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Ocean Engineering 34 (2007) 83–93
OCEAN ENGINEERING
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Model test of the surface and submerged vehicles with the micro-bubble drag reduction

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Received 25 July 2005; accepted 21 December 2005
Available online 21 June 2006

Abstract

This study is based on the effective experiment observation and measuring technology to discuss the interaction influence between liquid turbulent boundary layer and a crowded group micro-bubbles. It is in order to understand and quantify the micro-bubbles clouds inside the turbulent boundary layer to eliminate the capacity of skin friction drag. Whenever the micro-bubbles are over supplied, pile up effect happened which makes micro-bubbles to integrate to each other as a large-size air film. Although they still have the drag reduction effect, the efficiency of drag reduction slowed down at this transition period. In the experiment of vertical type circulating water tunnel, when 1 μm porous medium is at 7 m/s flow speed, the C_v value at 0.056 has the best drag reduction efficiency of 26%. While 10 μm porous medium is at the same flow speed, the drag reduction efficiency is only around 23%.

Keywords: Skin friction drag; Drag reduction; Turbulent boundary layer; Micro-bubbles

1. Introduction

Vehicles are the current main source for Earth's energy consumption. It might decrease the energy loss in case it is able to reduce the drag of various vehicles. Meanwhile, how to raise the operation performance of vehicle and to suppress the noise production; these are the main points for researches in drag reduction in all countries.

Because the viscosity of water is higher than air, a vehicle has higher energy loss in movement in water. In order to overcome the drag and achieve movement performance to vehicles in water, it requires thrust boost as focus and overcome the drag limit by enlarging the horsepower output. In case we use streamline shape to lower its drag to the lowest degree and diminish the superficial friction drag with an economic method; it will lower the total resistance for water vehicle and achieve the purpose of energy consumption decrease than to add the velocity of movement and its operation performance.

The drag reduction technology for micro-bubble is by miniature emitting aperture on the surface of vehicles to use the gaseous air to be sprayed out from the interior in order to enable the object surface to be covered entirely the small bubbles; this can reduce the surface roughness, in the control of velocity gradient of boundary layer and lessen the skin friction resistance. But the bubbles must be slight enough to be allowed to lie in the fluid–gas interface to achieve the equilibrium. Generally speaking, the efficiency of drag reduction increases along with the lift of micro-bubble quantities in the boundary layer. From the relative research references (Madavan et al., 1985a, b; Kodama, 1998; Takahashi et al., 1995, 2000; Fontaine et al., 1999), it points out that this way of drag reduction should have efficiency to reduce the drag as high as 80%. The drag reduction technology for micro-bubbles has its different efficiency on resistance decrement in various fields. For detailed performance analysis please see Table 1 below.

McCormick and Bhattacharyya (1973) proposed to use a negative pole wire-connected dive model with a 36 in long and 5 in in diameter at the maximum. It produced the hydrogen bubbles by using the electrolysis way and

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doi:10.1016/j.oceaneng.2005.12.010

Nomenclature

A	test area (wetted area of the test model) [m^2]
C_f	local friction coefficient [$R_f/0.5\rho V^2 A$]
C_F	test model friction coefficient [$R_F/0.5\rho V^2 A$]
C_v	the void ratio (air injection ratio) [$Q_a/(Q_a+Q_w)$]
Q_a	air flow rate [min^{-1}]
Q_w	water flow rate [min^{-1}]
ρ	density [kg/m^3]
δ	boundary layer thickness [m]
δ^*	boundary layer displacement thickness [m]

measure the movement drag of this dive model. They find the relationships among the efficiency of drag reduction, the velocity of movement and the speed to produce hydrogen bubbles.

Bogdevich et al. (1977) once carried on the micro-bubbles release in the turbulent flow boundary layer between two plates of flow field experimental study, from which it was discovered that Reynolds number was the important parameter to influence partial friction drag. In the higher Reynolds number scope, it was allowed to promote the efficiency of bubbles drag reduction; Merkle and Deutsch (1989) proposed to make use of micro-bubbles drag reduction technology; he found that the micro-bubbles must allocate in the buffer area of boundary layer to perform the drag reduction effect.

Madavan et al. (1985a, b) proceeded with the micro-bubble drag reduction study by using the numerical computation. They used the sole mixing length boundary of viscosity equation to produce the fixed particle size of micro-bubbles in order to conduct the simulation analysis research. This considered the flow viscosity, the density and the effect of bubbles piling to influence the boundary layer characteristic; its result—when the bubbles piled up to the large particle size bubbles, the bubbles can destroy the formation of boundary layer and cause to reduce the efficiency of drag reduction.

In the drag reduction study of using bubble production mechanism, the bubble particle size controlled is roughly to be split into two categories: one is the smaller particle size of micro-bubble (smaller than 0.1 mm), the better efficiency in drag reduction; the other is that air film also has an excellent effect in drag reduction. But the air film grow is not easy to control.

Shirnoyama (2002) have experience with the ship in drag reduction research by utilizing air film to replace the blow micro-bubbles from which it was found to have a better performance in drag reduction. The air film experiment study is based on 7 and 16 m long flat model ships. The efficiency of drag reduction from 7 m model ship is around 10–15%; the one from 16 m model ship is approximately 20% at the speed of 7 m/s and 30% at the speed of 4 m/s.

Table 1
Performance compared table for micro-bubble drag reduction technology applied in various fields

Applied field	Drag reduction	References
Plate	Over 80%	Madavan (1985a, b)
Pipe flow	Reach 40%	Kodama (1998)
12 m Length ship	Reach 50%	Takahashi (1995)
50 m Length ship	Reach 32%	Takahashi (2000)
To integrate with high polymer	Over 80%	Fontaine (1999)

2. Experiment apparatus and measurements

The test platforms used in this research are the high-speed, vertical-type circulating water tunnel and the large-scale circulation water channel. The operating fluid is all fresh water purified by passing through filters. There are two sections of test measurement in the research: one is to discuss the basic characteristic of micro-bubbles drag reduction technique in the vertical type circulating water tunnel. Establishing the micro-bubble drag reduction technology to be applied in the turbulent flow boundary layer is an important controlled variable. The second stage experimental platform is to move into the large-scale circulation water channel to carry on. It is going to apply the micro-bubbles drag reduction technology to the experiment measurement of the surface ship model; this is in order to obtain the best effect of drag reduction from the ship model test.

Moreover, the attempt at union electrolysis and the chemical reaction ways to produce the slighter micro-bubbles, applies to the water-submerged body experimental study; the test model is a streamline submerged body model. Because the test model is completely submerged in the water, the total resistance suffered only considers friction resistance and two types of shape resistance.

During the whole experiment process, it uses the high accuracy resistance meter coordinating with data to pick up the analysis system. From which, it may reflect total resistance from the shell body model under the different flow field speeds. As for the relative experiment instrumentations used, please see details as below.

Please see the schematic drawing of high-speed, vertical-type circulating water tunnel as in Fig. 1. The operating fluid is fresh water after purification and filtering; the dimensions of test section for water tunnel is designed as 3600 m for length, 150 mm for width and 15 mm for depth. And its cross-section is 10:1 for width to height. Therefore, the test section flow field can be treated as the two-dimensional flow field. When flow field speed is high enough, the test section flow field will transform to be a turbulent flow field. In the same time, the section of

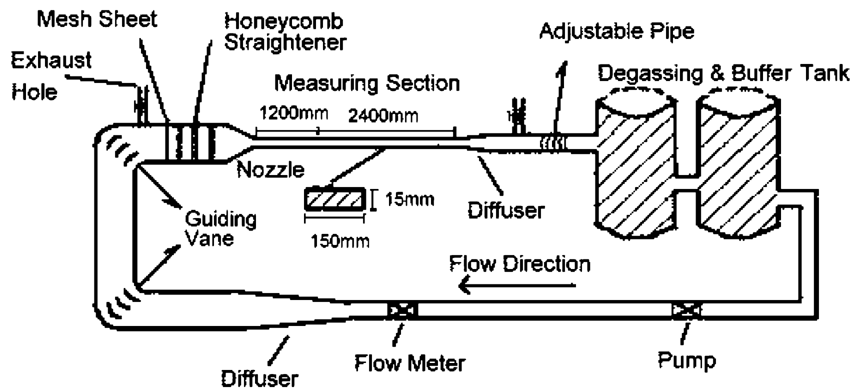

Fig. 1. Schematic diagram of high-speed vertical type circulating water tunnel.

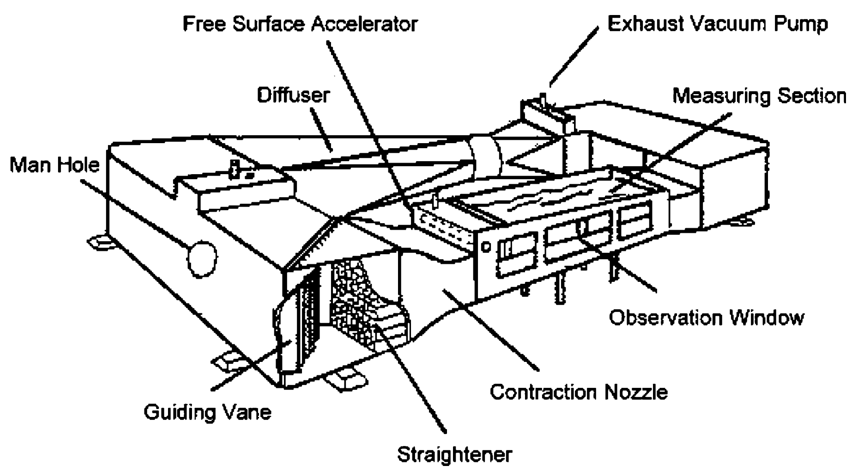

Fig. 2. Schematic diagram of horizontal-type circulating water channel.

1000 mm after the section entrance will develop to be fully developed flow. After injecting the micro-bubbles into the turbulent flow field, it can control the micro-bubbles in the similar turbulent flow boundary layer to have an observation and measured analysis for the drag reduction effect.

This main experiment platform is horizontal type circulating water channel; the water channel plane schematic drawing is shown as Fig. 2. The external sizes of water channel are: length: 14 m; width: 5.325 m; height: 2.2 m; water capacity: 80 m^3 and the dimension of observation and measured areas for the experiment is length: 5.5 m; width: 1.5 m and water depth is 1.1 m. The flow velocity of water channel depends on the host motor rotational speed to change; designed flow speed is from 0.2 to 2.0 m/s. The circulation water channel is an idea of comparative movement to fix the ship or submerged body model in the test sections. With adjusting the host motor speed of tank to change the water current speed, it is able to simulate the various water movements for actual ships or dive bodies. Its advantage is able to observe and measure the stable status for a long time to see the physical quantity and the flow field characteristics for the ship or dive models in the water movements.

In the experimental study of micro-bubbles application, test models may be divided into two types for the use in horizontal circulating channel platform. One is ship model influenced by the free surface effect; the other is the submerged body with streamline axial symmetry diving in the water. Please see the experiment models as follows.

The experimental ship model is made by acrylic materials; in order to avoid surface layer effect from happening, it is considered to install the model design in the large-scale, horizontal-type circulating water channel. So it adopts a ship model with total 1350 mm in length, the vertical range between front and rear parts is 1268 mm, the ship width is 240 mm and draft estimate is 42 mm. On the module arrangement for the micro-bubbles production, it use two section types to spread as the principle; one is at the rear part of 330 and 790 mm locations to settle a device for micro-bubbles production. This is in order to discuss the influences between the module spread locations produced by micro-bubbles to the drag reduction for surface ship model effect.

This submerged body model is 1325 mm in length and 120 mm in diameter. It installs the turbulence stimulator at the front-end section of 5% whole length to let the water current turn into turbulent condition when passing the surface of submerged body model. This is to simulate the actual object flow status in the real environment.

The circulating water channel is a close system. When it carries out the resistance-measured experiment, it will use the special-purpose support to fix the submerged body model above the water channel test section. Then it is designed to have a track-type slide support on two sides of the fix supports; and install the smoothly skid wheels in the chute to allow it to move in horizontal direction, as shown in Fig. 3.

At the present time, the ways to form the micro-bubbles are porous medium, electrolysis and chemical reaction. This research is based on the high-speed, vertical-type circulating water tunnel as the test platform and to use porous medium to produce micro-bubbles to further discuss the drag reduction effect from the supplied quantity of micro-bubbles, the particle size of porous medium copper powder and the pouring angle of micro-bubbles and so on to obtain the effective controlled parameters.

From the test result of high-speed two-dimensional circulating water tunnel platform, the initially findings are the relationship and efficient effect for the important parameters from micro-bubbles drag reduction technology. Besides the friction drag as one of the total resistances suffered by the ship, there also includes form drag and wave drag which are affected by free surface seriously.

Being not able to reflect adequately the performance evaluation from the test data between technology of micro-bubbles drag reduction and the ship, besides the water tunnel platform experiment, they also plan to design surface ship and water-submerged body models located on an experiment platform with large-scale horizontal water tunnel circulation; this is in order to obtain the expected drag reduction efficiency from the test of micro-bubbles drag reduction technology to the effect of free surface effect.

There is an obvious influence from the free surface effect suffered to the skin friction resistance of the ships. However, when the ship model comes under the free surface effect, it rolled the air up and resulted in the interruption to the released micro-bubble group by the larger size of bubbles involved in the effect. During the whole test process of surface ship model, the influence effect is obviously to be seen. So, the valid release location of the decision and arrangement for the micro-bubbles are the questions worthy to discuss.

The research of micro-bubble drag reduction application here tries to combine the ways of producing gas by electrolysis and chemical reaction to carry on the bubble production control. With employing the electrochemistry reaction way, it is able to integrate the advantages of electrolysis and chemical reaction to provide the slighter bubbles even to raise the speed of producing air. In order to expect having a higher efficiency in drag reduction during applying in the water submerged body model with larger wetted area it uses the air production from electrochemistry reaction to be tested in the water submerged body model.

In the ship model applied research, it uses the changes of the ship model velocity of movement and the supplied volume of micro-bubbles to have drag reduction effect as primarily. Also, it considers the released position of micro-bubbles to have efficiency effect to the drag reduction of ship model. This measure is in order to discuss the interaction relationship for drag reduction through

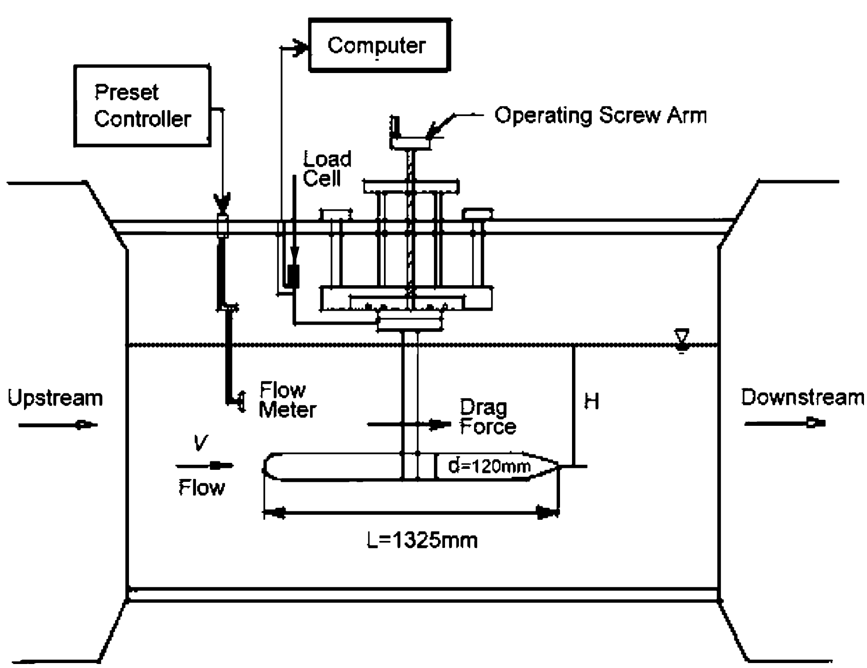

Fig. 3. Schematic diagram of the experimental set-up in submerged body.

combining movement velocity of ship model, micro-bubbles supplied volume and released position.

The way to produce the bubbles in the water submerged body model experiment is electrochemistry reaction; the final purpose expected is to integrate these two ways of bubbles production application in order to promote the speed of bubble production, then to increase the efficiency of drag reduction effect.

This research is focused to produce the micro-bubbles by the porous medium way, but the mean diameter for porous medium particle size it used is two kinds: 1 and 10 μm. In the experimental process, it was discovered if it uses the porous medium in the dimension control of micro-bubbles particle size, this easily causes the micro-bubbles mutually to unify to a bigger particle size of bubble. Even, it will result in air film effect if it is with oversupplying air. Although it still has a drag reduction effect, it is very different from the principle of micro bubbles drag reduction mechanism. The main reason is that the viscosity of air film being little far from the one of water; the effect of drag reduction mechanism is similar to the drag reduction for super cavitations. In fact, that is not belonged to be in the field of the micro-bubbles drag reduction. It can be improved to avoid the effect of accumulation of lots of bubbles by decreasing the volume rate of air supplied and raising the movement speed of experiment field.

In the experimental process, this research attempts to get conformity in electrolysis water and the chemical reaction ways to produce the micro-bubbles. Using magnesium alloy as the positive electrode and the sheet copper as a cathode, then pass electric power of 23 to the 396 W input to produce the micro-bubbles in the cathode sheet copper position. Simultaneously, applying the extremely lively characteristic of magnesium metal to meet with water, it finally produces the micro-bubbles. Under this kind of conformity pattern, the positive electrode magnesium alloy and the cathode sheet copper all can produce the hydrogen micro-bubbles. This may speed up the production for micro-bubbles; there is also a better effect on the good electrolyte. That shortening the available time to produce air under the condition of air production speed being higher is the only defect to be seen:

$$\text{Cathode}: \ Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2 \uparrow, \tag{1}$$

$$\text{Anode}: \ 2H_2O + 2e^- \rightarrow 2OH^- + H_2 \uparrow. \tag{2}$$

3. Results and discussion

This research has used two different ways to produce the air bubbles. Mainly two kinds that are general commonly used are porous medium and the electrochemistry reaction to conduct the experimental study. In the vertical type circulating water tunnel experiment, the porous medium used are with average 1 and 10 μm diameters. This tries to analyze the influence between different bubble particle sizes and micro-bubble drag reduction effect. Besides this, it also change the injecting angle of pressed air to see if there is any help from this to the bubble production and drag reduction effect. But the electrochemistry air production method is mainly to be applied in the water-submerged body model experiment; this is in order to discuss the advantages or shortcomings of micro-bubble drag reduction without limits to the free surface effect.

In order to be more convenient to discuss the micro-bubble flow rate (Q_a) to the drag reduction mechanism, air flow rates have to be injected with dimensionless. The C_V value of air injected dimensionless is defined as $Q_a/(Q_a+Q_w)$. Because the test section is a two-dimensional flat channel flow field in the vertical type circulating water tunnel and the air injection point is a fully developed flow, Q_w is defined as the water flow rate in the main flow field for test section. In the ship model experiment, we define $Q_w = W(\delta - \delta^*)V$; it is because of considering the limit in the boundary layer thickness. W is the ship model width, boundary layer thickness is $\delta = 0.382X/(\mathrm{Re}_L^{0.2})$. Also we can see the boundary layer displacement thickness δ^* is about equal to $\delta/8$. V is ship model speed and X is the measuring location.

3.1. Vertical high-speed circulating water tunnel

In the vertical-type circulating water tunnel, two kinds of porous medium, with mean diameters of 1 and 10 μm are proceeded with. Under four kinds of fixed flow field speeds of 4, 5, 6 and 7 m/s experiment measurements with adjusting air injection are needed, because it is based on $C_V = Q_a/(Q_a + Q_w)$, so the more higher the water current speed in the main flow field, the lower of C_V value is. This is based on the same air flow rate of Q_a. Hence, in case to keep the same C_V value under the different water current speed, it has to adjust the air flow rate appropriately.

Please see Figs. 4 and 5 for the ratio relations charts between the micro-bubble void ratio and friction resistance coefficient. In Fig. 4, it uses the 1 μm porous medium; Fig. 5 adopts 10 μm porous medium. The ordinate axis is the ratio between local friction resistance coefficient C_f from the released micro-bubbles and local friction resistance coefficient C_{f0} from unreleased the micro-bubbles. Whenever this ratio is smaller than 1, it means drag reduction happens. Abscissa on right has the air injection dimensionless quantity C_V value. In these two figures, the solid line represents intersection angle being vertical 90° for the high-pressured air passes through the porous medium and met with the horizontal flow direction. But the dashed line expresses the air input angle of 30°. For the drag reduction curve under different flow speed conditions in the figures, it is able to see the resistance drop slope from higher speed is steeper than the one from lower speed during the water current in main flow field. This means that the higher the speed is in the flow field, the better of micro-bubble drag reduction effect. Also, we can find that the drag reduction effect from 1 μm porous medium air production is better

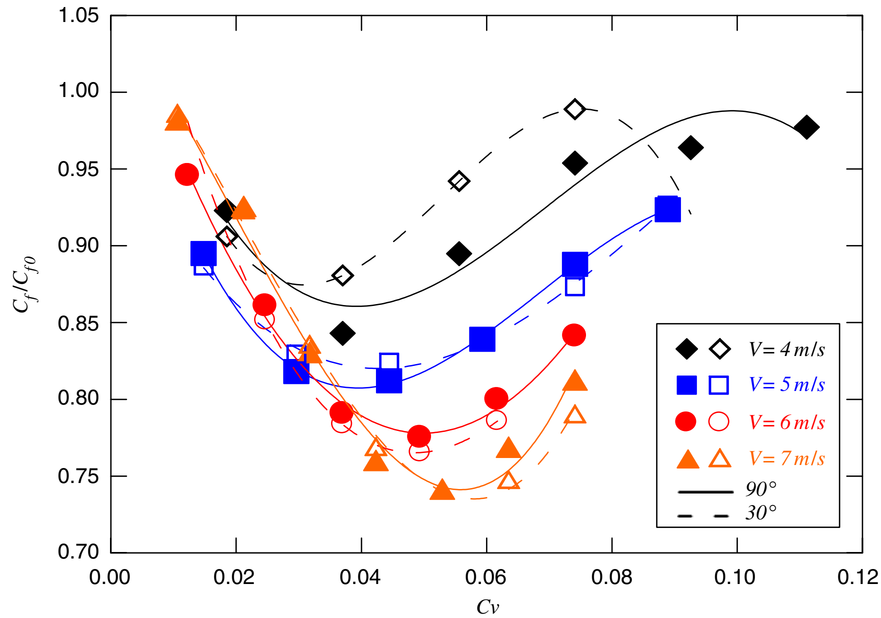

Fig. 4. Effect of void ratio on the local skin friction coefficient (1 μm porous medium).

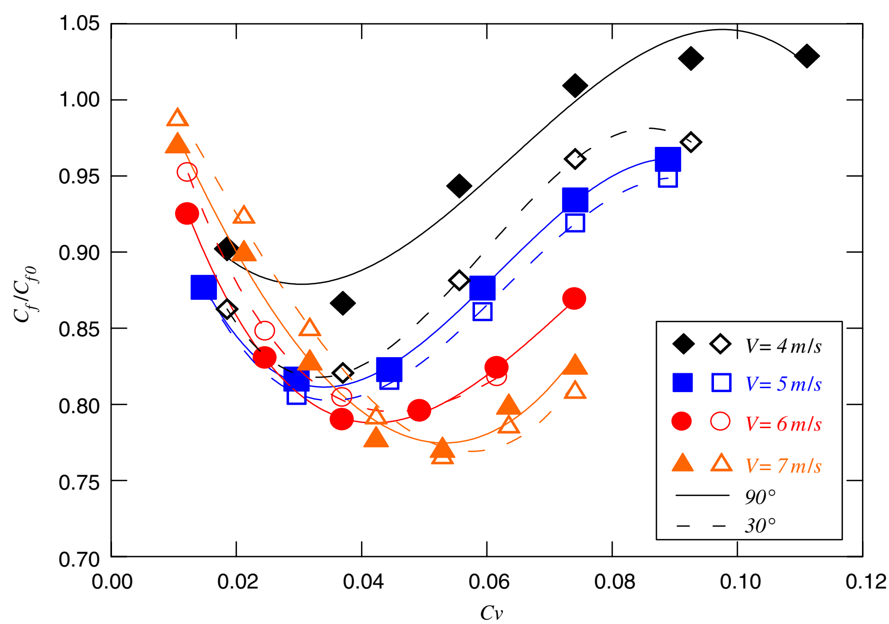

Fig. 5. Effect of void ratio on the local skin friction coefficient (10 μm porous medium).

than the one from 10 μm. It reflects the smaller particle sizes of micro-bubbles; the buoyancy effect can be neglected. Whenever micro-bubbles keep staying around the buffer layer, it has a better effect for drag reduction.

In the bubble particle diameter control study, it uses two different kinds of mean diameter of porous medium to proceed the air bubble particle to the test of drag reduction effect. The mean porosity diameters are 1 and 10 μm porous medium. It is found whenever the void ratio value (C_v) is higher than more than 0.03 in the low- to high-speed flow field experiment, the drag reduction effect from using 1 μm porous medium in micro-bubble production way will be higher than the one using 10 μm. But when the void ratio value is lower than 0.03, the drag reduction effect with using 10 μm porous medium will be better. This is due to the lower air-flow rate; the larger porosity rate helps the bubbles production than to raise the drag reduction in efficiency.

Excessive micro-bubble injection will destroy the turbulent boundary layer forming and result in the decrement in the drag reduction effect. Also it was found that whenever there is an excessive supplied quantity of micro-bubbles, they will have a piling-up effect. This make the micro-bubbles integrate mutually to be a larger size air film. Though it still has the drag reduction effect at this moment; the drag reduction effect still slow down at this transition period. From which, we can find that with the faster speed of flow field, the threshold limit value for air feed happened upward. This is because inertia is much stronger in high-speed flow field which permits massive micro-bubbles to be injected and drag reduction efficiency is higher obviously. In Figs. 4 and 5, the 1 μm porous medium at 7 m/s flow speed, the C_v value with 0.056 has the best efficiency of 26% in drag reduction. For 10 μm porous medium at the same flow speed, drag reduction efficiency is around 23%.

In the study of flow speed to drag reduction efficiency, the flow speed it used is in the 4–7 m/s to have an experiment measurement. With adjusting the compressed air injection ratio, it can control the production quantity of micro-bubbles. It is also found that higher the flow speed in the flow field, better the efficiency for the drag reduction especially if it can reach the 26% drag reduction effect at the 7 m/s flow field speed. In the result of 1 μm porous medium experiment (as shown in Fig. 4), it is able to see that with more air injection, the drag reduction effect is rising. But when the air is injected up to a certain ratio, the drag reduction effect is opposite to slow down and the threshold limit value for the air injected will be upward according to the increase of flow field speed. That is, the faster the flow speed in the flow field is, higher the threshold limit value of C_v is. This is because it allows larger air injection when flow field speed is higher and does not produce the distribution in the boundary layer flow field. While it is in the lower void ratio (less than 0.04), it is found that the drag reduction effect is not good as expected during high-speed movement. This point explains if it would like to raise the drag reduction effect from micro-bubbles with the increase of flow field movement speed, it has to add the micro-bubbles void ratio to keep the suitable drag reduction effect.

When the C_v value continues to elevate over 0.1, when compared to the low speed in the flow field condition, it can be found that the drag reduction effect is able to increase because of micro-bubbles' piling up effect to form an air film. Although it has a certain degree in drag reduction effect at this moment, the drag reduction mechanism and micro-bubble drag reduction ways are different mode. The purpose of air film drag reduction is to consider its range as being larger as possible, but it is really hard to form a large-scale air film in fact. Because the oversize air film is too difficult to keep the surface tension it results in being broken. Then it goes ahead to destroy the existence of boundary layer even to enlarge the wake range.

In the experiment study of compressed air input angle to the drag reduction effect, it makes use of two different angles to go ahead with the test. They are the horizontal flow direction intersection vertical 90° and 30° tilt way. The experiment result from 30° tilt angle is as in Fig. 4 and Fig. 5 in dashed lines. When the compressed air is input, it is found that the void ratio (C_v) is lower than 0.05, it is no help to raise the drag reduction effect with the way of 30° tilt angle passing by the compressed air but little drag increase happened. When void ratio is higher than 0.05, the drag reduction effect from the way of 30° tilt angle injected the compressed air better than the way of vertical air injection. This shows whenever there is massive air input, it is able to decrease the vertical inertia quantity from the micro-bubbles entering the flow channel; it is able to lift the drag reduction effect appropriately with eliminating the interruption to the boundary flow field.

3.2. Horizontal-type circulating water channel

In view of the effect for total resistance decreasing, the key points are to discuss the resistance test between surface ship model and water-submerged body model. To use the high accuracy load cell to measure the total resistance for the ship model and water-submerged body model in order to reflect preciously the best effect for the micro-bubble drag reduction and the relative control parameters.

3.2.1. Surface ship model

The ship model is with total length 1.35 m, under the consideration for turbulent flow condition; the first step is to install the stirring turbulence line in the 5% location of ship bow and to consider that the ship mode surface has a certain roughness degree. So a tiny sandpaper is adhered on the ship model surface to make it happened and let the flow field to reach the turbulent mode. From the test, it is found that this measure is able to reach certain degree for the drag reduction effect.

Fig. 6 is the ratio (C_F/C_{F0}) relative chart of micro-bubbles flow speed (V) released by the ship model bow to

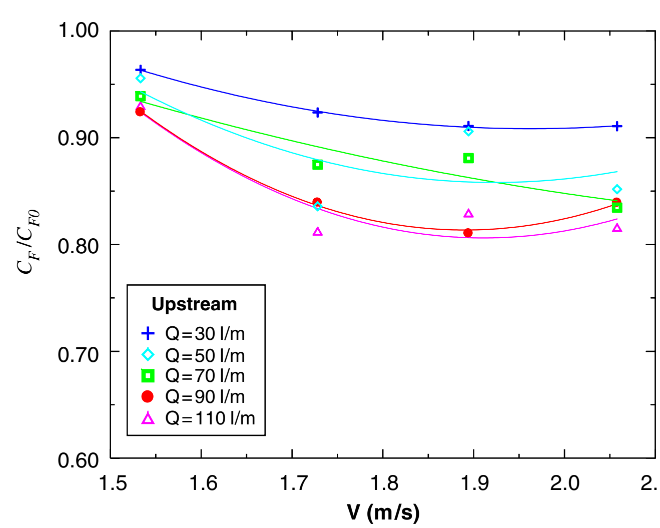

Fig. 6. Effect of velocity on the skin friction coefficient in ship (air injected in the front end).

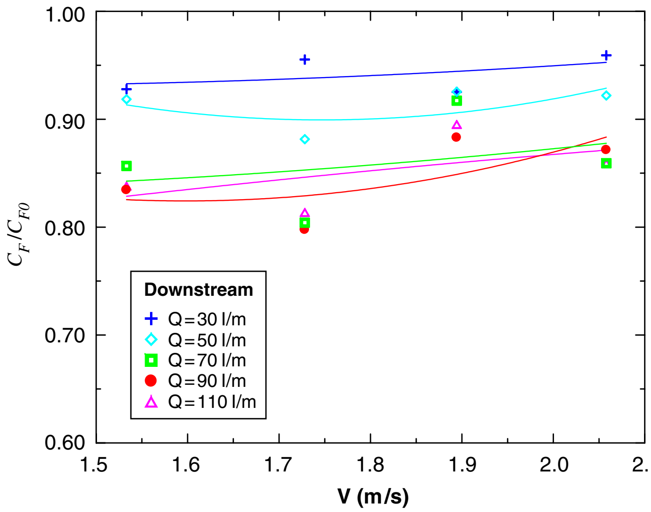

Fig. 7. Effect of velocity on the skin friction coefficient in ship (air injected in the rear end).

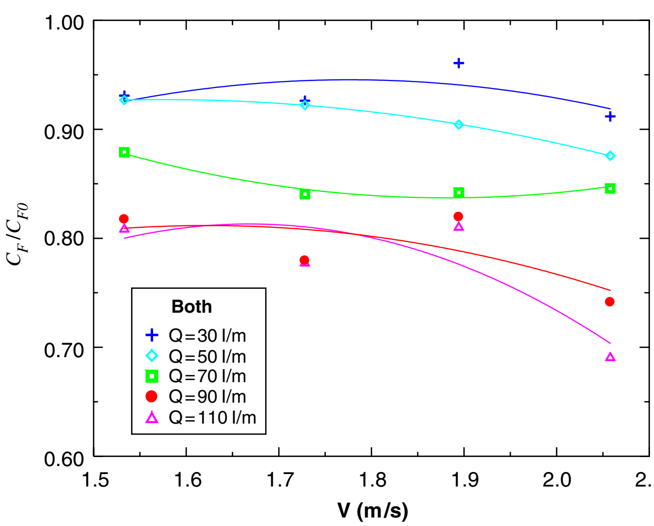

Fig. 8. Effect of velocity on the skin friction coefficient in ship (air injected simultaneously in the front and rear ends).

the corresponding friction resistance coefficient. When flow speed (V) is larger than 1.9 m/s, the drag reduction effect slows down. But the larger the flow speed, the drag resistance is able to continued increasing. Oppositely, it makes C_F/C_{F0} value to increase. This is possible and the main flow field speed is too high to make the boundary layer turning to be thinner. So it makes the micro-bubbles to flow out result in the decreasing for the area covered by micro-bubbles on the ship surface than to lower the drag reduction effect.

Fig. 7 is the ratio (C_F /C_{F0}) relative chart of micro-bubbles flow speed (V) released by the ship model rear end to the corresponding friction resistance coefficient. From it, it is clear to see drag reduction effect slows down with the increasing of flow speed (V). This is because of micro-bubbles released only on the rear end of ship model, so that the effective drag reduction area eliminates. Because the growth of ship mode resistance with the flow speed increasing is larger than the drag reduction effect from supplied micro-bubbles, this lets the drag reduction effect of micro-bubbles released at the rear end to lower gradually with the ship speed increasing.

Fig. 8 is the ratio (C_F/C_{F0}) relative chart of micro-bubbles flow speed (V) released by the ship model front and rear ends simultaneously to the corresponding friction resistance coefficient. From this, it is found that it has the best efficiency for the drag reduction when the micro-bubbles are released at the front and rear ends simultaneously; this is able to reach the 30% drag reduction effect. As the air-flow rate is larger, the drag reduction effect is increasing when the flow speed is higher. This is possible when the effective drag reduction area of micro-bubbles is enlarging when air supplied is from the front and rear ends, so the drag reduction effect is relatively higher. According

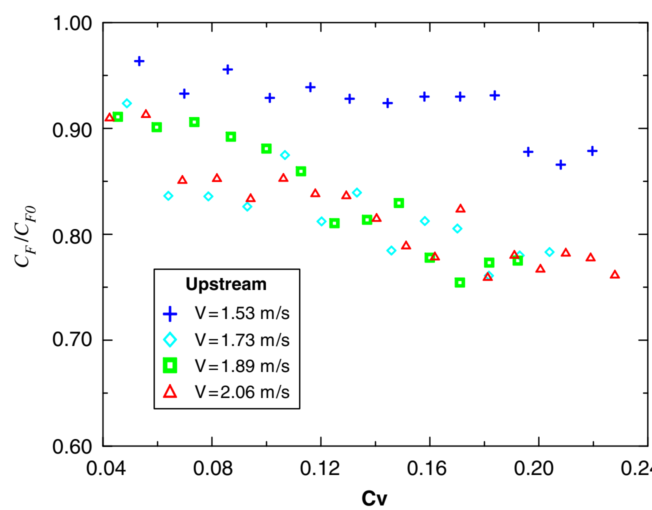

Fig. 9. Effect of void ratio on the skin friction coefficient in ship (air injected in the front end).

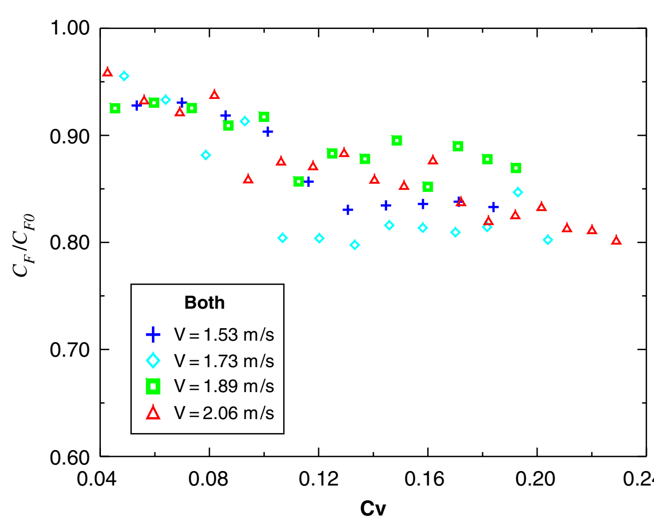

Fig. 10. Effect of void ratio on the skin friction coefficient in ship (air injected in the rear end).

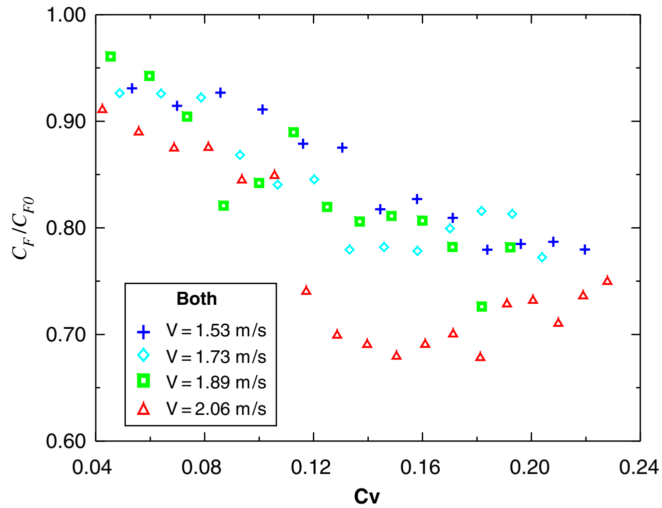

Fig. 11. Effect of void ratio on the skin friction coefficient in ship (air injected simultaneously in the front and rear ends).

to Figs. 6 and 8 comparisons, whenever the movement speed is higher for ship model, the drag reduction effect of micro-bubbles released by front and rear ends is higher than the ones released only by the front end with the increasing of flow speed (V). There is an evidence to show that with the higher speed of ship mode movement, it needs to have separate sections to supply air in order to increase the drag reduction effect if it is for micro-bubbles covering the turbulent boundary layer of surface ship.

Figs. 9–11 are the ratio (C_F/C_{F0}) relative charts of void ratio (C_v) for the air supplied by ship model of the front, rear and both simultaneously to the corresponding friction resistance coefficient. According these figures, it is found that the higher of air injected, the better the drag reduction effect.

When the micro-bubbles start to be released by front end, at speed of flow $V = 1.53$, because of lower speed for ship mode movement it make micro-bubbles unable to be transmitted to the rear end and then be separated from the boundary layer and result in a inefficiency for drag reduction. In the same situation, if micro-bubbles are released from the front and rear ends simultaneously, its drag reduction effect is only higher than the ones released by the front end.

Fig. 10 shows that the drag reduction effect is not as good as expected; it is because of smaller area covered by micro-bubbles; its best drag reduction effect is less than 20%.

Fig. 11 discovers that the drag reduction is better with the higher void ratio. But when C_v value is bigger than 0.16, the drag reduction effect is no more to increase; oppositely, it slower down. It is possible for the oversupply for the air which results in destroying the boundary layer flow field.

Fig. 6–11 show that its drag reduction is better when the air injected is by ship front and rear ends simultaneously. In case, there are only injects from the rear end, the drag reduction effect is not good enough. This is totally different from the point of view that it is better from the air supplied by the rear end. With the repeated experiments and discussions, we find that it is possible to consider to user the certain roughness surface value for ship model; this make the flow field on the front end to turn into the turbulent condition resulting in enlarging the effective areas for the micro-bubbles around the turbulent boundary layer.

3.2.2. Submerged body

The production way about micro-bubble, this part adopts the electrochemistry reaction method, it combine the electrolysis and the chemical reaction way. Expect to be able to stably control the micro-bubble particle size. Because the corrosion of metal in electrolyte involves electrochemical function, the electric current from a metal surface passes over electrolyte to flow into another metal. So the electric current out from the metal surface to the electrolyte part (that is the corrode part) is called the anode. And the metal section for the input electric current is called negative pole. It is by the way of anode and cathode outside the water to be connected with lead and power supply to constituted in a return route. This stage uses the fresh water in the water channel as the electrolyte; magnesium as the anode and copper as a negative pole. Input DC voltage and by the way of the electrochemistry reaction to produce the magnesium hydroxide then to releases the hydrogen, this is to achieve the goal of micro-bubbles production. In the experiment, because it installs the micro-bubbles production device additionally, it results in submerged body model drag to increase. After the experiment data analysis, it deducts the additional resistance result from the micro-bubbles device installed.

In the experiment, the electric power used is 0, 23, 100, 232 and 396 W. The production of micro-bubbles rise accompanies the electric power increase. Fig. 12 shows that the submerged body model has almost no drag reduction

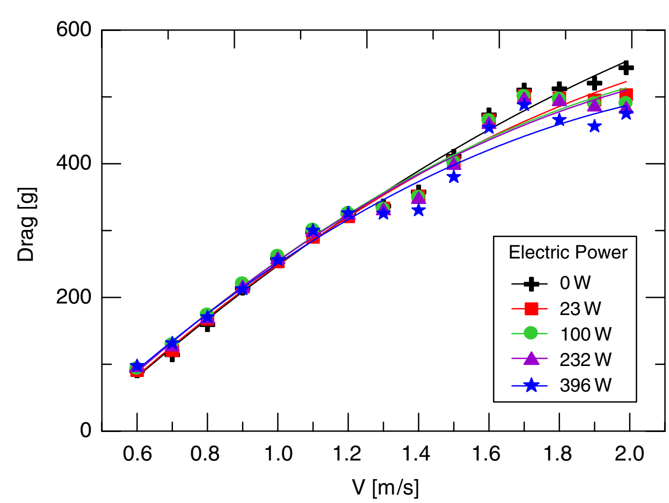

Fig. 12. Effect of velocity on the skin friction in submerged body.

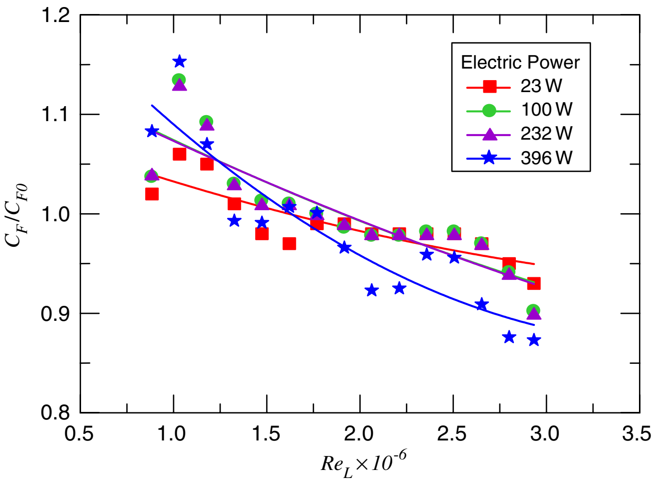

Fig. 13. Effect of Reynolds number on the skin friction coefficient in submerged body.

effect at the movement speed below 1.5 m/s; the only obvious efficiency happened in drag reduction during high speed. When the input electric power is 396 W, it is more apparent to have better drag reduction only at high speed. While higher the input electric power, larger the micro-bubbles production quantity is. So it is to figure out that as the micro-bubbles quantity is higher, the drag reduction effect can be complete to be displayed.

Because input electric power of 396 W has been the quite power, it is hard to have the drag reduction effect at the slow flow field. There are two reasons: One is the high electric power input, followed with high heat which cause the boundary layer flow field being influenced by the heat buoyancy effect; this make the drag reduction unable to be in efficiency. For this to improve, it can use the better electrolyte to accelerate the chemical reaction because the electrolyte used in this experiment is fresh water which can affect the electrochemistry response speed. Furthermore, from most literatures for the micro-bubbles drag reduction, it is shown that the suitable environment for micro-bubbles drag reduction is the turbulent boundary layer of high-speed movement. From Fig. 12, it is seen that the micro-bubbles drag reduction has its efficiency during the high-speed flow field. It can be suggested to have a better drag reduction effect if it is in flow speed with much higher speed range.

Fig. 13 discovers that the water-submerged body still has the resistance increasing phenomenon happening when the micro-bubbles drag reduction is at lower flow field. This is possible for the heat buoyancy effect produced by the electrolysis reaction. But in the high-speed flow field, it is found that the drag reduction effect of micro-bubbles drag reduction way is increasing.

4. Conclusion

Excessive micro-bubble injection will destroy the turbulent boundary layer's forming and result in the decrement in drag reduction effect. Also it was found that whenever there is excessive-supplied quantity of micro-bubbles, a stack effect happened. This make the micro-bubbles integrate mutually to be a larger size air film. Though it still has the drag reduction effect at this moment, its efficiency diminished at this transition period. At 7 m/s flow speed, the best efficiency in drag reduction 1 μm porous medium has is 26% when C_v is 0.056. At the same flows speed, the drag reduction efficiency from 10 μm porous medium is around 23%.

When the C_v value is around 0.16 during surface ship mode experiment, it can be treated as a critical condition. The best drag reduction efficiency is around 25% if the air filling is from the front end; the best drag reduction efficiency is around 20% if the air feed is from the rear end. In case the air feed is from both front and rear ends simultaneously then the best drag reduction efficiency is around 30%. When C_v value is larger than 0.16, its drag reduction efficiency will be gentle. Even the drag will be increased as there are over lots of air bubbles injected.

In the submerged body experiment, it was found though using the way of the electrochemistry reaction can obtain the smaller particle size and numerous micro-bubbles, but the drag reduction effect is not good as expected. This is due to being in the lower speed flow movement, it is easy to be interfered with the heat flow field. While the submerged body in the high-speed movement can increase the bubbles production rate through combining with the electrolysis and chemical reaction two kinds of bubbles production ways, but it is still limited to the electrolyte being with the general fresh water in this study; so the drag reduction is only able to keep 10% effect during the high-speed movement. In the test process, it is also discovered that the way to use electrochemistry to produce bubbles is faster than the one from normal electrolysis; with the raising of the bubble production rate, it results in shortening the available bubbles production period. It may be a chief defect for using the way of electrochemistry to produce the micro-bubbles.

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