SKIN FRICTION REDUCTION

BY

MICRO BUBBLES IN PIPE FLOW

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Recently, micro bubbles injection has emerged as a promising drag reduction device in ships due to their significant reduction in frictional drag, cost-effectiveness, environmental-friendly and easy to implement in an existing ship. Frictional drag reduces up to 80% by injecting micro bubbles to the boundary layer. However, the mechanism of drag reduction by micro bubbles is complicated and poorly understood. Therefore, this study is sought to clarify the mechanism of drag reduction by micro bubbles in the most basic flow condition as the mechanism remains unknown. Several controllable factors associated with the efficiency of micro bubbles in drag reduction were investigated to identify the optimum condition for skin friction reduction by micro bubbles. As the results, a higher reduction rate was obtained with larger distribution area of attached micro bubbles at the tube wall in smaller Reynolds number. Moreover, the distribution area and size of micro bubbles at the tube wall increase with time and contributed a great effect in pipe friction loss. Furthermore, void fraction contribute a significant effect in micro bubbles efficiency. Flow pattern and the bubble's behaviour were observed by flow visualization. The ideal bubble size and distribution were evaluated by the measurement of skin friction. Based on the tube's visualization, the wall shear stress in the upper half of the tube decreased as the bubbles were injected into the boundary layer.

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1.1 Micro bubbles properties

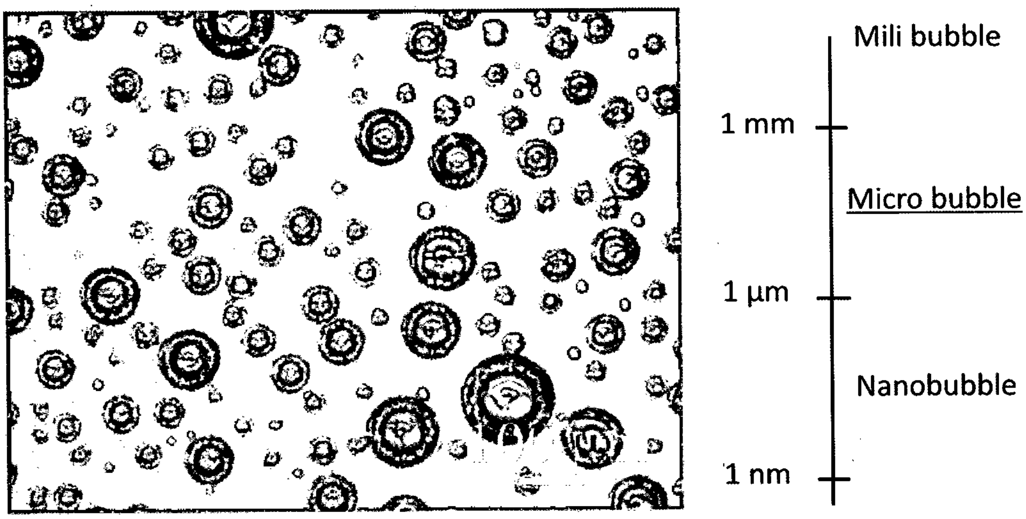


Fig 1.1: Micro bubbles (10μm-50μm in diameter)

Micro bubbles are defined as small bubbles which smaller than 50μm but larger than 10μm in diameter. These tiny bubbles are much bigger than they sound. Unlike the ordinary bubbles around us (with diameters more than 1 millimeter), they are characterized by having special and unique characteristics as follows;

(a) Rising speed

Since the volume of the micro bubbles is small compared to normal bubble, its buoyancy is also less, so it reaches the surface very slowly. As shown in figure 1.2, in general, the ordinary bubbles around us or also known as macro bubbles (with diameter more than 50μm) will usually rise up, expand and burst at the surface of the water. However, these micro bubbles will gradually rise, and then the gas within the bubbles will disperse into the water, shrinking and finally disappear. Therefore, the rising speed of milibubbles (diameter >1mm) is about 3610 times faster than the micro bubbles. Bubble's rising speed can be calculated by using stokes law as shown below.

$$V = \frac{1}{18} \text{ x } g\frac{d^2}{v}$$

V (m/s) = bubble's rising speed

d (m) = bubble's diameter

g (m/s^2) = gravitational acceleration

v (m^2/s) = liquid viscosity

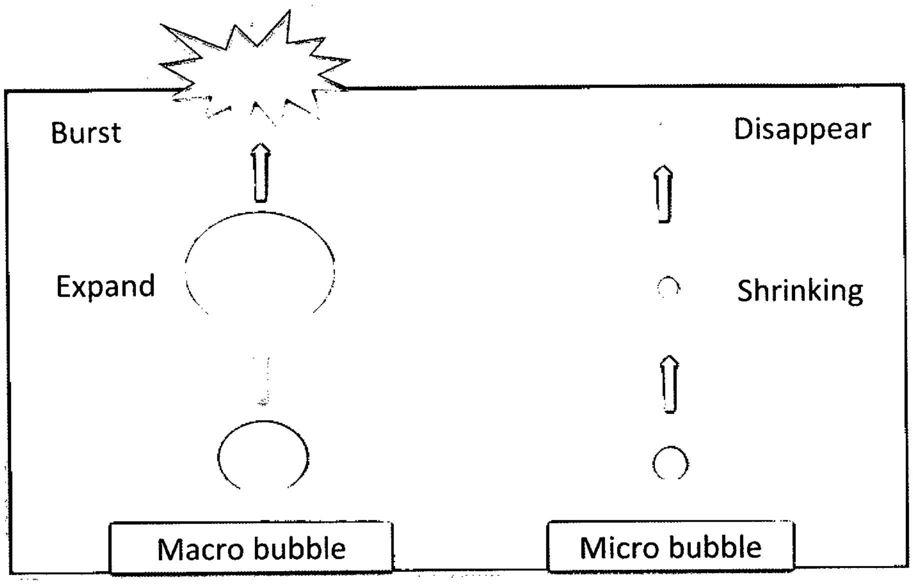


Fig 1.2: Micro bubbles life-span

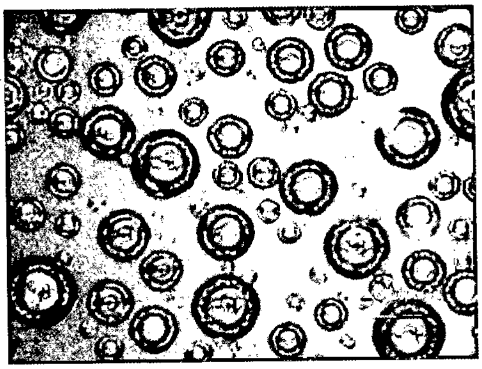
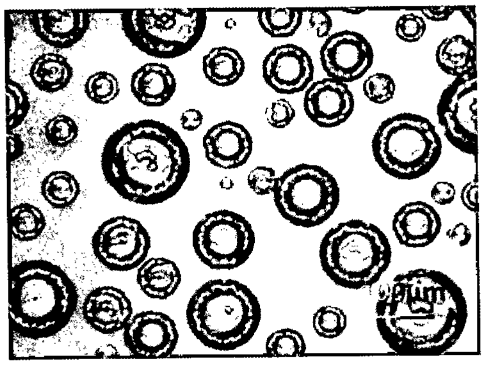
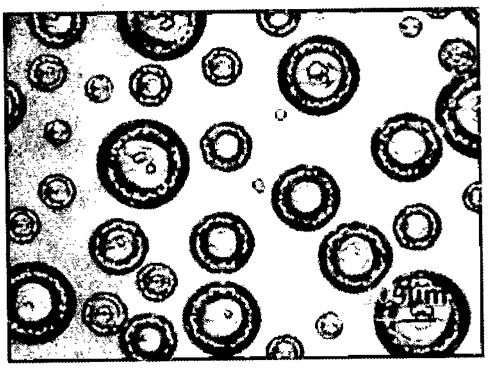
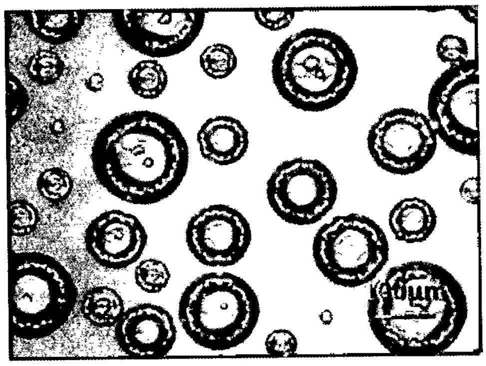
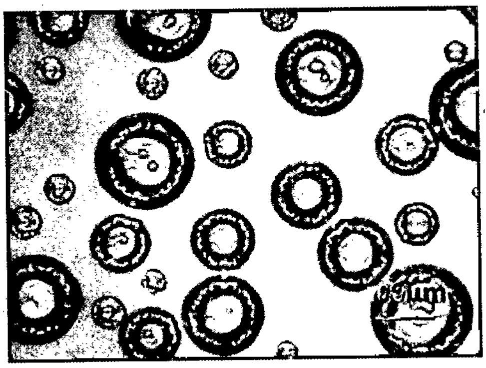
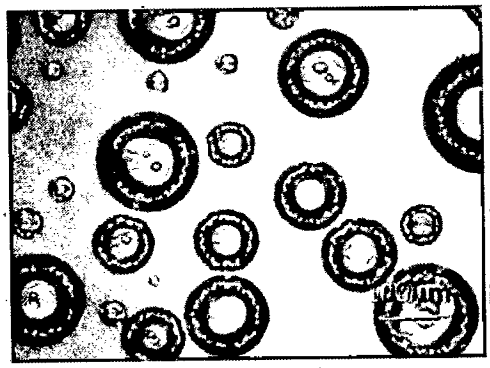
(b) Self-pressurization

With diameter less than 50μm, the surface tension of a micro bubble is higher than the internal gas expansion which causes it to shrink as the time goes by. Table 1.1 shows the process of self-pressurization by micro bubbles in 50 minutes.

In this experiment, samples of micro bubbles generated in tap water were collected by using a Petri dish and were observed by using USB microscope. The micro bubbles characteristic of self-pressurization was investigated by observing the dish every 10 minutes for 50 minutes. However, the existing microscope only allows us to observe bubbles with more than 50μm in diameter, therefore the existence of nanobubbles were ignored in this experiment.

From the table, the distribution of micro bubbles in the first few minutes is larger compared to the ones in the next 50 minutes. This phenomenon is caused from shrinkage of the smaller bubbles and coalescent of the larger bubbles. In the former case, bubbles with diameter less than 50μm became smaller in time due to self-pressurization. Furthermore, a few bubbles seemed to disappear after 50 minutes. On the other hand for the latter case, bubbles with more than 50-60μm in diameter expand and merge with the neighboring bubbles as the time goes by.

Table 1.1: Micro bubbles properties (self-pressurization)

	
(a) 0 minutes	(b) 10 minutes
	
(c) 20 minutes	(d) 30 minutes
	
(e) 40 minutes	(f) 50 minutes

(c) Electrical charges

Being smaller in size, these micro bubbles also characterized by having electrical charges. However, the mechanisms of the gas-water interface electrical charge in micro bubbles remain unknown.

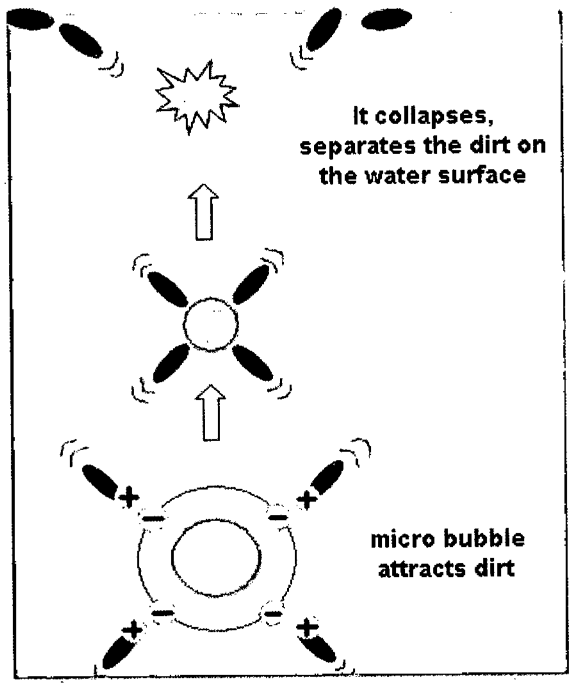


Fig 1.3: Micro bubbles properties (electrical charges)

As stated by Takahashi (ζ Potential of microbubbles in aqueous solutions: Electrical properties of the gas-water interface), generally, OH^- and H^+ are crucial factors for the charging mechanism of the gas–water interface. As the micro bubble shrinking, the negatively-charged ions were released. Hence, ion concentration around the gas-water interface of the bubbles increases and causes repulsion effect when two micro bubbles become close. Due to this characteristic, they also known as are able to attract positively charged materials such as dirt and impurities. Therefore, they have been widely used in numerous fields such as sterilization, agriculture, aquaculture and many more.

(d) Free radical

Radicals or often referred to as free radicals are atoms, molecules, or ions with unpaired electrons or an open shell configuration. Free radicals may have positive, negative or zero charge. It plays an important role in combustion, atmospheric chemistry, polymerization, plasma chemistry, biochemistry, and many other chemical processes. Being able to decompose the chemical substance makes micro bubble valuable in engineering applications. However, an extreme reaction field called hotspot is needed for this purpose. Hotspot refers to a localized region around the micro bubbles with temperature higher than surrounding and able to ionize the molecules and atoms.

Recently, the formation of free radicals in a solution containing micro bubbles was identified. The formation of radicals may involve breaking of covalent bonds, a process that requires significant amounts of energy. However, up until now the relation between micro bubbles and the formation of free radicals is still unclear.

2.1 Micro bubbles Applications

(a) Agriculture

As mentioned before, one of the most significant characteristics of a micro bubble is it collapses and dissolves more oxygen to water or also known as ozone water. By using ozone water, growth of crops can be accelerated faster than the normal growth stage. In Hyogo prefecture Japan, experiments were carried out on lettuce in hydroponic culture and micro-nano bubbles technology was used. As the result, the lettuce growth increased about 20% faster than it normally does on conventional hydroponic culture. An increment in oxygen supplement in ozone water might be the reason behind this application. More in Japan, a special program named 'Resuscitation of Enclosed Coastal Seas and its aquaculture and Reconstruction of Aquaculture by large scale of micro-bubbles generators' will be carried out. The project is expected to bring good results such as improvement of seawater quality, getting rid of bacteria such as colon bacillus, and increasing glycogen in oysters. A chemical reaction in the high temperature and high pressure bubbles stimulates growth of oyster. As shown in figure below, the differences between the common oysters grew in the sea and the ones grew in ozone nano-bubbles water.

Fig 2.1 Oysters in sea water and ozone-nanobubbles

(b) Sterilization

In sterilization application, micro bubbles are utilized in water waste and polluted soil treatment. Localized impact and heat generated when bubbles burst increases the sterilizing effect. University of Utah in China succeed by using micro bubbles in removing oil and gas from water, removing organics and heavy metals from industrial sites, and removing harmful algae from lakes. Furthermore, recently, micro-bubbles bath has been widely known with its beneficial in improving one's skin. These tiny negative charged bubbles will penetrate gently into the pores, bond to impurities and lift them away for a deeper cleansing. Moreover, as the bubbles collapsing in the water they release their heat energy, which helps maintain a consistently warm bath experience. These micro bubbles bath is popular not only for humans but also for pets.

(c) Medical treatment

Due to their size, micro bubbles can pass through the veins and even the smallest of blood vessels. Furthermore, these tiny bubbles will rupture, disappear and release gas content when expose to sufficient intense ultrasound, therefore it have been used to dissolve blood clots and deliver drugs. Micro bubbles are known as excellent contrast agents for ultrasound imaging. They can circulate easily within the vascular system, deforming as necessary to pass through the finest capillaries, and they create a unique echo that sounds significantly different to an ultrasound scanner than the adjacent body tissue.

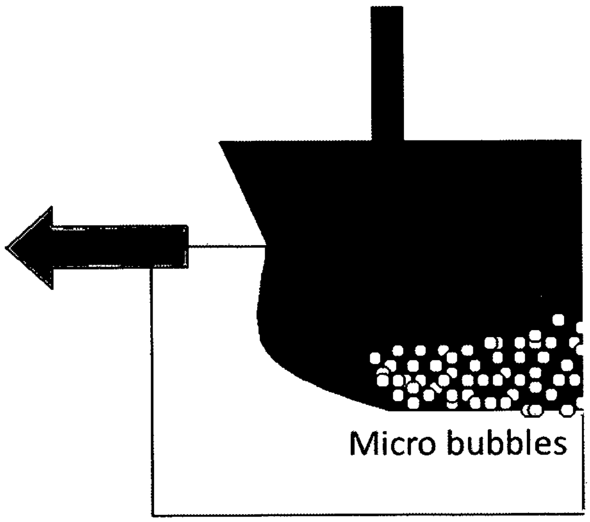


Fig 2.2: Drag reduction device in ships

(d) Drag reduction device in ships

Micro bubbles injection is a drag reduction device that reduces skin friction of a solid body moving in water by injecting small bubbles into the turbulent boundary layer developing on the solid body as shown in figure 2.2. Ships such as tankers are especially suited to micro bubbles. And one of the reasons is that their skin friction drag component occupies about 80% of the total drag. However, much energy is required in order to inject the bubbles at the hull bottom of such ships as they have large water depth.

Based on the experimental results, the efficiency can be increased up to 80% by injecting the air bubbles near the bow. Because of that, many researchers believe that this mechanism can also be applied into other technologies other than ships. Moreover, several explanations about the mechanism have been proposed in the past few years. However up until now, there are no established explanation regarding this mechanism were made.

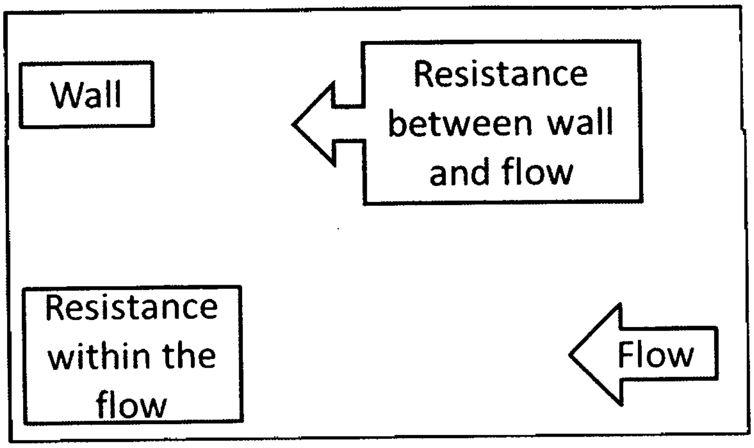


Fig 3.1: Skin friction loss mechanism

Drag is a mechanical force which acts opposite to the direction of motion, generated by the difference of velocity between the solid object and the fluid. A body moving through a fluid experiences a drag force, which usually divided into two components: frictional drag (viscous drag) and pressure drag (profile drag). In the former case, friction comes from the interaction between the fluid and the surface of the body that is moving through it. Meanwhile in the latter case, the friction arises because of the form of the object.

Recently, due to the increasing demand and limited availability of fossil fuels, numerous attempts have been made by researchers to reduce the energy-usage. A variety of environmental problems are now affecting the entire world including ship problems. The pollution produced by ships is affecting biodiversity, climate, food, and human health. 3.5% to 4% of all climate change emissions are caused by shipping which are considered to be a significant source of air pollution. Since the numbers of voyages are expected to continue increasing, a lot of studies regarding the air lubrication method have been carried out in order to reduce the frictional resistance and to improve the ship's efficiency.

In general, air lubrication methods in ships application can be divided into three; air cavity, air sheet and micro bubbles.

Table 3.1 Air lubrication methods in ships

Injection method	Percentage of drag reduction	Advantages	Disadvantages
Air cavity	<15%	• No possibility of increasing in frictional drag	• Need conversions for existing ships • Leads to instability
Air sheet	<90%	• Higher drag reduction rate	• The efficiency in drag reduction is unstable • Need conversions for existing ships
Micro bubbles	<85%	• Higher drag reduction rate • Persists for a longer distance	• The mechanism remains unknown • The efficiency is unstable

Air cavity

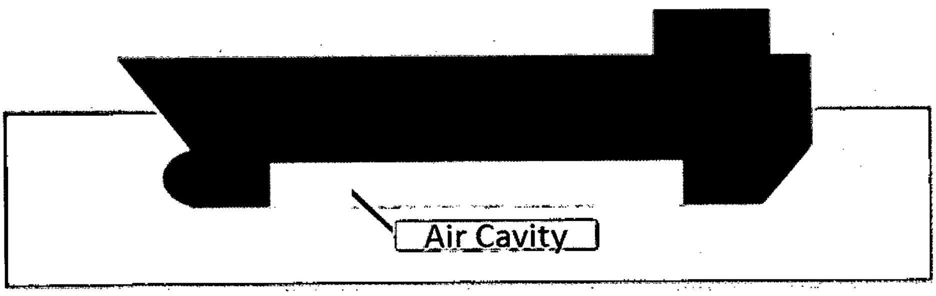


Fig 3.2: Drag reduction method in ships (air cavity)

Air cavity or also known as air space filled with compressed air is build underside of the ship hull in order to reduce frictional drag as shown in figure 3.2. A big reduction in frictional drag which is up to 15% can be achieved as the cavity area minimizes the wetted hull surface area. The wave drag can also be reduced due to smaller pressure gradients in the flow around the ship hull. Furthermore, dysfunctional of this method will not contribute to the increment in frictional drag of the ship. However, modifications for example additional free surfaces on the hull of a ship may lead to instability while moving. Moreover, by using air cavity method, conversions are required in the existing ships in order to create the air space, which means more cost and time will be needed.

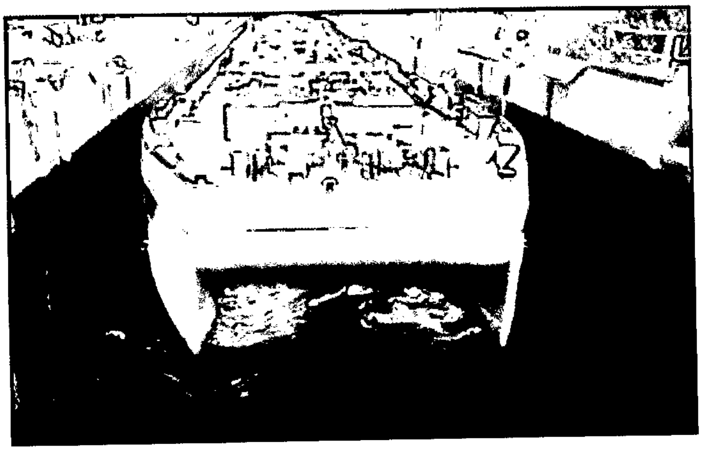


Fig 3.3: Air cavity in actual ship

Air sheet

The air layer method is also an often-named candidate in reducing the frictional drag in ships. The air layer concept can be seen as a combination of air cavity and micro bubbles method as shown in figure 3.4. Unlike the micro bubbles injection method, a massive amount of air is injected at the hull bottom of a ship in order to create a thin air film or sheet covering the ship's hull. With an air film of half a millimeter thick, a maximum 90% of drag reduction can be obtained. However, it is difficult to obtain a stable air film in higher Reynolds number which cause and adverse effect; an increment in ship's frictional drag. It is stated that the frictional drag of a ship is increased when the liquid-gas interface become instable, resulting in breaking up the layer in larger bubbles that also may reduce the frictional drag.

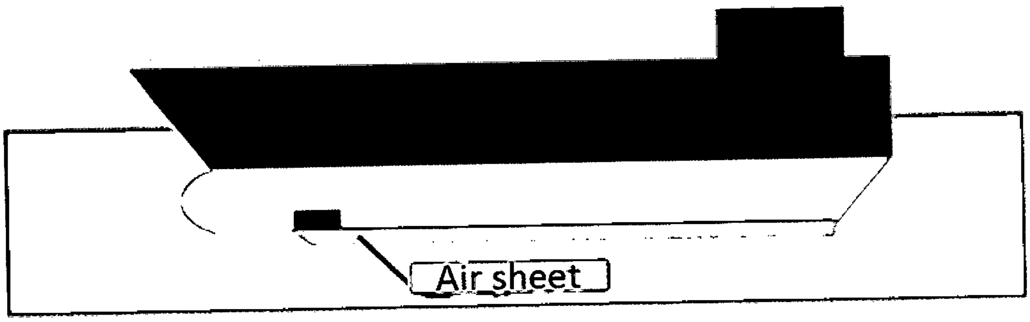


Fig 3.4: Drag reduction method in ships (air sheet)

Micro bubbles

In Japan, micro bubbles injection has been studied intensively in the past few years toward its application on ships. When micro bubbles, i.e. small bubbles are injected into the turbulent boundary layer on a solid surface moving in the water, a significant skin friction reduction occurs with no harm to the environment. Micro bubbles are the most suitable drag reduction device in ships especially tankers based on two reasons. One, the tanker's skin friction drag component consists about 65~85% of the total drag. The drag of a ship that moves on the water comprises of two components, skin frictional drag and wave-making drag. When the micro bubbles injection is applied, skin frictional drag of such ships can be decreased dramatically and consequently causes a significant drag reduction. Meanwhile, the wave-making drag component of tanker is very small according to their low velocity. Another reason is, since the tankers have a wide flat bottom shape (except for bow and stern regions), when the bubbles injected near the bow, they will spread over and stay at the surface of the hull bottom by buoyancy, and thus causes a large drag reduction.

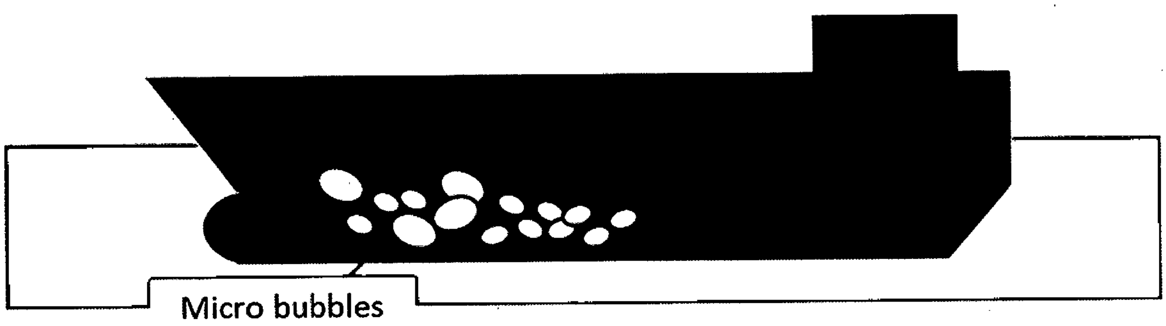


Fig 3.5: Drag reduction method in ships (Micro bubbles)

Studies on micro bubbles are pioneered by McCornick and Bhattcharyya (1973). At first they were recognized as an indispensible skin friction reduction agent and being used in military for high-speed ships or torpedoes. Then, in the age of the Cold War, their studies were being moved to the United States and the former Soviet Union. In the 1970s, micro bubbles studies were carried out intensively in the former Soviet Union, e.g. Bogdevich (1977). In the 1980s, headed by a group from Pennsylvania State University, the study was continued in United States. In the 16th Symposium on Naval Hydrodynamics, Merkle et al. (1987) gave an interesting observation on the relation between the bubbles distribution in the boundary layer and the skin friction reduction effect. Then, Merkle and Deutch (1990) reviewed the history of micro bubbles studies and described in detail the research activities in Penn. State.

In the 1990s, the centre of the study moved to Japan, aiming at their application to commercial ships which play an important role in the world wide transportation. Due to their characteristics, large at size and move slowly, ships that carry heavy loads such as crude oil, ore and grain are suited to micro bubbles. The University of Tokyo carried out both experimental and theoretical studies, jointed by IHI (Kato et al. 1994, Guin et al. 1996, Kato et al. 1998, Yoshida et al. 1998, Watanabe et al. 1998). In the National Maritime Research Institute, Japan (NMRI), formerly the Ship Research Institute, the micro bubbles studies were carried out, first on the basic characteristics (Takahashi 1997, Kodama 2000), and then on the scale effects using a 50m-long flat plate ship (Takahashi 2001). Recently, computational studies were also has been widely recognized among the researchers (Kawamura 2001).

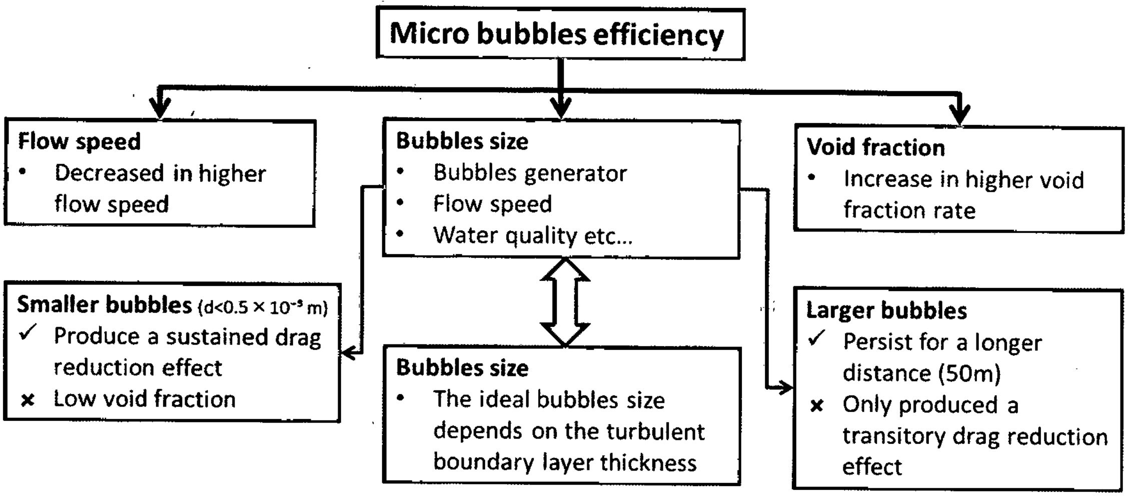


Fig 5.1 Flow chart of factors that can affect the micro bubbles efficiency

This study pioneered by McCormick and Bhattharcharrya [1] has triggered a large number of investigations on the mechanism of skin friction reduction by micro bubbles. They reported that the drag force of fully-submerged body decreased up to 65% by using micro bubbles which were created by electrolysis. It is found that the reduction increased as gas flow rate increases.

Experimental results from several studies have been shown that drag reduction by micro bubbles is influenced by void fraction. Bogdevich [2] reported that the reduction rate positively correlated to void fraction in boundary layer. Later, an extensive study by Guin [3] has shown that the reduction efficiency is associated with near wall void fraction compared to overall void fraction.

The results by McCormick and Bhattharcharrya [1] and Kodama [4] have agreed on the effect of drag reduction by micro bubbles in different flow speed. The reduction rate declined in higher flow speed and improves with the increasing of air injection rate. A decrease in the Reynolds number was observed.

The bubbles size in comparison to turbulent boundary layer thickness is also one of the most important factors that greatly affect drag reduction by micro bubbles as shown in several studies. Kodama and Kato [5] found that micro bubbles efficiency is declined because void fraction is reduced as smaller bubbles (diameter; $d<0.5\times10^{-3}\ m$) dispersed faster than larger bubbles. By using 50 m flat plate, they also found that the reduction rate is independent in bubbles diameter between $0.5{\sim}2\times10^{-3}\ m$.

However, micro-sized bubbles whose are widely known with its special characteristics also contribute a significant reduction in drag frictional. Besides the results reported by McCormick and Bhattharcharyya [1], related studies by Serizawa proposed that the two-phase flow is "laminarized" by injecting micro bubbles into the boundary layer [6]. For a single-phase in a pipe flow, the turbulent transient is known to take place when Reynolds number=2300. However, when micro bubbles are injected into the flow, this transient region initiated at the Reynolds number=10000~12000. Merkle and Deutsh [7] suggested that the ideal bubble size for an optimum efficiency was not fixed and strongly influenced with the flow characteristics.

Meanwhile, a numerical investigation of the phenomenon was carried out by Madavan et. Al. in an effort to clarity the effect of the micro bubbles on the physical properties values (density and viscosity) of the fluid in the boundary layer. The drag reduction rate was found to be strongly depend on the bubble volumetric and concentrations and their location.

In addition, properties of micro bubbles changed in different water quality as reported by Eric S. [8]. Because of the bubbles diameter generated in salt water and fresh water is different, the efficiency in drag reduction was also affected. Therefore, earlier studies in fresh water regarding the reduction efficiency in seawater may not precisely assume.

Problem statements

Micro bubbles are indeed a suitable drag reduction device for big ships; however a lot of energy is needed for injecting bubbles at the hull bottom of such ships since they have a large water depth. Hence, in order to put micro bubbles to practical use, the energy consumed for injecting air has to be reduced. Furthermore, until now, there is no established theory for the mechanism of skin friction reduction by micro bubbles. It is stated that the injected bubbles in the turbulent boundary layer modify positively the turbulent intensity and thus decrease the skin friction.

As mentioned in previous chapter, the skin friction reduction efficiency by micro bubbles depends on some extensions for examples Reynolds stress, pressure gradient, velocity profile, or viscosity of the air–fluid mixture changes. And based on previous study, there are also possibilities in increasing the resistance of a ship as micro bubbles injection is adapted. Therefore, in order to reduce errors and inaccuracies, a lot of innovation and ideas have been implemented in the previous research project for the betterment of current study.

In conclusion, further study on these following points may lead to improvement in skin friction efficiency by micro bubbles:

(1) The mechanism of skin friction reduction by micro bubbles.
(2) Factors that affect the efficiency of skin friction reduction by micro bubbles.

Objectives

As discussed in the previous section, micro bubbles have an undoubtedly large potential as a drag reduction device for ships because of their significant skin friction reduction, cost-effectiveness, and environmental-friendly nature. Many researchers believe that the application of skin friction reduction by micro bubbles should be developed and applied in many fields and machines not only in ships.

The main goals of the study on micro bubbles in present research are twofold. Since the mechanism of micro-bubble drag reduction has not been fully investigated, one is to elucidate the skin friction reduction mechanisms by micro bubbles. Thus, by refining our current understanding of the mechanisms, the skin friction reduction efficiency can be extrapolated to the highest level. This study will also explore other research and particularly related to the characteristics of micro bubbles as the skin friction reduction agent. The main objective of the study is:

(a) To broaden the understanding of the skin friction reduction mechanisms by micro bubbles
(b) To investigate the factors that affect the efficiency of skin friction reduction by micro bubbles

In this study, considering that the bubbles quantity and size are the main parameters in this mechanism, we have decided to focus on the effect of void fraction in drag reduction by micro bubbles. Furthermore, besides Reynolds number, this study also investigated the effect of fluid velocity and surface inclination in micro bubbles efficiency. This is because, full hull forms such as tankers have wide and flat bottom, which can keep bubbles for a long distance with the help of buoyancy and are regarded leading to large drag reduction. The distance between micro bubbles generator and the test section, time interval effect and also the relation of skin friction reduction effect and micro bubbles distribution at the tube wall were also evaluated in order to fulfill the objectives of this study.

(1) Distance between micro bubbles generator and the test section
(2) Time interval effect
(3) The relation of skin friction reduction effect and micro bubbles distribution at the tube wall
(4) Void fraction:
(5) Surface inclination:

Last year's experimental apparatus

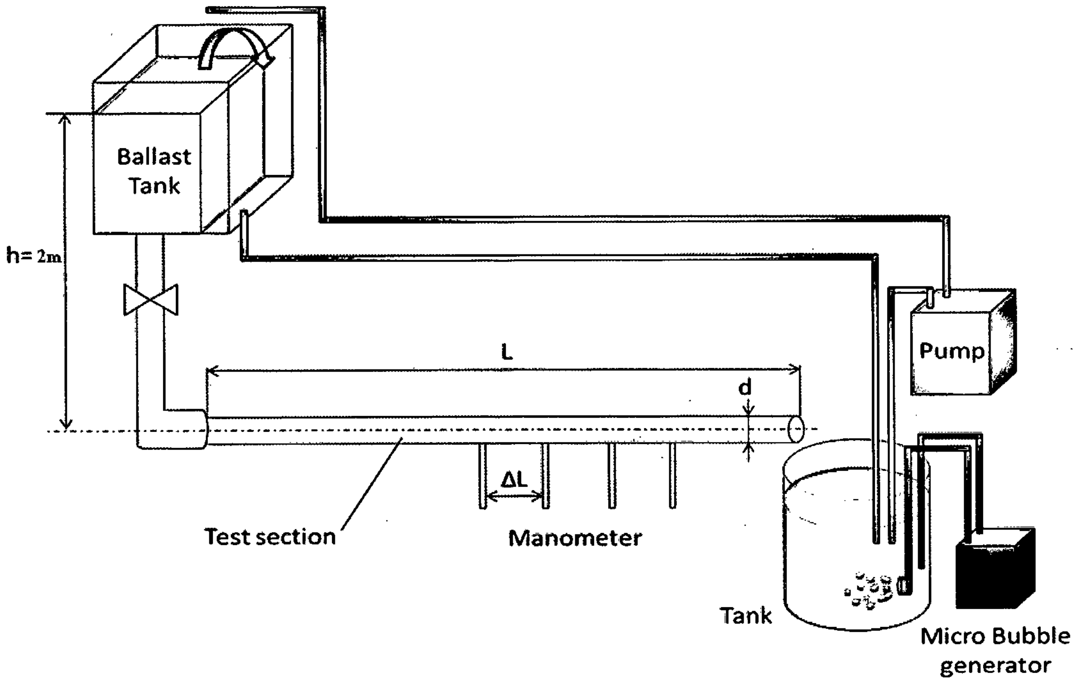


Fig 7.1 Experimental apparatus for previous year

In the past research project, as shown in figure 7.1, a circulating water system which basically designed to measure pipe friction loss were used as the main experimental apparatus. The micro bubbles efficiency in drag reduction was evaluated by comparing the friction reduction made by micro bubbles to non-bubble condition. An isolated manometer method is used whereby the pipe to be tested can be changed without removing the whole equipment.

Water is pumped from a bucket to the upper tank, which is located 2m from the test pipe and ensures a constant pressure head. It flows through the network of pipes and fittings to the test section which consists of a test tube. And then the water is fed back to the bucket via the exit tube. Flow rates through the apparatus can be adjusted by controlling the opening of the pipe placed between the tank and the manometer.

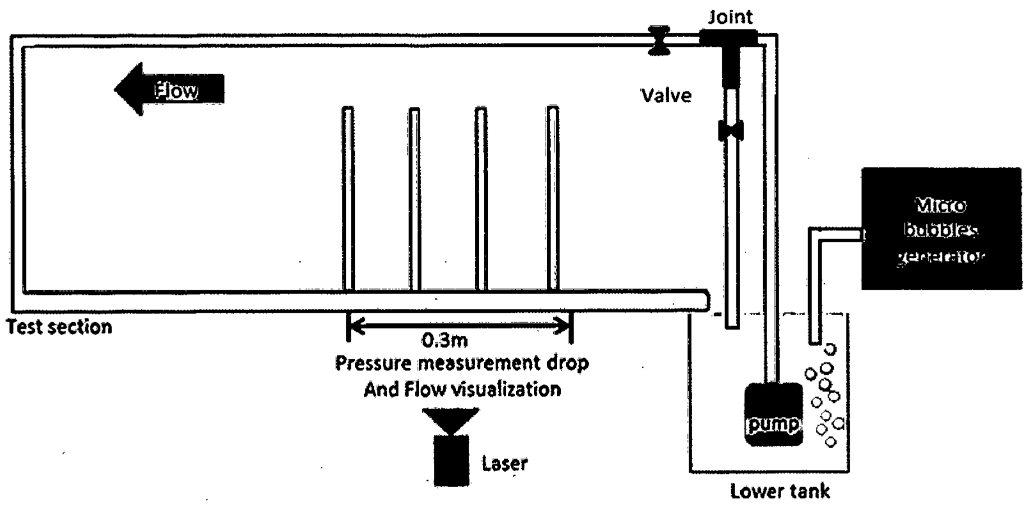


Fig 7.2 Experimental apparatus for current study

However, considering distance from the lower tank (where the micro bubbles were generated) to the test section was about 6 meters, the noise gained might negatively affect the results. Thus, we have decided to improve the system and cut down the interval range by pumping the water straight from the lower tank to the test section.

In present research, micro bubbles were generated in the lower tank which will be pumped to the test section located about 3 meters downstream. Furthermore, by using this apparatus, a bigger Reynolds number up to Re35000 can be generated as the pump is capable to produce a higher flow speed.

In both apparatus, a temperature controller machine was used to control the water temperature. Micro bubbles were generated continuously throughout the experiment. Pressure drop is measured from the manometer located at 1 *m* downstream from the valve. The manometer was built 30° from the ground to reduce inaccuracies and errors in taking measurement. In order to observe the bubbly flow, photographs by using USB microscope were taken near the tube wall. Laser sheet is projected vertically through the tube cross-section and in the area where the pressure drop is measured to illuminate the viewing area. All experiments were carried out in basic conditions as follows;

- Type of water: Tap water
- Water temperature: 20°c

(a) Micro bubbles generator

In this study, ASK3 micro bubbles generator from Asupu Company was used. By using this device, micro bubbles are generated 7-10L/min from shear stress due to mixtures of water and gas at a high pressure along with a high speed of rotation. The generator was placed in the bucket. Micro bubbles were generated 20 minutes earlier before the experiments started in an attempt obtaining an uniform distribution of the bubbles in 100L of water. The bubbles will be observed by using USB Microscope.

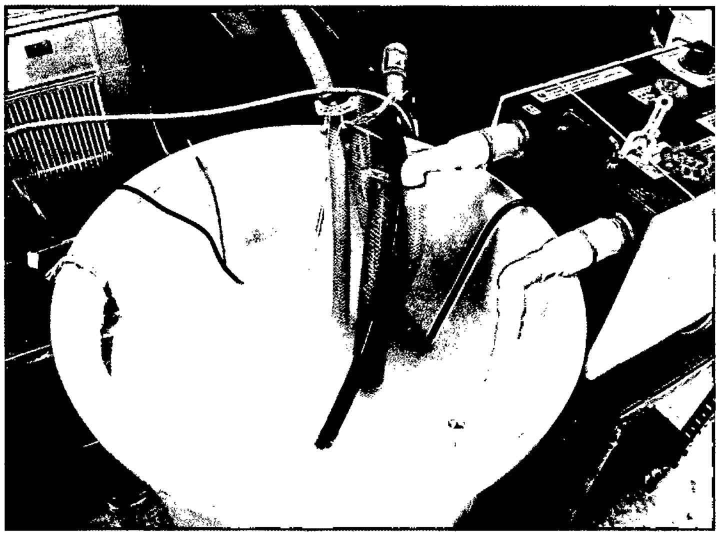


Figure 7.3: Micro bubbles generator and lower tank

Table 7.1 Micro bubbles generator features

Model	ASK3
Dimension	360mm(height)x450mm(length)x240mm(width)
Weight	15kg
Power supply	AC100V
Frequency supply	50/60Hz
Power consumption	550W
Generation Capacity	7-10litre/min