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Characteristics of surface oscillation in thermocapillary convection

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ABSTRACT

The characteristics of surface oscillation in a rectangular pool of silicone oil have been investigated experimentally. The horizontal cross-section of the pool is 52 mm × 36 mm, and the depth of the silicone oil layer is in the range of 1.1–4.8 mm. The applied temperature difference between the two sidewalls leads to shear flow along the free surface from hot to cold and a back flow in the underlying layer. With the increase of the temperature difference, the original steady flow will become unstable to unsteady flow. A CCD laser displacement-sensor with high resolution is used to measure the position of the liquid surface dynamically. And the Hilbert–Huang transform is chosen to analyze the experiment data which is nonlinear and non-stationary. The characteristics of surface oscillation have been obtained. And the relationship of the characteristics with the temperature difference and liquid layer depth has been discussed in details.

1. Introduction

When a temperature gradient is imposed along a free liquid–gas interface, thermocapillary convection is driven by the surface tension gradient. Such convection has been of interest for it occurs in many processes such as thin-film coating and crystal growth from the melt. The instability of the convection has been paid more attention for it leads to oscillating convection, which produces poor crystal quality in the process of crystal growth [1]. Temperature oscillation and surface oscillation are the main characteristics of the instability.

A linear stability analysis of thermocapillary instability was given by Smith and Davis [2,3]. They considered a liquid layer of infinite horizontal extent bounded by a rigid adiabatic plane at the bottom and a free surface subjected to a constant temperature gradient at the top. When the free surface is assumed to be flat and non-deformable, the hydrothermal wave, which is traveling waves propagating in a lateral direction, is derived as the thermocapillary instability. The characteristics for the hydrothermal wave, such as the critical condition for onset and the propagating direction, depends on the Prantl number of the liquid and the Biot number of the interface. When the free surface is considered to be deformable, another thermocapillary instability was obtained, which is called surface wave. The surface wave is also traveling wave, and the characteristics of the instability are similar to that of the two-dimensional waves in an isothermal layer subjected by wind stresses analyzed by Smith and Davis [4]. So hydrothermal wave and surface wave are different thermocapillary instabilities with different characteristics, which were derived with different assumption.

Experiments have been conducted by Riley and Neitzel [5] to investigate the thermocapillary instability in a rectangular pool filled with silicone oil (Pr = 13.9). They have observed two kinds of instabilities which depend on the Bond number of the liquid layer. For small-Bo fluids, the fluid convection transits from steady unicellular flow to hydrothermal waves which are similar to the instability predicted by Smith and Davis [2]. For large-Bo fluids, it transits to steady multi-cellular flow, and then to oscillating multi-cellular flow, which is characterized with steady multi-cellular structures near the hot wall and a pair of oblique waves near the cold wall. Similar to Burguete et al. [6] has also observed the hydrothermal wave instability for thin liquid layer. However, for deep liquid layer, it is observed by him that the basic return flow transits to stationary rolls, which is characterized as a stationary pattern with a wave vector perpendicular to the applied temperature gradient. And the characteristics of thermocapillary waves such as frequency, amplitude and wave number have been studied in details.

Experiment research on thermocapillary instabilities of a thin liquid layer in the perspective of surface deformation was published by Schwabe et al. [7]. The shadowgraph technique was used in the experiment to observe the deformed liquid–gas interface dynamically. For $d < 1.4$ mm, short-wavelength instability was observed, which travels in the azimuthal direction with small surface deformation. While for $d > 1.4$ mm, long-wavelength instability was found, whose waves travel in radial at onset and in azimuthal directions later. The surface deformation of thermocapillary flow caused by temperature gradient along the liquid–gas interface has been investigated by Duan et al. [8]. A modified

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