CONTROL OF DRAG-REDUCTION BY CHANNEL HEIGHT MODIFICATION ----TRANSITIONAL TURBULENT CHARACTERISTICS FROM DRAG-REDUCING FLOW TO TURBULENT FLOW

P.W. Li
Mechanical Engineering Laboratory, AIST, MITI
1-2 Namiki, Tsukuba 305-8564, Japan
The Energy Conservation Center, Japan

Y. Kawaguchi, A. Yabe
Mechanical Engineering Laboratory, AIST, MITI
1-2 Namiki, Tsukuba 305-8564, Japan

ABSTRACT

It was proposed to control the drag-reducing flow of a surfactant solution by utilizing the "diameter" effect. Experimental investigation of the proposed method was conducted using a two-dimensional channel.

The turbulent quantities measured by LDV showed that the flow of surfactant solution from "large-diameter" channel experienced a transition from drag-reducing flow to turbulent flow in the "small-diameter" channel. The main velocity profiles varied from drag-reducing "pseudo-laminar" to turbulent in the transition process. The two components of turbulent velocity fluctuation were very small like turbulent drag-reducing flow in the transitional region till $x/H_2=21.3$ at the tested condition, after which they increased dramatically to be dominated by turbulent flow.

Because of the small contracting ratio of the channel, the turbulence produced in the contracted channel was still not completely the same as water flow. Anisotropy of the two components of velocity fluctuations was found, which may explain the destruction process of the rod-like micelles' super structure in drag-reducing flow of the surfactant solution.

INTRODUCTION

The turbulence eddy can be suppressed significantly by adding a small quantity of drag-reducing additives, like polymers, surfactants or pulp (Mysels,1949; Tom,1948, Inaba, 1997). The turbulent skin friction thus can be reduced dramatically up to 80% in some cases. It has been drawing attentions over the last forty years in significantly reducing the pumping power in fluid transportation (Steiff, and Klopper, 1996, Kawaguchi et al., 1997a, 1997b, Pollert et al., 1994)

Two categories of additives, i.e., macromolecules like those of polymers or surfactants, and simple solids like fine grains or fibers, have been found effective in drag-reduction (Shenoy, 1984). Of those additives, macromolecules are more effective, usually providing a maximum drag-reduction of about 80%. However, polymers are susceptible to degradation, notably mechanical and thermal degradation in circulation. This makes them unstable and unreliable. Surfactants suffer no serious mechanical degradation and have been the primary candidates as drag-reducing additives recently, especially in district heating and cooling systems.

The drag-reducing function of a surfactant solution works at the condition that there are rod-like micelles and there is aggregation of micelles as a super structure at a shear induced state (SIS) in the flow (Ohlendorf et al., 1986, Bewersdorff et al., 1988). At very high shear stress, the super structure of rod-like micelles can be disintegrated and the drag-reducing flow degrades into turbulent flow like that of solvent alone. This is because of the loosening of SIS under very high shear condition. Once the high shear stress is relieved, the flow becomes drag-reducing again.

As a unique parameter needed to define drag-reduction, wall shear stress was adopted to identify the conditions under which the surfactant solution keeps its drag-reducing ability at wall shear stress without exceeding the critical wall shear stress. Corresponding to the critical wall shear stress, there is a critical Reynolds number strongly dependent on the diameter of the flow duct. Under otherwise equal conditions, the difference of diameter of flow duct can result in a significant difference of the critical Reynolds number. This is called the "diameter" effect (Li et al., 1998, Usui et al., 1998, Gasljevic and Mattys, 1995), which is a special rehological property of a surfactant solution - a type of non-Newtonian fluid.

Based on this characteristic of the "diameter" effect, the authors propose in this study to use a two-dimensional channel with different channel height to control the flow turbulent in the narrow section, and drag-reducing in the section with large channel height. This type of control of drag-reduction may be very useful when a local turbulence is needed in the flow. The surfactant solution flowing in such a channel, however, experiences a transition from drag-reducing flow to turbulent flow when it goes from the large-height section to narrowed section. In this study, an investigation on the turbulence in developing from drag-reducing flow to turbulent flow in the narrowed channel was conducted.

EXPERIMENTAL SETUP AND PROCEDURE

As shown in Fig.1, a circulation system was constructed for the tests, which consisted of a 2m^3 tank, a centrifugal pump, two-dimensional water channel, connecting pipes and measuring instruments.

The tank served as a reservoir for the surfactant aqueous solution. The temperature of the surfactant solution could be conditioned through electric heating and tap water cooling in the tank. Instruments were used to control the temperature fluctuation in the tank to be within ±0.2℃ of the set value during test circulation.

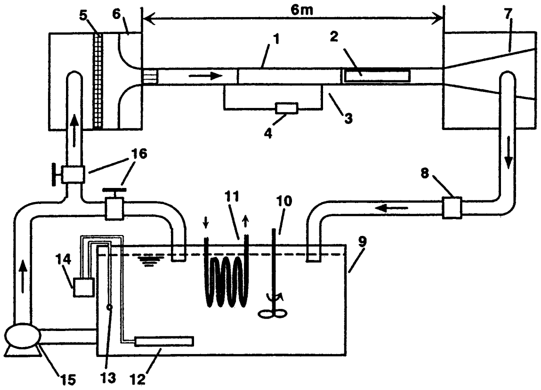

Figure 1 Diagram of the Test Facility and 2D-Channel
Notations: 1-2Dchannel; 2-Window for LDV laser shoot; 3-Pressure taps; 4-Pressure transducer; 5-Filter; 6-Contractor; 7-Defuser; 8-Flow meter; 9-Tank of solution 10-Agitator; 11-Cooling coil; 12-Heater; 13-Thermometer; 14-Thermostat; 15-Pump; 16-Valve

The perspex water channel is 6 meters in length, 500mm in spanwise width. The channel height can be varied from 40mm to 30mm in order to control the drag-reduction. Since, the aspect ratio of the channel is larger than 10, it can be approximated as a two-dimensional channel. At the entrance of the channel, a 150mm-long honeycomb rectifier with 10mm ×10mm rectangular cells was used to remove large eddies. A specially designed settling chamber equipped with a distributor and a smooth contraction nozzle was used in front of the honeycomb entrance and a collection chamber was installed at the end of the channel in order to bump pressure disturbance. The channel was connected with three sections in case a modification of channel height could be easily done. The narrowed section in this study was 1.6 meters in length, starting 4.3 meters downstream from the inlet of the whole channel. The coordinate of velocity component adopted for the testing section of the narrowed section is shown in Fig.2.

A flow meter with a calibrated resolution of 0. 01 m^3/min was used. Pressure drop was measured with a high precision pressure transducer with a resolution of 0.1 Pa. The uncertainty for our measurement of friction coefficient is estimated to be about 2 percent.

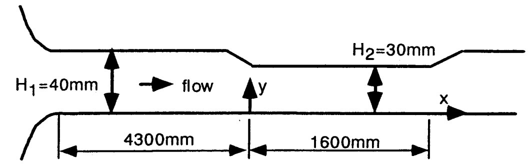

Fig.2 The Two-Dimensional Channel with Contracted Section

As the concentration of the surfactant was very small, the viscosity of the solvent was used in the data reduction. This also made it convenient to compare the results of surfactant solution with those of water. The height of the channel was taken as the characteristic length for Reynolds number.

The surfactant tested in our experiment was Cetyltrimethyl ammonium chloride (CTAC). This surfactant is effective in drag-reduction at a temperature range of 10 °C to 40 °C. The chemical formula of CTAC is $C_{16}H_{33}N(CH_3)_3Cl$ with a molecular weight of 320.00 g/mole. The surfactant solution was prepared by adding a same mass concentration of CTAC and Sodium Salicylate to tap water. Although the surfactant concentration was marked by concentration of CTAC, the same mass concentration of Sodium Salicylate was always added to the solution as a counter-ion material.

An LDV measurement system was installed on a mobile platform, which could be positioned streamwise to measure the two-dimensional velocity at different stations downstream from the entrance of the narrowed section. The LDV system consisted of an argon-ion laser, standard DANTEC 55X optics system working in a two-color three-beam mode, two photo-multipliers, and two counter-processors. The probe volume was of 1.3 mm long and the beam waist diameter was 0.08 mm. Polyethylene beads of 5 μm diameter, were used as scattering particles.

RESULTS AND DISCUSSION

The Proposed Method to Control the Drag-Reduction and Turbulence

The friction factors for fully developed flow of the surfactant solution at a concentration of 30ppm were measured at 30°C. Fig.3 plots the friction factor against the Reynolds number. The critical Reynolds numbers were greatly affected by channel height. Large channel corresponded to a large critical Reynolds number.

For the two-dimensional channel, on the other hand, we have the same Reynolds number under one flow rate as expressed in Eq. (1), even if the channel height is different.

$$\mathrm{Re} = \frac{G}{B\nu} \qquad (1)$$

Here, the channel height is used as a characteristic length for Reynolds number; G is volume flow rate and B is the spanwise width of the two-dimensional channel. Assuming that we select the flow rate properly to ensure the Reynolds number is within the range as marked in Fig.3 by Re_i , it is interesting that a drag-reducing flow can be kept in the channel in height of 40mm while the flow in the channel in height of 30mm may be turbulent flow. However, this is only a deduction for the fully developed situation, i.e. a connection of two channels of different heights, with each being of sufficient length. It is necessary to investigate the developing character of the turbulent quantities in transition from turbulent drag-reducing flow to turbulent flow.

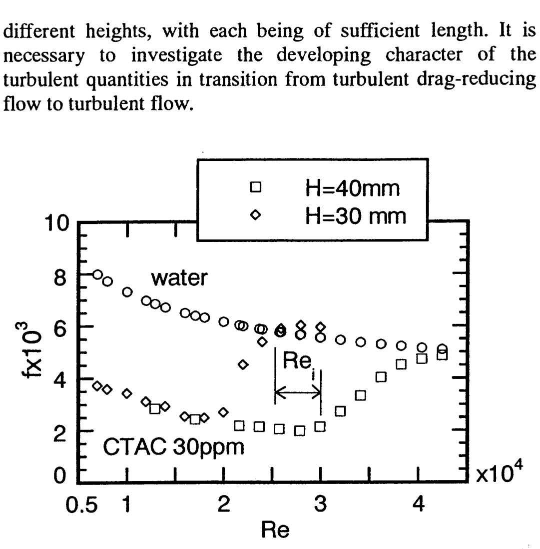

Figure 3 The Difference of Critical Reynolds number at Different Channel Height
(Re_i is the possible range for drag-reducing control)

The Character of Transitional Turbulent Quantities

Factors affecting the transition from turbulent drag-reducing to turbulent flow in the narrowed channel may include the concentration of the surfactant, the temperature of the solution, the ratio of contraction of the channel, the Reynolds number, etc.. A variety of tests are necessary to clarify these issues. As a first step, this study investigated general turbulent characteristics of this transitional process. To do so, the parameters were set at Reynolds number of $3.0x10^4$, fluid temperature of 30 °C, and CTAC concentration of 30ppm. The two-component velocities in streamwise and normal direction were measured at many stations downstream from the entrance of the narrowed section to catch the transitional variation of turbulence.

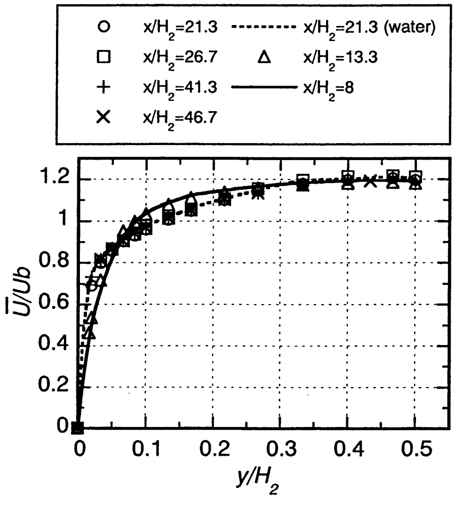

Figure 4 The Main Velocity Profiles

Main Velocity Profile. The main velocity profiles of the flow of the surfactant solution in the narrowed section are shown in Fig.4 at different streamwise stations. Referring to the main velocity profile of water flow as a turbulent case, a clear difference can be found among the streamwise stations. Roughly speaking, the main velocity profile gradually became flat downstream. The stations downstream of x/H_2=21.3 show turbulent flow, while upstream from x/H_2=21.3 is characterized by turbulent drag-reducing flow (Kawaguchi et al. 1996), which was named "pseudo-laminar" by Bewersdorff (1989). This main velocity developing character is opposite that of water in a contracted entrance region where a very flat velocity profile becomes parabolic (Brunn, 1987).

The Turbulent Quantities. The turbulent quantities were measured at many stations along the narrowed section for surfactant solution and water. Shown in Fig.5 are the two components of turbulent velocity fluctuation and turbulent Reynolds stress.

A very low level of turbulent fluctuation can be found in both directions within a certain distance from the entrance of the narrowed section. At a streamwise distance around x/H_2=21.3, a sudden increment of turbulent intensities occurred. For comparison, the turbulent quantities of water at the same Reynolds number are also shown in Fig.5. It is clear that the near wall turbulent fluctuation intensities of water flow were very strong, even near the entrance, for instance x/H_2=2.6 . Therefore, we can deduce that the flow going into the narrowed channel kept its turbulent drag-reducing character within a certain distance and than appeared turbulent. Judging from the rheological properties of the drag-reducing surfactant solution, the appearance of turbulence in the flow indicates the destruction of rod-like micelle structures.

It is well known that drag reduction in surfactant solutions requires the presence of rod-like micelles. When rod-like micelles aggregate as a super-structure under a shear induced state (SIS), the flow of the surfactant solution exhibits drag-reducing ability. Under SIS , the rod-like micelles in the super structure align in the flow direction which strongly dampens turbulence intensities. The destruction of the super structure of rod-like micelles takes place at a large wall shear stress exceeding a critical wall shear stress. As was suggested by Gasljevic and Matthys (1995) and Usui (1998), a wall shear velocity or bulk velocity also can represent the wall shear stress as a unique parameter to acknowledge the critical drag-reduction. Wall shear velocity is related to bulk velocity by the equation:

$$u^* = \sqrt{f/2} \cdot Ub \qquad (2)$$

Therefore, it is not difficult to understand that the super structure of rod-like micelles can be destroyed due to the accelerated bulk velocity in the narrowed channel.

The appearance of turbulence in the narrowed channel occurred somewhat suddenly, and it was not a process in which the turbulence began from near wall and then dissipated to the center of the flow. According to Bewersdorff (1989), the existence of SIS in the buffer zone of the boundary layer is the key element for causing the drag-reduction. The buffer layer actually forms a major part of the boundary layer. Therefore, once the SIS disappears at the buffer zone, turbulence occurs and dissipates to the whole boundary layer very quickly.

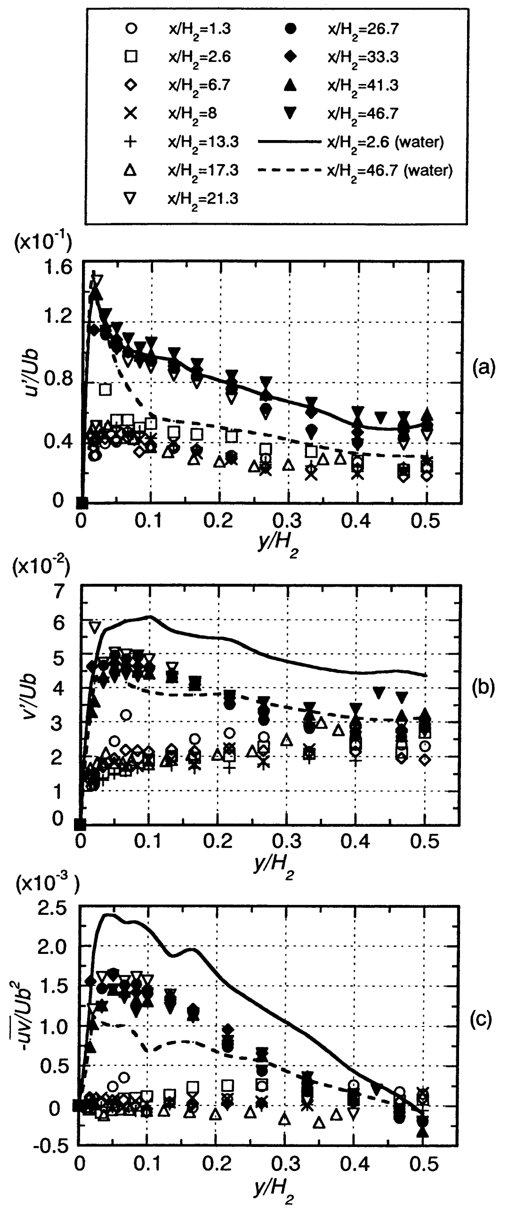

Figure 5 Turbulent Quantities at Stations in Streamwise Direction in the Contracted Section

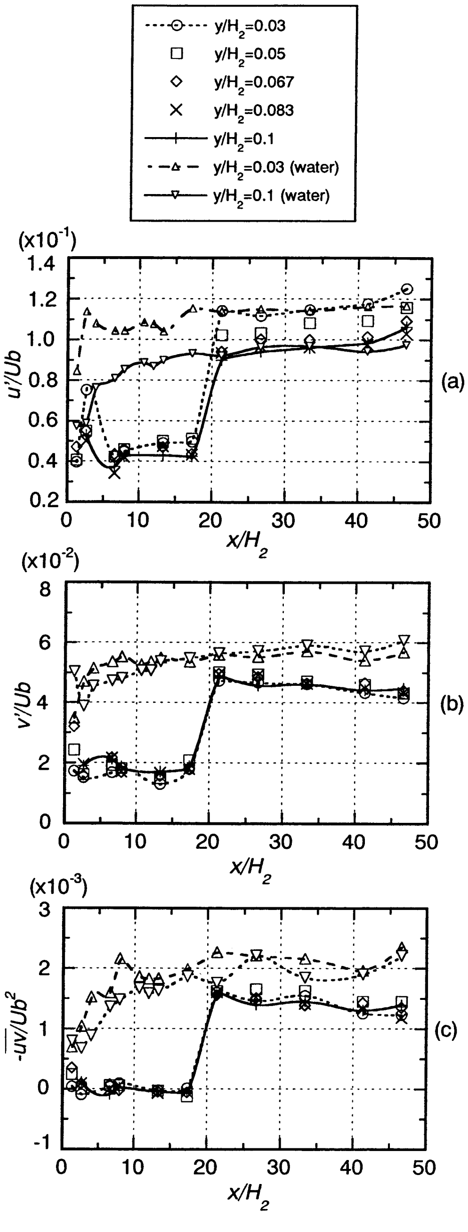

Figure 6 The Variation of Turbulence Quantities versus Streamwise Distance at Fixed Wall Distance

In Fig.5, two more characteristics of the observed turbulence can be seen- one is that the level of turbulence of the surfactant solution was still lower than that of water flow and the other is that the streamwise turbulent component could reach the same level as that of water. Therefore, there are at least three issues to be further investigated, which are the length or time where turbulence emerges in the flow, the intensity of the turbulence after the drag-reducing stage, and the anisotropy of the two turbulent components.

Fig.6 plots the two components of turbulent velocity fluctuation and Reynolds stress in the narrowed channel against the downstream distance from the entrance. It is clear that at around $x/H_2=21.3$, both the turbulent velocity components increase dramatically. This length corresponds to 0.78 second based on the bulk velocity. In regard to the rheological properties of micelle structures in the surfactant solution, such a time falls into the scale of relaxation time of the shear induced state (SIS) after a constant shear (Ohlendorf et al., 1986), although the relaxation in our experiment was caused by higher shear stress.

The relaxation time will be long when shear rate is low (Ohlendorf, 1986). If the flow duct contracts at a large ratio, there will be a high bulk velocity in the contracted section, which may cause a large shear rate. The relaxation time can be shortened significantly, which therefore need only a very short distance in the contracted duct for the drag-reducing flow to last. Nevertheless, more experimentation is needed to clarify this.

Even if both of the turbulent velocity fluctuation components show significant increment after a turbulent drag-reducing stage, only the streamwise component matches the same level as that of water flow. Because of this, the turbulent shear stress can not reach the same level as that of water. This indicates that the super structure of rod-like micelles is not completely destroyed because of the limitation of the bulk velocity or wall shear stress in the contracted channel. However, the two turbulent velocity fluctuation components show a strong anisotropy, even if the turbulent quantities are dominated by turbulent flow. This anisotropy reflects the turbulence generation and dissipation process in the transition from turbulent drag-reducing flow to turbulent flow.

It is known that the formation of a super structure of rod-like micelles in the buffer layer under SIS makes the flow of the surfactant solution become drag-reducing. The rod-like micelles integrate and align in the direction of the main flow in the super structures. Once at a high shear stress, the rod-like micelles in the super structure will first disintegrate and then with its alignment being random if the shear stress is high enough to destroy the super structure completely. However, in such a process, the disintegration of rod-like micelles may show an elastic property that is probably the reason for strong turbulent fluctuation in the main flow direction. The alignment of rod-like micelles in the main flow direction, however, can more or less bump the turbulent fluctuation in the normal direction. Therefore, the turbulent fluctuation components in the normal direction are weaker than in the streamwise direction. This is why the two components of velocity fluctuation show anisotropy approaching to that of water.

CONCLUSIONS

Based on the "diameter effect", this study proposed and experimentally proved it possible to control the drag-reducing flow of a surfactant solution by contracting the flowing duct properly and at certain Reynolds numbers. Because of the contraction of the two-dimensional channel, the high bulk velocity in the contracted channel could make the super structure of rod-like micelles under a high wall shear stress and to be destroyed.

The turbulent quantities in the contracted channel were measured at many stations along main flow direction by Laser-Doppler-Velocimetry.

The main velocity profiles in the contracted channel experienced changes from drag-reducing or "pseudo laminar" to turbulence.

The emerging of turbulence in the contracted channel is at a position around $x/H_2=21.3$ at the present conditions, which corresponds to a time of 0.78 second. It appears that such a time falls into the scale of the relaxation time of SIS in the flow of the surfactant solution.

The turbulent fluctuation intensity of normal component and Reynolds stress did not match the same values of that of water flow, probably because the contraction ratio of the channel was not large enough for the present situation.

An anisotropy of turbulent velocity fluctuation was found, which may explain the destruction process of the super structure of rod-like micelles by high shear stress.

More experiments are necessary to clarify the effect of concentration, the Reynolds number and the contracting ratio of the channel on the transitional length.

NOMENCLATURE

B	Spanwise width of the two-dimensional channel (m)
f	Friction factor $\tau_w/(0.5\rho U_b{}^2)$
G	Volume flow rate (m^3/s)
H_1	Channel height of the non-contracted section (m)
H_2	Channel height of the contracted section (m)
Re	Rynolds number U_bH/ν
u'	Root mean square of turbulence velocity fluctuation in stearmwise direction (m/s)
$u*$	Wall shear velocity (m/s)
$-\overline{uv}$	Term that times ρ (density of solvent (Kg/m^3)) representing Reynolds stress (m^2/s^2)
Ub	Streamwise bulk velocity (m/s)
v'	Root mean square of turbulent velocity fluctuation in normal direction (m/s)
x	Downstream distance from the entrance of the contracted channel (m)
y	Distance apart from wall (m)
ρ	Density of solvent (Kg/m^3)
ν	Kinematic viscosity (m^2/s)

ACKNOWLEDGEMENT

The authors wish to express sincerely thanks to NEDO (New Energy and Industrial Technology Development Organization, Tokyo, Japan) in supporting this research as one of its industrial technology research program.

REFERENCE

Bewersdorff, H. W., and Ohlendorf, D., 1988, "The behavior of Drag-reducing cationic surfactant solutions", Journal of Colloid and Polymer Science, Vol. 266, No. 10 (1988), pp941-953.

Bewersdorff, H. W., 1989, "Drag reducing in surfactant solutions", Structure of turbulence and drag reduction, Edited by A.Gyr, IUTAM Symposium, Zurich, Switzerland, 1989, pp293-312.

Brunn, P. O., "Some modern developments in the flow of dilute polymer and surfactant solutions", PhysicoChemical Hydrodynamics, Vol.8, No.4, pp449-459, 1987.

Gasljevic, K., Matthys, E.F., 1995, " On the Diameter effect for turbulent flow of drag-reducing surfactant solutions", FED Vol. 231, Development and applications of non-newtonian flows". ASME MD-Vol 66: 237-243

Inaba, H., Haruki, N., Horibe, A., Ozaki, K., 1997, "Flow Drag and Heat Transfer Behavior in a Pipe Water Flow with Fibrous Material", Proceeding of Japan Thermal Engineering Conference, November 5, 1997, pp65-66.

Kawaguchi, Y., Tawaraya, Y., Yabe, A., Hishida, K., and Maeda, M., 1996, "Turbulent transport mechanism in a drag reducing flow with surfactant additive in vestigated by two component LDV", Proc. 8th International Symposium on Application of Laser Techniques to Fluid Mechanics, Lisbon, July, 8-11, 1996.

Kawaguchi, Y., Daisaka, H., Yabe, A., Hishida, K., and Maeda, M., 1997, "Existence of Double Diffusivity Fluid

Layers and Heat Transfer Characteristics in Drag Reducing Channel Flow", Proc. 2th International Symposium on turbulence Heat and Mass Transfer, June,1997, Delft.

Kawaguchi, Y., Daisaka, H., Li, P.W., Yabe, A., Hishida, K., and Maeda, M., 1997, "Study on a thermal boundary layer of drag-reducing surfactant solution- Measurement of temperature fluctuation", ASMA IMECE, forum on Measurement Techniques in Multiphase flows, Dallas, Nov. 1997.

Li, P.W., Daisaka, H., Kawaguchi, Y., Yabe, A., Hishida, K., Maeda, M., 1998, "Experimental investigation of heat transfer enhancement for turbulence drag-reducing flow in a two-dimensional channel", 2nd Engineering Foundation Conference in Turbulent Heat Transfer, Manchester, UK,1998, Vol.2, P21-29.

Mysels, K.J., 1949, "Flow of Thickened Fluids", U.S. Patent 2,492,173,December 27, 1949.

Ohlendorf, D., Interthal, W., and Hoffmann, H., 1986, "Surfactant system for drag reduction: Physic-chemical properties and rheological behaviour", Rheol Acta Vol.25, pp468-486 (1986).

Pollert, J., Zakin, J.L., Myska, J., and Kratochivil, P., 1994, Czech Republic, Proc. Int. District heating and Cooling 1994 conference, pp.141-156.

Steiff, A., Klopper, K., 1996, "Application of Drag-Reducing Additives in District Heating Systems", Fluid Division Conference, Summer Meeting, 1996 ASME, FED-Vol.237. pp235-242.

Shenoy, A. V., 1984, "A Review on Drag Reduction with Special Reference to Micellar Systems", Colloid & Polymer Science, Vol. 262, pp.319-337.

Toms, B.A., 1948, "Some observations on the Flow of Linear Polymer Solutions Through Straight Tubes at Large Reynolds Numbers" in Proc. 1st Intern. Congr. on Rheology, Vol. II, pp135-141, North Holland, Amsterdam 1948.

Usui, H., Itoh, T., Saeki, T., 1998, "On pipe diameter effects in surfactant drag-reducing pipe flows" Rheologica Acta, Vol. 37, No.2, pp122-128.