# ACTIVE CONTROL OF OSCILLATORY THERMOCAPILLARY CONVECTION

**Junichiro Shiomi**
Department of Mechanics, KTH
S-100 44 Stockholm, Sweden
shiomi@mech.kth.se

**Gustav Amberg**
Department of Mechanics, KTH
S-100 44 Stockholm, Sweden
gustava@mech.kth.se

**Henrik Alfredsson**
Department of Mechanics, KTH
S-100 44 Stockholm, Sweden
hal@mech.kth.se

## ABSTRACT

Active control of oscillatory thermocapillary flow was applied in an open cylindrical container filled with silicone oil ($Pr = 14$). Thermocapillary convection was driven by imposing a radial temperature gradient on a flat free surface. The control was realized by locally heating the surface at a single position using the local temperature signal at a different position fed back through a simple algorithm. Significant attenuation of the oscillation was achieved in a range of supercritical Marangoni numbers, with the best performance in the weakly non-linear regime. As the non-linearity became strong, a low fequency modulation was observed in the controlled signal, which suggested the appearance of neighboring modes. Simultaneously measuring the temperature oscillation at two positions gives us a good insight in how the control influences the whole temperature field on the free surface.

## INTRODUCTION

In the production of single crystals, the container less processing has advantages in order to increase the purity of the crystal. In the float-zone method, where a raw material rod is slowly pulled through a ring heater, the small zone near the heater is molten and resolidified as a single crystal. This system has been proposed for space processing, since the flow in the melt is influenced by gravitational convection. Experiments in microgravity conditions revealed that even with the absence of buoyancy, thermocapillary convection could be significant. Furthermore, the time dependent oscillatory state of the thermocapillary convection was found to cause detrimental striations in the chemical composition of the finished crystal.

Thermocapillary convection is a fluid motion driven by the variation of surface tension with temperature. The basic mechanism can be understood by considering a horizontal force balance over small piece of the interface. The difference in surface tension can be balanced only by the viscous shear stress, which implies that the fluid needs to be set in motion. The strength of the driving force of the convection is commonly characterized by the Marangoni number ($Ma$), the ratio between thermal diffusion and convection. It is well know that the convection experiences a transition from 2 dimensional steady flow to 3 dimensional time dependent flow at well defined critical Marangoni number.

Being a rich stability problem of fundamental fluid motion, the industrial need has also motivated a number of studies to clarify the onset mechanism of the instability has motivated a number of studies. Numerically, linear stability theory was studied by Neitzel et al. (1993) and Kuhlmann and Rath (1993). Kazarinoff and Wilkowski (1989), (1990) made numerical simulations of 2-d axially symmetric full float-zone. Rupp et al. (1989) presented a 3 dimensional simulation of a half zone with an aspect ratio of 0.6 and found $m = 2$ to be the most dangerous mode. The mechanism for the onset of oscillatory flow in a half zone for a low Prandtl number liquid was identified by Levenstam and Amberg (1995) as a purely hydrodynamic instability, very similar to the instability of a vortex ring. Wanchura et al. (1995) made similar interpretations of the linear stability at high Prandtl numbers liquid.

Many experimental studies have been done on the half zone-model, where a liquid drop is held between two coaxial rods that are maintained at different temperatures to impose axial temperature gradients on the free surface (Ostrach, 1985), (Velten, 1991). The oscillatory thermocapillary flow was detected first by Schwabe et al. (1979) and Chun and Wuest (1979). Later, Preisser et al. (1983) showed that the azimuthal wave number and frequency are determined by the aspect ratio of the liquid zone.

In the present work, generic flow of a character similar to that found for instance in the float zone method has been studied in a annular configuration. The geometry is shown in figure 1. A flow in this geometry was first examined by Kamotani et.al. (1992) for high $Pr$. The limit of the container size below which Marangoni convection dominates over buoyancy convection was identified (Kamotani et al., 1996), (Kamotani et al., 2000). The major advantage of the annular configuration is that, having the gravity vector normal to the free surface, the surface can be kept flat, thus better quantitative analysis can be achieved.

The system is an attractive object for control since its closed geometry makes feed back control possible. There have been only a few reported works in control of oscillatory thermocapillary convection. An attempt to stabilize the thermocapillary wave instability in an experiment on a plane fluid layer was made by Benz et al. (1998). The temperature signal sensed by a thermocouple near the cold end of the layer was fed forward to control a laser which heated the fluid surface along a line. For an axisymmetric base state, Petrov et al. (1996) attempted to stabilize oscillations in a half-zone, by applying a non-linear control algorithm using local temperature measurement close to the free surface and heating a thermoelectric element placed at a location diametrically opposite the measurement. A successful control was reported for $Ma = 17750$, but the control scheme failed for $M \geq 19000$ because of the strong non-linearity of the dynamics.

The aim of this work is to apply a simple control method on oscillatory thermocapillary convection in an annular configuration. The control was applied for a range of overcritical Marangoni number. The method makes use of a temperature sensor and a wire heater. The control was realized by locally heating the surface at a single position using the local temperature signal at different position fed back through a simple algorithm.

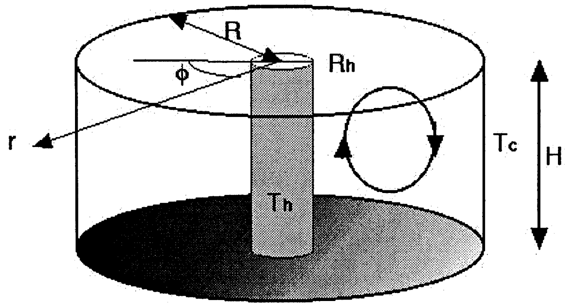


Figure 1: *Geometry*

## EXPERIMENT

The experimental apparatus is shown in figure 2. The test cell consists of a copper cylinder with 6mm inner diameter, a thin co-axial pipe heater, and an insulated bottom made of Teflon. The cell was filled with 1cSt silicone oil with a Prandtl number around 14 till a flat free surface was achieved. In order to obtain the flat surface, the heater pipe was machined to have a smaller diameter above the surface. Then the parts of the pipe heater and the copper cylinder above the surface were coated with Fluorad (3M Scotchguard). This inhibits the liquid from wetting the lips, thus the contact lines can be pinned. A constant temperature gradient was imposed along the free surface by circulating warm water through the pipe heater and cold water through the copper cylinder. The aspect ratio of the test section, defined as $Ar = (R - R_h)/H$, was kept at 1 throughout the experiments. The ratio between the inner and outer diameter of the cell $Hr = R_h/R$ was 0.21. The temperature was measured using the cold wire technique. The cold wire sensor has a U-shape, and the bottom part made of platinum wire is installed through the surface. The distance between the prongs is $0.2mm$ and the diameter of the platinum wire is $2.5\mu m$. The tip of the wire reaches as far as approximately $100\mu$ down the surface.

It was confirmed that the wire was thin enough not to cause any appreciable deformation when installed through the free surface. The heater was made in the same manner as the sensor but with 10 percent rhodium-platinum wire which has more resistance per unit area than pure platinum. Then the heater was placed above the surface within a distance less than $100\mu$. The power output from the heater was obtained by measuring current and voltage over the heater.

Sensor1 and Sensor2, were positioned at $\phi = 0^o$, $\phi = -60^o$. The radial positions was $r = R_h + (R - R_h)/2$ for both sensors. Figure 3 shows the time history of two calibrated temperature signals simultaneously measured with Sensor1 (solid line) and Sensor2 (dashed line). The phase shift between the temperature signals are out of phase, which implies that the oscillation has an azimuthal wavenumber of three (mode 3) for this particular geometry. This was confirmed by the flow visualization. The flow visualization of the horizontal section is presented in figure 4. The flow was seeded with flakes (Irodin 120 Pearl Lustre) and illuminated from above. The white part is where the seeded flakes, lying parallel to the surface, reflected the illumination the most. The deformation of the vortex ring was observed to have a triangular triangle shape which confirms that the azimuthal wave number was three. Furthermore the wave was identified to have a traveling structure, which means that the amplitude of the oscillation is independent of $\phi$ for constant $r$ and $z$. Since the azimuthal wave number is three, placing a heater 120 degrees away in azimuthal direction from Sensor1, $(r, \phi) = (R_h + (R - R_h)/2, 120^o)$, temperature oscillations at the positions would be in phase. A simple cancellation scheme is then realized by making the heater output proportional to the inverted temperature oscillation at Sensor1. Thus the heater delivers heat locally when the oscillation has a cold spot at the heater location. The minimum heater output was kept at 0, in order not to generate unnecessary heat which might raise the mean temperature of the flow. The control was applied to flows for various $\epsilon = (Ma - Ma_{cr})/Ma_{cr}$, where $Ma_{cr}$ is the critical Marangoni number. Here, the Marangoni number is defined as $Ma = \gamma \Delta T R/\mu\alpha$, where $\gamma$, $\alpha$, $\mu$, and $\Delta T$ are the surface tension coefficient, thermal diffusivity, dynamic viscosity, and the temperature difference imposed on the free surface respectively. $\epsilon$ was varied from 0.05 to 0.89, and for each $\epsilon$, the feed back amplification was varied to detect its optimum value where the most damping of the oscillation amplitude was obtained.

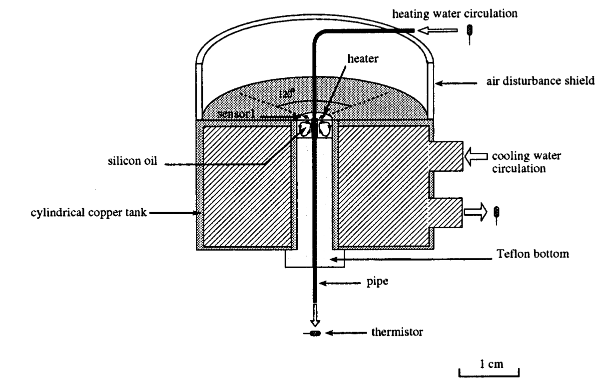


Figure 2: *Experimental setup*

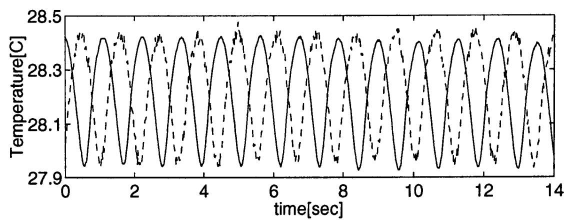


Figure 3: *Time histories of the temperature signals of uncontrolled oscillation simultaneously obtained from Sensor1 (solid line) and Sensor2 (dashed line).*

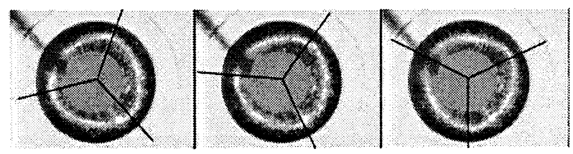

Figure 4: *Flow visualization of the horizontal section (Lavalley,1997).*

## RESULTS

Figure 5 demonstrates the time history of the temperature signal from Sensor1 and the corresponding heater power output for $\epsilon = 0.11$. When the control is turned on, the amplitude of the temperature oscillation is quickly suppressed to 10 $\sim$ 20 percent. Once the oscillation is stabilized, the heater power drops to less than 10 percent of its initial value. Removing the control, the system rather slowly goes back to the unperturbed state. This control can be maintained for infinite time, and is qualitatively repeatable.

Figure 6 is plotted in the same manner as figure 5 for $\epsilon = 0.81$, a parameter in the strongly non-linear regime. Applying the control, the amplitude of the oscillation is reduced

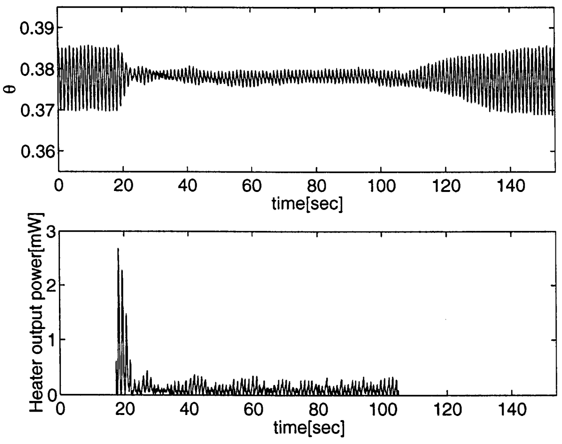


Figure 5: *Top: Time history of the temperature sensor signal. Bottom: Simultaneously measured heater power output.* $\epsilon = 0.11$. $\theta = (T - T_c)/\Delta T$, *where* $T$*: local temperature,* $T_c$*: cold wall temperature,* $\Delta T$*: imposed temperature difference*

significantly in a few seconds, though the reduction of the amplitude is much less than the case for $\epsilon = 0.11$. The controlled signal has an envelope, a low frequency ($\sim 0.05Hz$) modulation of the oscillation amplitude. A corresponding periodic increase is observed in the heater output power. An attempt to damp the envelope by raising the feed back amplification merely resulted in an amplification of the fluctuation. When the control is removed, the envelope disappears and the amplitude increases to its original value in about $10s$.

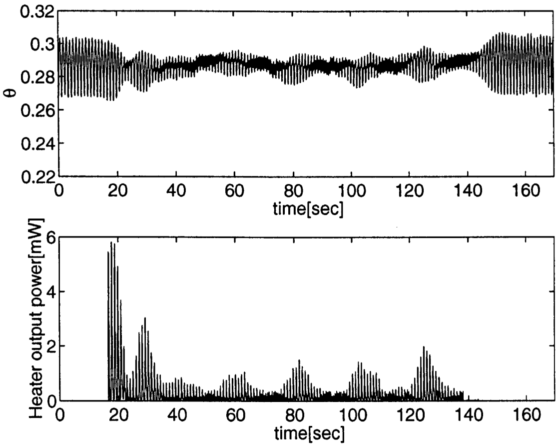


Figure 6: *Top: Time history of the temperature sensor signal. Bottom: Simultaneously measured heater power output.* $\epsilon = 0.81$. $\theta = (T - T_c)/\Delta T$, *where* $T$*: local temperature,* $T_c$*: cold wall temperature,* $\Delta T$*: imposed temperature difference.*

The power spectrum densities for the signals in figure 5 ($\epsilon = 0.11$) and figure 6 ($\epsilon = 0.81$) are shown in figures 7 and 8 respectively. The dashed curves show the spectra with control, solid curves show the ones without control. Taking the energy around the peaks into account, the first harmonics are rather amplified while the others are damped in both figures. Especially when the non-linearity of the uncontrolled oscillation is strong ($\epsilon = 0.81$), the energy around the first harmonic is comparable to the one around the fundamental frequency. The nature of the control scheme suggests that the control should be able to damp any overtones to some extent as long as they originate from oscillations which are in phase at Sensor1 and the heater. In this regard, the energy around the first harmonic is not purely detected from the mode 3 oscillation. It must originate from the oscillation which has a spatial structure that is amplified by the control scheme.

In both the high and the low $\epsilon$ cases, the power spectrum density of the fundamental frequency ($\sim 1Hz$) is decreased by the control. Furthermore, around the base tone, the spectra have two peaks in the frequency components lying close to each other. The difference between the two peaks corresponds to the frequency ($0.05Hz$) of the envelope observed in the controlled signal for $\epsilon = 0.81$. Hence, the envelope can be identified as due to a superposition of two waves with slightly different frequency. The experiments carried out in the same set up by Lavalley (1997) suggests that the origin of the new frequency component be mode 2. He has shown that a slight change in $Hr$, the ratio between inner and outer diameter of the cell, from 0.21 to 0.16 causes the transition in mode number from 3 to 2. This implies that, for the given geometry ($Ar = 1, Hr = 0.21$), the potential for both modes to dominate the flow is comparable. Therefore when the mode 3 oscillation is suppressed, the next dangerous mode, mode 2, may appear. The frequency of mode 2 was identified by Lavalley (1997) to be around $1Hz$ which corresponds to the frequency of the newly emerged mode. As the choice of the most dangerous mode strongly depends on aspect ratio of the geometry, when the aspect ratio becomes close to the point where the most dangerous mode switches from one to another, the $Ma_{cr}$ for two modes should become similar. For the half-zone geometry, Wanschura et.al. has presented the dependency of the most dangerous mode on the aspect ratio, and showed that $Ma_{cr}$ of two neighboring modes become similar in certain range of the aspect ratio.

The performance of the control method for a range of $\epsilon(0.05 \leq \epsilon \leq 0.89)$ is shown in figure 9. The suppression rate $\gamma$ is the ratio between amplitude of the oscillations with and without control. The amplitudes of the oscilla-

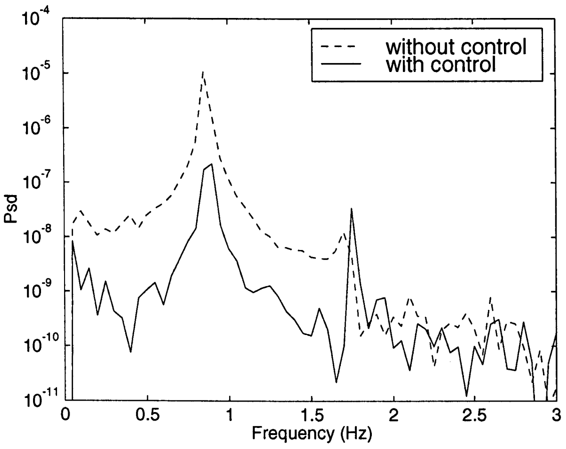


Figure 7: *Top: The power spectrum density for the temperature signal (θ) with control (solid line) and without control (dashed line).* $\epsilon = 0.11$.

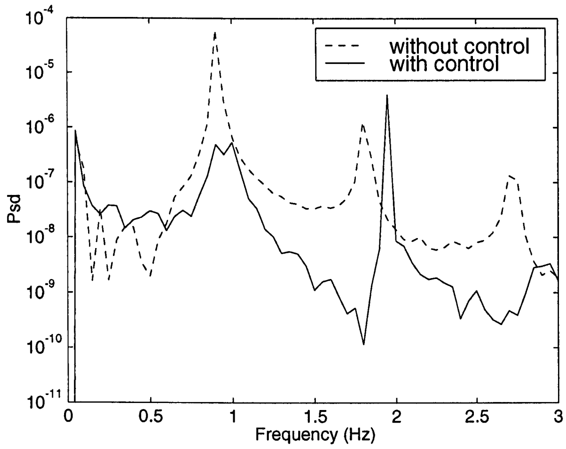


Figure 8: *Top: The power spectrum density for the temperature signal (θ) with control (solid line) and without control (dashed line).* $\epsilon = 0.81$.

tions are obtained as $2\sqrt{2}Trms$, where $Trms$ is the root mean square value of the temperature signal. For the data from Sensor1 (circles), the control scheme shows excellent performance for the smallest $\epsilon$. Increasing $\epsilon$, $\gamma$ increases proportional to $\epsilon$. The trend changes when $\epsilon$ reaches around 0.35, above which the amplitude ratio is almost constant and below 35 percent. The change in the characteristic of the controlled signal appears because the non-linearity of the system becomes strong above this point. This corresponds to $\epsilon = 0.36(Ma = 19000)$ reported by Petrov et.al. to be the limit above which the control scheme fails because the dynamics become highly non-linear.

Data from Sensor2 (stars) give some hints to grasp how the control influences the whole flow field. In the regime with weak non-linearity, the trend of plots correlate with that of Sensor1. Once the non-linearity becomes stronger, $\gamma$ starts to decrease which implies that the influence of the control becomes more global.

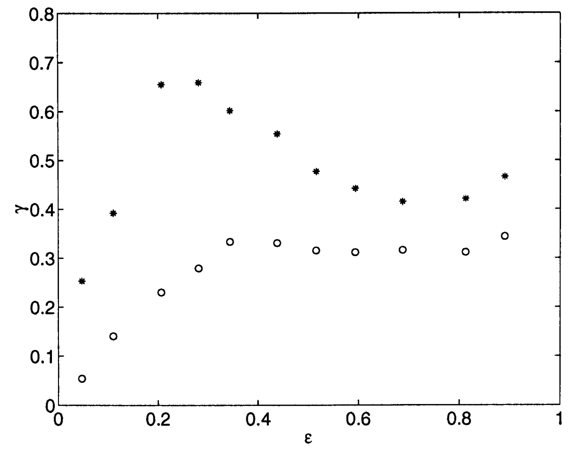


Figure 9: *Performance of the control method for a range of* $\epsilon(0.05 \leq \epsilon \leq 0.89)$. $\epsilon = (Ma - Ma_{cr})/Ma_{cr}$. *γ is the suppression ratio.*

## CONCLUSIONS

Active control was applied to oscillatory thermocapillary flow in an annular configuration. Significant attenuation of the oscillation was achieved in a range of $\epsilon(0.05 \leq \epsilon \leq 0.89)$, with the best performance in the weakly nonlinear regime. There, the ratio $\gamma$ of the amplitudes of oscillations with and without control, increased as $\epsilon$ increased, while in the strongly non-linear regime, $\gamma$ was almost constant. The characteristic of the control changed at $\epsilon = 0.35$ due to strong non-linearity. The spectrum analysis suggested the appearance of mode 2 oscillation when suppressing mode 3 oscillation. Measuring the temperature oscillation at two positions simultaneously showed that the influence of the control becomes more global in space as the non-linearity becomes stronger.

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