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Review of Micro-bubble Ship Resistance Reduction Methods and the Mechanisms that Affect the Skin Friction on Drag Reduction from 1999 to 2015

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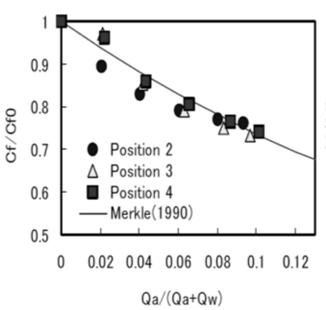
Graphical abstract



Skin friction reduction from the experimentby Kodama *et al.* on the position 2 (front), position 3 (midship) and position 4 (aft) at v =7 m/s.

Abstract

In order to lower down the fuel consumption and to achieve higher speed of ship, reduction in ship resistance has been the major topic of research for a long time. The most important factor in ship resistance is skin friction resistance. Micro-bubble has been shown to be able to reduce skin friction. This micro-bubble method gives the possibility to lower the friction without any change in the present hull form of a ship. The application of the micro-bubble technique reduces the surface friction by a variation of the viscosity of the fluid around the ship and makes a modification in the structure of the turbulent boundary layer. However, not much is known about the correct size, quantity, area of coverage which can effectively form a skin friction reducing mechanism. There are many established methods, such as Venturi tube type generator, tangential water-jet and forming of dissolve air and also a chemical process, such as electrolysis, may result in bubble production [1]. The use of micro-bubble as reducing agent of drag can lead to the creation of bubbly mixture near the flow surface that can significantly advances in the understanding of the underlying physical process of drag reduction. The current applications of these techniques to surface ships are discussed.

Keywords: Skin friction; micro-bubble; turbulent boundary layer; electrolysis;drag reduction

1.0 INTRODUCTION

Reduction in ship resistance has been one of the crucial part of research and development by naval architects over the last three decades. The drag reduction technology can be extensively applied to many industrial field such as hydraulic machines, oil well operations, pumping systems, slurry pipe line systems, oil pipe line transport, automobiles, aircrafts, submarines, ships, etc. [2]. It was reported that the fluid frictional drag accounts for as much as 60-70% of the total drag for cargo ship, and about 80% of that for a tanker, thus there is a strong demand for the reduction in the fluid frictional drag, especially in the marine transportation business [3].

Currently, in order to control the turbulence to reduce the skin frictional drag of the fluid transportation in pipes and the ship navigation in water, many drag-reducing techniques have been developed, including microgrooves(or riblets), compliant coatings, addictive injections (such as polymer, surfactant and micro-bubbles), active blowing or suction, electromagnetic excitation and an acoustic excitation [4-6]. Of many drag reducing techniques, the drag reduction technology by micro-bubble is paid more and more attentions due to obvious advantages such as environmental friendships, easy operations, low costs and high saving of energy. It was reported that the drag reduction by micro-bubbles is able to achieve a drag reduction rate as high as 80% [7-9] pointed out that even a relatively small reduction of the total drag can result in a substantial fuel saving for both commercial and naval ships or shortened transit time.

As a result, many researcher have devoted themselves to explore the drag reduction technology by micro-bubbles [10]. Reference [11] firstly reported experimental result of the drag reduction by micro-bubbles with electrolyzing to produce hydrogen bubbles on the hull of a submersible body. A drag reduction rate as high as 30% was attained. Subsequently, several experimental studies of the drag reduction by microbubbles were successfully conducted in Russia [12-15] obtained the drag reduction rate as high as 80% by injecting air through a porous plate to produce bubbles.

Recently, a number of experimental studies on the drag reduction by micro-bubbles were reported by many researchers [16-32].

2.0 MICRO-BUBBLE DRAG REDUCTION

Microbubbles, less than 1 mm in diameter [33], are currently in the focus of attention due to their potential use in many processes. Comprehensive reviews on the drag reduction by micro-bubbles can be referred to the references [34-36]. Those reviews show that the drag reduction by micro-bubbles is related to numerous factors such as gas type, gas injection velocity, gas injection place, distance of micro-bubbles away from the solid surface, surface roughness, presence of surfactant, bubble size and shape, bubble splitting and coalescence, flow velocity, surface configuration, Froude number, Reynolds number, and global void fraction, etc. All the factors that affect the micro-bubbles drag reduction will briefly discussed here.

2.1 Micro-bubble Characteristics

Over the years, many studies have been done in order to reduce skin friction. Since the usage of microbubbles is the most promising way as a drag reduction, herein, the characteristics of microbubbles that would give an optimum impact on skin friction reduction should be figured out.

According to [37], bubble size is one of the major factors influencing frictional resistance. Bubbles of a few millimeters in diameter can increase the frictional resistance. It is happened possibly because the turbulence generated in bubble wake. When micro-bubbles are ejected through a hole or porous plate, the bubble size is decided by the main flow velocity and the air flow rate, and not by the size of the hole [36].

The research work in [30] and [38] pointed out that the bubble size is a critical factor; the drag reduction can be attained only when the bubble diameter is less than about 1 mm; and the drag reduction rate is generally higher when the bubble diameter is smaller.

The researchers in [34] indicated that the size of the bubbles as an alternative important parameter for drag reduction. The diameter of the bubbles affects their trajectories and consequently, their concentration and location in the boundary layer. For instance, [36] investigated some experiments to clarify the influence of bubble diameter on frictional resistance reduction. The results showed that air bubble diameter mainly depends on flow velocity at the place where air injection occurs and that microbubble diameter has no effect on the reduction of frictional resistance.The photographic records of [39] showed that mean bubble diameter decreased monotonically with increasing salinity and that bubble size could have a significant effect on microbubble drag reduction.

Authors in [40] examined microbubble drag reduction at Re_x as high as 25 million and found that variations in bubble size and boundary layer thickness did not significantly influence the level of drag reduction. Reserachers in [41] found a similar insensitivity to bubble size for bubble radii of 250 to 1000 μm at similar Re_x values. Study in [42] indicated that the size and shapes of the bubbles in the near-wall flow showed that bubble splitting is not dominant and that bubble coalescence must be more prevalent as bubbles move downstream.

From the time-resolved image measurement, [36] observed oscillatory bubble motion in the vertical direction. Such a motion is more relevant upstream. As bubbles convect downstream, their typical size boecomes greater due to coalescence; consequently the interaction of bubbles with vortical structures in turbulence near the wall diminishes downstream. The researchers is [30] suggested that the magnitude of drag reduction using microbubble is not a strong function of bubble size. While [43] indicated that the expansion of the bubble layer is quasilinear with the distance downstream with a rate of expansion depending on the bubble diameter.

2.2 Micro-bubble Basic Parameters

The reduction of frictional drag depends on the wetted surface area of a ship and the fluid flow around it. However, it is quite difficult to change the wetted surface area. Thus, a mechanism to vary the viscosity of the boundary layer around the ship has to be figured out. There are some important basic parameters that would give an optimum impact to generate micro-bubble.

2.3.1 Bubble Size and Its Distribution

Central to the understanding of micro-bubble drag reduction, especially regarding how bubbles modify the momentum and energy transfer in the turbulent boundary layer is the issue of bubble size. Once the nucleation process has been completed, the bubble is free to grow, and eventually detach the substrate. The growth rate is influenced by a number of factors such as the rate of molecular diffusion to the interface of the bubble, liquid inertia, viscosity and surface tension [1]. Understanding how particles and bubbles affect the velocity fluctuations in fully developed turbulent flow is a subject of significant research. For example, it has been shown that the level of modification by dispersed particles to the energy-containing scales in turbulent flow is strongly correlated with the particle size [44]. Recent experimental [45] as well as direct numerical simulation (DNS) [46] results have demonstrated also a profound influence on the inertial and dissipation scales by either bubbles or dispersed solid particles.

However, it is still unclear to what extent such modification influences the friction drag near wall and whether any particular bubble size is superior to others in reducing friction drag. DNS results of turbulent boundary layers laden with rigid spherical bubbles [46]; [47] have produced increasing drag reduction with decreasing bubble size, indicating smaller bubbles are more effective in reducing friction drag. Moreover, DNS results of a turbulent channel flow with deformable bubbles [9] also demonstrated drag reduction, suggesting micro-bubble drag reduction is related strongly to the modification of the energy-containing scales by larger bubbles. Experimental investigation of the influence of bubble size on micro-bubble drag reduction has been limited by the difficulties in varying bubble size, in capturing the bubble trace and size distribution in turbulent boundary layer, and in measuring the turbulent characteristics in the bubbly turbulent boundary layer. Although the literature is replete with micro-bubble drag reduction experiments, there are only a few experimental efforts that have been devoted to address this issue. In a channel flow experiment with relatively large bubbles and moderate variation in bubble size, it has been observed that the influence of bubble size on the effectiveness of micro-bubble drag reduction was insignificant [21]. Friction drag reduction using micro-bubbles in a high speed water channel flow is studied experimentally, focusing on the influence of bubble size on the effectiveness of micro-bubble drag reduction [30]. The wall friction force is measured directly using a floating element force balance for both single-phase flow and the bubbly flow. The bubble size is determined from photographic imaging. Authors in [48] suggested that the bubble size can be scaled by the boundary layer thickness and by the size of the wall-turbulence structure. The bubble size distribution inside a bubble column depends on the size distribution of the injected bubbles (formed at some submerged orifice), on the coalescence and break-up phenomenon, on the bubble escape frequency, on the gas density changes with hydrostatic pressure and on a possible existing mass transfer process between the liquid and gas phases [49].

Bubble sizing is particularly important as the bubble size increases with decreasing threshold intensity [50]. On the other hands, [51] observed that the patterns of the trajectories of rising bubbles are strongly dependent on the Reynolds number. Researchers in [52] numerically studied the motion of a pair of spherical rising bubbles aligned horizontally by using DNS and showed that the direction of relative motion of the bubbles changes primarily in accordance with the Reynolds number.

In another flat plate test with a similar variation in bubble size, it was found that larger bubbles tend to remain closer to the solid surface, suggesting micro-bubble drag reduction favors larger bubbler [53]. Till now, our knowledge of the influence of bubble size on micro-bubble drag reduction is incomplete. To understand the influence of bubble size on micro-bubble drag reduction, controlled experiments with an extensive variation in bubble size, especially one that is capable of creating very small bubbles, are needed.

2.3.2 Location of Micro-bubble Injection

Microbubble injection location is one of the important parameters that need to be considered in reviewing the effectiveness of skin friction reduction by microbubbles. Researchers in [54] have established an experiment on high speed vessel model to test the efficiency of microbubbles on resistance reduction. The microbubble injector position is showed in Figure 1. The results showed that the location of microbubbles injection behind the midship (position 3) is the best location to achieve the most effective drag reduction and has caused about 6-9% of drag reduction. Below are the description of injection position made by them. Position 1 is at front of midship, position 2 at midship and position 3 at aft of midship.

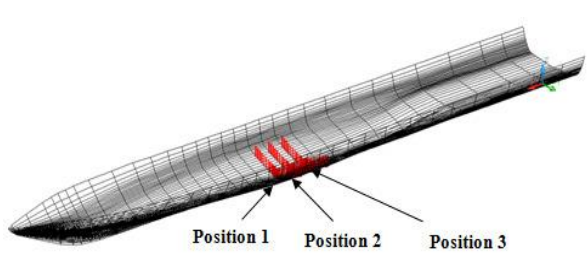


Figure 1 Lines plan and microbubble injector position [36]

These positions were investigated and compared regarding the influence of microbubble injection. Instead, [55] also stated that the skin friction reduction is greater in the aft injection case. However, [54] found that most researchers installed the microbubbles injectors near the bow of the model in the studies. For example, in the study of [56], the microbubbles injecting system is placed in front of the flat plate. The microbubbles injection location is not a factor that been considered on. For the world's first vessel that equipped with permanent air lubrication system, YAMATAI, the air outlet is also been placed near to the bow as shown in Figure 2 [57].

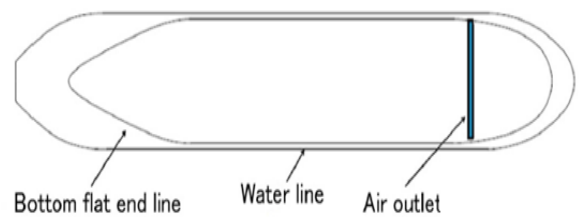


Figure 2 Location of air outlet viewed from the bottom [57]

The location of micro-bubbles injection behind the mid-ship section is the best location to get effective drag reduction. This statement was claimed by the experimental work of [19] at a circulating water tunnel. Meanwhile, [14] did extensive experiments on microbubble filled turbulent boundary layer and found that the bubbles were more effective when ejected from a plate on top than from a plate on bottom. A possible explanation of the phenomenon is the reduction of turbulence intensity caused by microbubble which increase the effective viscosity of the water-bubble mixture.

■3.0 MICRO-BUBBLE SKIN FRICTION REDUCTION MECHANISM

In order to understand the drag reduction mechanism by micro-bubbles, a great number of numerical investigations were also performed by many researchers [7], [9], [38], [46-48], [58-64]and etc. However, although many studies have been conducted, there is not a generally acceptable mechanism on the drag reduction by micro-bubbles due to the complexity of the problem itself.

The currently developed mechanisms are summarized as follows. Researchers in [61] though that the bubble splitting, denoting the extraction of the turbulence energy, is mainly responsible for suppressing the turbulence flow in the micro-bubble laden turbulent boundary layer. Authors in [64] attempted to associate the drag reduction with a bubble-passing frequency, and thus the pressure signature of the bubble at the wall hints the drag reduction mechanism.

The investigation of [38] showed that the bubble's existence prevents the sheet-like structure of the span wise vorticity near the wall from developing, which leads to the decrease of the streamwisevorticity because it comes from the evolution of the spanwisevorticity detaching from the wall. Accordingly, the drag reduction is attained. The study in [47] indicated that the drag reduction by micro-bubbles is associated with at least three mechanisms involved: the first one links to the bubble initial injection, the second relates to the density effect, and the third is governed by the definite correlation between the liquid turbulence and micro-bubbles. [46] showed that the bubble presence leads to a local positive divergence of the liquid velocity, creating a positive mean velocity normal to (namely away from) the wall which, in turn, reduces the mean stream wise velocity and moves the quasi-stream wise longitudinal vertical structures away from the wall. Those results in the fact that the span wise gaps between the wall streaks associated with the sweep events are increased, thus reducing the skin frictional drag; and the peak of the Reynolds stress is moved away from the wall to a zone of the smaller transverse gradient of the mean stream wise velocity, and therefore the production rate of turbulence kinetic energy and entropy are reduced. Studies [9] and [55] indicated that the drag reduction by bubbles is tightly related to the bubble deformation. The study in [25] concluded that the drag reduction by micro-bubbles depends simultaneously on the effective flow compressibility and on the bubble deformability. It was believed that many factors contributed the positive impact on the drag reduction, which among them are density effect, turbulence suppression, and Reynolds stress and near-wall void fraction.

3.1 Density Effect

The studies of microbubbles and skin friction are critical due to unwell established researches about that. One of the possible mechanism is the density effect, which means that, since the density of air is about 1/1000 of that of water, the layer of clustered bubbles near solid wall cuts off shear stress un water and reduces skin friction [65].

Meanwhile, a parametric study of the density ratio effect on the drag reduction was carried out by [7]. A gradual and substantial increase of the drag reduction up to the lowest density ratio indicated that simple mixture density variation effect plays one of the major roles in microbubbles drag reduction phenomenon. Contrastly, [66] determined that microbubbles drag reduction did not depend on the density or composition of the injected gas. [58], [60], [67] considered that the drag reduction by micro-bubbles is caused by the combination of the reduction in mixture density with the modification of effective viscosity inside the boundary layer. The research work in [58] also pointed out that the increase of the void fraction causes the increase of the local effective viscosity and the decrease of the turbulent momentum transfer. Authors in [47] discovered a few mechanism involved as the results from their simulation of direct numerical (DNS), in which one of them is associated with the density effects, where the bubbles reduce the turbulence momentum transfer.

3.2 Turbulence Suppression

Another possible of reduction mechanism is the turbulence suppression, in example bubbles suppress turbulence in the boundary layer, resulting in skin friction reduction. The reserahers in [68] measured turbulence intensity decreases as the skin friction increases. Authors in [69] suggested that bubble splitting was a possible basic mechanism for reduction turbulence in a microbubble-laden turbulent boundary layer. The study in [70] Found that bubbles deformed with a favourable orientation with respect to the flow, reduced turbulent stress as the flow field around the bubble was more isotropic.

Analytical calculations have been made by [15], [58], and [60]. Reserchers in [48] proposed a simple stress model in which eddy viscosity was assumed to decrease in direct proportionalto the density of the mixture. His result agreed well with the experiments by [12] except for low void ratios. Authors in [59] analyzed the water bubble mixed boundary layer using a mixing length model and expressing the van Driest damping coefficient by local properties of viscosity and density. An important finding of their analysis was that the bubbles were most effective when they were in the buffer layer.

Researchers in [58] assumed that viscous sublayer thickening was the mechanism in the reduction process by calculating the thickness of sublayer via comparison in the scale of turbulent eddies and scale of dissipation. While [71] suggested that the influence of bouyancy on the bubble motion becomes stronger with the increase of the magnitude of the gravitational acceleration. The results in [72] stated that the minute bubbles travel into the wall and outer regions of the turbulent boundary layer and both absorb the turbulent momenta and alter the characteristics of the drag producing vortices.

3.3 Reynolds Stress

Authors in [46] performed direct numerical simulation (DNS) at relatively low void fractions (a = 0.001–0.02) and demonstrated frictional-drag reduction on a spatially-developing boundary layer. They showed that the peak of the Reynolds stress (the streamwise vertical velocity fluctuation component, i.e. $u_0 v_0$) in the turbulent boundary layer shifts toward the freestream and suggested that this effect be the mechanism of drag reduction together with displacement of streamwise vortices from the wall. They subsequently performed DNS at a higher Reynolds number and concluded that the microbubble drag reduction becomes less effective at the higher Reynolds number [62].

In fact, [26] as well as [55] have probed the Reynolds stress in bubble-laden turbulent channel flows and captured some change associated with bubbles of relatively large diameters (≈ 0.5 mm). But, their interpretation of the Reynolds-stress effect is somewhat questionable. The study in [27] focused on the change in the Reynolds stress near the wall, while the Reynolds stress should vanish on the wall due to the non-slip boundary condition. Furthermore, [73] measured velocity fields in a boundary layer with microbubbles generated by water electrolysis using particle-tracking velocimetry (PTV), and [74] analyzed the Reynolds-stress components in detail using particle image velocimetry (PIV).

The researchers in [75] generated microbubbles in a boundary layer using ultrasonic forcing and also measured the changes in turbulent velocity fluctuations as well as mean flow with stereoscopic PIV. However, none of these studies have been able to quantify the relationship between the Reynolds stress and the frictional drag on a wall. Thus, the mechanism of microbubble drag reduction remains to be fully explained.

By examining the turbulence intensities and Reynolds stress, an insight can be obtained that the buoyancy effect of bubble phase is to enhance the turbulence fluctuations across the channel in the upflow case and to suppress them in the downflows [71].

3.4 Near-Wall Void Fraction

Based on a controlled experiment using a flat plate turbulent boundary layer, [5] discovered that the amount of drag reduction strongly depends on the near-wall void fraction and the importance of bubble buoyancy. Authors in [30] found that the most important parameter in determining the fraction of drag reduction during gas injection is the effective gas phase volumetric flow rate, which is influenced both by the injection rate and static pressure under the test conditions.

The air flow rate and location of the injection position are significantly influence to get the maximum drag reduction. An experimental approach by [76] with a 70 cm catamaran model to determine the effect of air injection rate on drag reduction was successfully reduced total drag by about 5-8%. They found that excessive air injection decreases the drag reduction effect. While [77] suggested that the larger the bubbles were then subject to greater buoyancy and lift forces, which result in a decreasing trend of the near-wall gas void fraction and a gentle loss of skin friction reduction effect.

3.5 Vorticity

It is believed that the mechanism of drag reduction by spanwise-wall oscillation strongly relates to the spanwisevorticity generated at the edge of the viscous sublayer by the periodic Stokes layer [4]. It was demonstrated in the present study that the positive spanwisevorticity created by the spanwise wall oscillation reduces the mean velocity gradient of the boundary layer near wall. At the same time, the spanwisevorticity reduces the stretching of the longitudinal vortices in the viscous sublayer to reduce their streamwisevorticity. As a result, the near-wall burst activity, which is associated with the downwash of high momentum fluid near the wall is weakened leading to a reduction in turbulent skin friction reduction.

Currently, there is a common outstanding that the turbulence frictional drag is tightly related to the near-wall vertical structures ant the associated ejection events [78]. The near wall streamwise vortexes are responsible for high turbulence frictional drag in the turbulent boundary layer [79].

■4.0 SKIN FRICTION REDUCTION EFFECT

Injection of microbubbles has contributed to skin friction reduction effect and thus plays a very significant role to improve energy efficiency of ships. [19], conducted a micro-bubbles test using a circulating water tunnel with a long test section which allows measurement on the persistance of skin friction reduction effect by microbubbles. In the experiment, the bubbles are generated in the air chamber through a porous plate made of sintered bronzed with nominal pore radius. The average test flow speed was 7m/s or 14 knots which is the corresponding to the typical cruising speed of a tanker. The bubbles are clustered to near the top wall and the bubbles size produced is 0.5mm to 1.0mm in diameter. Figure 3 show the skin friction reduction from the experiment following on the position 2 (front), position 3 (midship) and position 4 (aft).

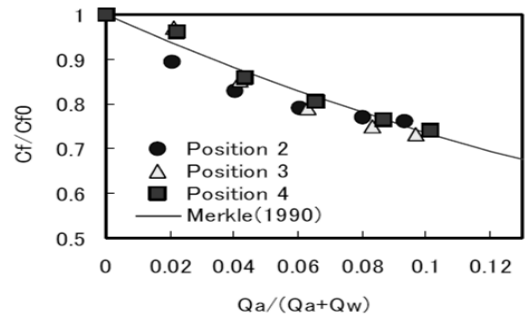


Figure 3 Skin friction reduction, ν = 7m/s [19]

The horizontal axis shows the average void ratio and vertical axis show the ratio of the wall skin frictionwith and without micro-bubbles. It is obviously seen that the skin friction resistance was greater at larger air injection at lower speed. The results agreed with the achievement of studies by many researchers, i.e the local void ratio close to the wall is important for skin friction reduction by microbubbles.

The authors in [15] have conducted test to study the reduction rate of skin friction by micro-bubbles, the result shows that the reduction of the frictional drag is possible up to 80%. On the other hands, the skin friction reduction by microbubbles measured on a 40 m-long flat plate ship [80] was much greater than estimated using [34].

■5.0 METHOD OF MICRO-BUBBLE GENERATION

Micro-bubbles can be generated by several methods. These including the electrolysis method, the porous method and the method of using a venturi tube type bubble generator. Different amount and sizes of bubbles can be produced from the different methods.

5.1 Electrolysis

Electrolysis is a method of producing micro-bubbles on the surface of metallic wire by applying high voltage or current. When an electrical power source is connected to two electrodes placing in water, hydrogen will be produced at the cathode and oxygen at the anode. The idea of drag reduction by microbubbles was first found by [11] using electrolysis method. A copper wire is used to wind around a fully submerged body of revolution to produce hydrogen bubbles by electrolysis and the drag force of the body is measured. The results show that the hydrogen bubbles is very effective in reducing the drag. The schematic diagram of the experiment is shown in Figure 4.

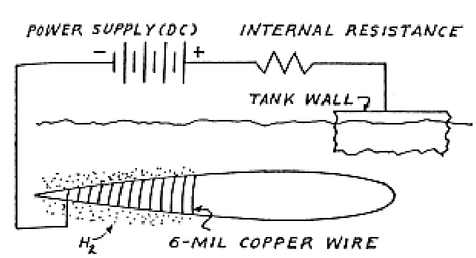


Figure 4 Schematic diagram of hydrogen microbubbles experiment [11]

5.2 Porous Method

The porous method is the simplest and most popular method that has been used by many researchers in the studies. It is a method where micro-bubbles are generated by injecting compressed air through a porous medium. There are a few types of porous medium can be used to generate tiny air bubbles. For example, [40] have used an array-of-holes plate with many regularly-spaced 1mm diameter holes (Figure 5) as the porous medium.

Researchers in [48] have used a porous medium which made of copper powder and [65] have injected the air through a porous plate made of sintered bronze with nominal pore radius of 2 μm. The schematic drawing of the micro-bubbles generation through porous medium is shown in Figure 6.

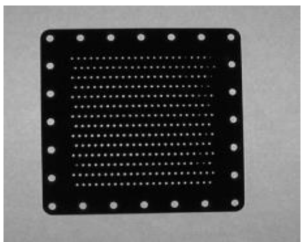


Figure 5 An array-of-holes plate with 1 mm diameter holes [40]

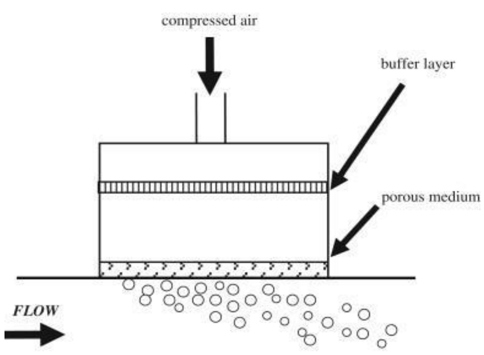


Figure 6 Schematic drawing of the microbubbles generation through porous medium [48]

5.3 Venturi Tube Type Bubble Generator

A venturi tube is a tubular setup which allows fluid to flow through a length of pipe of varying diameter. Due to the difference in pressure in the tube, bubbles are formed. Authors in [82] have used a venturi tube type bubble generator to produce micro bubbles. The air is first injected at the upstream side of the nozzle throat. As the mixture of the air and water passes the nozzle throat which has the minimum value of pressure, the bubbles grow. The recovery of the pressure at the diverging part of the nozzle will then cause the bubbles to break into pieces. Figure 7 shows the schematic sketch of the venturi tube type bubble generator used by [82].

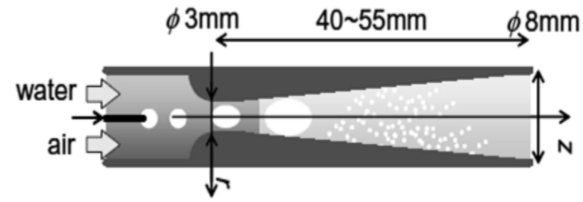


Figure 7 Schematic sketch of the venturi tube type bubble generator [82]

6.0 SKIN FRICTION MEASUREMENT

Many investigators have achieved micro-bubble drag reduction on a variety of methods, including flat plates, model scale of ship, towing tank experiments, rotary rotor, and by numerical computational method.

6.1 Flat Plate Experiment Method

The experimental study on micro-bubbles ejection method for frictional drag reduction through a single hole in a flat plate was intensively studied by [68]. They examined the relationship between the bubble sizes and drag reduction and found that the decrease in the bubble size due to the increase in the main flow velocity has contributed to a larger reduction rate of skin friction.

Meanwhile, [15] carried out an experiment using the boundary layer of the test section wall of water tunnel with injection of air from a porous plate. The result showed that with injection of micro-bubbles in the turbulent boundary layer of flat plate can reduce the drag of 15-80%. The bubble size and location of the injection points are important parameters in the persistence of drag reduction. Authors in [12] carried out experiments on the effect of microbubbles on the turbulent boundary layer along a flat plate and found that the surface friction depends on the maximum gas concentration in the boundary layer. The reduction of surface friction reached more than 80%.

Researchers in [83] performed an experimental characterization of the turbulent boundary layer over a flat plate in the presence of small amounts of micro-bubbles. The results obtained the drag reduction being up to 10%. The structure of flow turbulence in a water channel with micro-bubbles is studied using particle image velocimetry (PIV) at Re_x = 5128 [24]. They indicated that integral scales of micro-bubble flows with void fraction of 4.4% and 4.9% are corresponding to drag reduction of 29.8% and 38.4%, respectively. Authors in [84] performed an electrolysis in tap water using micro-fabricated devices in order to investigate the feasibility of generating mono-disperse micro-bubbles towards the development of high density bubble matrix. Experimental by injecting micro-bubbles mixed water through a slit into turbulent boundary layer was done by [85] to reduce frictional drag and obviously the drag became one tenth of the value without injection at optimum conditions.

Russian researcher, [86] developed a consistent asymptotic theory describing hydrodynamic and thermal boundary layers on a flat plate in zero pressure gradient and generalized direct consequences of the fact that in the boundary layer on a flat plate, the turbulent velocity field is determined by only three parameters, the density ρ, the kinematic viscosity υ, and the free-stream velocity u_e.

6.2 Model Scale Method

Skin friction reduction of full-scale ships has its own difficulties. [87] carried out experiments on ships at model and full scale, and the results of those experiments indicated a small increase in resistance of around 1%-2%. A model ship with scale 1/33 from a real 20000 ton cargo ship was made by [88] and achieved the maximum effect of small bubble method around 10.3% in a regular wave experiment.

6.3 Towing Tank Experiment

Recently, large-scale microbubble experiments were carried out in towing tanks. Researchers in [80] carried out a microbubble experiment by using a 40 m-long flat plate ship, and [89] also carried out a similar experiment using a 12 m-long flat plate ship. [76]investigated a model test results of a 70 cm catamaran model in the towing tank with length 25 m and achieved about 5%-8% of drag reduction with suitable injection rate.

6.4 Rotary Rotor Method

Scaling factor has caused a limitation associated with the flat plate. In order to overcome this problem, a further study about the effect of air bubbles at higher Reynolds number must be made. Herein, a rotary rotor method has been proposed. An experimental study of drag resistance of different painted surfaces and simulated large-scale irregularities, viz. dry spraying, weld seams, barnacle fouling and paint remains has been carried out by [24]. A laboratory scale rotary set-up was used to determine the drag resistance. Immersed surfaces were tested on the rotary rig shown schematically in Figure 8, which consists of two concentric cylinders with the innermost in rotation. The cylinder pair is immersed into a tank containing, 400 l of artificial seawater where the temperature is controlled using a heat exchanger. A similar method was used by [91] who carried out similar investigation.

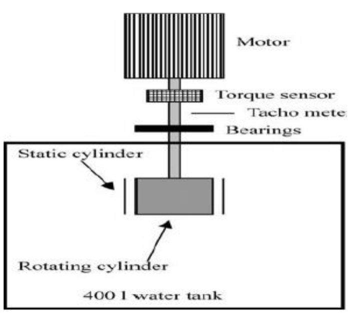


Figure 8 The laboratory scale rotary set-up [91]

6.5 Numerical Computational Method

The structure of flow turbulence in a water channel with micro-bubble is studied using particle image velocimetry (PIV) at Re_x = 5128 [24]. The results show that the integral scales of micro-bubble flows with void fraction, α, of 4.4% and 4.9% which are corresponding to drag reduction of 29.8% and 38.4%, respectively. Authors in [7] performed a two-dimensional single phase computational fluid dynamics (CFD) model of micro-bubble laden flow over a flat plate to access the role of mixture density variation in micro-bubble drag reduction. Their studies indicated that simple mixture density variation effect plays one of the major roles in micro-bubble phenomenon.

The drag reduction by micro-bubbles was investigated by [92] in detail with Euler-Lagrange two-way coupling method in order to understand the drag reduction mechanism by micro-bubble by using DNS method. Recently, [63] attempted to model microbubble coalescence and break-up and validated their numerical results against three sets of data; one with DNS, along with two sets of experiments.

[93] at the University of Michigan recently conducted a direct numerical simulation (DNS) study, demonstrating that the skin friction drag of a turbulent channel flow can be reduced by oscillating one of the walls in the spanwise direction. Their result show that a 40% reduction in turbulent skin friction drag can be obtained only after five periods of spanwise-wall oscillation with the non-dimensional period T^+ set at 100. The basic findings of this investigation were later confirmed by [94] in their DNS study. They also investigated the effect of the wall velocity on the total energy balance of this drag reduction technique and found that net energy savings are possible at a low wall-oscillation velocity.

These numerical simulations were followed by an experimental investigation by [95], which demonstrated that the mean velocity gradient of the boundary layer is reduced near an oscillating wall. The reductions in turbulence intensities across the boundary layer were also shown, suggesting that the skin friction drag of the turbulent boundary layer may be reduced by the spanwise-wall oscillation.

The reduction of skin friction drag in the turbulent boundary layer with the spanwise-wall oscillation was later confirmed by [96] in their experimental study. They measured the streamwise variation of wall-shear stress over an oscillating plate and showed that the skin friction coefficient begins to reduce just upstream of the leading edge to reach the maximum level of drag reduction near the middle of the plate. Their results indicate that the skin friction coefficient is reduced as much as 45% compared with a stationary wall.

Meanwhile, the use of a discrete vortex model (DVM) simulations made by [97] show that the entrainment and accumulation of bubbles within the large-scale coherent structures tended to reduce the vorticity strength and pressure gradients throughout the vortex, resulting in larger bubble dispersion. The numerical model [98] assumes that the bubble makes a point contact with the wall (horizontal plate). Like many studies of isolated bubbles [57] and [99-101] this work assumes that the effect of liquid velocity can be ignored ($\varepsilon = 0$), and that the bubble is small enough to remain spherically symmetric because of the presence of the wall. The study from [102] employs the molecular dynamics (MD) simulation method to investigate the surface tension of small bubbles and their characteristics. To define a bubble, a void grid structure is constructed and the calculation domain is centered artificially on the mass center of void packets.
Unfortunately, the major worry about turbulence modelling by using this simulation is that one cannot estimate the errors of the computer results [103]. Indeed, it is impossible even to define error bounds.

■7.0 APPLICATION OF MICRO-BUBBLE DRAG REDUCTION ON SHIPS

In order to apply micro-bubble to full-scale ships, net drag reduction must be achieved. That is, the energy saved by skin friction must be at least greater than the energy spent to generate bubbles against the hydrostatics pressure at the bottom of a ship.

The concept of using micro-bubble to reduce the drag of ship hulls has been present for many years, and [11] came first with their experiment by using a copper wire wound a towed body of revolution to produce hydrogen bubbles via electrolysis. [8] discussed the net drag reduction of micro-bubbles to ships based on the experimental data of skin friction reduction by defining the water flow rate $Q_w$as Q_w= Ub.(δ-δ*), where b is the boundary layer width, δ is the boundary layer thickness and δ* is the displacement thickness. This relation assumes that the boundary layer thickness is the representative length of this phenomenon.

Researchers in [80] measured in their towing tank, the skin friction reduction by micro-bubbles on a flat plate 20 or 40 m long and 0,6 m wide, using skin friction sensors similar to those used in the present study, and [89] carried out a similar experiment using 12 m-long flat plate ship. [104] have experience with the ship in drag reduction research by utilizing air film to replace the blow of micro-bubble from which it was found to have better performance in drag reduction. The air film experiment studied is based on 7 and 16 m flat plate model ships. The efficiency of drag reduction from 7 m model ship is approximately 20% at the speed of 7 m/s and 30% at the speed of 4 m/s.

■8.0 CONCLUDING REMARKS

As discussed above, many researchers have been struggled so much to investigate the effectiveness of microbubbles to apply to ships. Yet, there are a lot of questions could not get the exact answer about the mechanisms of microbubbles production. Further research should be continued to enable the development of modification of turbulent boundary layer and thus increasing the ship efficiencies.

Nomenclature

Symbols	
Re_x	Reynolds number
V	velocity
Q_w	water flow rate
b	boundary layer width
Greek symbols	
α	local void fraction
Ø	diameter of nozel
ρ	density
υ	kinematic viscosity
U∞	free stream velocity
ε	free space permittivity
δ	boundary thickness
δ^*	displacement thickness
Superscript	
T^+	non-dimension of period

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