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An Experimental Study on Friction Reduction by Additives in a Water Channel

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Abstract

An experimental study has been carried out as a basic research for the development of the friction drag reduction technology for water-borne vehicles by injecting microbubbles or polymer solution. Experimental apparatus and procedures have been devised and prepared to measure the changes of the wall friction with the injection of additives and the basic experimental data on friction drag reduction are obtained for fully developed channel flows. The effects of key controlling parameters were investigated for higher drag reduction with varying the concentration and the injection rate of additives. The frictional drag has been reduced up to 25% with the microbubble injection and 50% with the polymer solution injection.

Keywords: friction reduction, microbubbles, polymer solution, water channel

1 Introduction

1.1 Some perspectives on drag reduction for water-borne vehicles

Whenever there is a relative motion between a solid body and the fluid in which it is immersed, the body experiences a net force due to the action of the fluid. The component of this force parallel to the direction of motion is termed the drag(sometimes called the resistance). The total drag consists of skin friction and pressure drag, equal to the streamwise component of integral of all shearing stresses and normal forces over the body's surface, respectively. Major sources of the pressure drag are flow separation, displacement effect of boundary layers, wave resistance in a supersonic flow or at an air-water interface, and the drag induced by lift on a finite body.

There have been continuous concerns on reducing the drag of water-borne vehicles for the purpose of increasing speed, saving operational cost, and improving survivability. The way of reducing drag would be different among water-borne vehicles, depending upon the effect of air-water interface, the operating depth, the shape of body and appendages, and the purpose of vehicles. If pressure drag is a major portion, due to wave generation, flow separation, or thick boundary-layer development, the efforts should be directed to optimizing the shape of body and appendages. However, for many water-borne vehicles in regular operational conditions, skin friction is a dominant component. For a commercial ship with moderate speed such as a container carrier, skin friction is 60 ~ 65% of total drag. However, for a VLCC with slower speed, even bigger portion of drag is due to skin friction. For the underwater vehicle such as a submarine, frictional drag is 60 ~ 80% of total drag, depending on the shape of body and appendages. Thus, an obvious conclusion can be drawn that the skin friction reduction should be a primary interest on the drag reduction of water-borne vehicles.

There are some candidates, which can be utilized for the friction reduction of water-borne vehicles. The first one is the so-called passive device. Riblets or grooves in streamwise or transverse direction on body surface can reduce friction in turbulent boundary layers, mimicking shark's skin(Sellin and Moses 1989, Choi 1991). Yacht skippers have noticed quite a while ago that they can speed up their yachts by scraping the ship skin with a sand paper. Cellophane tape with small grooves had been actually applied on airplane wings. However, if the huge real ships are considered, the scaling law of groove height in turbulent flow parameters and the anti-fouling paint on ship hull surface prohibit the practical application of riblets. Compliant coating like latex rubber or large-eddy break-up unit for outer layers, have been applied in mechanical systems, but they are impractical for big vessels.

The application of additives can be the next choice, which is the topic of the present study. It has been known for many years that the small amount of polymer solution or microbubbles can reduce friction dramatically. The polymer has been used to reduce pressure drop due to frictional loss in piping petroleum from oil well to distillery, to improve efficiency in circulating hot water for regional heating system, to speed up sewage and rain discharge, and to help fire-fighting water reaching taller buildings (Gyr and Bewersdorff 1995). The surfactant was preferred later to polymer solution, since it is recyclable and free from the so-called mechanical degradation (Zakin and Qi 2001). However, some environmental concerns hinder the use of polymer or surfactant. The polymer or surfactant can be harmful substance to marine animals. The utilization of ambient air to generate microbubbles provides a good opportunity for surface ships, since air bubbles are harmless and they don't leave any residues in water (McCormick and Bhattacharya 1973, Madavan et al 1984, Kato et al 2000, Kodama et al 2000). However, blowing air against higher static pressure on the flat bottom surface of a ship would cost a lot. The effect of bubbles on propeller efficiency and cavitation is another issue. In the naval point of view, trail of bubbles can be a prominent signature of ship's passage.

Another way to reduce integrated skin friction is reducing the wetted surface of the vessel. Air cavity or film formed beneath the bottom surface of a ship can reduce over all frictional drag by eliminating wetted area (Jang and Kim 1999). The cost of blowing excessive air should be considered. This method would be probably useful only for small fast planning crafts with shallow draft.

The most modern technology on friction reduction is the active control utilizing micro-electronic control surfaces (Breuer 2003). For the practical application, micro-sensors and actuators should be applicable on huge curved surface of giant vessels. The painting and the maintenance of surface as well as the cost for manufacturing and installing the sensor-actuator assemblies should be considered.

The perspectives on friction reduction for water-borne vehicles listed above are probably disappointing. However, the evolution of hull forms reducing the pressure drag, such as wave resistance and form drag of commercial and naval ships, reaches almost optimal phases. The fundamental issue of friction reduction should be reminded, since there is left very little room in reducing the pressure drag of water-borne vehicles. The economic perspective of a commercial ship as well as the survivability of a naval ship can be changed by reducing only the small portion of friction drag.

1.2 The scope of the present study

Among various friction reduction methods, in the present study, the injection of additives is considered. If the practical application to commercial and/or naval ships is the objective of the present research, the utilization of polymer solution and microbubbles has most possibility among others. Some theoretical and experimental research reports on the utilization of polymer solution for drag reduction by Russian and US naval research groups were found (Meng 1998). On the other hand, many microbubble-related researches have been performed in Japan for the application to commercial ships (Kodama et al 2002). The present study is inspired by the preceding studies listed above. As the first step for the practical application of additives to reduce friction, the phenomena should be investigated in the laboratory and the control parameters should be examined. The present paper deals with the device and procedure of the experiments for friction reduction by additives along with measurement results.

The effect of the injection of polymer solution or microbubbles on the frictional drag of fully developed turbulent boundary layer was examined in a water channel. A 2-D water channel was built for the direct measurement of local friction changes with additive injection. The microbubble and polymer solution injector was installed at the upper wall of water channel far downstream of tunnel contraction to ensure that injection occurred in 2-D fully developed channel flow. Four friction sensors were used to directly measure the local friction at four different downstream locations simultaneously. Pitot probe is utilized to identify local flow properties at friction measurement locations. An electrically driven piston was utilized to inject dilute solution of Polyethylene Oxide (PEO) through the slot on the upper wall of the channel, while air was blown through the array of holes to supply microbubbles.

Friction changes on the upper wall of the water channel were documented when either microbubble or polymer solution with various injection rate and concentration was injected at upstream upper wall. The aim is to investigate the optimum injection parameters for friction reduction on the flat plate or the bottom of full ships, although the present apparatus could not avoid streamwise favorable pressure gradient inside the water channel. In the sequel, the details of the experimental setups and the injection system used for the two-dimensional water channel experiment are given. The friction measurement results with various injection rates of polymer solution and microbubbles are reported.

2 Experimental facility and setup

2.1 Water channel

A newly designed water channel was constructed and the structure is shown in figure 1. The overall size is 5,500×1,510×500 mm and the size of the test section is 2,200×180×10 mm. The dump tank on the right is not usually filled full and the flow is well under control up to 12 m/s in the bulk velocity at the test section. The dump tank is required to prevent microbubbles supplied through the slot ahead of measurement location from re-entering into the test section.

In figure 2, upper part of the test section is schematically shown. A fully-developed turbulent channel flow is to be formed at the injection location of the additives where x=0. Following the additive injection plate, 6 openings are installed for various measurements along the downstream. The injection plate is replaceable. Different measuring devices, such as skin friction sensor, Pitot tube, hot film or void meters can be inserted through the holes. The spacing between holes is 300mm.

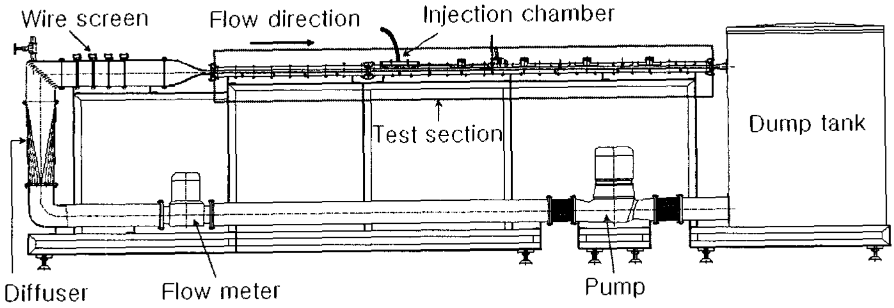


Figure 1: Water channel

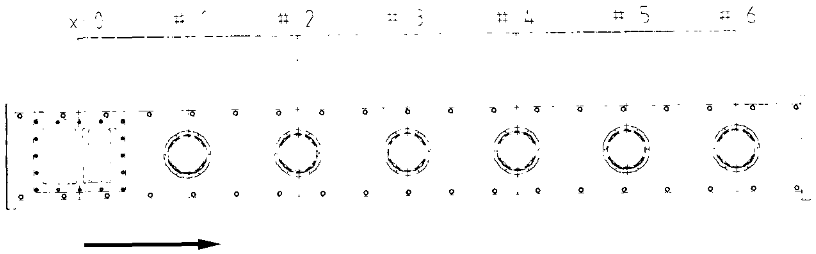


Figure 2: The test section seen from the top

2.2 Microbubble injection unit

The microbubble injection unit is mainly composed of a compressor, a flow meter, a plate with array of holes(hereafter, AOH). Regulated compressed air is supplied to the air chamber through the flow meter and the microbubbles are formed as the air is being ejected through the AOH. The size of the bubble formed in diameter is known to be proportional to the square root of the ratio of the volume flow rate of air to the water speed in the test section (Kato et al 1998). In this experiment an AOH with 0.5 mm hole was mainly used and the size of the bubble was estimated less than 1.0 mm (Takahashi et al 2001). In figure 3, different plates used in the test are shown and they are a porous metal plate and the plates with AOH of 0.5 and 1.0 mm holes from the left. The air was observed primarily ejected through the two or three rows at the downstream side due to the pressure gradient along the stream.

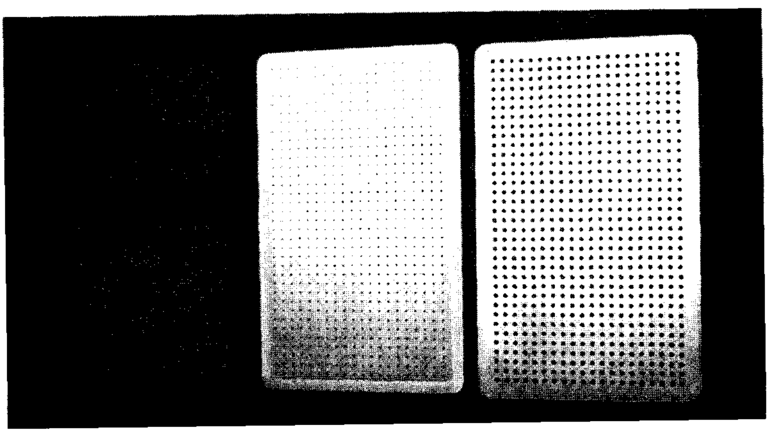


Figure 3: Porous metal plate and plates with array of holes (AOH)

2.3 Polymer solution injection unit

Polyethylene Oxide (PEO) was chosen among polymers of long-chain molecular structure. Polyacryl Amide or Xanthan Gum had been used in other experiments. However, PEO is cheap and available as the product name of WSR-301. When PEO solution is prepared, water is to be stirred gently while putting a small amount of PEO powder little by little. The electric stirrer was designed and utilized with low-speed motor to prepare the PEO solution of predetermined concentration efficiently (Kim et al 2002).

The injection unit of polymer solution is composed of the solution container, a controlling motor, a flow meter and an injection slit. The cylindrical container is 300×500 mm in diameter and height and made of stainless steel. A piston is controlled in the cylinder by a DC motor (Panasonic, 80 mm/min) to eject the polymer solution at a required rate. The flow meter is S37J by Dwyer and accurate up to 3.0 liter/min. The injection slot is divided into two up and down plates and the mean inclination of the two faces is 12.5°. The gap size is 1.0 mm and the shape is shown in figure 4.

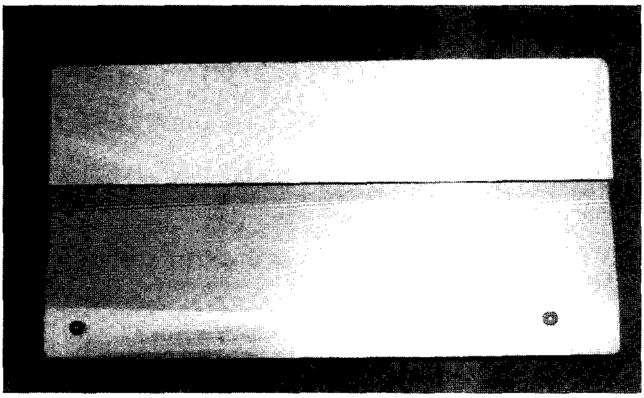


Figure 4: Polymer injection slot unit

2.4 Sensors and data acquisition

A newly designed skin friction sensor was used to measure the friction at the upper wall of the water tunnel. In the beginning a very sensitive floating element sensor of Sankei Co. was used to measure shear stress directly. However, the installation and the calibration of the sensor with the capacity of several grams were very difficult. After an extensive preliminary study we came up with a design applicable to the measurement up to 500gf. The load-cell having four thin supporting columns was manufactured. Each column has four strain gauges, i.e. 16 total, to compensate the unwanted deformation by normal forces due to streamwise or transverse pressure gradient inside the water channel. It allows 150% overload and the schematics and the photo are shown in figure 5 and 6, respectively.

For velocity measurements Pitot tubes of 1/8" and 1/16" connected to a pressure transducer (DP15-48) and digital transducer indicator (CD23) by Validyne were used. Pitot tube was installed at position #6 of figure 2 during the measurement of friction to monitor the bulk velocity inside the test section.

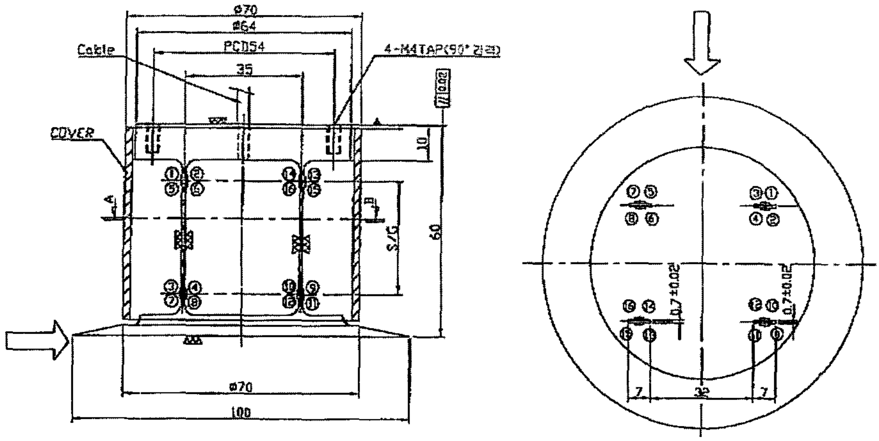


Figure 5: Schematics of skin friction sensor by Dana Load Cell Korea (500gf)

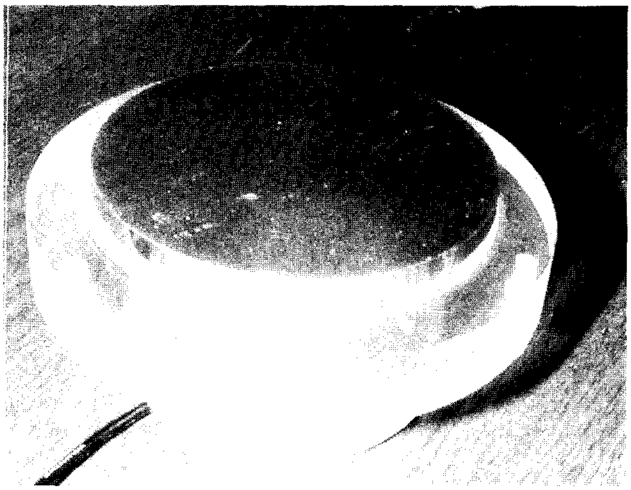


Figure 6: Photo of the skin friction sensor

For data acquisition Daq-book and DBK-1 by Quatech were used. It provides 16 channels at 100kHz sampling rate in the range of ±5 Volts. Based on the results of preliminary tests, we fixed the sampling rate at 20Hz and all the values are the mean of 200 sampling data. The measurement data of 10 seconds interval were averaged to provide the shearing force on friction sensor or velocity head of Pitot tube.

3 Calibration of the sensor and the flow

3.1 Skin friction sensor and pressure transducer

For the calibration of the friction sensor, the frame in figure 7 was constructed and the verification was carried out by adding weights on the sensor as shown in the figure on the left. We confirmed that the effect of the pressure gradient along the stream was fully eliminated and the results are shown in figure 8. It shows good linearity and hysteric characteristics. The pressure transducer was calibrated up to 4.5m water head and showed reliable characteristics.

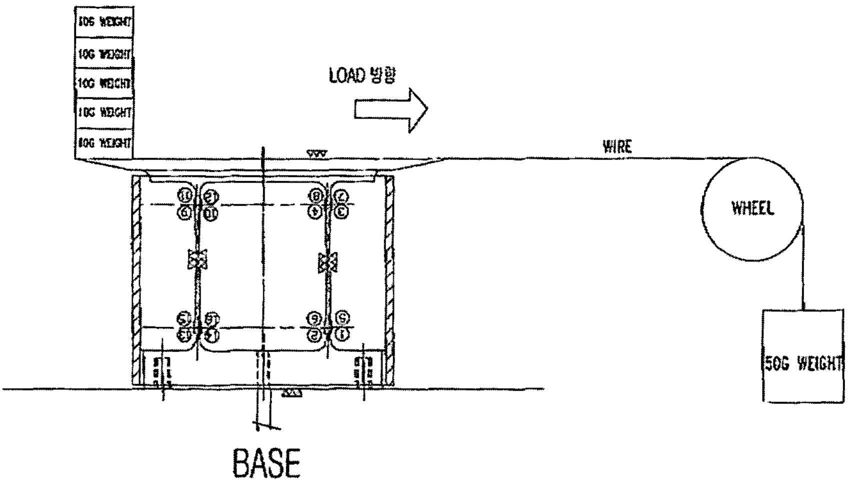


Figure 7: Calibration scheme for skin friction sensor

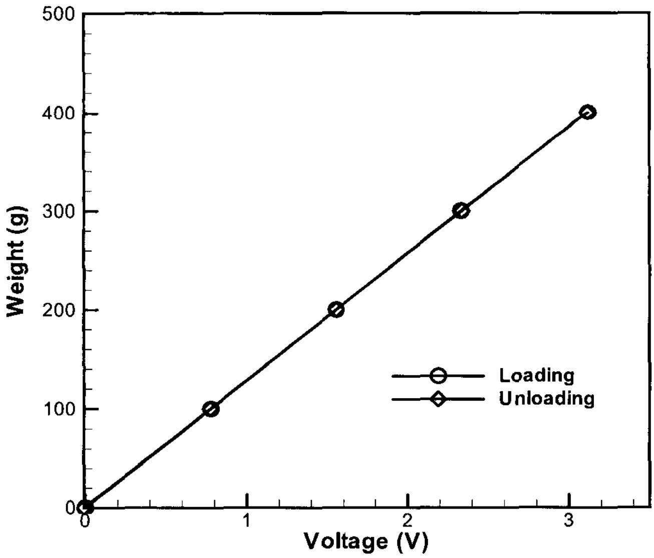


Figure 8: Weight versus sensor output

3.2 Velocity profile in the test section

Figure 9 shows the profile of the stream velocity U at the center plane of the test section. In the figure, U_0 is the velocity at the center point, h the channel height (10 mm) and y the vertical coordinate measured downward from the channel's ceiling. The upper half dimensionless velocity is compared with the Pai's formula (White 1990) based on Laufer's data for fully developed turbulent channel flow. It is confirmed that our flow is in fact a fully developed turbulent channel flow.

It should be mentioned that bulk velocity inside the test section of the water channel was changed due to the injection of microbubbles and polymer solution. However, in the present study, the bulk velocity was adjusted to be the same for both base and additive injection cases by changing the pump power of the tunnel.

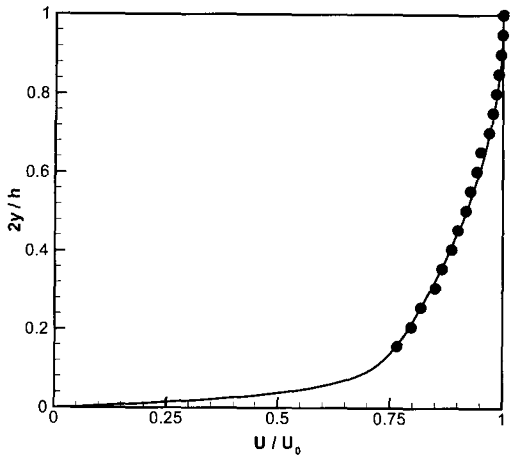


Figure 9: Stream velocity at the center plane of the test section on position #6

4 Results and discussion

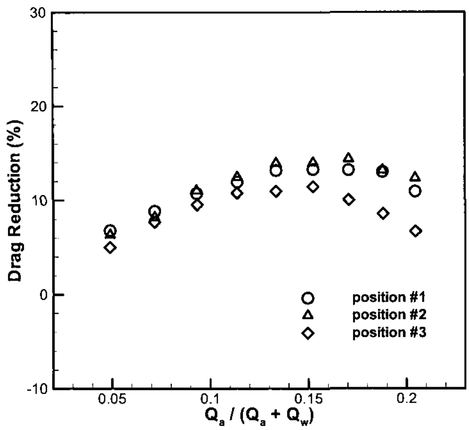
4.1 Procedure of the experiment

The procedure of the experiment was examined and verified through extensive pretests for better accuracy and repeatability and can be briefly summarized as follows. Fill the dump tank and run the channel at predetermined driving motor speed; Read the velocity signal coming from the Pitot tube installed at the center of far downstream test section and make a fine tuning of the flow speed; Read the basic friction force from the sensor; Start injecting the air or polymer solution into the channel; Read the increase in the Pitot tube velocity due to additional volumetric flow and adjust the channel flow speed if necessary; Read the altered friction force associated with the additives. Thus measured friction is at the same velocity for both base and additive injection cases. The whole procedure was repeated with varying the conditions of the injection after replacing the water.

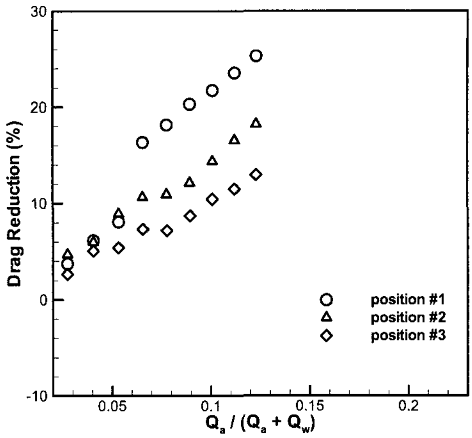
4.2 Frictional drag reduction with microbubble injection

Figure 10-(a) shows the reduction of the friction, $(c_{f0} - c_{fa})/c_{f0}$, in percentile at 6m/s flow speed with varying the bulk void ratio, $Q_a/(Q_a + Q_w)$. Here, c_{f0} and c_{fa} are basic and altered frictional coefficients and Q_a and Q_w are air and water volume rates, respectively. The drag decreases with the increase of the airflow, but the trend ceases at a certain value. The maximum effect, 14%, was obtained at the void ratio 0.153 (real air flow is 7,000 liter/hour) and the reduction kept decreasing up to the maximum void ratio tested. The reason for this unexpected trend is not clear yet. While for the two positions near the AOH the effects are apparently the same, the reduction becomes less where the location is further downstream. The speculative reason can be associated with the merging of the bubbles and the dynamics related to them.

The similar information obtained for the flow speed of 11m/s is shown in figure 10-(b). Over 25% drag reduction was measured at the position #1 with the void ratio of 0.123. Because of the limited capacity of the airflow controller the void ratio was not increased beyond 0.123, so it is difficult to say whether maximum void ratio exists where maximum reduction is achieved. The amount of effect depending on the distance from the AOH is even more prominent here at higher flow speed.

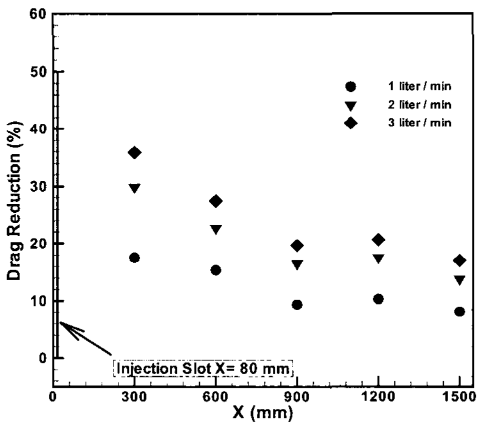


(a) 6 m/s

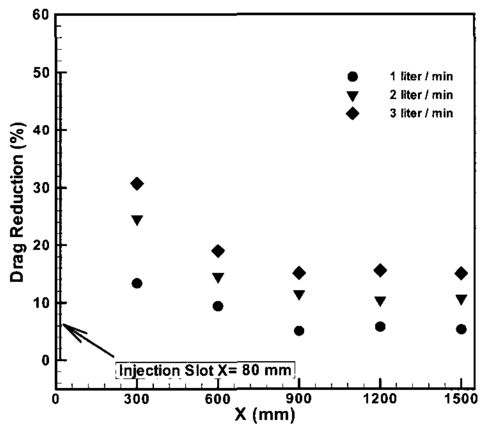


(b) 11 m/s

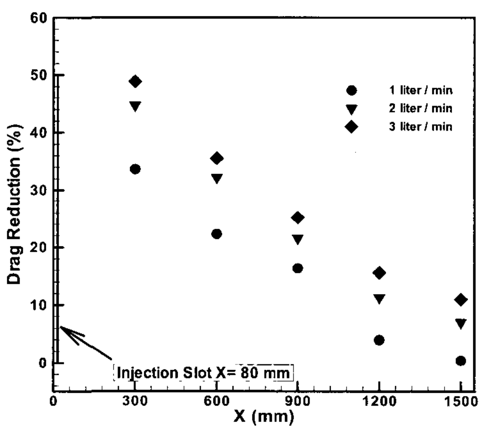
Figure 10: Drag reduction with air bubbles versus bulk void ratio at 6 m/s and 11 m/s



(a) 200 ppm PEO Solution injection



(b) 300 ppm PEO Solution injection



(c) 400 ppm PEO Solution injection

Figure 11: Drag reduction with polymer solution versus distance from injector (11 m/s)

4.3 Frictional drag reduction with polymer solution injection

The effect of the polymer solution of WSR-301 (Polyethylene Oxide, PEO) on the drag reduction was tested with varying the polymer concentration and the injection rate at a fixed flow speed of 11 m/s. The results of the drag reduction, defined the same as in figure 10, with 200, 300 and 400 ppm solutions are shown in figure 11. For each set, three different injection rates, i.e., 1, 2 and 3 liter/min, were used.

Apparently, the effect of the polymer solution on the friction drag reduction decreases along the downstream and then becomes more or less stable beyond X=900 mm with exception of the case for the 400 ppm solution. The maximum reduction was obtained at the nearest position from the slit, and the amount becomes larger for higher concentration and injection rate. The value itself reached up to 48% for the case of the 400ppm solution with the injection rate of 3 liter/min.

Assuming minor entrance effect, the change we can expect along the stream is the dilution of the polymer hence the less drag reduction along the downstream than near the injection. However, almost negligible drag reduction at downstream for the case of the 400ppm solution and 1 liter/min is questionable, and further analysis is required.

5 Closing remarks

As a basic study for the development of techniques for drag reduction of water-borne vehicles, frictional drag reduction by injecting microbubbles of air or polymer solution has been measured in a two-dimensional water channel. For a fully developed turbulent channel flow, the frictional drag reduction over the flat ceiling of a newly built water channel was directly measured by a specially designed skin friction sensor of floating element type with varying the injection flow rate of air or polymer solution as well as its concentration. From the experiment, important parameters for the injection of microbubbles or polymer solutions are examined for an effective reduction of the turbulent skin friction. The integrated frictional drag reductions up to 25% for the microbubble and 50% for the polymer injection are observed.

Acknowledgment

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