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Experimental study on Prandtl number dependence of thermocapillary-buoyancy convection in Czochralski configuration with different depths

You-Rong Li*, Lu Zhang, Li Zhang, Jia-Jia Yu

Key Laboratory of Low-grade Energy Utilization Technologies and Systems of Ministry of Education, College of Power Engineering, Chongqing University, Chongqing 400044, China

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ABSTRACT

A series of experiments on thermocapillary-buoyancy convection in Czochralski configuration with different liquid depths have been conducted. Prandtl numbers of the working fluids vary from 10 to 29 and the depth of the liquid pool is between 1.5 mm and 8 mm. Results show that the critical Marangoni number increases with the increase of the liquid pool depth. Prandtl number has a little impact on the critical Marangoni number for the shallow liquid pool, but a significant influence for the deep liquid pool. The flow pattern transits from the concentric multi-rolls to the hydrothermal waves in the shallow liquid pool with the increase of Marangoni number. Furthermore, with the increase of Prandtl number and the liquid pool depth, the hydrothermal waves can be suppressed, and thus the concentric multi-rolls flow pattern is easier to appear. In deep liquid pools, the number of the spokes decreases with the increase of Marangoni number and the liquid pool depth, and the spokes move from the crystal edge to the crucible sidewall. In addition, the radical waves close to the crystal edge have been observed at deep liquid pools and large Marangoni numbers.

1. Introduction

As is known to all, when the free surface is subjected to a horizontal temperature gradient, thermocapillary-buoyancy convection driven by the coupled surface-tension gradient and buoyancy force will appear in the liquid layer. Prandtl (*Pr*) number of the working fluid as a key parameter has a significant influence on thermocapillary-buoyancy convection. For low Prandtl number fluid, the heat transfer depends mainly on the heat conduction; however, the convective heat transfer will become very important for higher Prandtl number fluid.

Up to now, a great deal of researches to explore the effects of Prandtl number on thermocapillary-buoyancy convection in different geometrical configurations have been implemented. Smith and Davis [1,2] conducted a series of linear stability analysis for thermocapillary convection in a thin fluid layer subjected to a tangential temperature gradient. They found that Prandtl number plays a very important role on the critical Marangoni number, and the critical propagation angle of the hydrothermal waves decreases from 90° to 0° with the increase of Prandtl number. Sass et al. [3], Xu and Zebib [4] performed the three-dimensional numerical simulation on thermocapillary convection in a cubic container with a free surface. It was found that the flow patterns are related to Prandtl number, the thermocapillary Reynolds number and the aspect ratio. Besides, Zhu and Duan et al. [5–7] carried out a large amount of experimental investigations of thermocapillary convection in a rectangular pool with the applied temperature gradients along the free surface. It was also certified that the critical temperature difference of the flow destabilization and transition routes of the flow pattern depend on Prandtl number and the Rayleigh number. Hoyas et al. [8,9] studied the linear stability of thermocapillary-buoyancy convection of the fluids with two different Prandtl numbers in an annular domain heated from below, and found the primary flow patterns can be divided into four types: stationary roll, oblique travelling waves, longitudinal rolls, standing hydrothermal wave. On the other hand, Shi et al. [10,11] conducted the numerical simulation on thermocapillary convection and thermocapillary-buoyancy convection in an annular pool subjected to a radial temperature gradient when Prandtl number of the working fluids varies from 0.011 to 57.9. Results showed that the critical phase velocity and the critical azimuthal wave number of the hydrothermal waves decrease monotonously with the increase of Prandtl number.

The Czochralski method as one of the effective methods to produce the single crystal is widely used. The coupled thermocapillary-

* Corresponding author.
E-mail address: liyourong@cqu.edu.cn (Y.-R. Li).

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Nomenclature

Bo	Bond number
d	depth, mm
f	frequency, Hz
m	number of the spokes
Ma	Marangoni number
Pr	Prandtl number
r	radius, mm
T	temperature, °C
t	time, s

Greek symbols

α	thermal diffusivity, m^2/s
ε	aspect ratio
β	thermal expansion coefficient, 1/K
γ	surface tension, N/m
γ_T	temperature coefficient of surface tension, N/(K·m)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts

c	crucible
cri	critical
s	crystal

buoyancy convection has a substantial influence on the quality of the single crystal [12–14]. Li et al. and Wu et al. [15–18] performed a series of three-dimensional numerical simulations of silicone melt (Pr = 0.011) in a Czochralski configuration with rotation crystal and crucible. The flow stability diagrams are drawn and the basic characteristics of the oscillatory flow after destabilization are observed. Schwabe [19] and Shen et al. [20,21] conducted a series of experiments in a model of Czochralski configuration with moderate Prandtl number fluid ($Pr \approx 7$). It was found that the critical temperature difference for the onset of the oscillation flow is related to the liquid pool depth and rotation rates of the crystal and crucible. Furthermore, Jing et al. [22] carried out a series of three-dimensional numerical simulations of $LiNbO_3$ (Pr = 16) in a Czochralski configuration in order to explore the influence of the Marangoni effect on the flow pattern. It was found that only straight spoken patterns appear on the free surface because of the larger depths of the liquid pool. Teitel et al. [23] studied the flow instabilities in a Czochralski configuration with a sets of silicone oils (Pr = 6.8–500) by experiment and simulation. It was confirmed that the cold plumes below the cold crystal will detach and descend toward the crucible bottom in a deep liquid pool, which hints that the hydrothermal waves did not appear. However, they did not show the flow patterns and the basic characteristic of the flow destabilization.

In this work, we reported a series of systemic experimental results of thermocapillary-buoyancy convection in Czochralski configuration with different liquid depths. The critical condition of the flow destabilization was determined. The evolution of the flow pattern structures with Prandtl number and the basic characteristics of the flow destabilization were focused on.

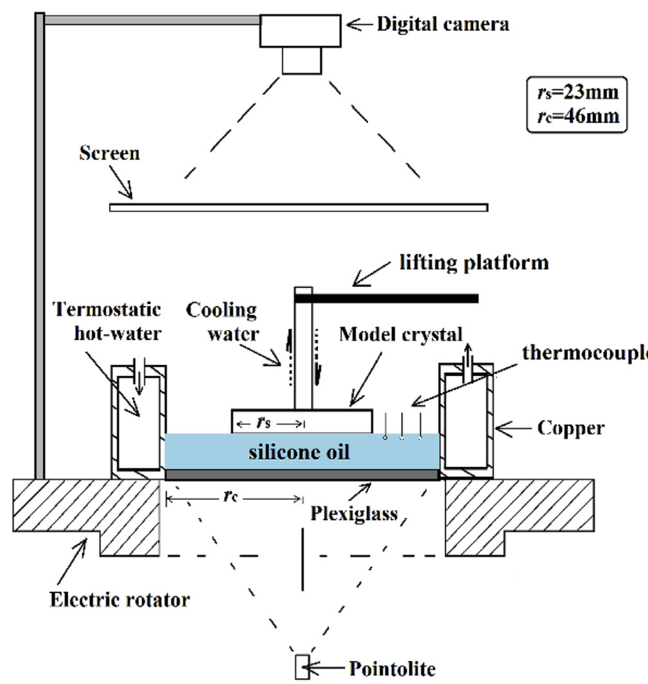

Fig. 1. The experimental apparatus.

2. Experimental setup and methods

The experimental apparatus is shown in Fig. 1. The cylindrical pool and a disk on the free surface are used to imitate the crucible and the crystal in industrial Czochralski growth technology. The radii of the crystal and the crucible are $r_s = 23 \pm 0.1$ mm and $r_c = 46 \pm 0.1$ mm, respectively. The automatic lifting platform with a precision of ± 3 μm is used to adjust the model crystal up and down to just touch the free surface of the working fluid. Besides, to avoid the influence of the meniscus, the side wall of the crucible is covered with anti-creeping liquid produced by the Minnesota Mining and Manufacturing Co., which can maintain a flat free surface. The model crystal and the crucible are made of red copper with good thermal conductivity, so that it is easy for two thermostatic baths to control the temperatures of the crystal (T_s) and the crucible sidewall (T_c). Four T-type thermocouples with a precision of ± 0.1 K are respectively embedded into the crystal and the sidewall of the crucible to measure the temperature difference between them ($\Delta T = T_c - T_s$). In addition, the other three T-type thermocouples are settled just below the free surface to monitor the temperature fluctuation characteristics of the working fluid. They are respectively located in 6 mm (3#), 11 mm (2#), 16 mm (1#) away from the crystal. The Plexiglass as the bottom of the crucible with the thickness of 10 ± 0.1 mm is transparent and adiabatic. Therefore, the light from the pointolite (150 W) can pass through it easily. The HP data acquisition (HP 34970A) is applied to get all the real-time temperature data.

The schlieren method is applied to obtain the temperature fluctuation patterns on the free surface. The lights emitted from the pointolite pass through the plexiglass and the liquid layer, and then project on the