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

Xudong Song, David S. Nobes\*

Mechanical Engineering, University of Alberta, Edmonton, Alberta, Canada

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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  $\sim$ 250 Pa to  $\sim$ 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.

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#### 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 heatmass 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 quanti-

ties 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:

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

where  $\gamma$  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;  $\eta$ , the dynamic viscosity of the liquid; and  $\alpha$ , 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

<sup>\*</sup> Corresponding author. Tel.: +1 780 492 7031; fax: +1 780 492 2200.

E-mail addresses: xudong1@ualberta.ca (X. Song), david.nobes@ualberta.ca (D.S. Nobes)

#### Nomenclature С dve concentration, Eq. (2) pressure D liquid layer thickness, Eq. (1) Q quantum efficiency, Eq. (2) T $E_{AVG}$ average evaporation rate temperature, Eqs. (1)–(3)light intensity horizontal axis x laser intensity, Eq. (2) vertical axis $I_0$ fluorescence intensity, Eq. (2) Ιf $I_{ORhB}$ laser intensity absorbed by RhB, Eq. (3) Greek symbols laser intensity absorbed by Rh110, Eq. (3) thermal diffusivity, Eq. (1) $I_{ORb110}$ fluorescence intensity of RhB, Eq. (3) surface tension, Eq. (1) $I_{RhB}$ γ fluorescence intensity of Rh110, Eq. (3) dynamic viscosity, Eq. (1) $I_{Rh110}$ η thermal conductivity molar absorptivity, Eq. (2) Ма Marangoni number, Eq. (1) $M^2$ beam quality factor

evaporating water [6–15]. However, a recent study [16] has suggested that the Pearson theory is not valid for a pure volatile liquid. This inconsistency indicates that more detailed study is required for characterizing the onset of Marangoni convection in volatile liquids. In this study, the Marangoni number was calculated and discussed to help understand the driving mechanism of the observed convection

The study of Marangoni convection has been well developed for many liquids other than water [6]. For the case of water, many researchers [7–11] have stated that Marangoni convection was not observed in their water evaporation experiments even when the Marangoni number had exceeded the critical threshold value. However, Ward and Duan's studies [12-14] have shown that evaporation of a liquid with a free surface could produce surface temperature gradients which would lead to interfacial instabilities and ultimately result in convection within the liquid. In these studies, by adopting a vacuum pump to control and increase the evaporation rate of water, Marangoni convection has been generated and was observed in pure water. As the vacuum chamber pressure decreases, the evaporation rate of water increases. As a result, the interfacial temperature gradients become larger and drive more intense Marangoni convection. Since water has its maximum density at 4 °C [15], these studies were able to conduct the investigation in the absence of buoyancy driven convection. In these experiments, water was continuously supplied to a stainless-steel conical funnel to maintain a spherical convex water-vapor interface at a constant level as it evaporated at various steady rates. The temperature in the bulk water was maintained at  $\sim$ 3.5 °C at the bottom of the container and decreased linearly with height except for a thin  $(\sim 50 \, \mu \text{m} \text{ to } \sim 800 \, \mu \text{m})$  uniform temperature layer at the surface. This was believed to be the result of mixing induced by Marangoni convection. The temperature profile was obtained using a 25 µm diameter thermocouple and indicated that throughout the experiment, the water in the funnel was density stabilized. Motion was also observed using a 12.7 µm diameter cantilevered probe inserted into the liquid to measure the flow velocity at the liquid-vapor interface. The measurement results were in accordance with the results calculated from the interfacial temperature gradients. As the vacuum chamber pressure was reduced, the interfacial flow velocity, along with the evaporation rate of water and the calculated Marangoni number were increased. This demonstrated that Marangoni convection became stronger as the rate of water evaporation increased.

In these studies [12–14] of Marangoni convection in water, the velocity field over the convection section was not visualized. In contrast, studies of volatile liquids [17–19] conducted by Buffone and Sefiane have visualized and characterized the Marangoni con-

vection in the bulk liquids using micro-particle image velocimetry (micro-PIV). The researchers investigated evaporation of volatile liquids in still air from the curved menisci formed in circular capillary tubes of various sizes (less than 1 mm in diameter). Strong convection beneath the interface were observed and visualized. The surface tension gradient, causing by the interfacial temperature variation induced by the non-uniform evaporation along the meniscus, was regarded as the driving mechanism for the convection. Marangoni convection was found to correlate with the evaporation rate, and sizes of the convection rolls scaled with the width of the capillary tubes. An infrared camera was used to measure the temperature profile along the capillary wall and the meniscus. When external heating was applied to change the interfacial temperature gradients along the meniscus, the convection pattern was altered and could be reversed. This revealed that the meniscus interfacial temperature profile played a key role for inducing the observed Marangoni convection.

A previous study by Hohmann and Stephan [20] has showed that the curved meniscus surface formed in circular capillary tubes can be divided into three regions, i.e., a macroregion, a microregion and an adsorbed film region. It was found that a large portion of the evaporation from the meniscus occurs in the microregion where the liquid-vapor interface approaches the wall. As a result, the local temperature in the microregion is the lowest among these three regions. For the case of a rectangular capillary cuvette, there are four corner menisci in addition to the bulk meniscus. Chauvet et al. [21] investigated the temperature distribution at an evaporating liquid meniscus formed in a square capillary tube with a cross-section of 1 mm × 1 mm using infrared thermography. The results showed that the temperature on the meniscus surface was the lowest at the tip of the corner meniscus and kept increasing towards the liquid bulk, indicating that the maximum local evaporation flux occurred at the tip of the corner meniscus. This indicates that evaporation of a liquid in a rectangular cuvette could also generate temperature gradients which would lead to surface tension gradients on the surface.

Although Marangoni convection has been detected during the evaporation of water in Ward and Duan's studies [12–14], the velocity field over the convection domain was unknown. To characterize the Marangoni convection in water, the velocity field needs to be investigated. Motivated by Buffone and Sefiane's studies [17–19], this work adopted stereo-PIV to measure the velocity distribution of any induced convection in water. In order to generate Marangoni convection in pure water, a custom vacuum system was designed and used to control and enhance the evaporation rate of water. To ensure that the generated convection is driven by surface tension rather than buoyancy forces, it was also

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