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On The Efficacy of Surface-Attached Air Bubbles as Thermal Insulators for Pressure-Driven Internal Flow

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Extended Abstract

The fields of superhydrophobic material development, application, and optimization have seen a surge in interest in recent decades. These materials are used in the broader context of water repellency, such as water-shedding fabrics [1], or in the creation of materials that are categorized as anti-reflection [2] or corrosion-resistant [3]. Microscale engineering ideas are frequently influenced by natural phenomena, with lotuses leaves serving as a prime example [4]. Elsewhere in nature, arachnids and insects can carry integument-attached bubbles underwater due to the superhydrophobic nature of their integuments [5, 6, 7].

A substantial corpus of literature has been published concerning the function of surface-attached air bubbles in reducing drag [8, 9]. Busse et al. conducted a theoretical investigation on this topic [10], examining several manifestations of Couette and Poiseuille flow. By determining the ideal thickness for minimizing drag for various flow geometries and configurations, they were able to characterize the effect of air layer thickness on drag reduction. The majority of this literature considers isothermal flows and so ignores temperature changes between the fluid phases and/or the solid boundary to which bubbles attach.

Inspired by the sophistication of Busse et al.'s analytical solutions, we would like to review their derivations, but this time with a focus on thermal energy transfer as opposed to momentum transfer. We question whether surface-attached air bubbles could be effective as thermal insulators in this research of internal flows by relaxing the isothermal assumption. For example, we consider a situation in which the temperature of the cargo liquid, which is assumed to be water, differs from that of the solid. For situations with a uniform surface heat flux (USF), theoretical and numerical solutions are provided, for example, for the variation of the Nusselt number with bubble thickness. We investigate two distinct flow geometries (channel flow and pipe flow) and take into account situations in which the (continuous) air bubble net mass flow rate is either non-zero or zero. On the other hand, analytical solutions require the use of higher-order theoretical techniques when the thermal boundary condition is modified to uniform surface temperature (UST). Thus, our exposition of the UST case focuses only on numerical solutions.

We discover and analyze an impressive relationship between the USF thermal insulation problem and the drag reduction problem. In other words, the corresponding variations of drag and of water temperature change with bubble thickness are equivalent. However, when the thermal boundary condition becomes UST, the above relation breaks down. The Nusselt number is a strong function of bubble thickness for all of the cases under consideration, i.e. we observe a rapid initial decrease of Nusselt number followed by a gradual relaxation to the limiting value of zero. Our solutions offer a novel metric for evaluating the effectiveness of superhydrophobic surfaces, such as in non-isothermal lab-on-a-chip flows. The talk discusses more applications to various forms of core annular flows.

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