Reviews on Skin Friction Drag Reduction by Micro Bubble Injection

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Abstract- The fluid frictional drag is found to be about 60- 70% of the total drag for cargo ship, and about 80% of that for a tanker. Frictional drag plays the major role of the overall resistance, especially in low speed merchant ships. The main influencing factors for reduction of skin friction are area of hull under water and flow over this surface. Modification of these factors is practically tough. Thus, a mechanism to vary the viscosity of the boundary layer around the ship becomes a necessity for the skin friction drag reduction. As flow velocity increases, turbulent effect become more critical in boundary layer and skin friction becomes stronger. Therefore, ship designers focus more efforts on surface characteristics improvement methods. To control the turbulence for reducing frictional resistance in boundary layer, so many methods were proposed by various researchers. Among these techniques, the drag reduction by micro bubbles has got wide acceptance mainly because of various benefits like environmental friendships, easy operations, low costs, high saving of energy etc. From various literatures, it was found that up to 80% drag reduction can be attainable using micro bubble injection method in flat plate experiments. Researchers also pointed out that substantial fuel savings can be achieved even at a very small gain in total drag reduction.

Keywords – Micro bubbles, drag, skin friction

I. INTRODUCTION

The transportation of 95% of world's cargo is through marine industries. In ships, the 85% of available energy is applied to overcome hydrodynamic forces. So reducing total hull drag has got primary importance in marine field. Hull resistance primarily affects the velocity of vessels, power requirements and consumption of fuels. Many methods are available for reducing pressure and viscous resistances. Improvement in vessel's shape with different hull forms and optimizing these forms can reduce the pressure drag. New hull forms are found to be effective in minimizing the level of residuary drag in major fields such as military application. This encouraged researchers to modify the physical features of new marine vehicles. To control the viscous resistance, other techniques are needed. Among these techniques, implementation of micro bubbles around the hull is best suited to reduce viscous resistance. By applying micro bubbles, the viscosity of fluid around the hull varies, which changes form of turbulent boundary layer, results in reducing surface friction. However, the optimization of the bubble parameters like diameter, mass flow rate, area of coverage, number of bubble injection points etc are still the significant areas of research in this topic. The initial part of this literature review gives an outline of various air lubrication techniques. Then, attention is focused on effect of bubble parameters, generation of these bubbles around the hull, micro bubble injection mechanism, measurement of drag etc. For every section, related numerical as well as experimental studies have been categorized and discussed.

II. AIR LUBRICATION TECHNIQUES

Air lubrication is the method of injecting air around the hull surface, which either creates a bubbly flow or a blanket of gas. In recent times, significant amount of researches of air lubrication have been conducted in various marine applications. Ceccio S.L. et al. [1] conducted study regarding the economic as well as environmental effects of air lubrication drag reduction method and obtained a skin friction reduction of 5 to 20 %. This technique was exemplified into three sections namely, Air Layer Drag Reduction (ALDR), Partial Cavity Drag Reduction (PCDR) and Micro-bubble Drag Reduction (MDR).

In ALDR method, a steady air sheet is applied between the vessel and water area. This method results more drag reduction than PCDR and MDR method. Elbing *et al.* [2] found that for attaining ALDR, the critical volumetric air flux seems proportional to second power of free-stream velocity. To form a stable air layer at a full irregular surface, around 50% more volumetric air flux is needed at free stream velocity up to 12.5 m/sec. They also suggested that inflow conditions affects air layer drag reduction. Sanders [3] proposed from his research that, a gas layer which forms under the flat plate will remain on the full length at low flow speed with high air injection rate. Based on this study, more than 80 % of drag reduction may be attained by such layers. From these researches, it is found that ALDR is an alternate solution for PCDR and BDR.

In Partial Cavity Drag Reduction method, the length of cavity is not expanded along the entire length like ALDR method at lower velocity situations. Bell J.W. et *al.* [4] tried to adapt artificial air cavity for the first time in flying boats. Butuzov *et al*. [5] in their work, tried to lengthen the cavity throughout entire bottom of hull. Matveev *et al.* [6] found that larger cavities are required for the air injection at low flow rates. Using this method, around 30% drag reduction can be attained in planing hulls. According to the findings by Butuzov A. *et al.* [7], 3% of engine power is utilized for retaining the low pressure air fans to maintain supply pressure. Matveev K.I. *et al.* [8, 9] proposed that there are some applications of air cavity in ship hydrodynamics such as: reduction of wave drag, lowering underwater hull noise radiation, shocks etc. especially on multi-hull vessels. Ceccio S.L. *et al.* [1] also found some disadvantages of this PCDR method which is that it needs changes at bottom of hull. One of the drawbacks of PCDR method is that it requires high primary investment. But the operating cost of this method is less. It also gives higher skin friction reduction at lesser gas flux.

III. MICRO BUBBLE DRAG REDUCTION

Injection of micro bubbles has contributed to skin friction reduction effect and thus plays a very significant role to improve energy efficiency of ships. Micro bubble drag reduction method is providing air bubbles in between hull surface and surrounding fluid to reduce skin friction. The important subjects in bubble injection technique are micro bubble characteristics, generation, distribution of bubbles around the hull, effects of micro-bubbles on turbulent boundary layer, the skin friction measurements etc.

IV. MICRO BUBBLE CHARACTERISTICS

Since micro bubble injection is one of the most promising way of drag reduction, the bubble characteristics has got very serious attention among researchers. The impact of these parameters should be figured out because the optimum combination of these factors during the time of will definitely produce maximum reduction of drag.

Kodama Y. *et al.* [10] and Merkle C.L *et al.* [11] proposed that bubble size is one of the major factors influencing frictional resistance. According to their studies, due to the turbulence generated in bubble wake, there is a chance of increase in frictional resistance, if the bubbles are of a few millimeters. According to Steven L. Ceccio *et al.* [12], speed of fluid and rate of ejection of air bubbles decides the bubble size. The hole size on plate has no role in diameter of bubbles. The research works of Kanai A. *et al.* [13] and Shen X. *et al.* [14] shows that reduction in drag can be obtained only when the size of bubble is less than about 1 mm and rate of drag reduction is higher when the bubble diameter is smaller. Xu J. *et al*. [15] got an increase in drag reduction with decrease in bubble diameter and suggested that small sized bubbles are more effective in reducing skin friction. The photographic records of Winkel. E. S. *et al.* [16] showed that the increase of salinity monotonically decreases mean bubble diameter which have a significant effect on drag reduction. Takahashi T. *et al*. [17] found that drag reduction is not influenced by variation in bubble diameter and thickness of boundary layer at Reynolds number of the order of 25 million. Bubble sizes of 250 to 1000 µm shows similar insensitivity to drag reduction at same Reynolds values obtained by researchers Kawamura T. *et al* [18]. From inspection of the size and shape of bubble near wall, Janssen L. J. J. *et al.* [19] indicated that bubble coalescence is much prevalent than bubble splitting when bubbles move downstream. From the measurement of time-resolved image, Steven L. Ceccio *et al.* [12], observed oscillatory bubble motion vertically, this is more relevant in upstream. In downstream, due to coalescence, the size becomes greater. So the interaction of bubbles and vertical structures near the wall diminishes downstream. While Gabillet C. *et al.* [20] found that the bubble layer got expanded in a quasi linear manner with the distance downstream at a rate of expansion depending on the bubble diameter.

According to the bubble nucleation studies of Jones S. F *et al*. [21], the bubble size has a major role in the modification of momentum and energy transfer in boundary layer by bubbles. The bubbles have the ability of growing and detaching from substrate once nucleation process has been completed. So many factors influences bubble growth rate like rate of molecular diffusion, fluid inertia, viscosity, surface tension etc. Profound influences by bubbles on inertial and dissipation scales have been demonstrated by the experimental work of Rensen. J. *et al.* [22] and direct numerical simulation (DNS) of Ferrante. A. *et al*. [23]. The DNS results of Lu. J. *et al.* [24] indicates that drag reduction by micro bubbles strongly related to energy containing scale modification by large bubbles. Experimentally investigating, various factors that influences bubble size on drag reduction are capturing the bubble trajectories, difficulties in bubble size variation, bubble size distribution in boundary layer and its measurements.

Moriguchi. Y. *et a*l. [25] through their experimental work with varying the bubble size proposed that bubble size is an insignificant factor for drag reduction. Shen X. *et al*. [14] studied experimentally the influence of bubble diameter on the effectiveness of frictional drag reduction in high speed channel flows. A floating element force balance used for measuring wall friction force for single phase flow and flow with bubbles. Photographic imaging was used for bubble size determination in this study. Kawamura T. *et al.* [26] proposed bubble size scaling with boundary layer thickness and wall turbulence structure. The experimental study of bubble size distribution was done by Lage P. L. C *et al*. [27]. They suggested that the size distribution of injection bubbles, escape frequency of bubbles etc affects the bubble size distribution inside a bubble column. The sizing of bubbles has got so much of importance according to the work by Ira Leifer *et al.* [28]. They found that when threshold intensity decreases, bubble size increases. Toshiyuki Sanada *et al.* [29] observed that the trajectory patterns of rising bubbles are strongly dependent on the Reynolds number. Legendre D. *et al.* [30] conducted numerical investigation using DNS about the motion of a pair of spherical rising bubbles which are horizontally aligned. They also showed that the direction of motion of the bubbles changes according to Reynolds number. In another flat plate experiment by Kawamura *et al*. [31] with same variation in bubble diameter, found that micro bubble drag reduction is favourable for larger bubbles because they tend to remain closer to hull surface. To fully understand the bubble size influence on skin friction drag reduction, experiments under controlled conditions with large variation in bubble size are necessary.

The position of bubble injection is another major parameter that needs to get attention in reviewing the frictional drag reduction by micro bubbles. Deutsch S. et al. [32] conducted an experiment to test the efficiency of micro bubbles on resistance reduction on high speed vessel model. They conducted experiments with varying the position of bubble injector as shown in figure 1. From the results, they suggested that position 3, i.e. behind the midship is the most suitable position for attaining the best drag reduction which is about 6-9%. Position 1 in the figure indicates front of midship and position 2 at midship.

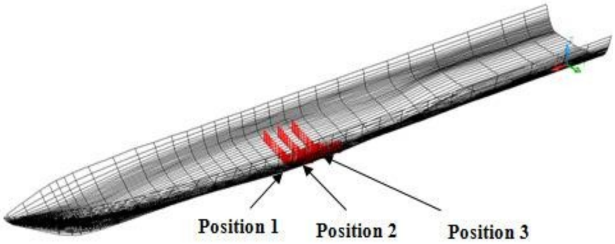


Figure 1 Micro bubble injector position

Kitagawa A. *et al.* [33] also suggested that the reduction of viscous drag is greater in the aft injection case. However, Tsai J.F. *et al*. [34] conducted their studies by placing bubble injector near the bow of the model. YAMATAI, the world's first marine vessel which is equipped with permanent air lubrication system placed its air outlet near the bow as shown in figure 2 [35].

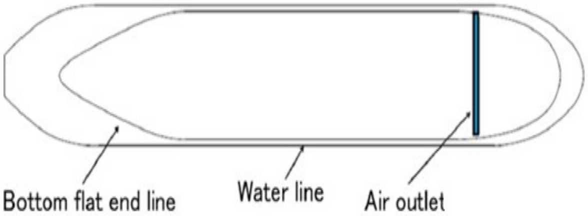


Figure 2 Location of air outlet viewed from the bottom, YAMATAI

Kodama Y. *et al.* [10] through their experimental work in a circulating water tunnel claimed that behind the mid ship is the most suitable position for attaining effective drag reduction. Madavan N. K. *et al.* [36] did various experiments on micro bubble filled turbulent boundary layers on a rectangular plate. They found that the effect of bubbles were best when ejected on top than from bottom. They explained this phenomenon in a way that the micro bubbles causes the reduction of turbulence intensity which increases the effective viscosity of the water- bubble mixture.

V. MICRO BUBBLE GENERATION

Several methods are used by marine engineers for the generation of micro bubbles. Each method has its own significance in bubble generation. Bubbles with different sizes and quantity can be produced with these methods.
The generation of bubbles was first conducted by McCormick M. E *et al.* [37] using Electrolysis method. They produced micro bubbles on metallic wire surface by applying high current and voltage. The fully submerged body was winded by using copper wire to produce hydrogen bubbles by electrolysis as shown in figure 3. From their experiments, they proved that hydrogen bubbles are so much effective for the skin friction drag reduction.

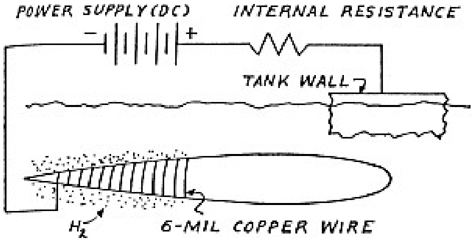


Figure 3 Schematic diagram of experimental setup for hydrogen bubble generation by electrolysis

The simplest and most widely used method for micro bubble generation is porous method. In this method, compressed air is injected through a porous medium to produce micro bubbles. Different types of porous medium are used by researchers for the tiny air bubble generation. Takahashi T. *et al.* [17] used an array of holes plate as porous medium with holes of 1 mm diameter regularly placed as shown in figure 4.

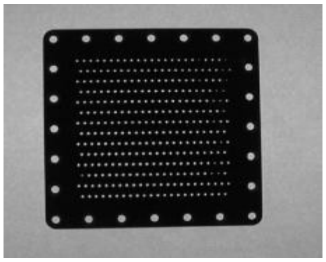
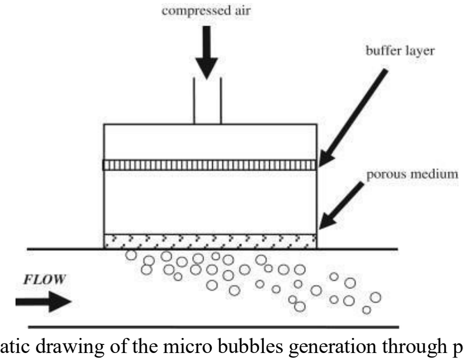


Figure 4 An array-of-holes plate with 1 mm diameter holes

Kawamura T. *et al.* [26] made use of porous medium which is made of copper powder and Kodama Y. *et al.* [38] produced air bubbles through porous plate made with sintered-bronze having hole size of 2 μm as shown in figure 5.



.Figure 5 Schematic drawing of the micro bubbles generation through porous medium

Another way to generate micro bubbles is by using a Venturi Tube Type Bubble Generator. This tube has a converging and diverging section. When fluid is allowed to flow through this pipe of varying diameter, bubbles are formed due to the pressure difference in tube. Figure 6 shows the schematic diagram of experimental set up to produce bubbles by Kawamura T. *et al.* [31]. In this setup, at the upstream side of the nozzle throat the air is injected. As the air water mixture passes through the throat of tube, the bubbles grow because of low pressure. Then this bubble passes through the diverging part which causes the bubbles to break into pieces.

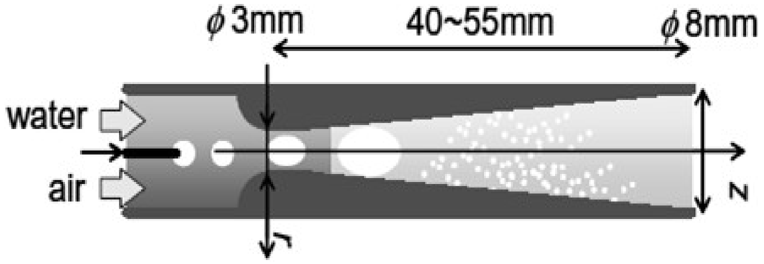


Figure 6 Schematic sketch of the venturi tube type bubble generator

VI. EFFECTS OF MICRO BUBBLES ON TURBULENT BOUNDARY LAYER

Due to complexity of the problem itself, a widely acceptable mechanism is not there to explain the micro bubble injection. One popular explanation is that the micro bubbles present in boundary layer increases the effective viscosity of fluid. This reduces the Reynolds stress which changes velocity profile that reduces velocity gradient of fluid near hull surface.

Mengs J.S.C. *et al*. [39] suggested that the main reasons for suppressing the turbulent flow in boundary layer is the splitting of bubbles. Guin M.M. [40] tried to associate bubble passing frequency with the drag reduction. Kanai *et al.* [13] showed that there is a decrease of stream wise vorticity due to the existence of bubbles which prevents developing sheet like structure of the span wise vorticity near the wall. Thus skin friction reduction is achieved. The study of Xu. J *et al*. [41] suggests that the drag reduction is associated with at least three mechanisms involved: the bubble initial injection, the density effect, and the definite correlation between the micro-bubbles and liquid turbulence. Studies of Lu J. *et al*. [24] and Kitagawa A. *et al*. [33] suggested that the bubble deformation causes drag reduction. The study of Van-den-Berg T.H *et al*. [42] suggested that the skin friction reduction by micro-bubbles related to bubble deformability and effective flow compressibility. From many researches, the main positive impact factors on drag reduction are found to be density effect, turbulence suppression, Reynolds stress, vorticity and near-wall void fraction.

According to Kodama Y. *et al*. [38], due to lower density of air, air bubbles near hull surface prevents shear stress formation in fluid that reduces viscous resistance. The influence of density of micro bubbles at turbulent boundary layer was studied parametrically by P.V.Skudarnov *et al*. [43]. A gradual increase of resistance reduction at the lower density ratio shows that simple mixture density change plays major part in declining skin friction. But A. A. Fontaine *et al.* [44] found that density or composition of applied bubbles have no effects on micro bubbles drag reduction. Legner. H.H. *et al*. [45], Marie. J.L. *et al*. [46] and Lvov. V.S. *et al*. [47] suggested that the combined effects of reduction in mixture density and modification of effective viscosity inside the boundary layer is the reason for drag reduction by micro-bubbles. Xu. J. *et al.* [41] from their Direct Numerical Simulations DNS), explained drag reducing mechanisms associated with the density effects, with the reduction in turbulence momentum transfer due to bubbles.

Turbulence suppression in the boundary layer is another possible mechanism for skin friction reduction. The researchers Kato. H. *et al*. [48] found that as skin friction increases, measured turbulence intensity decreases. Authors Meng. J.C.S. *et al.* [39] suggested that reduction of turbulence in a boundary layer is due to bubble splitting. From studies of Kitagawa. A. *et al.* [49], with respect to the flow, bubbles deformed with a favorable orientation, and as the flow field around the bubble was more isotropic, turbulent stress reduces. Madavan. N. K *et al.* [50], Legner H.H *et al.* [45], and Marie J.L *et al.* [46] did analytical calculations of micro bubble drag reduction. A simple stress model in which eddy viscosity was assumed to decrease in direct proportion to the density of the mixture is proposed by researchers Kawamura. T. *et al.* [31]. An analysis of mixed boundary layer using mixing length model was done by Madavan. N.K. *et al.* [51]. They used the local properties of viscosity and density for expressing the van Driest damping coefficient. From their analysis, an important finding was that the bubbles were most effective when they were in the buffer layer. By comparing the scale of turbulence eddies and scale of dissipation, Researchers Legner. H.H. *et al.* [45] calculated the thickness of sub layer and suggested that viscous sub layer thickening was the mechanism in the drag reduction. While Xiang M. *et al.* [52] conducted studies on the effect of buoyancy and gravitational acceleration on bubble motion. Xu. J *et al.* [41] stated that the moving minute bubbles which travel into the wall and outer regions of turbulent boundary layer absorbs turbulent momentum along with changes in characteristics of the drag producing vortices.

Ferrante. A. *et al.* [53] demonstrated direct numerical simulation (DNS) for drag reduction on spatially-developing boundary layer at relatively low void fractions. They suggested that the shifting of Reynolds stress and change of position of stream wise vortices are the mechanism of drag reduction. From further Direct Numerical Simulation studies, they found that micro bubble drag reduction becomes less effective at the higher Reynolds number. In fact, Akoi. K. *et al.* [54] as well as Kitagawa A. *et al.* [49] have captured some change associated with large diameter bubbles and examined the Reynolds stress in bubble-laden turbulent channel. Murai. Y *et al.* [55] focused their studies on the change in the Reynolds stress near the wall, while due to the non-slip boundary condition, the Reynolds stress should vanish on the wall. Furthermore, Ortiz-Villafuerte J. [56], Gutierrez–Torres C. C [57] made use of Particle Tracking Velocimetry (PTV) for the measurement of velocity fields in a boundary layer and particle image velocimetry (PIV) for the Reynolds-stress components in detail. Using ultrasonic forcing method, the researchers Park Y. S. *et al*. [58] created micro bubbles in a boundary layer. They measured the changes in turbulent velocity fluctuations as well as mean flow with stereoscopic PIV. Xiang M. *et al.* [52] examined the turbulent intensities and Reynolds stress, suggested that in up flow case, the buoyancy effect of bubble phase enhances turbulent fluctuations and suppress them in down flows. The mechanism of micro bubble drag reduction still remains to be fully explained, because no studies have been able to explain correctly the relationship between Reynolds stress and frictional drag.

The influence of void fraction in drag reduction was initially studied by Legner. H.H. *et al.* [45] and found that increase in void fraction rises local effective viscosity. That decreases turbulent momentum transfer. Janssen. L. J. J *et al.* [19] also suggested that the near wall void fraction and bubble buoyancy strongly affect drag reduction. Shen X. *et al.* [14] found that effective gas phase volumetric flow rate is the most important factor in determining micro bubble drag reduction. Under test condition, the injection rate plus static pressure are parameters which influences volumetric flow rate. Sayyaadi H. *et al.* [59], through their experimental approach reduced total drag by about 5-8 % on a 70 mm catamaran model and suggested that for getting maximum drag reduction, air flow rate and location of injection positions are the main factors. They also found that excessive air injection decreases drag reduction effect. While Liu Nan-sheng *et al.* [60] found that larger bubbles due to their higher buoyancy and lift forces, decreases the trend of near wall gas void fraction, thus the effect of skin friction gently losses.

The effect of Vorticity in micro bubble drag reduction was effectively studied by Lee C. *et al.* [61], Choi K. S *et al.* [62] and Fukagata K. *et al*. [63]. Lee C *et al*. proposed that high turbulence viscous drag in turbulent boundary layer is the primary reason for near wall stream wise vortexes. Choi K S *et al*. found that the span wise vorticity generated near viscous sub layer strongly affect the span wise wall oscillation which is related to mechanism of drag reduction. The span-wise wall oscillations generates span-wise vorticity that minimizes mean velocity gradient of turbulent boundary layer adjacent to wall and stretches longitudinal vortices in viscous sub layer, thus stream wise vorticity reduces. As result, the near wall burst activity is weakened and the drag reduction loses. Currently, Fukagata K. *et al.* suggested that turbulent skin friction strongly related to near wall vertical structures and the associated ejection events.

VII. MEASUREMENT OF FRICTIONAL DRAG

There are so many researches which made use of Flat plate experiment method from ancient years. The first attempt in this area was done by Madavan N. K. *et al.* [50]. They injected air through a porous plate to the boundary layer of the test section and measured the reduction of drag as 15 – 80%. They also suggested that bubble size and location of injection points are the main factors for efficient drag reduction. Kato H *et al.* [62] passed the bubbles through a single hole in a flat plate. Bogdevich V. G. *et al.* [79] through their flat plate experiment found that skin friction mainly depend on maximum bubble concentration in the boundary layer. They got a reduction in skin friction as 80%. Kato H. *et al*. [64] through their experiment, injected bubbles mixed with water though a slit into the boundary layer and got a drag reduction of one tenth of the value without applying optimum condition. Hassan Y A. *et al*. [65] made study of structure of flow turbulence using Particle velocimetry and considered the effect of void fractions. Jacob B. *et al*. [66] experimentally measured drag reduction as 10% on boundary layers of flat plates. Russian researcher Vigdorovich I. I. [67] developed a consistent asymptotic theory for the hydrodynamic and thermal boundary layers on a flat plate and suggested that the main parameters which affect drag reduction are density, kinematic viscosity and free stream velocity.

Model Scale Method is another approach used by a few researchers recently for measurement of skin friction in vessels. Foeth E. J *et al.* [68] conducted model and full scale experiments, but found that there is a small increase of about 1 – 2% in resistance. Phan Anh Tuan *et al.* [69] carried out experiment in model ship with scale 1/33 from a real 20000 cargo ship and they claimed the drag reduction of 10.3% in a regular wave experiment.

In order to overcome the limitations of scaling factor associated with flat plate method, another method called rotary rotor method is proposed to find the effect of micro bubbles at higher Reynolds number. Hassan Y. A *et al.* [65] successfully carried out experimental studies on various surfaces, done simulations on large scale irregularities. For determining the skin friction, a laboratory scale rotary setup was used in this study. As seen in the schematic diagram of figure 7, submerged areas were tested on rotary rig. This set up has two concentric cylinders and the inner cylinder is able to rotate. The temperature can be controlled by heat exchanger. Artificial sea water is contained in a tank where the two cylinders are immersed. A similar investigation was also conducted by Haosheng C. *et al*. [70].

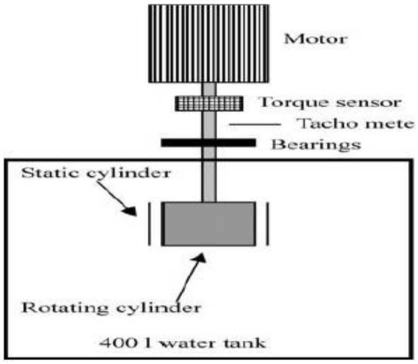


Figure 7. The laboratory scale rotary set-up

Recently, Towing tank experiments are carried out in large-scale micro bubble experiments. Researchers like Watanabe O. *et al.* [71], Lee C. *et al.* [61] and Sayyaadi H. *et al.* [59] successfully carried out frictional drag tests using 40 m-long flat plate ship, 12 m-long flat plate ship and a 70 cm catamaran model respectively in the towing tank with length 25 m and achieved about 5%-8% of drag reduction with suitable injection rate.

Due to the advancement in computational facilities, Numerical simulations using Computational Fluid Dynamics (CFD) is found to be one of the most effective tool for the measurement of complex frictional drag analysis problems. So many researches are going on in marine industries nowadays using CFD mainly because of the advantage that this acts as a non destructive testing method. P.V. Skudarnov *et al.* [43] studied effect of mixture density variation on flows over a flat plate, using CFD analysis. Mingjun Pang. *et al.* [72] used Euler-Lagrangian two-way coupling method on micro-bubble using DNS. Recently, Kunz R.F. *et al.* [73] modeled the bubble coalescences and break-ups. Later they validated the DNS numerical results with two sets of experiments. Jung W. J. *et al*. [74] recently conducted a DNS study at the University of Michigan, demonstrated that reduction of viscous drag in turbulent flow may be minimized by the oscillation of one wall in span wise direction. They resulted that after five periods of span wise wall oscillation, 40% lose in drag may be obtained. These investigations were validated by Baron A. *et al.* [75] using DNS studies. After that Laadhari F. *et al*. [76] experimentally demonstrated these numerical simulations and suggested that the mean velocity gradient of the boundary layer is reduced near an oscillating wall. The skin friction drag of the turbulent boundary layer may be reduced by span wise-wall oscillation. Choi K. S. *et al*. [62] later experimentally reduced viscous drag in turbulent boundary layer with span wise wall oscillation. According to their results, the skin friction coefficient is reduced by 45%. Meanwhile, Yang X. *et al*. [77] conducted discrete vortex model (DVM) simulations and found larger bubble dispersion due to the reduction in vorticity strength and pressure gradients throughout the vortex because of accumulation of bubbles within large scale coherent structures. Some researchers conducted the numerical simulations on fluid properties for drag reduction. Sandra Kentish *et al.* [78] numerically modelled the bubbles which made point contact with the solid wall. Park S. H. *et al.* [79] conducted Molecular Dynamic (MD) simulation to investigate the effect of surface tension of small bubbles and their characteristics. They ignored the effect of liquid velocity and assumed that the bubbles are small enough to remain in spherical shape due to the presence of wall. But their work got a disadvantage that one cannot estimate the errors of the computer results.

VIII. CONCLUSION

The first part of this paper describes various Air lubrication techniques implemented in marine industry. On the later stage, the attention is focussed into the area of micro bubble injection method for the reduction of frictional drag for improving hydrodynamic performance of ships. This literature survey is classified into four important areas such as bubble characteristics, its generation, influence of bubbles on turbulent boundary layer, measurements of drag etc. The energy saved from skin friction drag reduction should be greater than the energy spend for the generation and distribution of bubbles against hydrostatic pressure under hull. Then only, this method becomes effective to implement in full scale ships. This survey reveals that air lubrication techniques got proper effects on minimizing skin friction drag.

Various numerical and experimental investigations in each of the above mentioned areas were conducted by researchers from early 70s. But, it was found that further researches are still need to improve the micro bubble performance. The numerical study of the influence of bubble parameters and a suitable methodology to optimise these parameters for effective results are future scope in this area. It is suggested that due to the advancement in computing technology, Computational Fluid Dynamics is proposed to be one of the effective tool to address these problems. From this review, it is observed that the substantial works are focused on the effects of bubbles, their generation and measurements. But the studies regarding the issues of stability and proper distribution of these generated bubbles is to be well addressed for maximum drag reduction. So it is suggested that research improvements associated with these inevitable considerations are largely opened for the researchers in near future in the area of ship hydrodynamics.

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