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Free surface heat loss effect on oscillatory thermocapillary flow in liquid bridges of high Prandtl number fluids

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Abstract

The effect of free surface heat loss on oscillatory thermocapillary flow is investigated in liquid bridges of high Prandtl number fluids. It is shown experimentally that the critical temperature difference changes by a factor of two to three by changing the air temperature relative to the cold wall temperature. In order to understand the nature and extent of the interaction between the liquid flow and the surrounding air, the heat transfer from the liquid free surface is investigated numerically for the conditions of the present experimental work. The airflow analysis shows that even when the heat loss is relatively weak (the Biot number is unity or smaller), the critical temperature difference is affected appreciably. It is shown that the heat loss effect is significant in widely conducted tests near room temperature and that the critical temperature difference is much larger than the room temperature value when the heat loss is minimized. The analysis suggests that an interaction between the surface heat loss and dynamic free surface deformation near the hot wall is responsible for the observed heat loss effect.

1. Introduction

It is known that thermocapillary flow in the half-zone configuration, in which a liquid column is suspended between two differentially heated walls, becomes oscillatory under certain conditions. Despite the fact that many experimental and theoretical studies have been conducted, the cause of oscillatory flow for high Prandtl number (*Pr*) fluid is not yet fully understood. It has been shown recently that the heat loss from the free surface, caused mainly by the natural convection of the surrounding air (no imposed forced convection), affects the onset of oscillations significantly [1]. The critical temperature difference is shown to change by a factor of two to three by varying the air temperature relative to the cold wall temperature. This strong heat loss effect has been largely neglected in the past work, except when the heat loss is relatively large, which may be one important reason for the lack of our complete understanding of the cause of oscillations. In particular, the Marangoni number (*Ma*) is often used to specify the onset of oscillations (e.g. Preisser et al. [2]), but available experimental data, taken over wide conditions, suggest that an additional parameter is needed to sufficiently specify the onset of oscillations [3,4]. Since thermocapillary flow experiments with high *Pr* fluids (mainly silicone oils) are conducted in room air, the heat transfer from the free surface is usually neglected. However, that is not the case according to the data in [1]. For this reason, the airflow around liquid bridges is investigated numerically in the present work in order to understand the nature of the interaction between the liquid and air flows and also to find a relation between the heat loss and the oscillation mechanism.

2. Experimental work

The liquid flow configuration is illustrated in Fig. 1. The experiment and apparatus are described in detail in Kamotani et al. [1], so they are briefly discussed herein.

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Nomenclature

Ar	liquid bridge aspect ratio, L/D
Bi	average Biot number, $Q/(2\pi Lk\Delta T)$
$Bi_{,\mathrm{loc}}$	local Biot number, $qR_0/(k\Delta T)$
D	liquid bridge diameter
H	total height of computational domain (see Fig. 2)
k	thermal conductivity of liquid
L	liquid bridge length
Ma	Marangoni number, $\sigma_T \Delta TL/\mu\alpha$
Ma_{cr}	critical Ma for onset of oscillations
Nu	average Nusselt number for liquid flow, total heat flux through liquid/$(k(\Delta T/L)\pi R_0^2)$
Pr	Prandtl number of liquid, ν/α
Q	total heat transfer rate over liquid free surface
q	local rate of heat loss at free surface
R_0	radius of liquid column
R_C	radius of computational domain (see Fig. 2)
S	S-parameter, $(\sigma_T\Delta T/\sigma)Ma^{3/14}/Pr$
T	temperature
T_C	cold wall temperature
T_H	hot wall temperature
T_R	surrounding air temperature
T_S	temperature at free surface
(R, Z)	global coordinates for airflow study defined in Fig. 2
(r, z)	coordinates for liquid flow defined in Fig. 1

Greek symbols

α	thermal diffusivity
ΔT	overall temperature variation in liquid, $T_H - T_C$
ΔT_{cr}	critical ΔT for onset of oscillations
ε	emissivity of liquid free surface
μ	liquid viscosity
ν	liquid kinematic viscosity
σ	surface tension
σ_s	Stefan–Bolzmann constant
σ_T	temperature coefficient of surface tension

The top and bottom rods are made of copper. The top rod is heated by a nichrome wire, and the bottom rod is cooled by circulating water from a constant temperature bath. 2 and 3 mm diameter rods are used. The test fluids are 2 and 5-centistokes (cSt) silicone oils. The pertinent properties of the fluids can be found in Lee [5]. The apparatus is placed in an oven in order to vary the free surface heat transfer over a wide range. The oven has the interior dimensions of 28 cm (width) × 25 cm (height) × 25 cm (depth). Hot air is circulated within the oven by natural convection (a gravity convection oven). The environment in the oven will be discussed in detail later.

The flow is visualized by adding a small amount of alumina particles (about 10–20 μm in diameter) to the test fluid. The flow is observed by a video camera attached to a microscope. The onset of oscillatory flow is identified from the particle motion.

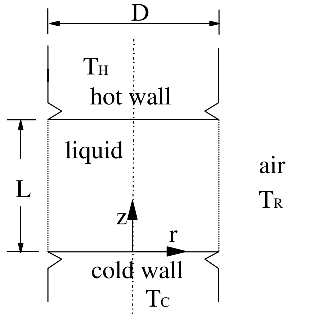

Fig. 1. Liquid bridge configuration.

T_H and T_C are measured with 0.1 °C accuracy. The error involved in the measurement of the critical temperature difference, ΔT_{cr}, is estimated to be within 5%. The liquid column length and shape are kept within ±2% of the specified values.

3. Important parameters

The important dimensionless parameters for the thermocapillary flow in the liquid are known to be Ma, Pr, and Ar (aspect ratio). Based on our past work [6], the effects of buoyancy and gravity on the onset of oscillations are not important in the present experiments. Only liquid columns with nearly flat free surfaces are investigated herein.

The heat loss from the free surface to the surroundings is due to convection in the air and radiation. Therefore, many parameters affect the free surface heat transfer. Experimentally, we vary the surface heat transfer mainly by varying the temperature difference $T_R - T_C$ and determine the critical temperature difference for each case. Then, we simulate the airflow for this critical condition and compute the heat transfer rate at the free surface. We then compute the dimensionless heat transfer rates as follows. We start with the expression for the amount of heat loss per unit free surface area, namely $q = k\partial T/\partial r$. By normalizing this expression, we obtain a dimensionless parameter based on q, namely $qR_0/(k\Delta T)$. This parameter is called the local Biot number ($Bi_{,\mathrm{loc}}$) herein. We also define a parameter based on the total heat loss from the free surface (Q). By integrating the equation $q = k\partial T/\partial r$ over the free surface, it can be shown that the average dimensionless temperature gradient at the free surface is represented by the parameter $Q/(2\pi Lk\Delta T)$, which is called the average Biot number (Bi) herein. It can be shown that the ratio of the total free surface heat transfer rate to the total conduction heat transfer rate through liquid is related to Bi as $8Ar^2Bi$. The test fluids evaporate slightly during the tests. However, based on the measurement of the rate of evaporation, it is estimated that the heat loss by the evaporation is less than 1% of the loss by the air convection for the 5-cSt fluid and less than 4% for the 2-cSt fluid in the present experimental range.

The parametric ranges covered by the present experiments for the liquid flow are: $Ma < 5 \times 10^4$, $21 \leqslant Pr \leqslant 50$, and $Ar = 0.4$–0.7. For Ma and Pr, the fluid properties are evaluated at the fluid mean temperature, $1/2\ (T_H + T_C)$. The free surface heat transfer is varied in the range $0.2 < Bi < 1.5$.

4. Numerical simulation of heat transfer in air

Since it is difficult to investigate the air motion in detail and to determine the heat transfer rate at the liquid free surface experimentally, the motion is simulated numerically, and based on this, the Biot number is computed. The airflow and the liquid flow are solved simultaneously.

The flow in the liquid is assumed to be steady and axisymmetric. We have developed a numerical code based on SIMPLER [7] to analyze steady thermocapillary flows and its predictions have been extensively tested (e.g. [8]). We use the same program herein. Its accuracy for flow analysis in the half-zone configuration has been discussed [3]. A non-uniform grid is employed with meshes graded toward the hot and cold walls and toward the free surface. For the present analysis, the main quantity of interest from the thermocapillary flow analysis is the temperature level of the bulk liquid. For this reason, we check the effect of the numerical grid on the average Nusselt number Nu under the condition of a thermally insulated free surface. For the conditions of $Ma = 3.9 \times 10^4$, $Pr = 41$, and $Ar = 0.65$ (near the maximum Ma in the present experiment), three different grids are tested: 31×37 ($r \times z$), 51×58, and 80×100, with the smallest axial mesh sizes next to the hot and cold walls being, 0.003, 0.001, and 0.0005, respectively. With those grids the computed values of Nu are 9.20, 8.93, and 8.90, respectively. Therefore, the 51×58 grid is employed for the liquid domain in the present analysis.

The same program is modified to analyze the airflow around the liquid column. The airflow is assumed to be laminar and axisymmetric. The Boussinesq approximation is employed. The Prandtl number of the air is set equal to 0.7. The computational domain for the airflow analysis is defined in Fig. 2. The cold wall, including the copper block, is maintained at T_C. The radius of the cold copper block (12 mm) defines the radius of the outer computational boundary. As will be shown later, the temperature boundary layer along the liquid surface is well within the outer boundary, so its location can be justified. The upper boundary is defined by the end of the top heating rod. A part of the top rod is covered by the nichrome wire, the temperature of which is higher than that of the heating rod. However, a measurement of the nichrome wire temperature shows that the temperature difference between the wire and the ambient air is at most only 10% higher than the difference between the heating rod and the air. Therefore, for simplicity, the top rod is approximated by a straight cylinder with uniform temperature. Along the open boundaries, the airflow comes in or goes out. In the region where the flow comes in, the temperature is set equal to the ambient temperature, and in the region where it goes out, the temperature gradient is set to be zero normal to the boundary. Both velocity components are assumed to have zero normal gradients along the open boundaries.

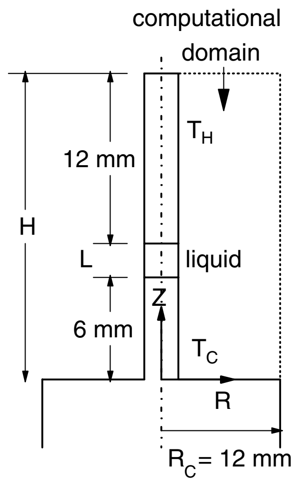

Fig. 2. Computational domain for airflow study.

At the free surface, the velocity, temperature, and heat flux are continuous. The viscosity ratio of air to silicone oil is roughly 0.005, while the thermal conductivity ratio is much larger (about 0.23). Therefore, the effect of shear due to the air motion on the thermocapillarity condition is neglected. In addition to the heat loss due to convection, the loss due to radiation is included. Since the overall temperature variation in the air is small compared to its absolute temperature level, the radiation condition is linearized, namely, the radiation heat transfer rate is expressed as $4\varepsilon\sigma_s T_R^3(T_S - T_R)$. The emissivity of the test fluids is known to be 0.9 [9]. It is found that the radiation contribution to the total heat loss is less than 15%.

The computational mesh is non-uniform. In the horizontal direction, smaller grids are used towards the inner vertical boundary in order to resolve the velocity and temperature boundary layers. In the vertical direction, in the segment that faces the heater or the cold wall at the inner boundary smaller grids are used towards the solid–liquid interface. The segment facing the liquid at the inner boundary is divided according to the above liquid flow analysis, namely into 58 non-uniform grids. The main quantity of interest in the present work is Bi. It is found that the computationally most taxing situation is when T_R is between T_H and T_C so that the airflow is downward near the cold wall but it is upward in the rest of the domain. For the condition of $T_H = 86.3$ °C, $T_C = 19.6$ °C, and $T_R = 59.7$ °C with $Pr = 45.2$, the following grids are tested: 31×119 ($R \times Z$), 51×159, and 80×238, with the smallest radial mesh next to the inner vertical boundary being 0.002 and 0.0005, and 0.0002, respectively. The computed Bi's are 0.328, 0.350, and 0.356, respectively. Therefore, the 51×159 grid is used for the air domain.

5. Results and discussions

5.1. Validation of numerical results

First, the numerical results are compared with experimental data in order to show the accuracy of the present airflow simulation. We measure the air temperature by a traversing thermocouple probe and compare the result with the numerical prediction. A typical comparison is presented in Fig. 3. As the figure shows, the numerical predictions agree well with the data. Since the air velocity is on the order of a few cm/s or smaller, the Peclet number for the airflow around the liquid bridge is of order unity in the present experiments. Therefore, the convection is relatively weak and the thermal boundary layer thickness is on the order of the liquid column dimension. Since it is very difficult to measure such a small air velocity accurately, we do not compare the velocity field. Noting that our main interest in the present work is the temperature field, we can conclude that our numerical model simulates the airflow temperature field with sufficient accuracy for the present work.

5.2. Effect of free surface heat loss on onset of oscillations

In a typical test, we fix T_C and T_R at desired values, and then gradually increase T_H until the flow becomes oscillatory (judged by flow observation). The temperature difference ΔT at the transition is called the critical

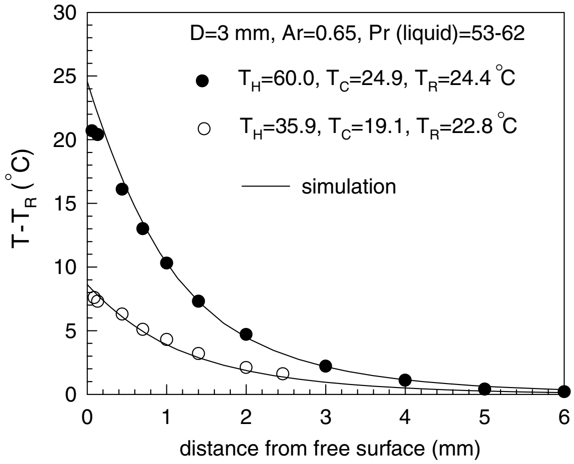

Fig. 3. Comparison of measured and computed air temperature distributions at liquid mid-height.

temperature difference, ΔT_{cr}. The data taken in our room-temperature tests, where T_R is around 23 °C, have been presented in [1]. We present here mainly oven test results. It is important then to know the environment in the oven.

When we use an oven, we usually expect some flow and thermal disturbances inside. For this reason, we check the temperature conditions inside our oven carefully by several thermocouples. During this measurement, the experimental setup is placed in the oven, and our main interest is the condition near the liquid column (within about 5 cm from the column). The various parts of the experimental apparatus tend to damp the disturbances near the liquid column.

It takes about 15 min for the oven temperature to stabilize after the start. Even after the stabilization, the oven air temperature increases when the oven heater is on and decreases when it is off. When the oven temperature is set at 65 °C, the air temperature variation is observed to be about ±2 °C and the fluctuation period is about 2 min. When the set temperature is 35 °C, the variation is ±1 °C and the period is about 5 min. At any given time and at any temperature setting, the oven air temperature within 5 cm from the liquid column is uniform within ±1 °C.

In the present experiment we vary the amount of free surface heat loss by varying the temperature difference $T_R - T_C$. Since T_C is accurately controlled by the circulating water from the constant temperature bath, the temperature variation level in the oven determines the accuracy of $T_R - T_C$. In the present work, $T_R - T_C$ is varied over a wide range (−16 to 40 °C), and the largest oven temperature variation (±2 °C) occurs when $T_R - T_C$ is large. Therefore, when we investigate the data trend over such a wide range of $T_R - T_C$, the oven temperature variation does not significantly affect the trend. Another quantity of interest that is affected by T_R is the temperature difference $T_H - T_R$. It has been shown that the onset of oscillations is mainly determined by this temperature difference [1]. For $D = 3$ mm and for 5-cSt silicone oil, the value of $T_H - T_R$ at the critical condition is about 30 °C over a wide range of $T_R - T_C$ [1]. Since the oven temperature variation of maximum ±2 °C is small compared to the value of $T_H - T_R$ at the critical condition, the error in the determination of the critical condition is relatively small.

We did not measure the air motion in the oven. The oven air motion is expected to be most active when the oven heater is on. However, the steady flow in the liquid column does not show any visible change whether the heater is on or off. Moreover, the critical temperature difference is reproducible within the experimental error whether the heater is on or off. These facts suggest that the oven air motion does not significantly change the air motion of interest, which is induced by the heating-cooling arrangement of the experiment.

The air convection around the liquid column is controlled by the temperature difference $T_R - T_C$ in the present work. Both T_R and T_C are varied in order to obtain a wide range of the temperature difference. The critical temperature difference for the liquid flow, ΔT_{cr}, is shown in Fig. 4 over a range of $T_R - T_C$ and for $D = 2$ and 3 mm. As the figure shows, ΔT_{cr} varies substantially by varying $T_R - T_C$, or by varying the airflow. It has been identified that this effect is due to a change in the free surface heat transfer [1]. As will be shown later, the heat is lost from the free surface for the conditions of Fig. 4, and the loss increases with decreasing $T_R - T_C$. Therefore, ΔT_{cr} decreases with increasing free surface heat loss, or the heat loss destabilizes the flow. Also, the difference in ΔT_{cr} between the two diameters in Fig. 4 narrows as the heat loss is decreased. In the negative $T_R - T_C$ range of Fig. 4, T_R is kept near 25 °C and T_C is varied (room temperature tests), while in the positive $T_R - T_C$ range, T_C is kept near 25 °C and T_R is varied (oven tests). If we determine ΔT_{cr} at a fixed value of $T_R - T_C$ but with T_C or T_R set at different values from those in Fig. 4, the value of ΔT_{cr} is slightly different from that shown in Fig. 4 for the same $T_R - T_C$, mainly because the liquid viscosity, which varies with temperature, is different in those cases.

ΔT_{cr} is non-dimensionalized as Ma_{cr} in Fig. 5. Ma_{cr} increases with increasing $T_R - T_C$ (decreasing heat loss). The liquid viscosity variation with the temperature mentioned above is now taken into account in the definition of Ma. The effect of heat loss is stronger when the liquid diameter is larger. Note that Ma_{cr} is about 1.5×10^4 for both $D = 2$ and 3 mm in the tests conducted near room temperature. One may then conclude that Ma_{cr} is the proper parameter for the onset of oscillations if the tests are conducted only near room temperature, as done by many investigators in the past. But this conclusion is misleading because data taken in near room temperature tests are very much affected by the heat loss.

5.3. Study of airflow around liquid bridge and its effect on thermocapillary flow

The above results show that it is important to study the airflow and the heat transfer at the liquid free surface. The computed streamline and isotherm patterns are shown in Fig. 6 for a typical room temperature test, near the experimentally determined critical condition. The streamlines and isotherms shown herein are all equally spaced from the maximum to minimum values in

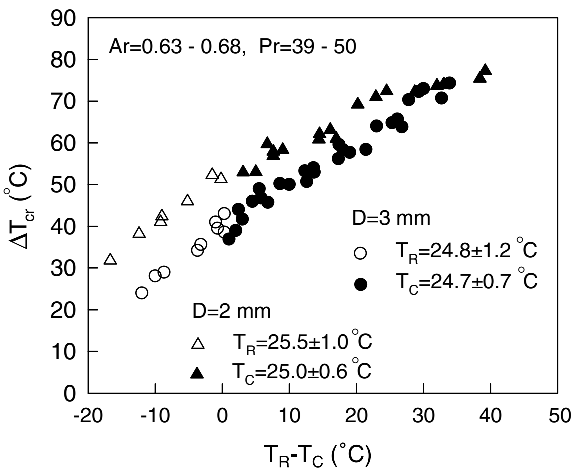

Fig. 4. Critical temperature differences measured under various free surface heat transfer conditions.

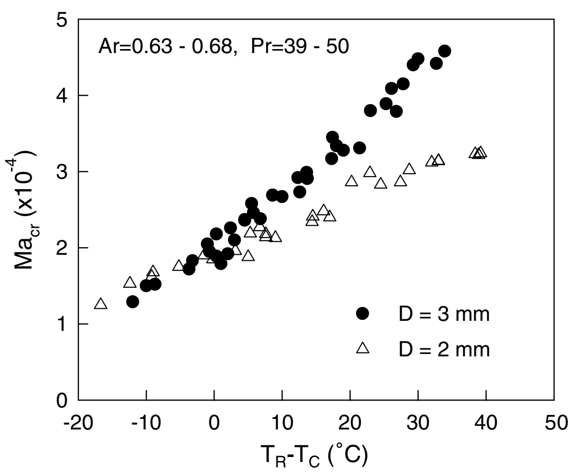

Fig. 5. Critical Marangoni numbers for various free surface heat transfer conditions.

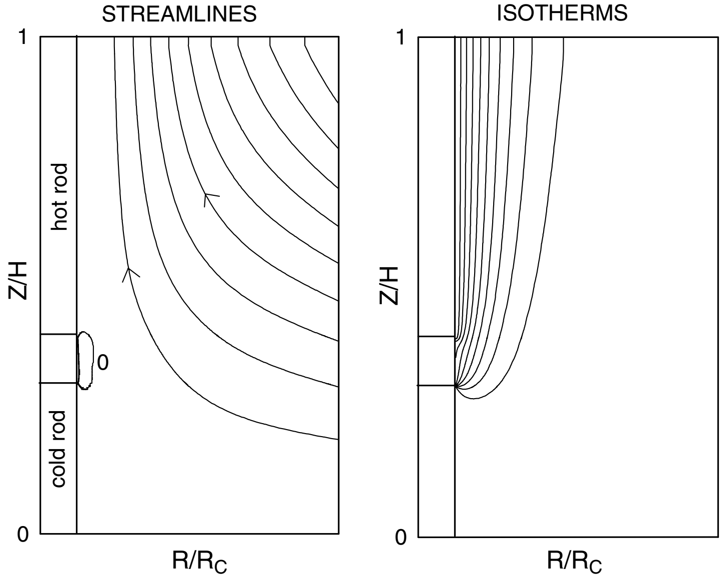

Fig. 6. Computed streamline and isotherm patterns of airflow ($T_H = 65.0$ °C, $T_C = T_R = 25.0$ °C, $D = 3$ mm, $Ar = 0.65$ and $Ma = 1.9 \times 10^4$, $Pr = 49$ for liquid flow).

the computational domain. The airflow is driven by both the liquid shear and buoyancy. The flow is mainly upward, except in the region near the liquid surface where the flow recirculates as the flow caused by the surface shear is in the downward direction. The present analysis shows that the liquid free surface velocity is nearly the same as the buoyancy driven flow velocity, both on the order of a few cm/s. However, the total air volume affected by this liquid motion is relatively small, as seen in Fig. 6. Consequently, the numerical simulation shows that the liquid shear effect on Bi is also small.

Assuming that the free surface heat loss is important, we correlate the experimentally determined critical conditions with the numerically computed heat loss. Ma_{cr} is correlated with Bi in Fig. 7. Bi is positive in Fig. 7, meaning that the heat is lost from the free surface on the average. Several important observations can be made in Fig. 7. (i) As seen in Fig. 7, Bi is relatively small, unity or smaller. Therefore, small heat loss is responsible for nearly fourfold change in Ma_{cr}. (ii) The figure shows that Ma_{cr} increases with decreasing Bi, but, in the case of the higher Pr fluid, if Bi is reduced to less than about 0.3, Ma_{cr} appears to reach a maximum value for each diameter. This plateau in Ma_{cr} is considered to be the situation where the free surface heat loss is negligibly small. (iii) Overall, the data correlation by Ma_{cr} and Bi is not satisfactory. However, Fig. 7 suggests that there exists a minimum Ma_{cr}, about 6000, below which no oscillations appear. As discussed by Kamotani and Ostrach [3], since the convection in the liquid plays an important role in the oscillation mechanism, a necessary condition for the oscillations is that Ma must be sufficiently large. (iv) In our earlier investigations of oscillatory thermocapillary flows of high Prandtl fluids, we proposed the S-parameter to specify the onset of oscillations (under negligible free surface heat transfer) [3]. Therefore, the critical data are correlated by S and Bi in Fig. 8. This correlation is better than the correlation by Ma_{cr} and Bi in Fig. 7. However, the data for two different viscosities cannot be correlated by S and Bi. In the following we discuss various implications of the above observations.

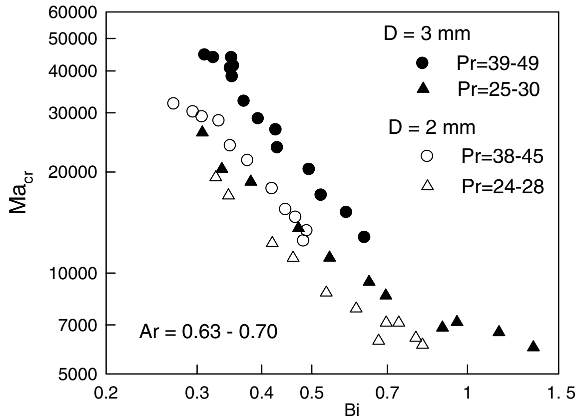

Fig. 7. Correlation of critical Marangoni number with average Biot number.

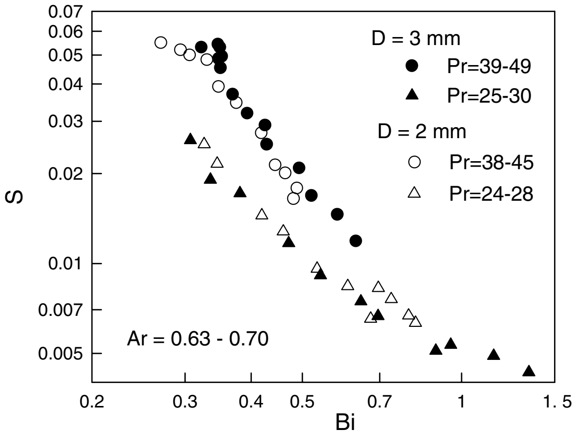

Fig. 8. Correlation of S-parameter at critical condition with average Biot number.

Ma_{cr} is associated with linear stability analysis of thermocapillary flow with negligible dynamic free surface deformation. If the present oscillation phenomenon is a linear stability problem, the free surface heat loss affects Ma_{cr} by changing the basic velocity and temperature fields of the liquid flow. With free surface heat loss, the surface temperature gradient will increase and as a result, the surface velocity will also increase, if ΔT is fixed. Therefore, if the heat loss is to destabilize the flow by changing the basic flow field, the destabilization could be due to this increased surface velocity. However, since ΔT_{cr} decreases with increasing heat loss, the dimensional velocity actually decreases. The computed dimensional surface velocity distributions for three critical conditions are shown in Fig. 9. The velocity at the critical condition clearly decreases with increasing heat loss. Moreover, the dimensionless heat transfer rates for the liquid flow at the critical condition, the Nusselt numbers at the hot and cold walls (they are different in the presence of free surface heat transfer), also decrease with increasing heat loss, as given in Fig. 9. Therefore, the convection in the liquid is actually getting weaker at the critical condition with increasing heat loss, so the observed destabilization is not due to increased convection.

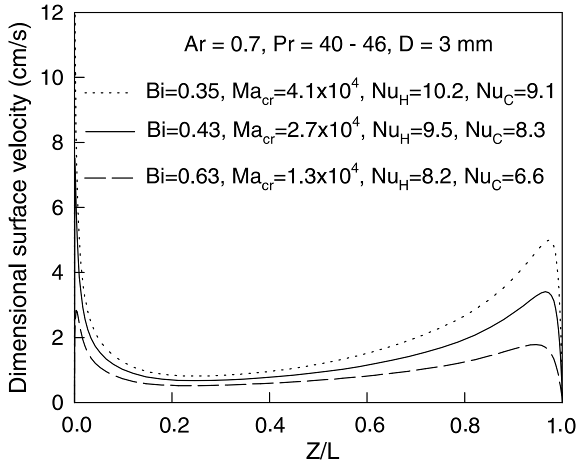

Fig. 9. Free surface velocity distributions at critical conditions.

The linear stability analysis in [10] and the numerical simulation in [11] of thermocapillary flow show that the free surface heat loss tends to stabilize the flow, opposite of what was found in the present work.

Based on the above discussions, together with the fact that the Ma_{cr}–Bi combination cannot correlate the critical data generally (Fig. 7), the present work suggests that the oscillation phenomenon is not a result of linear instability of thermocapillary flow with negligible dynamic free surface deformation.

In order to improve the correlation by the S–Bi combination in Fig. 8, we have to look into the local heat transfer on the free surface. In Fig. 10, we present the local Biot number distribution near the critical condition for one case. One notices that there is a large peak in $Bi_{,loc}$ near the cold wall. This peak comes about because the liquid surface temperature stays warm up to very close to the cold wall so that there exists a sharp temperature gradient from the liquid surface to the cold wall in the air in this region (see Fig. 6). Since this heat loss near the cold wall is relatively large, a question arises as to whether it is responsible for the observed heat loss effect, which is addressed below.

It has been reported earlier that a thin plastic plate has a strong effect on the onset of oscillations when it is placed at a certain height around the liquid column without touching the free surface (see Fig. 11) [1]. The plate changes the airflow and the free surface heat transfer. When the plate is placed below the mid-height of the liquid column, it does not affect the critical condition. This is true even when the plate is placed near the cold wall so that the afore-mentioned large free surface heat transfer near the cold wall is substantially altered. This suggests that the large heat transfer near the cold wall does not contribute to the observed change in the critical condition. When the plate is placed at the hot wall level, the flow is found to be more stable because the heat loss is reduced as the plate slows the upward air convection and hot air accumulates below the plate. However, when the plate is somewhat below the hot wall but above the liquid column mid-height, the flow is destabilized. When the plate is below the hot wall, it disrupts the warm upward air motion along the free surface, and as a result, the surface heat loss is increased above the plate, especially near the hot wall. Therefore, the heat loss and the flow stability depend very much on the location of the hot corner relative to the plate, which

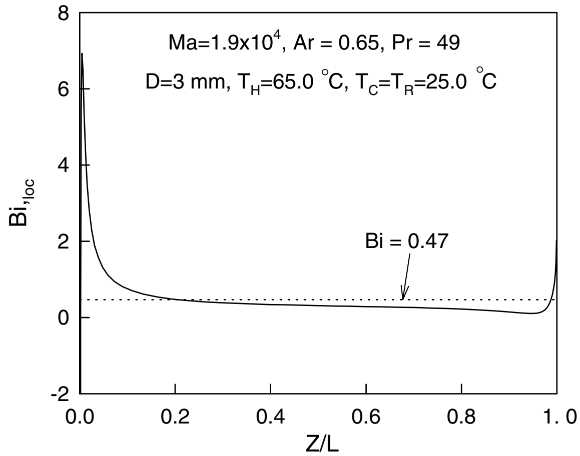

Fig. 10. Local Biot number distribution.

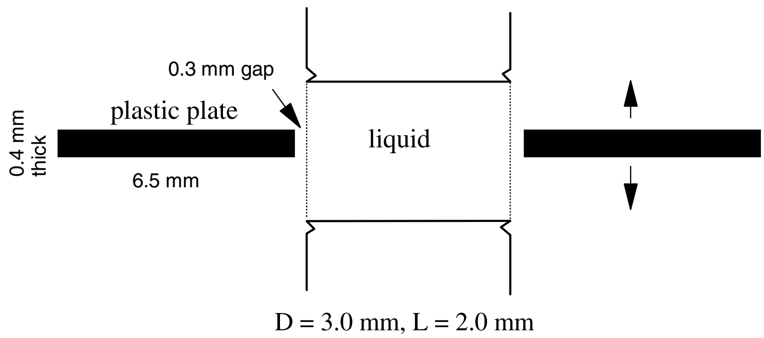

Fig. 11. Sketch of thin plate used to alter airflow.

shows the importance of the free surface heat transfer in the region near the hot wall, called the hot corner.

The concept of the S-parameter is based on the dynamic free surface deformation in the hot corner. It has been shown above that the free surface heat transfer near the hot corner is responsible for the observed heat loss effect, so the two factors must be related. Since the basic flow is mainly driven in the hot corner in the case of high Pr fluid, the oscillation process originates from this region [3]. The main effect of dynamic free surface deformation in the hot corner is that after the surface flow (the flow along the free surface) is altered for some reason, the response of the return flow (the interior flow from the cold to hot region) is slightly delayed because the free surface must deform first. One oscillation period consists of an active period and a slow period, based on the activity level of the surface flow. At the beginning of an active period, the surface flow accelerates in the hot corner, and the free surface depresses by transporting some fluid near the free surface out of the region. The additional convection along the free surface associated with this surface deformation initiates the non-linear oscillation process in which the flow and temperature fields are continuously altered [3]. The S-parameter represents the time lag or the relative amount of increased convection due to the deformation. Although the free surface deformation is relatively small, it can sufficiently augment the oscillation process at the beginning of each active period when the S-parameter becomes large enough.

One important aspect of high Pr fluid is that viscous diffusion proceeds faster than thermal diffusion in a transient situation. It is known that the ratio of two diffusion speeds scales with the square-root of Pr. In the present oscillation process for high Pr fluid, the free surface deformation is associated with viscous diffusion, so it interferes with the thermal diffusion process near the free surface significantly, which is the basic cause of the oscillations. Now, in the presence of free surface heat loss, the fluid near the free surface is somewhat cooler than the interior fluid. Therefore, at the beginning of an active period when the fluid is removed from the free surface, warmer fluid is exposed, which helps to increase the convection along the free surface with increasing time. Thus the heat loss augments the dynamic free surface deformation effect and makes it easier for the flow to become oscillatory, as the present experiment shows. Although the heat loss is relatively small, it does not require much heat to affect the surface deformation effect.

It can be shown that the hot corner defined in [3] extends to the location where $Bi_{,loc}$ becomes minimum near the hot wall (see Fig. 10) and that the average Biot number in the hot corner is approximately equal to Bi (see also Fig. 10).

If the deformation (or the viscous diffusion) proceeds much faster than the thermal diffusion, the heat loss effect does not penetrate much into the fluid so that the effect of the above convection augmentation is much smaller. That is why the critical condition is affected less (S is larger), for a given Bi, when Pr is increased, as seen in Fig. 8. Knowing that the ratio of these diffusion speeds scales with the square-root of Pr and knowing also that the effect of Bi is modified by this ratio, we correlate the critical conditions by S and $Bi/Pr^{0.5}$ in Fig. 12, where the results for $Ar = 0.4$–0.45 are also included. The correlation is reasonably good covering ranges of Pr and Ar, which supports the various arguments made above. Fig. 12 tells us that the dynamic surface deformation effect is the fundamental cause of the oscillations since the critical condition is specified by the S-parameter alone when the heat loss is negligible: the value of S is about 0.055 when the heat loss effect is negligible. The heat loss effect, if important, modifies this basic oscillation cause, decreasing S with increasing $Bi/Pr^{0.5}$.

Further work is needed to understand the relationship between the dynamic surface deformation and the heat transfer in more detail, but this is left for future work.

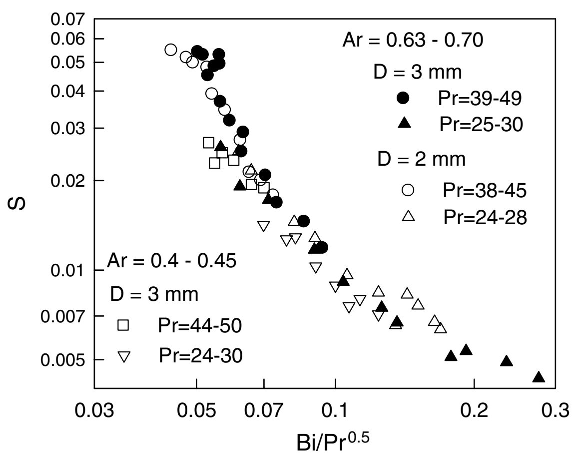

Fig. 12. Correlation of S-parameter at critical condition with modified Biot number.

6. Conclusions

The effect of free surface heat loss on the onset of oscillatory thermocapillary flow is investigated in liquid bridges of high Pr fluids. It is found that Ma_{cr} changes when the temperature of the cold wall or the ambient air is varied due to a change in the heat loss at the liquid free surface. In order to determine the free surface heat transfer rate, the airflow around the liquid bridge is investigated numerically. It is shown that the Biot number for the heat transfer is small, at unity or smaller, but the flow is destabilized substantially with increasing heat loss. The destabilization occurs despite the fact that the convection in the liquid becomes weaker at the critical condition. The observed transition cannot be described by Ma_{cr} and Bi. The present work suggests that the oscillation phenomenon can be explained only when dynamic free surface deformation is taken into account, which is represented by the S-parameter. It is shown that the critical condition can be correlated well by S and the modified Biot number.

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