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Experimental investigation of evaporation-induced convection in water using laser based measurement techniques

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ABSTRACT

Recent studies have shown that the evaporation of water can induce surface tension gradients along the water surface that ultimately lead to a surface driven flow, known as Marangoni convection. To visualize and characterize the Marangoni convection in water, this study generated evaporation driven convection in pure water with a vacuum pump to control and increase the evaporation rate of water within a rectangular cuvette that was placed within a vacuum chamber, and investigated the velocity and temperature distributions of the generated convection. The investigation was performed as the vacuum chamber pressure ranged from ~250 Pa to ~820 Pa. The temperature field obtained from thermocouple measurements and temperature planar laser induced fluorescence (temp-PLIF) measurements indicated that no buoyancy driven motion was generated during the investigation. Velocity vector fields captured with stereo particle image velocimetry (stereo-PIV) demonstrated a convection pattern that was strong and symmetric with the centerline of the cuvette. The strength of the convection was found to be correlated with the mean evaporation rate of water. The estimated Marangoni number exceeded the critical value typically used to characterize the onset of Marangoni convection. The convection had a similar pattern as Marangoni convection observed in volatile liquids evaporated from capillary tubes. In both cases, the convection scaled with the width of the liquid container even though the sizes of the containers differ by an order of magnitude. In addition, the size of the convection in this study was much larger than the Marangoni convection in water that was observed in previous studies.

1. Introduction

An important property of any liquid surface is surface tension which is caused by the attraction among the liquid's molecules by intermolecular forces. Variation of temperature, concentration or electric potential along the liquid surface can result in a gradient in the surface tension. This gradient has been observed to induce a fluid motion known as Marangoni (or thermocapillary, or surface tension driven) convection [1]. These surface tension gradients drive liquid from low surface tension regions to high surface tension regions along the liquid surface. This type of convection is known as a key parameter in many applications, including heat-mass transfer, surface coating, and production of materials [2].

In order to determine how the surface tension may affect the stability of the liquid layer, Pearson [3] performed a small disturbance analysis for the theoretical case of an infinite homogeneous thin liquid layer of uniform thickness. The liquid layer had a free upper surface and a lower surface in contact with a fixed plane. Evaporation of the liquid was neglected. The only physical quantities that were assumed to vary within the liquid are temperature and parameters that were considered to depend on temperature only, including surface tension and the rate of heat loss from the surface. The temperature in the liquid layer was assumed to decrease from the bottom to the surface linearly. Pearson indicated that the onset of surface tension driven convection can be characterized by a dimensionless parameter, the Marangoni number (Ma), which is defined as the ratio of surface tension to viscous forces and can be expressed as:

$$Ma = \left(-\frac{\partial\gamma}{\partial T}\right)\left(\frac{\partial T}{\partial D}\right)\frac{D^2}{\eta\alpha} \quad (1)$$

where γ is the surface tension; T, the local temperature of the liquid; D, the liquid layer thickness (characteristic length); $\partial T/\partial D$, the temperature gradient in the liquid; η, the dynamic viscosity of the liquid; and α, represents the thermal diffusivity in the liquid. While evaporation was ignored which is a prime factor in generating a surface tension gradient, Pearson found that Marangoni convection exists only when Ma exceeds a threshold value of 80. The Pearson theory is a classic method to characterize the onset of Marangoni convection. It has been experimentally examined to be applicable for non-volatile liquid [4,5] and has been used in many studies for

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