case.

To acquire more valuable information from this complicated drag-reduced flow with inhomogeneous polymer solutions via the wall-blowing method, research on the characteristics and influences of polymer diffusion is necessary. In addition, owing to the connection between drag reduction and mass transfer in this drag-reduced flow, investigation of the intrinsic relationship between momentum transfer and mass transfer in the drag-reduced flow seems to be important for furthering our understanding of the drag-reducing process and mechanism. A conceptual model of this intrinsic relationship is shown in Fig. 1.