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Flow transition and hydrothermal wave instability of thermocapillary-driven flow in a free rectangular liquid film

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ABSTRACT

Thermocapillary-driven flow in a free liquid film, which has two gas-liquid interfaces, is experimentally investigated. Silicone oil of 5 cSt is employed as the test fluid. Two-dimensional basic flow known as 'double-layered flow' after Ueno and Torii (2010) is realized under small-enough Marangoni number *Ma*, the non-dimensional number to describe the intensity of thermocapillary effect, under the geometry considered in the present study. The flow exhibits a transition from the two-dimensional steady flow state to the three-dimensional oscillatory state when the intensity of the imposed thermocapillary effect along the free surfaces exceeds the threshold. In this oscillatory regime, two types of hydrothermal wave instabilities are observed: the traveling-wave flow and the standing-wave flow. We especially focus on the traveling-wave instability and compare it with a hydrothermal wave in a liquid layer with a single free surface investigated by other researchers.

1. Introduction

Pettit performed a series of experiments using a liquid film that had double-free surfaces (hereafter a free liquid film) on The International Space Station in 2003 [2]. In the experiments, Pettit formed a thin free liquid film of water in a ring made by metal wire and exposed the film to non-uniform temperature distribution by placing a heated iron close to one end of the wire ring. It was realized that the fluid was driven in the film toward the heated part, that is, a flow was induced from a colder region to a hotter region in spite of the negative temperature coefficient of the surface tension. These experiments showed that the free liquid film had a potential to be one way to obtain a new kind of crystallization process of materials and/or mass transport. We were inspired by these performances and started this study.

In the case of a thin liquid layer formed on a base plate, that is, a film with a single free surface (a thin liquid layer, hereafter), Smith and Davis [3] predicted thermal fluid instability in an infinite liquid layer imposed by a constant-temperature gradient along a free surface by performing a linear stability analysis. It was named 'hydrothermal wave (HW) instability. Daviaud and Vince [4] predicted instabilities under a coupling of thermocapillary and buoyancy effects, and then a variety of experiments were conducted with a liquid film in a narrow long channel [5–7] and shallow cavity [8,9] by various research groups. Riley and Neitzel [8] realized the HW predicted by Smith and Davis [3] in an experiment for the first time in a rectangular cavity with a temperature difference between both end walls. They reported a stability diagram and indicated the criterion to realize the HW in the film as a function of the dynamic Bond number Bo_D as $Bo_D \leqslant 0.22$. Shevtsova et al. [10] carried out a series of two-dimensional numerical simulations to show the stability diagram and indicated the HW criterion as $Bo_D \leqslant 0.25$.

There are few studies, on the other hand, on the thermocapillary-driven flow in a free liquid film. The longitudinal solidification of a two-dimensional single-component free liquid film was discussed by simulations [11,12]. In the case of a two-surface film, Ueno and Torii [1] indicated two types of basic flows by a series of experiments: the double-layered flow and single-layered flow. The effect of the liquid film shape in terms of the volume ratio was experimentally indicated on the selection of the basic flow and the direction of the net flow inside the film by measuring the liquid film profiles and the surface temperature distribution in the case of steady flows by [13]. Such an effect was confirmed through a series of parabolic flight experiments [14] as well as on-orbit experiments [15]. The Pettit demonstration was reproduced numerically by Yamamoto et al. [16] and the effect of the film shape near the heated area was shown. Concerning the

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physical mechanism of the selection of basic flows in the free liquid films, a discussion has been given [17,18], but we have never obtained a comprehensive explanation for the selection of the basic flows.

As for the three-dimensional oscillatory flows in the free liquid film, much less knowledge has been accumulated. Ueno and Watanabe [19] indicated the flow transitions from the time-independent steady flow to time-dependent 'oscillatory' flow for both basic flows. Ueno and Torii [1] and Limsukhawat et al. [20] conducted numerical simulations on the steady and oscillatory flows in the case of the double-layered basic flow.

The present study aims to illustrate the characteristics of the HW in a free liquid film. In particular, it deals with the transition processes of the induced flow patterns of the traveling wave as a function of the geometry of the free liquid film under the conditions of double-layered basic flows, by making comparisons with results in the system of a thin liquid layer formed in a rectangular cavity with a single-free surface.

2. Experimental setup

The experimental geometry is shown in Fig. 1. A liquid is filled in the rectangular hole made in a flat aluminum plate. In the present geometry, two kinds of aspect ratios are defined: the horizontal aspect ratio $\Gamma_x = L_z/L_x$ and the vertical aspect ratio $\Gamma_y = L_x/d$, where L_x is the distance between the different temperature-controlled end walls of the hole, d is the depth, and L_z is the distance between the side walls. The volume ratio between the liquid filled in the hole and the hole itself, $V/V_0 = V/(L_x d L_z)$, is kept very close to unity. One end wall is heated to maintain the temperature at $T = T_\mathrm{h}$ and another is cooled at $T = T_\mathrm{c}$ to realize a designated temperature difference $\Delta T = T_\mathrm{h} - T_\mathrm{c}$ between the end walls sustaining the free liquid film. The surfaces of the test plate, except the end and the side walls, are chemically coated with a fluoro-coating agent, Marvel Coat® (Ryoko Chemical Co., Ltd.), to prevent the leakage of the test fluid. Silicone oil of 5 cSt ($Pr = 68.4$ at 25 °C) is employed as the test liquid. The thermo-physical properties of the test fluid [21,22] are listed in Table 1. Gold-nickel-alloy coated cross-linking acrylic particles of 15 µm in diameter are suspended in the test fluid as the tracer particles. The test fluid with particles is fully illuminated to visualize the flow patterns and monitored by a charged coupled device (CCD) camera at 30 frames per second (fps). The surface temperature of the free liquid film is simultaneously monitored by an infrared (IR) camera at 30 fps.

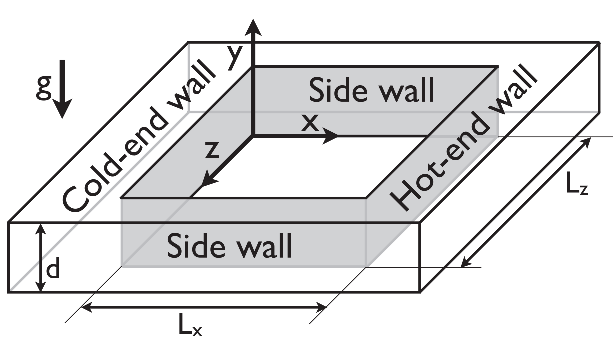

Fig. 1. Target geometry: a free liquid film exposed to a horizontal temperature gradient.

The intensity of the thermocapillary-induced flow is described with a nondimensional laboratory Marangoni number Ma_L after Riley and Neitzel [8] as follows:

$$Ma_\mathrm{L} = \frac{|\sigma_T|(\Delta T/L_x)d^2}{\rho \nu \kappa}, \quad (1)$$

where σ is the surface tension, σ_T $(= \partial\sigma/\partial T)$ the temperature coefficient of surface tension, and ρ, ν, and κ are the density, kinematic viscosity, and thermal diffusivity of the test fluid, respectively. In this definition, the temperature gradient is approximated by $\Delta T/L_x$. We also consider the theoretical Marangoni number [8] defined as follows:

$$Ma = \frac{|\sigma_T|(\partial T/\partial x)d^2}{\rho \nu \kappa}, \quad (2)$$

where $\partial T/\partial x$ indicates a temperature gradient. In the present study, we measured the surface temperature distribution using the IR camera along the center line perpendicular to the end walls and took the value in the middle region. Note that the temperature dependence of the viscosity is considered in the evaluation of both Marangoni numbers. The fluid viscosity at a temperature T [°C] is evaluated using an empirical correlation [21]:

$$\frac{\nu(T)}{\nu_0} = \exp\left(5.892\frac{25 - T}{273.15 + T}\right), \quad (3)$$

where ν_0 is the kinematic viscosity of the test fluid at 25 °C and T is the temperature in Celsius. The characteristic kinematic viscosity $\nu = \nu_\mathrm{exp}$ is evaluated by:

$$\nu_\mathrm{exp}(T) = \frac{\nu(T_\mathrm{h}) + \nu(T_\mathrm{c})}{2}. \quad (4)$$

We describe the intensity of the buoyancy effects relative to Marangoni effect by the dynamic Bond number Bo_D [8,10]:

$$Bo_\mathrm{D} = \frac{\rho g \beta d^2}{|\sigma_T|}, \quad (5)$$

where β is the thermal expansion coefficient and g the gravitational acceleration. This number corresponds to the ratio between the Rayleigh number $Ra = (g\beta(\Delta T/L_x)d^4)/(\nu\kappa)$ and Ma_L. The intensity of deformation of the free liquid film is described by the static Bond number,

$$Bo = \frac{\rho g d^2}{\sigma}. \quad (6)$$

In our study, the experiments were conducted with five types of test plates made of aluminum with different thickness: d [mm] = 0.2, 0.4, 0.6, 1.0, and 1.2. The size of the hole in the plate is varied in the interval $1.0 \leqslant L_x$ [mm] $\leqslant 6.0$ and $2.0 \leqslant L_z$ [mm] $\leqslant 18.0$. These test plates were processed by wire electrical discharge machining with an accuracy of ±0.005 mm. The dynamic and static Bond numbers under these conditions are listed in Table 2. The thermocapillary effect mainly dominates the flow induced in the film, and a little surface deformation is generated by the gravity.

In addition to the series of experiments with the liquid-film holder made of aluminum, we prepared the test section made of quartz glass of 0.6 mm in thickness and (L_x, L_z) = (2 mm, 4 mm)

Table 1
Physical properties of the test fluid: the temperature coefficient of surface tension is referred from [21], and the others from [22].

ρ (kg/m^3)	ν (m^2/s)	κ (m^2/s)	σ (N/m)	σ_T (N/(m K))	β (1/K)	Pr (–)
9.12×10^2	5.0×10^{-6}	7.31×10^{-8}	19.7×10^{-3}	-6.37×10^{-5}	1.09×10^{-3}	68.4