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On multi-point gas injection to form an air layer for frictional drag reduction

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ABSTRACT

Air layer drag reduction has been shown to be a feasible drag reducing technique at the laboratory and at full ship scales. In most studies, the air layers have been generated *via* gas injection from two-dimensional spanwise slots. However, given ship's structural considerations, it would be preferable to use discrete holes. The present study expands on the work on single orifice gas injection to multi-hole injection. When compared with slot injection, multi-point injection lead to a reduced range of gas fluxes that formed an air layer. Gas injected from a series of discrete holes can exhibit complex flow patterns, including roll-up into the core of liquid vortices that form as part of the process of injecting gas into the liquid boundary layer. The finite span and length of the model utilized for the present experiments was modest. It remains to be shown if a larger model with similar scaled up geometry (and with more beanwise holes) would enable the formation of a stable air layer with a gas flux per unit span that is similar to that required for slot injection. Nevertheless, the results presented here illustrate the complexity associated with gas injection through multiple perforations in a hull.

1. Introduction

Air Layer Drag Reduction (ALDR) has been shown to reduce the frictional drag by over 80% on the surface covered (Ceccio, 2010; Elbing et al., 2013; Mäkiharju et al., 2012). Similar results have been achieved also by Partial Cavity Drag Reduction (PCDR), which is a related technique with the rough distinction being that the “layer” (better described as a cavity) of gas is much thicker than the boundary layer. PCDR was investigated by Gokcay et al. (2004), Matveev (2007), Lay et al. (2010), Mäkiharju et al. (2013) and others. Distinctions between discrete bubble drag reduction, ALDR and PCDR techniques were more thoroughly described in Mäkiharju et al. (2012), and more recently a survey of some of the different frictional drag reduction techniques utilizing gas injection was also provided by Murai (2014). Also, Perlin and Ceccio (2014) reviews a wide variety of frictional drag reduction techniques, ranging from passive to active methods. However, in the present work we will focus solely on practical issues one may encounter when trying to practically implement ALDR.

In most ALDR experiments gas has been introduced *via* continuous spanwise slots that are either open or filled with porous material to ensure the creation of a nominally spanwise uniform gas layer. And, while an air layer may be generated utilizing such a slot with air forced solely by a compressor (*e.g.* Elbing et al., 2013), some authors have also suggested use of hydrofoils below the slot to reduce the require air pumping power (*e.g.* Kumagai et al., 2015). Also, recent paper by Park et al. (2016) discusses nominally spanwise uniform gas injection to boundary layers. However, for practical application of ALDR it is desirable to implement the least complex arrangement for the introduction of the gas while maximizing the hull's structural integrity. Indeed, the simplest method (and one that may prove to be easiest to implement particularly if retrofitting an old hull) is to introduce the gas *via* a series of plain round orifices penetrating the hull. Such an injection configuration would produce a gas jet in liquid cross-flow. Despite its geometric simplicity, such an injection configuration can yield a quite complex multiphase flow.

Jets in cross-flows of similar fluids have been studied extensively, and a recent review was provided by Mahesh (2013). However, not much data is available on the complex flow resulting from the normal injection of a gas jet into a liquid cross-flow over the range of Reynolds and Froude numbers of interest. In particular, the Froude numbers for practical applications are such that the influence of buoyancy is significant, *i.e.* whereby the gas jet injected beneath a surface rises. The injection of gas from a single hole with gravity oriented streamwise was studied by Vigneau et al. (2001a, 2001b), and with gravity oriented normal to the surface (*i.e.* relevant for ALDR) by Lee (2015) and Mäkiharju et al. (2017). Lee (2015) and Mäkiharju et al. (2017) conducted studies to

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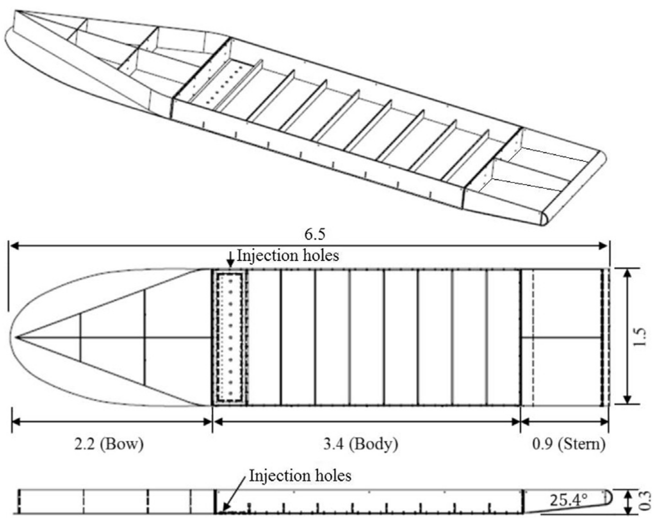

Fig. 1. A schematic diagram of the model used in the experiments (same as utilized by Lee, 2015; Mäkiharju et al., 2017). To reduce air leakage from the sides due to finite span of the model, adjustable strakes (set to be 7.5 cm tall) were installed on both sides of the model and extended from bow to stern (*i.e.* as measured from the bow: 2.2–5.4 m in streamwise direction). All dimensions listed in the figure are in meters, except where degrees are explicitly identified for the transom's rise angle.

examine gas injected into a cross flow from an orifice placed beneath a hull. For flows of moderate Froude number, buoyancy drives the ejected gas plume toward the hull surface downstream of the injection location, often creating a "V" shaped cavity. Under some conditions, the cavity forms two gas branches that are separated by a mainly liquid flow, or the region between the two legs may be filled with a thin layer of gas. The topology of the cavity is dependent on a variety of parameters, including the Froude, Reynolds, and Weber Number of the flow and the volume flow, mean velocity, and angle of the injected gas, the incoming boundary layer thickness, and the orifice diameter.

While injection from multiple holes for drag reduction was tested by Insel et al. (2010) on a towed ship model, the data presented did not yield generalizable answers nor were the gas fluxes likely sufficient to form an air layer, although the general features of the flows they report are similar to those observed in the present study.

In the present work, the ability to form an air layer using discrete multi-hole gas injection is investigated experimentally in a tow tank at Reynolds numbers $O(10^6)$, where Reynolds number is defined based on distance from the leading edge to gas injection location. This work expands on that reported by Lee (2015) and Mäkiharju et al. (2017) for gas injected from a single orifice by extending the study to include the interaction of multiple gas pockets formed by nominally uniform gas injection. In Section 2 we will discuss the experimental setup. In Section 3 we briefly summarize single hole gas injection results from previous work by Mäkiharju et al. (2017), followed by Section 4 that present the multi hole gas injection data. We conclude in Section 5 with a brief summary discussion of the results and proposed future work.

2. Experimental setup

A 6.5 m long and 1.5 m wide barge with a flat bottom was utilized in the University of Michigan's Marine Hydrodynamics Laboratory physical modelling basin that is 109.7 m long, 6.7 m wide and 3.2 m deep. The model was designed to produce a near zero pressure gradient streamwise and nominally span-wise uniform turbulent boundary layer at the location of gas injection, which was found to be 54 ± 3 mm thick. To have a nominally two-dimensional inflow that is free of significant corner vortices, an elliptic leading edge shape was used on the flat plate that formed the bow. The draft of the model was such that the flat plate at the bow was always immersed below the surface, and a V-shape superstructure above this flat plate was used to deflect the liquid flow of the free surface away from the model that is shown in Fig. 1. The bow was followed by a 3.4 m long body that had a stiff aluminum structure and a flat bottom made of single seamless clear acrylic plastic to enable visualization trough the bottom. The stern was a simple two-dimensional shape rising at an angle of 25.4°. The barge was mounted such that the flat bottom was nominally normal to gravity, and bottom angle was checked to be nominally zero with AccuRemote digital protractor with manufacturer specified accuracy of ±0.2°. The surface roughness of the bottom of the bow and the acrylic plate of the body was measured using a Mititoyo SJ-210 roughness meter. For the bow and acrylic plate we found surface roughness [Ra, Rq] to be [2.41, 3.92] μm and [0.18, 0.33] μm, respectively. Particles with 150 μm mean diameter were randomly scattered and affixed across the span of the model 1.7 m from the leading edge of the model on a 0.2 m wide strip to induce turbulent boundary layer transition upstream of the gas injection location.

As the focus of this study was on the effect of gas injection method on formation of an air layer, the barge was rigidly fixed to the carriage, and the draft of the model was held constant at 12 cm. For air layer drag reduction on a real ship, the situation would be further complicated by vessel motions and external flow which may have large perturbations, and these factors need to be further examined. During the measurement campaign, the model basin water temperature was nominally constant at 18 °C. Between experiments, up to a 30 min pause was taken between runs to achieve nominally calm water condition. Compressed air was injected out of 1–6 pipes that had inside diameter, D_i, of 23.8 mm and a straight pipe section that was $38D_i$ long to achieve nominally fully developed turbulent pipe flow profile at the orifice exit. The pipes went through compression fittings and the injection plate, and terminated flush on the bottom surface of the gas injection plate. The pipe exits had

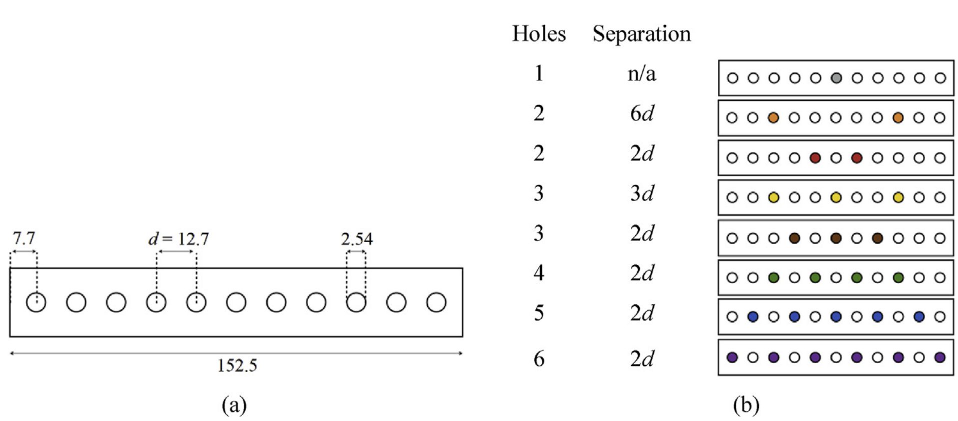

Fig. 2. Schematic diagrams of (a) the injection plate with dimensions in centimeters, and (b) the combinations of gas injection holes used.