Dissipation in Small Scale Gaseous Flows

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We discuss the effect of shear work at solid boundaries in small scale gaseous flows where slip effects are present. The effect of shear work at the boundary on convective heat transfer is illustrated through solution of the constant-wall-heat-flux problem in the slip-flow regime. We also present predictions for the dissipation in terms of the mean flow velocity in pressure-driven and gravity-driven Poiseuille flows for arbitrary Knudsen numbers. All results are verified using direct Monte Carlo solutions of the Boltzmann equation. [DOI: 10.1115/1.1571088]

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In this paper we discuss two aspects of dissipation in small scale ideal-gas flows. We first discuss the effect of shear work at the boundary in slip flow and how this affects convective heat transfer in small scale channels. Shear work at the boundary has, incorrectly, been neglected in recent studies of viscous heat dissipation in slip-flow convective heat transfer. We show that this effect scales with the Brinkman number, and subsequently derive an expression for the fully developed slip-flow Nusselt number under constant-wall-heat-flux conditions in the presence of viscous dissipation and compare this expression to direct Monte Carlo solutions of the Boltzmann equation. The second aspect discussed is related to dissipation in transition-regime flows. Using the solution of the Boltzmann equation for gravity and pressure-driven flows in two-dimensional channels and energy conservation arguments, we provide expressions for the energy dissipation in these flows as a function of the flow speed for arbitrary Knudsen numbers. Our results are verified using direct Monte Carlo solutions of the Boltzmann equation.

For simplicity, we consider two-dimensional smooth channels of length L in the axial (x) direction, with perfectly accommodating walls that are a distance H apart in the transverse (y) direction. The flow in the axial direction is sustained either by an imposed pressure gradient or external field g. The gas velocity field is denoted \( \tilde{u} = (u(x,y), u_y(x,y), u_x(x,y)) \), and \( T = T(x,y) \) and \( P = P(x,y) \) denote the temperature, pressure and density fields respectively.

We first consider the case of pressure-driven flow that is heated or cooled by a constant wall-heat-flux. The channel dimensions are such that the flow and heat transfer characteristics are in the slip-flow regime where the usual slip-flow boundary conditions

\[
\left. u_{\text{gas}} \right|_{\text{wall}} = \alpha - \sigma_v \frac{d u}{d \tilde{y}} \text{ at wall}
\]

\[
T_{\text{gas}} - T_w = \frac{2}{\gamma + 1} \frac{2 - \sigma_v}{\sigma_T} \frac{d T}{d \tilde{y}} \text{ at wall}
\]

are known to provide a good approximation to the velocity and temperature fields, respectively. Here \( \lambda \) is the molecular mean free path, \( \sigma_v \) is the momentum accommodation coefficient, \( \tilde{y} \) is the coordinate normal to the wall, \( T_r \) is the local wall temperature, \( \sigma_T \) is the energy accommodation coefficient, \( Pr \) is the gas Prandtl number, and \( \gamma \) is the ratio of specific heats. The coefficients \( \alpha \) and \( \beta \) introduce corrections to the original results of Maxwell (\( \alpha = \beta = 1 \)) that were obtained through an approximate method [1]. For air, \( \alpha \) and \( \beta \) are usually taken to be equal to unity [2]. Linearized solutions of the Boltzmann equation [3,4] show that for hard spheres \( \alpha = \beta = 1.1 \). In what follows we will assume, without loss of generality, that both accommodation coefficients are equal to unity, or equivalently that their contribution has been absorbed in \( \alpha \) and \( \beta \).

Under the assumption of a long channel (\( L \gg H \)) and low speed flow (small pressure gradient or external field) we approximate the flow as hydro-dynamically and thermally locally fully developed; we also assume that the temperature changes and compressibility cause the flow to deviate negligibly from this state. Under these assumptions we assume that locally the pressure gradient is constant, \( u_x = u_x(y) \), \( T = T(x,y) \) and \( \tau_{xy} = \tau_{xy}(y) \), where \( \tau_{xy} \) is the xy component of the shear stress tensor. The velocity profile is then given by the slip-flow (\( Kn \ll 0.1 \)) Poiseuille profile

\[
u_x = \frac{u_b}{\alpha Kn + \frac{1}{6}} \left( \frac{1}{4} \frac{\gamma^2}{H^2} \right)
\]

where \( u_b \) is the bulk (average) velocity over the channel cross-section and the Knudsen number is given by \( Kn = h/H \).

The temperature equation in the presence of viscous heat generation and flow work reduces to

\[
\rho c_p \frac{\partial T}{\partial x} = \frac{dP}{dx} - \frac{\partial q_y}{\partial y} + \tau_{xy} \frac{\partial u_x}{\partial y}
\]

where \( c_p \) is the specific heat at constant pressure, and \( q_i \) is the component of the heat flux vector in the \( i^{th} \) direction. Our constitutive definitions follow those of [5]. Note that conservation laws will be given in their general form (without continuum constitutive models) applicable in all Knudsen regimes. Explicit use of the continuum constitutive models will be limited to the derivation of the Nusselt number in the slip-flow regime. The integral form of the above equation in the transverse direction under the assumption of negligible density variation in this direction is
\[ \rho c_p \mu u_b \frac{dT_b}{dx} = \eta \frac{d^2 u_b}{dx^2} = 2q_o + \int_{-h/2}^{h/2} \tau_{xy} \frac{\partial u_s}{\partial y} dy \]  
(5)

where \( q_o \) is the thermal energy transferred from the wall to the fluid, and \( T_b \), the bulk temperature, is defined by

\[ T_b = \int_{-h/2}^{h/2} \frac{u_s T dy}{u_b H} \]  
(6)

In addition to the thermal energy transfer, there is also dissipation due to shear work between the wall and the slipping gas. It is the sum of these two contributions that is responsible for the axial energy equation

\[ \rho c_p \mu u_b \frac{dT_b}{dx} = \eta \frac{d^2 u_b}{dx^2} = 2q_o + \int_{-h/2}^{h/2} \tau_{xy} \frac{\partial u_s}{\partial y} dy \]  
(5)

Equations (5) and (7) are linked by the mechanical energy balance

\[ 0 = -u_s \frac{\partial P}{\partial x} + u_b \frac{\partial (u_s \tau_{xy})}{\partial y} + \tau_{xy} \frac{\partial u_s}{\partial y} - \tau_{xy} \frac{\partial u_b}{\partial x} \]  
(8)

which integrates to

\[ \left[ \tau_{xy} u_b \right]_{H/2}^{H/2} + \int_{-H/2}^{H/2} \tau_{xy} \frac{\partial u_s}{\partial y} dy + u_b \frac{dP}{dx} = 0 \]  
(9)

and shows that the viscous heat and flow work terms in Eq. (5) are, in effect, representing the contribution of the shear work at the wall (Eq. (7)).

We proceed by nondimensionalizing Eq. (4) using \( \theta = \frac{T - T_b}{\eta \phi} q_o \phi \) and \( \text{Br} = \frac{u_s^2}{(q_o H)^2} \), where \( \kappa \) is the thermal conductivity of the gas, and \( \eta = \gamma H \). When acceleration effects are negligible, for constant wall-heat-flux under fully developed conditions, \( \frac{d\phi}{dx} = \frac{d\phi}{T_b} \), \( dx \) = const. We thus substitute for \( \frac{d\phi}{dx} \) from Eq. (5) and for this slip-flow calculation use the Fourier conduction law to obtain

\[ \frac{2}{u_b} \left[ 1 + 6 \text{Br} \left( 1 - \frac{u_s}{u_b} \right)^2 \right] \text{Br} \left( \frac{\partial u_s}{\partial \eta} \right)^2 = \frac{\partial^2 \theta}{\partial \eta^2} \]  
(10)

where \( u_s \) is the slip velocity, \( u_s \), \( H/2 \), given by

\[ \frac{u_s}{u_b} = \frac{6 \alpha K_n}{1 + 6 \alpha K_n} \]  
(11)

We solve for \( \theta \) using a symmetry condition at \( \eta = 0 \) and the slip-flow relation (2), and from this solution proceed to calculate \( T_w/T_b \). The fully developed slip-flow Nusselt number based on the thermal energy exchange is then given by

\[ \text{Nu} = \frac{q_o H}{\kappa (T_w - T_b)} \]  
(12)

\[ \text{Nu} = \frac{140}{17} \text{Br} \left[ 1 - \frac{u_s}{u_b} \right] \left[ \frac{34}{17} u_s + \frac{12}{51} \frac{u_s}{u_b} \right]^2 \]  
(13)

where \( \text{Br} = \frac{u_s^2}{(q_o H)^2} \). The fully developed slip-flow Nusselt number based on the total energy exchange between wall and gas is then

\[ \text{Nu} = \text{Nu} + \frac{(\tau_{xy} u_b)_{H/2} \frac{dH}{dx}}{\kappa (T_w - T_b)} = \text{Nu} - 12 \text{Br} \frac{u_s}{u_b} \left[ 1 - \frac{u_s}{u_b} \right] \]  
(13)

Although the above expression is exact, it is only expected to hold for small Brinkman numbers since high velocities will violate the assumption of negligible compressibility and fluid acceleration. A more detailed discussion (albeit for the continuum case) of the competition between cooling and viscous heat dissipation, which ultimately leads to \( \text{Nu} \to \infty \) for fairly large negative \( \text{Br} \), can be found in [6].

We performed DSMC simulations [7] to verify Eq. (13). Our simulations were performed on a hard sphere system since for theory verification purposes it is preferable to perform simulations on a molecular system whose properties are well characterized. A constant wall-heat-flux was achieved by applying a linearly varying wall temperature. Our simulations represent the best compromise between high speeds for low relative statistical error and low speeds for negligible compressibility effects. Because the effect of the wall shear stress is of the order of 10 percent for \( |\text{Br}| \leq 0.1 \), we tried to minimize all possible sources of error. As a result, we used the fourth order approximations for the transport coefficients (approximately 2 percent different from the typically used first order approximations [8]) and also used the values \( a = 1.11 \) and \( b = 1.13 \) recommended by [3,4]. We additionally corrected our results for the effects of finite cell sizes and timestep [9,10,11] in our numerical solution. Our resulting error estimate including statistical fluctuations is approximately 4 percent. The ratio of the expected average thermal creep velocity [12] to the bulk velocity, \( u_s/u_b \), was less than 0.1.

The agreement between the DSMC simulations and the theoretical results is very good (see Fig. 1). This verifies the contribution of shear work at the boundary but also shows that the slip-flow prediction is accurate to within 4 percent at \( \kappa_n = 0.07 \). Also, despite the relatively large pressure gradients used (\( P_{in}/P_{out} \sim O(1.5) \), \( P_{out} = 1 \) bar, \( L = 20 \mu m \) the assumption of negligible compressibility and fully developed flow and temperature fields seems to be reasonable. Given that slip-flow does not describe the correct state of the gas close to the wall (due to the presence of the Knudsen layer) but rather provides a recipe for obtaining the hydrodynamic fields far away from the wall [1], the importance of wall effects in this phenomenon makes the good agreement all the more remarkable.

In view of the interest in ever decreasing device sizes, it is interesting to explore dissipation in the transition regime (0.1 \( \leq \kappa_n \leq 10 \)). It is well known [2] that Poiseuille profiles in this regime become flat (Eqs. (3) and (11) are not valid) and large amounts of slip are observed at the walls leading to significant dissipation there, which, as we saw above, does not affect the temperature field inside the channel. In the interest of simplicity, we will discuss steady, fully developed, Poiseuille-type flows with constant-temperature walls. These flows are the extension to arbitrary Knudsen numbers of the Poiseuille flow assumed in the con-
vective heat transfer problem solved above and are thus interesting to study in their own right as well as in connection with convective heat transfer in the transition regime [7]. Note that no linear constitutive closures for the shear stress tensor and heat flux vector are now assumed.

For these flows, the total energy equation simplifies to
\[
\frac{\partial}{\partial y} (T_s u_s q_s) = \rho c_v u_s \frac{\partial T}{\partial x} = 0
\]
which shows that there is no net energy exchange with the boundary, and thus the thermal energy flux at the wall is balanced by the shear work at the boundary. Using Eq. (9) or the thermal energy equation we obtain
\[
[q_s]_{-H/2}^{H/2} = u_b \frac{dP}{dx} H + \int_{-H/2}^{H/2} \tau_{sy} \frac{\partial u_s}{\partial y} dy
\]
Note that the fully developed temperature profile will, in general, be non-uniform in the y direction with an average temperature that is different from the wall temperature. The temperature profile can be calculated if closures for the shear stress tensor and heat flux vector are provided.

The bulk velocity in Poiseuille flow for arbitrary Knudsen numbers is given by [12]
\[
\frac{H u_b}{R} = -1 \frac{dP}{dx} \sqrt{\frac{RT}{2}} \sqrt{\frac{2}{\overline{Q}}}
\]
where \( R = k_b / m \) is the gas constant, \( k_b \) is Boltzmann’s constant, \( m \) is the molecular mass and \( \overline{Q} = (\dot{Q}/\text{Kn}) \) is a proportionality coefficient that has been determined semianalytically by solution of the Boltzmann Eq. [1] and found to be in good agreement with molecular simulations and experimental data [1,2]. In the transition regime, \( \overline{Q} \) (Kn) varies slowly about its minimum value (1.5 \( \leq \overline{Q}(0.1 \leq \text{Kn} < 10) \leq 3 \)) occurring at Kn~1.

Since the flow is steady and fully developed \((dP/dx)H = [\tau_{sy}]_{-H/2}^{H/2} \). Thus,
\[
[q_s]_{-H/2}^{H/2} = [\tau_{sy} u_s]_{-H/2}^{H/2} = -\frac{\rho u_b \sqrt{2RT}}{\overline{Q}} u_s
\]
and
\[
\int_{-H/2}^{H/2} \tau_{sy} \frac{\partial u_s}{\partial y} dy = \frac{\rho u_b \sqrt{2RT}}{\overline{Q}} (u_b - u_s)
\]
The above equation suggests that as the Knudsen number increases and the velocity profile becomes flatter, most of the energy is dissipated at the walls, as expected.

For a steady and fully developed gravity-driven flow, we have
\[
\frac{\partial}{\partial y} (T_s u_s q_s) + \rho g u_s \frac{\partial T}{\partial y} = 0
\]
The total energy transfer to the wall, \( q_t \), is equal to the work done by the gravity force
\[
q_t = [q_s - \tau_{sy} u_s]_{-H/2}^{H/2} = \rho g u_s H
\]
Here we use the fact that the bulk velocity in gravity-driven flow can be determined by utilizing the similarity between gravity and pressure-driven flows. Malek Mansour et al. [13] have shown that although from a Boltzmann equation perspective gravity and pressure-driven flows are different, the difference in the solutions scales with the square of the characteristic gravity parameter \( \varepsilon = g m H / (2 k_b T) \) which is expected to be small in practical applications. This parameter in our simulations was very small (significantly less than 0.1) so we expect that the solutions of the Boltzmann equation for pressure-driven flow to be valid for gravity-driven flow. Figure 2 shows that upon replacing \( -dP/dx \) by \( pg \), \( \overline{Q} \) as determined for pressure-driven flow accurately describes gravity-driven flow. Substituting from above, we obtain
\[
q_t = \frac{\rho u_b \sqrt{2RT}}{\overline{Q}} (u_b - u_s)
\]
The energy dissipated inside the channel is
\[
q_t = \int_{-H/2}^{H/2} \tau_{sy} u_s dy = \frac{\rho u_b \sqrt{2RT}}{\overline{Q}} (u_b - u_s)
\]
We performed direct Monte Carlo simulations to verify these predictions. We show here results from the gravity-driven flow for

Fig. 2 Nondimensional flowrate \( \overline{Q} \) as a function of the Knudsen number. The solid line denotes the numerical solution of the Boltzmann Eq. [12], the stars denote DSMC simulations of gravity-driven flow and the dashed line denotes the slip-flow prediction. Error estimates are given by the star size.

Fig. 3 Nondimensional total heat exchange \( q_t \) as a function of the Knudsen number. The solid line denotes the theoretical prediction Eq. (21), the stars denote DSMC simulations of gravity-driven flow and the dashed line denotes the slip-flow prediction. Error estimates are given by the star size.
which a net energy exchange between wall and gas occurs and can thus be measured. Figure 3 shows that Eq. (21) is in good agreement with simulation results.

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References


The Effect of a Cationic Surfactant on Turbulent Flow Patterns

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The thermal pattern on a heated wall was studied for the flow of water and drag-reducing surfactant solutions in a channel. The wall of the channel was made of a thin foil, which was heated by direct current. The temperature of the foil, which reflects the local flow velocities, was measured by an infrared technique with high spatial and temperature resolution. The microstructure of the surfactant solution was studied by direct imaging cryogenic temperature transmission electron microscopy (Cryo-TEM). The most prevalent structures observed are thread-like micelles, which have been suggested to cause the modification of the thermal patterns. [DOI: 10.1115/1.1609482]

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1 Introduction

Reduction of friction losses in turbulent flows caused by the presence of polymer additives was first reported about fifty years ago. Virk [1] examined friction factor and velocity profile results for a large number of high polymer solutions, mostly but not all, in water. He noted that at relatively low concentrations many solutions reached lower limiting values in their friction factor/Reynolds number data. Virk [1] proposed an equation for the limiting maximum drag reduction asymptote (MDRA). Polymer effectiveness depends on the presence of high molecular weight species, which limits their applications because of the susceptibility of a high molecular weight components to degradation in high shear flows.

In the past decade considerable interest has developed in “re-pairable” drag reducing additives, such as surfactants for use in technological processes. Though surfactant drag reducing additives require higher concentrations than high polymers, their long life and greater percent of drag reduction make them very attractive for recirculation flows. Chara et al. [2] showed that the MDRA proposed by Virk [1] is not valid for the surfactant Habon G. (hexadecyldimethyl hydroxyethyl ammonium-2-hydroxy-3-naphthoate) solutions.

Investigation of the thermal development region for surfactant solutions was conducted by Gasljevic and Matthys [3]. Turbulent transport mechanism in a drag reducing flow with surfactant additive was investigated by Kawaguchi et al. [4]. They found that only large eddies are dominant near the wall. Warholic et al. [5] presented measurements of turbulence properties of a solution of triis-hydroxyethyl-ammonium acetate (Ethoquad T13-50) and sodium salicylate (NaSal) flowing in a 5.08 cm x 61 cm rectangular channel. The profiles of average velocity obtained by Warholic et al. [5] differ from those presented by Chara et al. [2] for surfactant solutions. If turbulence production depends on the properties of the surfactant solution, one should expect different systems to produce different velocity and temperature fields. Thus, it might be useful to connect the behavior of high drag-reducing surfactants with their microstructure.

One of the most outstanding characteristics of the near wall turbulence structure in a boundary layer of a channel flow is the presence of coherent structures. Coherent structures are responsible for most of the turbulence production, dissipation and transport phenomena. Donohoe et al. [6], and Achia and Thompson [7] considering the near-wall coherent structures in so-called low
drag-reducing solutions, in which the drag reduction did not exceed 30%. Hetsroni et al. [8] studied this problem in high drag-reducing solution (drag reduction varied in the range of 46–85%). It was shown that the dimensionless streak spacing depends on the Reynolds number, based on wall-shear velocity of the solution.

On the other hand, the relation of streak spacing to the onset of turbulent drag reduction was not clarified. The first objective of the present study was to check whether or not the onset of turbulence drag reduction might be connected to spacing of near-wall turbulence structures. It was achieved by comparison of the experimental results obtained in the present study with data reported in [6,7].

Considerable research was also carried out to investigate microstructures of drag-reducing cationic surfactant systems [9]. The second aim of the present study was to gain more insight into the near-wall turbulence structure in high drag-reducing flow by analyzing solution micro-structure.

2 Experiment

2.1 Experimental Facility. The experiments were conducted in a rectangular channel. The two-dimensional channel flow offers several advantages for studies of near-wall coherent structures, as flow visualization is then relatively easy.

The channel flow system is shown in Fig. 1. The 7.2 m long, 0.2 m wide, and 0.02 m deep rectangular channel comprised, twelve Plexiglas sections of length 0.6 m each. The sections were carefully joined to ensure a hydraulic smooth surface throughout. The temperature measurements were carried out in the test section. The heating strips 0.6×0.2 m each were installed inside the channel from the front end of the development section to a distance of 0.6 m beyond the test section. These strips were made of 0.05 mm thick stainless steel and arranged so that the boundary layer could be heated along different distances from the inlet to the test section. The latter was provided with two 0.2×0.16 m windows to which the strips were bonded with contact adhesive and coated on the air side with black mat paint about 0.02 mm thick. DC current up to 300A was applied to the heating strips, and measurements were taken at different lengths of the heated stretch. It was found that at the location of the test section, the temperature field was fully developed, i.e., the temperature distribution on the heated wall did not change in the streamwise direction. The test section is shown in Fig. 2.

2.2 Measurement Techniques. To measure the temperature field on the heated wall a Thermal Imaging Radiometer was used with a typical horizontal and vertical resolution of 256 pixels per line, spatial resolution 0.05 mm, response time 0.04 s, sensitivity 0.1 K. Since the heating strip was very thin (0.05 mm), the temperature difference between its surfaces did not exceed 0.1 K. [8]. A computer program made it possible to store the information and to compute the statistics of the thermal field.

The water temperature was measured by a precision mercury thermometer with an accuracy 0.1 K. The mean flow velocity was measured with an accuracy ±1%, the electric power was determined with an accuracy ±0.5%. The pressure drop was measured by pressure transducers with an accuracy ±1.5%. The shear velocity was calculated with an accuracy ±4%.

2.3 Properties of the Surfactant Solution. The surfactant used was Habon G—a cationic surfactant of molecular weight 500. The content of delivered active material is 53.5% active surfactant, 10.2% isopropanol and 36.3% water. Concentrations reported are the concentrations of active surfactant. The head group of the surfactant is hexadecyl(dimethyl)hydroxyethyl ammonium and the counter-ion is 3-hydroxy-2-naphthoate. The surfactant molecules form large thread-like micelles which are effective in causing drag reduction. In the present study we used an active surfactant concentration of 530 ppm (parts per million by weight in filtered, deionized water). Our data, based upon pressure drop and heat transfer measurements, did not show degradation of the solution during the experiments.

The kinematic viscosity was determined by a Cannon-Fenske capillary viscometer. The kinematic viscosity is \(\nu = 1.35 \cdot 10^{-6} \text{ m}^2\text{s}^{-1}\) at \(t = 20^\circ\text{C}\) and \(1.15 \cdot 10^{-6} \text{ m}^2\text{s}^{-1}\) at \(t = 40^\circ\text{C}\). In the experiments performed, the temperature of the surfactant solution was 22 ± 0.5°C, and the heated wall temperature ranged from 32 to 40°C. Thus, the Reynolds numbers for the 530 ppm Habon G solution were calculated based on a kinematic viscosity \(\nu = 1.25 \cdot 10^{-6} \text{ m}^2\text{s}^{-1}\).

2.4 Microstructure Information. We examined the Habon G solution by direct imaging cryogenic temperature transmission electron microscopy (Cryo-TEM) [9]. Transmission electron microscopy is a direct imaging technique that affords microstructural information that does not require modeling for interpretation (contrary to indirect methods such as light and x-ray scattering). Cryo-TEM does not involve any staining or drying of the studied samples, thus it provides reliable images of the original microstructures in the studied systems.
We prepared vitrified specimens for Cryo-TEM in a controlled environment vitrification chamber (CEVS) to ensure preservation of the original concentration, temperature, and thus the microstructure of the examined sample. As with all other types of material systems, TEM specimens of liquid systems have to be quite thin. The penetration power of even high energy electrons is rather limited. To avoid inelastic electron scattering that leads to image deterioration, and to take full advantage of phase-contrast in direct imaging, one needs to limit specimen thickness to about 0.2 μm.

The surfactant solution specimens were prepared for Cryo-TEM imaging by applying a small drop of the studied solution onto a perforated carbon film supported on an electron microscope grid, blotting it to form a thin (~0.2 μm) film. By avoiding crystallization of water the microstructure is not disturbed and the images obtained reflect true microstructures in the original solutions. The solutions were quenched from 25°C, and 100% relative humidity. Specimens were examined in a Philips CM120 microscope, operated at 120 kV, using an Oxford CT-3500 cryo-holder maintained below −178°C. Micrographs were collected digitally [10] by a Gatan 791 MultiScan CCD camera with the DigitalMicrograph software package, using low-dose protocols to minimize electron-beam radiation-damage.

3 Results

3.1 Cryo-TEM Images. The most prevalent structures we observed are thread-like micelles, shown at high magnification in Fig. 3(a). Micrographs like this one show quite clearly inner structural details of the micelles such as branching domains (arrow) and overlap of micelles (arrowhead). It should be noted that threadlike micelles have been suggested as the one, possibly the most important, microstructural feature that modifies flow patterns in a flowing fluid and reduces drag [10].

Another feature seen in the examined solutions are vesicles, denoted by “V” in Fig. 3(b). These are balloon-like structures made of a double-layer membrane. Such structures are found in many biological and synthetic amphiphiles [11]. In this micrograph we see vesicles coexisting with threadlike micelles (arrows). Much to our surprise we have detected junctions between vesicles and threadlike micelles. In fact, three such junctions, one denoted by an arrowhead are seen in the lower left part of the field of view of Fig. 3(b). The three micelles connecting the three vesicles are connected by a three-fold junction seen just above the arrowhead. Zheng et al. [12] hypothesize that the straining actions of flow disrupt vesicles and thus induce structural instability of the fragments that leads to their reconstruction into networks of branching threadlike micelles.

3.2 Thermal Streaks at the Wall. One important aspect of turbulent flow is believed to be streamwise vortex structure with its accompanying low-speed streaks. The temperature distribution on the heated wall can be considered as a trace of the flow structure there, i.e., the turbulent structures in the boundary layer cause
the temperature distribution on the wall, including the thermal streaks. The streak spacing results were obtained by IR visualization and from spatial correlation of the temperature. The images of thermal streak structures are shown in Figs. 4(a) and 4(b). Figure 4(a) shows a typical example of frames reproduced from a video motion picture of surfactant drag reducing flow. Figure 4(b) is a representative image of the thermal streak structure, at the same shear velocity, for water flow. These pictures are plan view, the flow moves from the bottom to the top of the figures. The thermal streak spacing was calculated by two-point correlation’s [8].

The dimensionless thermal streak spacing $\lambda^+ = \lambda u^*/\nu$ ($\lambda$ is the streak spacing, $u^*$ shear velocity, calculated from the pressure drop, $u^* = \sqrt{\tau/\rho}$, $\tau$ shear stress, $\rho$ density, $\nu$ kinematic viscosity) obtained from the temperature field on the heated wall in water flow was $\lambda^+ = 100 \pm 10$. The result agrees well with data reported by Iritani et al. [13]. In the drag reducing flows $\lambda^+$ increase when the shear velocity increases.

Figure 5 represents streak spacing measurements for different drag reducing solutions. The data of Donohue et al. [6] and Achia and Thompson [7] for polymer solutions are also shown for comparison. Points E, F, G, at which the lines $\lambda^+ = f(u^*)$ cross the line $\lambda^+ = 100$ indicate a threshold value of wall shear for the particular drag reducing solution. The increase in the value of $\lambda^+$ associated with drag reduction takes place at values of $u^*$ higher than the onset wall shear. Thus, the drag reducing effect starts with wall shear stresses larger than a threshold value, which depends on the nature of the additive and its concentration. When surfactant flow is compared with flows of polymer solution, one can see that the 530 ppm Habon G solution has a significantly lower value of onset shear velocity. The correlation between $\lambda^+$ and the percentage of drag reduction was given by Oldaker and Tiederman [14]: $\lambda^+ = 1.9\Delta \rho + 99.7$. The fact that we refer here to parallel shift of the $\lambda^+$ profile, means that at the same value of friction velocity, the percentage of drag reduction increases with the decrease of the onset velocity. Correspondingly we consider the value of $\nu/\Delta u^\text{on}$ as the length scale and the value of $\nu/\Delta u^\text{on}^2$ as the time scale. Different drag-reducing solutions produce velocity field with different length and time scale.

Conclusion

The shear velocity for onset of drag reduction for Habon G surfactant solutions is significantly lower than those for polymer solutions. Changes in the shape of thermal streaks and an increase in streak spacing are the main features in drag reduced flow. Dimensionless streak spacing, at given value of wall-shear, depends on onset of wall-shear, velocity of the solution. The results are consistent with the hypothesis that one of the prerequisites for the phenomenon of drag reduction is sufficiently enhanced length and time scale of the velocity field. Different drag-reducing solutions produce velocity field with different length and time scales.

The existence of an extremely low value of onset velocity is associated with microstructure of the solution. From the study of microstructure one can conclude that the surfactant used in the present study contains threadlike micelles with junctions between them. These data provide the first experimental demonstration that well developed network, including branched micelles, is connected with streak formation.

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Nomenclature

- $D_H$ = channel hydraulic diameter
- $L$ = channel length
- $u^* = (\tau/\rho)^{0.5}$, shear velocity
- $u^\text{on}$ = onset shear velocity
- $\lambda$ = thermal streaks spacing
- $\lambda^* = \lambda u^*/\nu$, dimensionless thermal streaks spacing
- $\rho$ = density
- $\nu$ = kinematic viscosity
- $\Delta \rho$ = pressure drop
- $\tau$ = shear stress

References