Fundamental study on the effect of Reynolds number on pipe frictional loss reduction by microbubbles

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Abstract. Microbubbles (MB) injection method is undeniably a promising drag reduction device in water transport. However, the mechanism of drag reduction by MB is complicated and poorly known. This paper presents the effect of Reynolds number on the frictional reduction by MB in a piping system. A fluid friction apparatus and a hydraulic bench were used to execute the experiment. To verify the ability of MB in reducing frictional loss, experiments were carried out in two conditions, without MB and with MB. In order to investigate the effect of turbulent flows, experiments were performed in three different flow rates ranging from $9 \times 10^{-5}$ to $0.008 \text{ m}^3/\text{s}$ in two types of pipe diameter (20 mm and 33 mm) to yield different Reynolds number. As the results, MB able to reduce frictional loss in pipe up to 20%. However, regarding the Reynolds number effect, no apparent tendency of the frictional reduction efficiency can be observed between Reynolds number 4000-9500. Overall, MB holds potential in reducing pipe frictional loss in turbulent flow. However, further study in wider range of Reynolds number is required to comprehend its tendency.

1. Introduction

Exhaust emission from ships has been a major concern as it is regarded as a dominant contributor to global air pollution. Based on previous study, shipping industry emits about 5-7 Tg/year of nitrogen oxides, 4.7-6.5 Tg/year of sulphur oxides, and 1.2-1.6 Tg/year of particulate matter (PM) [1]. As the consequence, this industry has been associated with the increment of mortality rate due to cardiopulmonary and lung cancer near the coastal area [2]. While stringent laws are being imposed on land vehicles to improve local air quality, the exhaust emission from marine industry inclining steadily. This matter has triggered many studies on methods to maximise total energy efficiency which will lead to reducing exhaust emissions. Many methods have been proposed and applied in recent years including operational measures (such as moving at low speed and route optimization), incremental measures (improving hull and propeller design), the usage of alternative fuel, and many more. However, implementation of the aforementioned methods requires significant physical modifications which will consume time, money and human labours. Therefore, in order to alleviate these problems, air lubrication is regarded as the most convenient method to cut down the emission by reducing the frictional drag of a ship. By using air, as the drag reduction agent, the frictional drag on a ship’s surface can be reduced significantly, and thus enhancing the energy consumption efficiency which will lead to reduction in the emission.
The microbubbles (MB) size is highly controversial and depends on the application. In fluids terminology, bubbles with diameter of few hundred microns or less are regarded as MB. However, in physiological activity study, MB are defined as bubbles with 10-40 \( \mu \)m diameter [3]. Meanwhile, Li et al. interpreted that MB are bubbles with relatively small diameter (size range is from a few tens of microns) and having distinct properties as compared to ordinary bubbles (mili bubbles) [4]. MB are characterized by having unique properties such as low rising speed, self-pressurization, having ion charges and many more. As drag reduction agent, these characteristics play a vital role as they are able to suspend in the water for a long time. As shown in figure 1, unlike mili-sized bubbles, these MB will slowly rise up to the surface of water, shrinking and finally disappear by dissolving all its content to the water.

![Figure 1. MB characteristics MB as air lubrication method.](image)

Air lubrication methods can be divided into three types, namely, air cavity, air films, and small bubbles injection method. Among these methods, small bubbles injection or also known as microbubbles (MB) is the most prominent method as it is able to save up to 10-15\% of total energy consumption [5]. Moreover, unlike air cavity and air films method, MB injection method can be implemented in the existing ships as none modifications on the ship’s hull is necessary. The pioneer study of drag reduction by MB was carried out by McCormick and Bhattacharyya [6]. They reported up to 65\% of frictional drag reduction was obtained using MB generated via electrolysis. Copper wire was wrapped around floated bodies and MB were generated when electric current passed through it. They stated that that model velocity is proportional to the rate of hydrogen bubbles and changes in viscosity in the near wall is the main key to the frictional reduction mechanism by MB. Thenceforth, research and applications of MB as a drag reduction agent has attracted many attentions including in piping system. However, up until now, the mechanism of drag reduction by MB remains inconclusive. Based on previous studies, this mechanism are due to complex phenomenon which involved viscosity and density [7, 8, 9], positive modification in the turbulent boundary layer [10, 11, 12] and many more. Lacking fundamental knowledge in the mechanism leading to difficulties in optimizing its efficiency. Thus, in this paper, fundamental investigation regarding frictional drag reduction using MB in pipes with different Reynolds Number will be discussed. This study will give insights on the fundamental understanding on parameters affecting MB efficiency as a drag reduction agent in piping system.

2. Methodology
In figure 2 and figure 3, fluid frictional apparatus and hydraulic bench were used to measure pipe frictional loss. These losses are represented in terms of head loss calculated from the manometer reading. This manometer can be attached to the desired section to get the frictional loss value. This study focuses on two sections, straight pipes with 20 mm and 33 mm diameters. MB were generated in sump tank in the hydraulic bench located at the lower part of the fluid frictional apparatus. Pump is used to supply
water to the pipelines and the flowrate is adjusted by using a valve. Three types of turbulent flow rates (4100<Re<9100) were carried out for each pipe using water with temperature between 23-29 °C. Both data of head loss with and without the microbubbles were collected for comparison purposes. Data were collected after 10 minutes of switching on the MB generator in order to ensure MB is uniformly distributes in a tank. MB is generated by using a modified 60 watt submersible water pump. An air inlet is attached to the water suction part which cause the air is drawn into the pump and MB are generated due to shear stress by the rotating propeller inside the pump. The range size distribution of generated MB is about 40-130 µm.

Figure 2. Fluid friction apparatus, (a) pipe with 20 mm diameter (b) pipe with 33 mm diameter.

Figure 3. Hydraulic bench.
3. Results
In the former subsection, results of comparison between without MB and with MB will be discussed to analyse the capability of MB in reducing frictional loss in a pipe. In the latter section, the efficiency of MB in reducing pipe frictional loss in regard to Reynolds number will be analysed.

3.1. Straight pipe with 20 mm diameter
Figure 4 shows the frictional head loss in pipe with small diameter correspond to flow rate for both conditions, with MB and without MB. The horizontal and vertical axis represents volume flow rate and frictional head loss, respectively. In general, the frictional head loss increases steadily along with the increment of flow rate. As for comparison between values with bubbles and without bubbles, the head loss for water with bubbles is slightly lower than those without bubbles. However, no apparent tendency can be observed in terms of percentage of frictional reduction in small diameter pipeline. Besides the mass flow rate at 0.0058 m$^3$/s, the drag reduction for another two points are almost the same. This result suggested that the flow rate does not play a significant role in reducing frictional loss in smaller diameter pipes.

![Figure 4](image)

**Figure 4.** Head loss in regard to flow rate for 20 mm diameter pipe for both conditions, without MB and with MB.

3.2. Straight pipe with 33 mm diameter
Results for the correlation between frictional head loss in pipe with a bigger diameter of pipe and volume flow rate for both with and without MB are indicated in figure 5. Overall, similar to previous subsection, the pipe frictional loss is proportional to the volume flow rate. The head loss for water with MB is noticeably lower in comparison to that for the water without MB. Up to 20% of frictional reduction was recorded by using a bigger diameter of pipelines at the highest mass flow rate. A tendency can be observed as the percentage of frictional reduction by using MB increases as the flow rate increased. The small flow rates obtained minimum value of frictional reductions, while, the highest is recorded at the largest flow rate. However, similar to previous results, no apparent tendency of frictional reduction can be observed.
3.3. Drag reduction efficiency in regard to Reynolds number

From figure 6, in order to investigate the effect of frictional reduction by MB efficiency, results from subsection 3.1 and 3.2 were analysed in regard to Reynolds number. The triangle dots represent data from smaller pipe, while the circle dots are from larger pipe. In general, data at almost all Reynolds number show a significant frictional reduction by using MB. However, the fluctuated results depict no obvious tendency of MB efficiency can be observed when Reynolds number is between 4000-9500.

4. Conclusion

In this study, the capability of MB in reducing frictional loss in pipelines was investigated by using a frictional loss apparatus. Experiments were performed at different flow rates and pipe diameters to examine the effect of Reynolds number on the MB efficiency as a drag reduction agent. The following conclusions were achieved:
i) By mixing water with microbubbles, a significant reduction in frictional loss in pipe can be achieved.

ii) The efficiency of MB in reducing frictional loss in pipe appears to be independent to Reynolds number between 4000-9500. Larger range of Reynolds Number might yield an obvious tendency of frictional reduction.

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