1. Investigations for High Prandtl Fluid

1.1 Study of Oscillatory Thermocapillary Flow of High Prandtl Number Fluid

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INVESTIGATION OF FREE SURFACE HEAT TRANSFER EFFECT ON OSCILLATORY THERMOCAPILLARY FLOW OF HIGH PRANDTL NUMBER FLUID

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Oscillatory thermocapillary flow in liquid bridges of high Prandtl number fluid is investigated. The effect of heat transfer at the free surface on the conditions for the onset of oscillations is studied experimentally. In order to vary the surface heat transfer over a wide range, the experiments are conducted in an oven. The surface heat transfer results in net heat loss or net gain depending on the oven temperature relative to the hot wall temperature. The heat loss situation is of main interest in the present work. It is shown that the critical Marangoni number (Ma_{cr}) increases substantially with decreasing free surface heat loss. The air motion is simulated numerically in order to compute the free surface heat transfer rate. The numerical results show that the critical conditions cannot be correlated by two parameters, Ma and mean Biot number. It is shown that the S-parameter correlates the critical conditions well when the surface heat transfer is minimized. When the free surface gains heat at high oven temperature, the critical temperature difference now decreases with increasing heat gain. How the oscillation mechanism is affected by the free surface heat transfer is discussed.

1. INTRODUCTION

Our past work has shown that the heat transfer at the free surface of a liquid bridge of high Prandtl number fluid has a significant effect on the onset of oscillatory thermocapillary flow [1-3]. Since this is new information and gives us an important insight into this complex subject, we continue to investigate the effect of free surface heat transfer. Previously we reported the effect of the cold wall temperature (T_C) on the onset of oscillations in room temperature tests [1-3]. The free surface heat transfer can be changed also by changing the surrounding air temperature (T_R), or the temperature difference T_R - T_C. Since we can cover a wider range of T_R - T_C by changing T_R in an oven, we performed experiments in an oven. Some results from the oven tests are presented herein. As before, the air motion is simulated to compute the free surface heat transfer rate. In room temperature tests, the free surface loses heat to the surrounding air. Many experimental data taken in near room temperature are available in literature, so our main interest is this heat loss situation. By increasing the oven temperature, eventually the loss becomes a gain. The results taken under this heat gain conditions are also presented and discussed.

It is important to identify the dimensionless parameters to characterize the critical conditions for the transition to oscillatory flow in order to understand in what way the surface heat transfer affects the oscillation mechanism. The oscillation mechanism for high Prandtl number fluid is not yet fully understood. There are two important dimensionless parameters that are associated with thermocapillarity, namely Ma and S-parameter. Another dimensionless parameter, Bi* (modified Biot number), represents the free surface heat transfer. It is attempted herein to correlate the critical conditions by those parameters.

The present work is motivated by the planned Marangoni convection experiment aboard the International Space Station. In normal gravity, the heat loss is caused mainly by the natural convection of the surrounding air. In microgravity, the air motion is substantially reduced so that the heat loss is very much different. Therefore, it is important to understand the surface heat transfer effect in normal gravity tests to design the microgravity experiment properly.

2. EXPERIMENT

The experimental apparatus, which is sketched in Fig. 1, is described in [1-3]. The top copper rod is heated by a nichrome wire, and the bottom copper rod is cooled by circulating water from a constant temperature bath. The rod diameters are D = 2 and 3 mm. The length-to-diameter ratio of the liquid column is fixed at 0.65-0.7. In our earlier report, we showed that the effect of heat transfer at the free surface is important only when the free surface is nearly flat [1], so only flat free surface is considered in the present report. The test fluid is 5 centistokes silicone oil. A small amount of alumina particles are mixed in the test fluid for flow observation. The onset of oscillations is identified by the flow visualization.

The present tests are conducted in a gravity convection oven. The interior dimensions of the oven are 30 × 30 × 30 cm. The cover of the oven is replaced by a transparent plexiglass board so that the inside can be seen to observe the test section. The temperature conditions inside the oven will be discussed later.

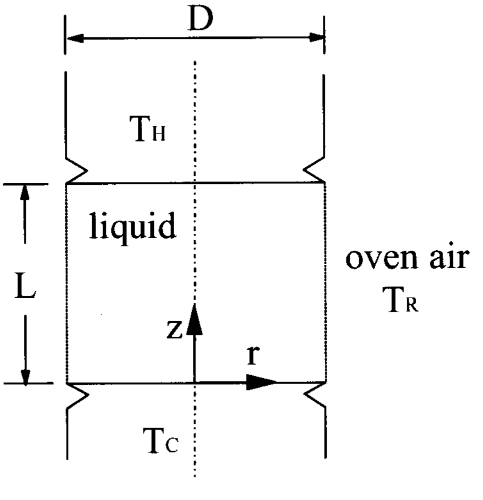


Fig. 1 Half-zone configuration

3. NUMERICAL SIMULATION OF AIR MOTION

Since it is difficult to determine the heat transfer rate at the liquid free surface experimentally, it is computed numerically by simulating the airflow around the liquid column. The airflow and the liquid flow are solved simultaneously. The numerical scheme is discussed in our earlier report [2]. The computational domain for the airflow analysis is defined in Fig. 2. The diameter of the cold copper block defines the diameter of the outer computational boundary. The height of the computational domain is from the cold block surface to the top of the heating rod. The temperature of air coming into the computational domain is equal to the ambient temperature. In addition to the free surface heat transfer due to convection, the heat loss due to radiation is included. The computation is only for steady axisymmetric flow.

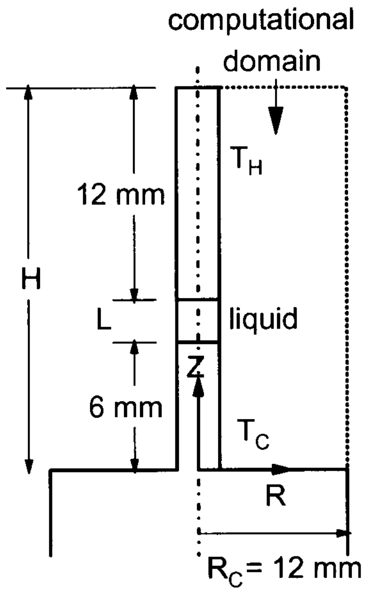


Fig. 2 Computational domain for airflow analysis around liquid bridge

4. IMPORTANT PARAMETERS FOR LIQUID AND AIR FLOWS

The important dimensionless parameters for the thermocapillary flow in the present configuration are known to be: Marangoni number $Ma = \sigma_T \Delta T L/\mu\alpha$, Prandtl number $Pr = \nu/\alpha$, and aspect ratio $Ar = L/D$, where σ_T is the temperature coefficient of surface tension, ΔT (= $T_H - T_C$) is the overall temperature variation in the liquid, μ is the dynamic viscosity of the liquid, ν is the liquid kinematic viscosity, and α is the liquid thermal diffusivity. T_H and T_C are the temperatures of hot and cold walls, respectively. L is the liquid column length and D is the liquid column diameter. In the present work, we minimize the effects of buoyancy and gravity by using small dimensions (D = 2 and 3 mm). We have shown for the present experimental configuration that if D is less than or equal to 3 mm, as in the present experiment, these effects can be neglected in normal gravity tests [4].

If the above parameters are the only important parameters, the critical condition for the onset of oscillations should be specified by Ma (called the critical Marangoni number, Ma_{cr}) for a given Pr and Ar. However, available experimental information shows that Ma alone cannot specify the critical condition [4]. For that reason, Kamotani and Ostrach [5] introduced an additional parameter called S-parameter. The S-parameter represents the effect of dynamic free surface deformation on the oscillation phenomenon, and is expressed, for the present configuration, as

$$S = \frac{\sigma_T \Delta T}{\sigma} \frac{1}{Pr} Ma^{3/14} \quad (1)$$

In addition, we need parameters representing the free surface heat transfer. By normalizing the thermal boundary condition at the free surface, $q = k\partial T/\partial r$, where q is the surface heat transfer rate and k is the thermal conductivity of the liquid, one can define the local (modified) Biot number $Bi^*_{loc} = qR/k\Delta T$, where R is the radius of the liquid column. By integrating the above q expression over the whole free surface and normalizing it, we obtain a parameter representing the total heat transfer rate from the entire free surface (Q) called modified Biot number, $Bi^* = Q/(2\pi kL\Delta T)$ [2]. Experimentally, we vary the free surface heat transfer by changing the airflow. Since the air motion is induced mainly by buoyancy, the airflow is determined by two temperature differences, $T_R - T_C$ and $T_H - T_R$ for a given configuration, where T_R is the temperature of the surrounding air. In a test, we fix T_C and T_R at desired values and increase T_H until the onset of oscillations. Then, since our interest is the effect of surface heat transfer on the critical condition, T_H is not a controlled parameter. Therefore, we vary the airflow by adjusting $T_R - T_C$, and after determining $T_H - T_R$ at the critical condition experimentally, we compute the airflow and free surface heat transfer numerically.

The following parametric ranges are covered in the present work: $Ma < 4.5 \times 10^4$, $40 < Pr < 60$, and $Ar = 0.65\text{-}0.7$. For Ma and Pr, the fluid properties are evaluated at the fluid mean temperature, $\frac{1}{2}(T_H + T_C)$.

5. RESULTS AND DISCUSSION

5.1. Conditions Inside Oven

From our earlier study, it is known that the onset of oscillations is very sensitive to the air convection and the thermal condition around the liquid column. When we use an oven, we usually expect some flow and thermal disturbances inside. For that 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.

When the oven temperature is set at 65 °C, it takes about 15 minutes for the oven temperature to stabilize after the start. The start-up time is shorter when the set temperature is lower. Even after the stabilization, the oven air temperature increases (decreases) when the oven heater is on (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 minutes. When the set temperature is 35 °C, the variation is ±1 °C and the period is about 5 minutes. 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 °C to 40 °C), and the largest oven temperature variation (±2 °C) occurs when $T_R - T_C$ is large. Therefore, when we investigate 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. This suggests 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.

5.2. Effect of Free Surface Heat Loss on Critical Condition

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. 3 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 [2]. As will be shown later, the heat is lost from the free surface for the conditions of Fig. 3, and the loss is reduced with increasing $T_R - T_C$. Therefore, ΔT_{cr} increases with decreasing free surface heat loss, or the heat loss destabilizes the flow. Also, the difference in ΔT_{cr} between the two diameters in Fig. 3 narrows as the heat loss is decreased. In the negative $T_R - T_C$ range of Fig. 3, 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. 3, the value of ΔT_{cr} is slightly different from that shown in Fig. 3 for the same $T_R - T_C$, mainly because the liquid viscosity, which varies with temperature, is different in those cases.

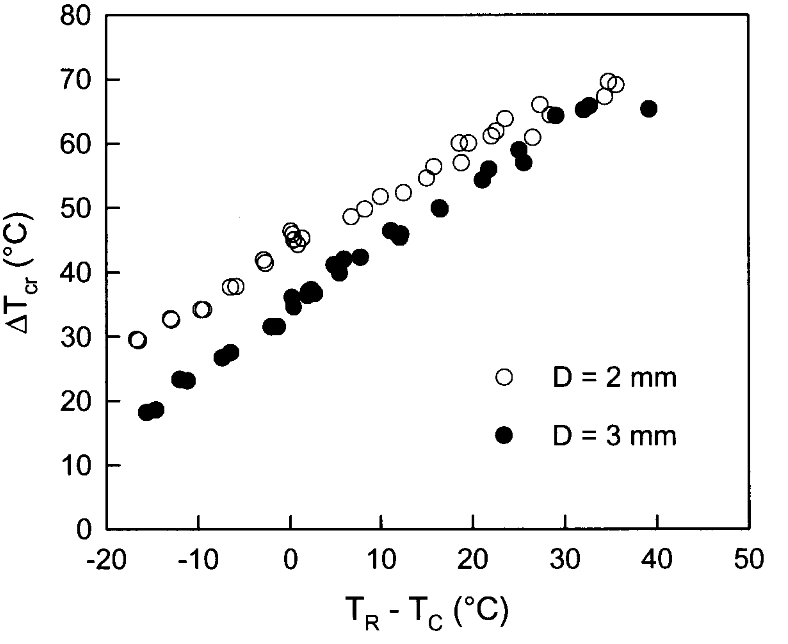


Fig. 3 Critical temperature differences for D = 2 and 3 mm (T_C = 25 °C when T_R is varied, and T_R = 25 °C when T_C is varied)

ΔT_{cr} is non-dimensionalized as Ma_{cr} in Fig. 4. Ma_{cr} increases with increasing $T_R - T_C$ (decreasing heat loss). The liquid viscosity variation with temperature mentioned above is now taken into account in the definition of Ma so that more data taken under various conditions are presented in Fig. 4. 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.

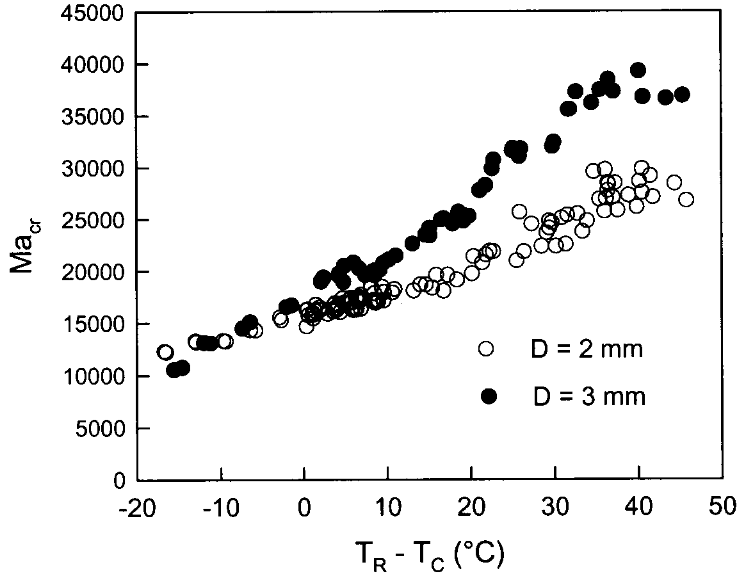


Fig. 4 Critical Marangoni numbers for various conditions

In order to relate $T_R - T_C$ to the airflow, the airflow is simulated numerically and the surface heat loss is computed for each case. Assuming that the total free surface heat loss affects the critical condition, Ma_{cr} is correlated with the Biot number Bi* in Fig. 5. Bi* is positive in Fig.5, meaning that the heat is lost from the free surface. Several important observations can be made in Fig. 5. (i) As seen in Fig. 5, Bi* is relatively small, less than unity. Therefore, small heat loss is responsible for nearly fourfold change in Ma_{cr}. The oscillation mechanism must explain this sensitivity to the heat loss. (ii) The figure shows that Ma_{cr} increases with decreasing Bi*, but when Bi* is reduced to less than about 0.25, Ma_{cr} reaches 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) Under this negligible heat loss situation, Ma_{cr} cannot correlate the data for D = 2 and 3 mm. This is another fact suggesting that Ma_{cr} is not the proper parameter to specify the onset of oscillations for high Prandtl fluid. (iv) Fig. 5 suggests that Bi*, or the total heat loss from the free surface, is not an appropriate parameter, because it is unreasonable that Ma_{cr} (or ΔT_{cr}) changes so sharply with Bi* when the heat loss effect is still rather small (Bi* between 0.25 and 0.3).

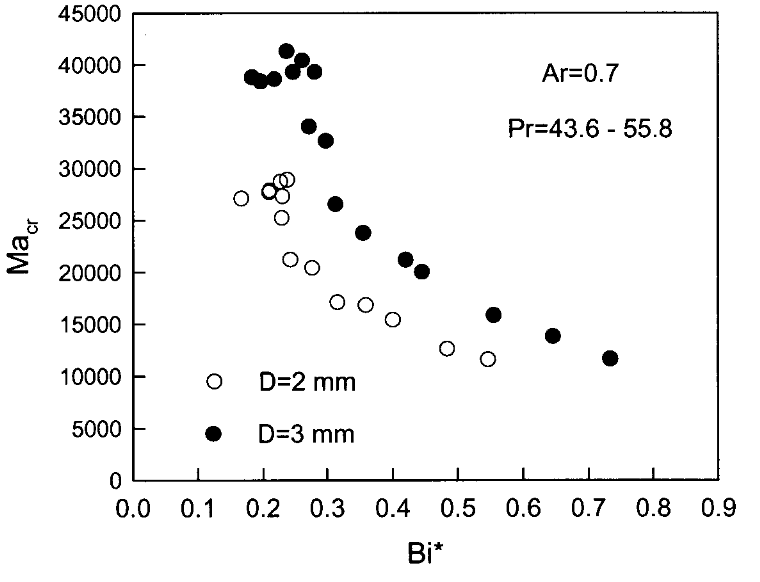


Fig. 5 Ma_{cr} versus Bi* for D = 2 and 3 mm

In the following we discuss various implications of the above observations. 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) [5]. From the definition of the S-parameter (Eq. (1)) one sees that ΔT_{cr} is nearly independent of the liquid column size. As seen in Fig. 3, ΔT_{cr} becomes nearly the same for D = 2 and 3 mm as $T_R - T_C$ increases, or as the heat loss effect becomes smaller. For that reason, we plot the critical data in terms of the S-parameter in Fig. 6. The figure shows that the present

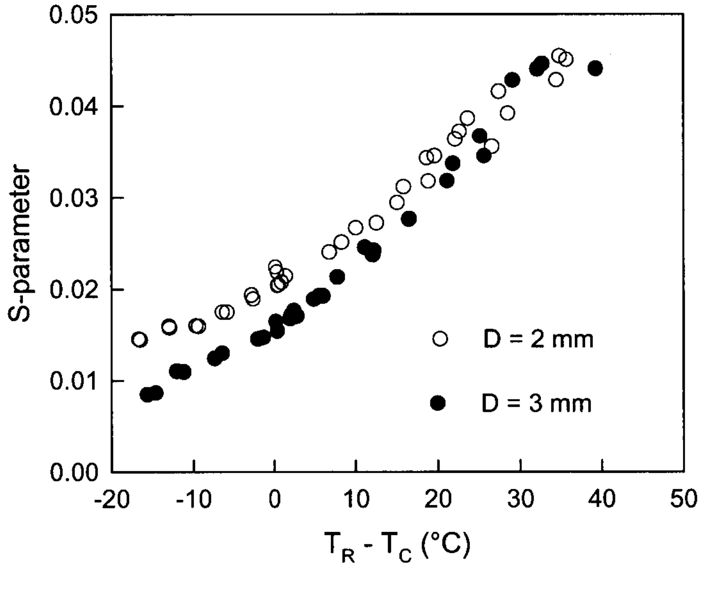


Fig. 6 S-parameter for D = 2 and 3 mm

experimental data can be correlated by the S-parameter when the heat loss is negligible. Previously we thought, based on ground-based, room temperature tests with small liquid columns, that Ma is the proper parameter when the liquid diameter becomes small (less than 5 mm). However, we did not realize the heat loss effect in room temperature tests. The present work shows that the S-parameter is the parameter even for small liquid columns as long as the heat loss is made negligible.

Ma_{cr} arises from 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. In the following we investigate the relation between Ma_{cr} and the basic flow field.

Fig. 7 shows the surface temperature distributions at the critical conditions for two different diameters with the same Bi*. Ma_{cr} is substantially different despite the fact that the surface temperature distributions are not much different. It is unlikely that the difference in Ma_{cr} is due to the difference in the basic flow field.

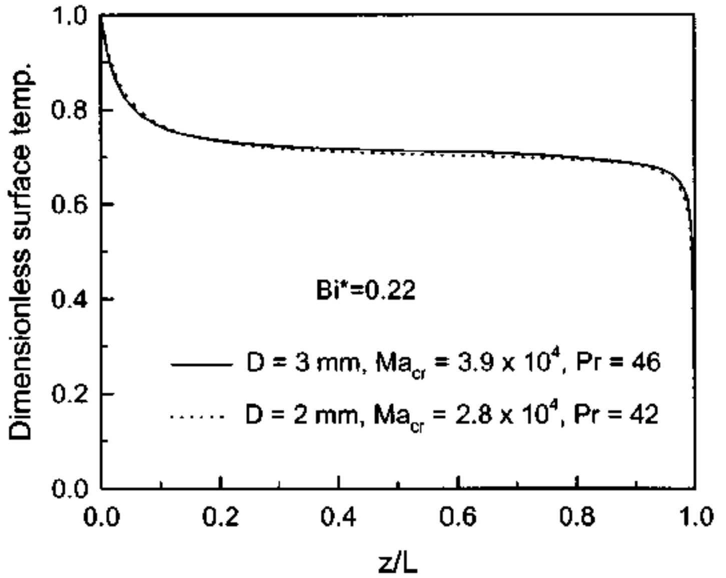
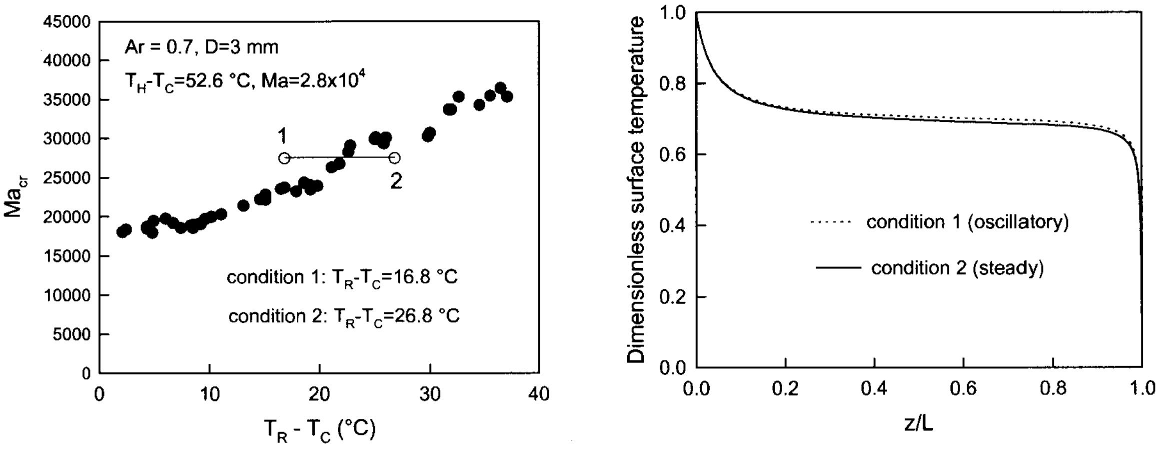


Fig. 7 Dimensionless surface temperature distributions at two critical conditions

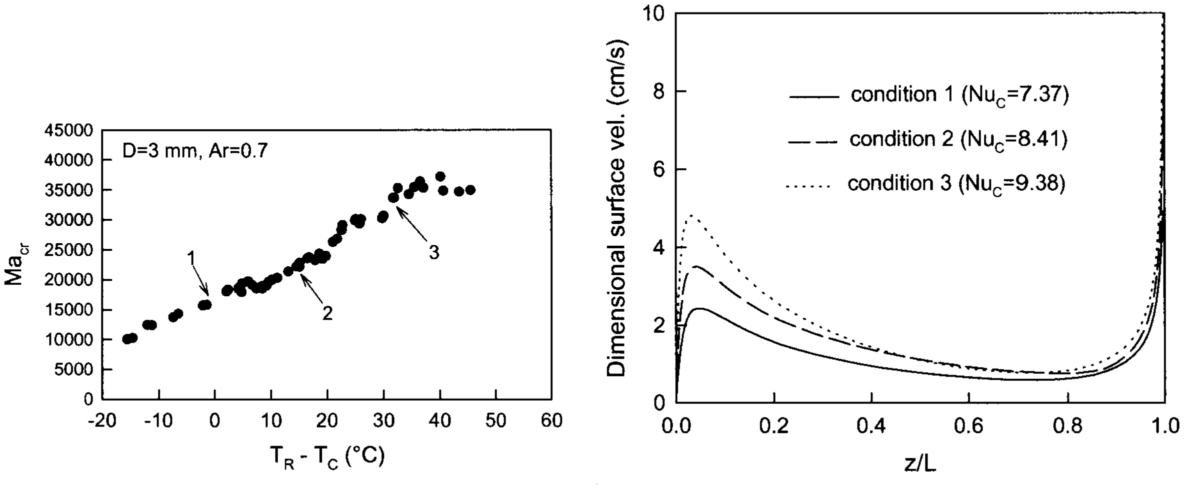
In Fig. 8 we choose two conditions indicated in Fig. 8a. We go from condition 2 to condition 1 by changing T_R (oven temperature). T_R is 5 °C below the critical for condition 1, while it is 5 °C above the critical for condition 2. Experimentally, the flow is quite stable under condition 2 and strongly oscillating under condition 1. In this test, Ma is kept constant, so that the oscillations appear only because the free surface heat transfer is changed. In Fig. 8b we show the computed surface temperature distributions for the two conditions. They are almost indistinguishable. By looking at such a small difference in the basic temperature field it is very difficult to explain why one flow is so stable and the other flow so unstable.

With free surface heat loss, the surface temperature gradient will increase and as a result, the surface velocity will 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 (specified in Fig. 9a) are shown in Fig. 9b. The velocity at the critical condition clearly decreases with increasing heat loss (or decreasing $T_R - T_C$). Moreover, the dimensionless heat transfer rate at the critical condition, the Nusselt number (Nu_C), also decreases with increasing heat loss, as given in Fig. 9b. Therefore, the convection in the liquid is actually getting weaker at the critical condition with increasing heat loss. The fact that the flow becomes more unstable despite the fact that the convection becomes weaker shows that this heat loss effect is a complex phenomenon.



(a) (b)

Fig. 8 Surface temperature distributions for two different heat loss conditions

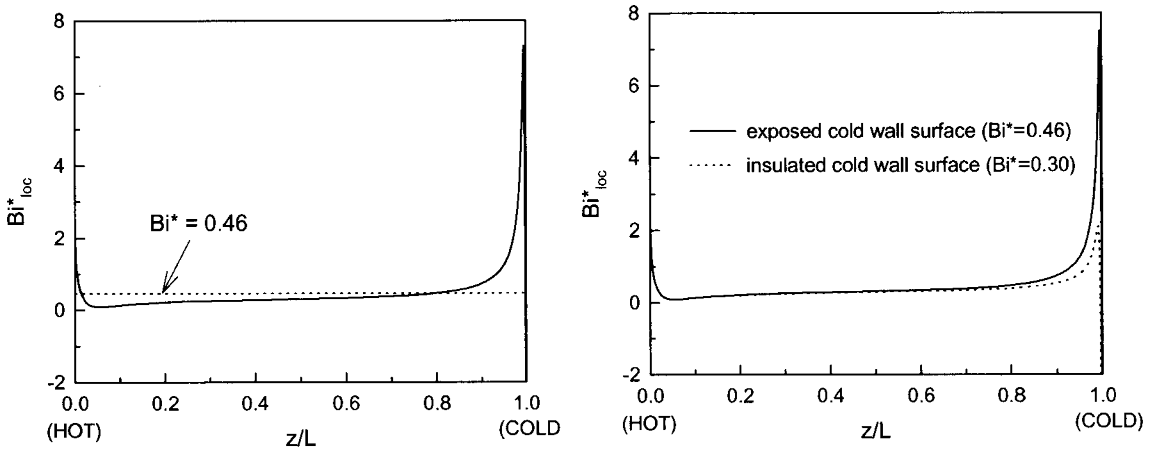


(a) (b)

Fig. 9 Dimensional surface velocity distributions at three different critical conditions

Based on the above discussions, it is clear that the basic flow change by the heat loss cannot explain the observed change in the critical condition. Considering also the fact that Ma is not an appropriate parameter to specify the critical condition when the heat loss is negligible, one can conclude that the oscillation phenomenon is not a result of linear instability.

Whether we use Ma or the S-parameter, Bi* cannot correlate the experimental critical conditions. But, we know that the surface heat transfer is somehow responsible for the observed data trend. Therefore, we have to look into the local heat transfer on the free surface. In Fig. 10, we present the local Biot number distribution for one case. One notices that there is a large peak in the local Biot number near the cold wall, and the average Biot number is very much affected by this. This peak comes about because the liquid surface temperature stays warm up to very close to the cold wall (see Fig. 8b) so that there exists a sharp temperature gradient from the liquid surface to the cold wall in the air in this region. Consequently, much heat is lost from this region to the cold wall. In Fig. 10b, we show a situation where we hypothetically insulate the cold wall surface for the airflow (not for the liquid flow), which significantly reduces the heat loss near the cold wall. Since this heat loss near the cold wall is so large, a question arises as to whether it is responsible for the observed heat loss effect, which is addressed below.



(a) (b)

Fig. 10 Local and average Biot numbers (D = 3 mm, L = 2 mm, $T_H = 63$ °C, $T_C = T_R = 23$ °C, Ma = 2.0×10^4, Pr = 53)

The net effect of the heat loss near the cold wall is that since it occurs near the cold wall, it is like an additional cooling at the cold wall so that the heat loss makes the return flow cooler and this cooler return flow reduces the free surface temperature as it moves towards the hot corner. Therefore, this local heat loss somewhat indirectly changes the surface temperature distribution. In this sense, the large heat loss near the cold wall is not directly affecting the overall thermocapillary driving force during oscillations. It has been reported earlier that a thin plate has a strong effect on the onset of oscillations when it is placed at a certain height around the liquid column (without touching it) [1]. When the plate is placed near the cold wall, however, it has no appreciable effect despite the fact that the heat loss near the cold wall is very much altered. Therefore, one can conclude that the large heat loss near the cold wall has no direct influence on the onset of oscillations. Note that this cold wall heat loss is mainly due to the conduction through the air so that it still exists even in microgrvaity.

In addition to the cold corner, the local Biot number is relatively large near the hot wall (Fig. 10). The local Biot number distribution between the hot and cold corners is rather uniform and represents the overall free surface heat transfer, or Bi*. We have already shown that Bi* cannot explain the observed heat loss effect. Therefore, the heat loss effect must be associated with the hot corner. We have conducted a test with a small ring heater placed around the liquid column, as illustrated in Fig. 11. When the ring heater is placed at a certain distance away from the hot wall (approximately the location shown in Fig. 11), the ring heater most effectively stabilizes the flow. For example, when the ring heater temperature is 6 °C higher than the surrounding air temperature, ΔT_{cr} is found to be about 16% greater. In this situation the ring heater decreases the heat loss. Therefore, decreasing heat loss in this region stabilizes the flow. We have shown in the aforementioned tests with the plate that the plate placed close to the hot wall stabilizes the flow. However, when the plate is somewhat below the hot wall but above the liquid column mid-height, the flow is destabilized. With the unheated plate placed close to the liquid surface, the heat loss increases. Therefore, the above two experiments show that decreasing (increasing) heat loss around the hot corner stabilizes (destabilizes) the flow. The trend is consistent with that found by varying $T_R - T_C$. This shows that the local free surface heat transfer near the hot corner is important for the oscillation phenomenon.

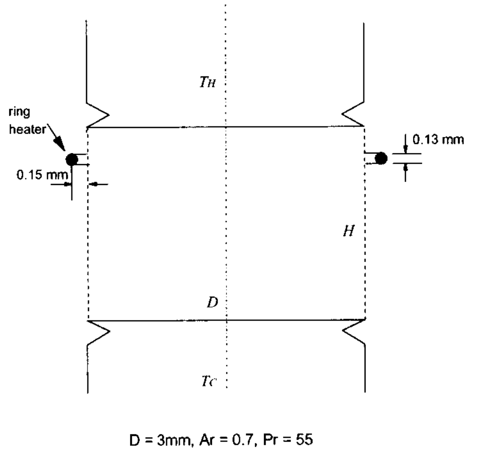


Fig. 11 Small ring heater placed around liquid column

The concept of the S-parameter is based on the dynamic free surface deformation in the hot corner, and 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. Air is drawn into the hot corner by the shear of the liquid surface flow. The liquid temperature is close to T_H very near the hot wall but the temperature of the air drawn into this region is somewhat cooler than that, resulting in the heat loss very near the hot wall. Away from this region, the liquid surface temperature decreases quickly, resulting in the minimum local Biot number at a small distance from the hot wall. The minimum value becomes negative (heat gain) when Bi* is small. This minimum Bi^*_{loc} location approximately coincides with the extent of the hot corner [5].

One important trend of heat loss in the hot corner is shown in Fig. 12. The z-location is non-dimensionalized by the hot corner extent Δ in order to show the trend in the hot corner clearly. Δ is the location of the surface velocity maximum near the hot wall [5]. Fig. 12 shows how the dimensional heat loss changes when we change T_C while keeping T_H and T_R fixed near the critical condition. If we increase T_C, the bulk liquid temperature increases, and thus the air drawn into the hot corner becomes warmer. This warmer air decreases the heat loss very near the hot wall where the liquid temperature is near T_H, but the heat loss away from this region increases as the bulk liquid temperature is increased. This effect of the liquid bulk temperature on the heat loss in the hot corner may explain the observed heat loss effect on the critical condition, as will be discussed later.

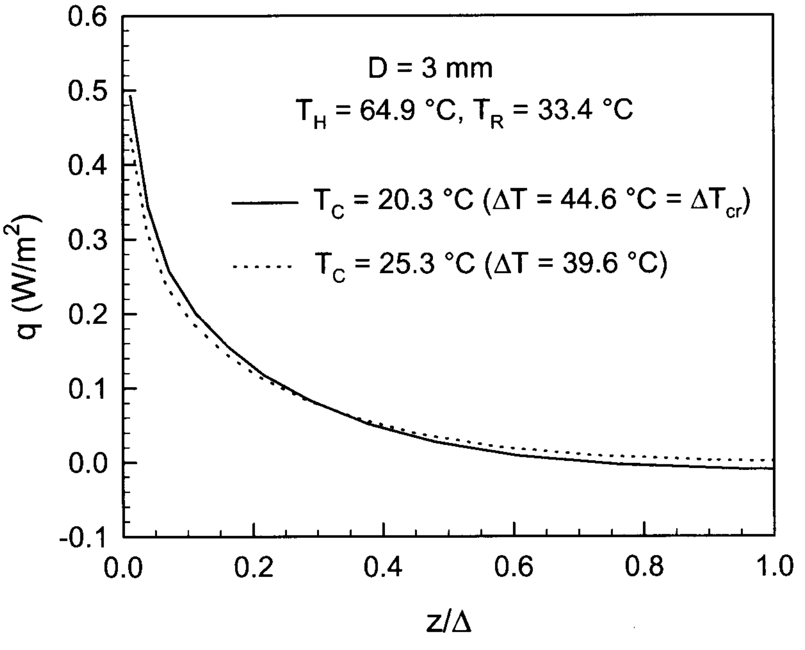
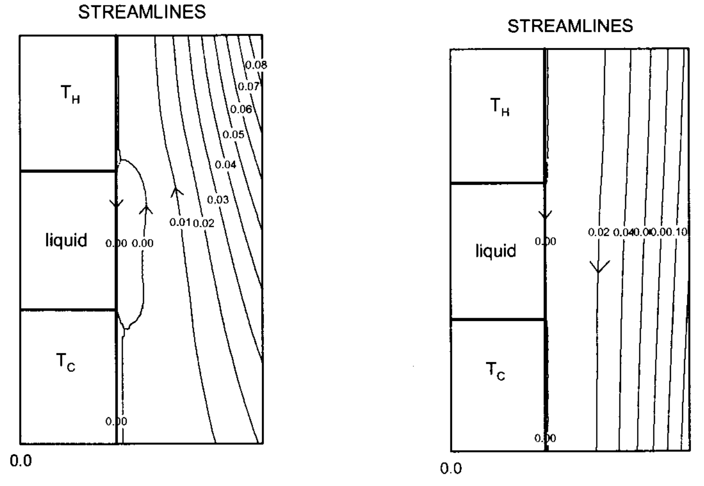


Fig. 12 Effect of cold wall temperature on dimensional heat loss in hot corner

5.3. Effect of free surface heat gain

In the oven test we can change the overall heat loss to gain by maintaining T_R above T_H. This requires no or weak power input to the heater or even cooling of the top wall. It is found that the liquid flow under the heat gain condition is different from that in the heat loss tests. The liquid flow does not remain steady and appears to be randomly and intermittently disturbed. The amplitude of disturbances increases with increasing $T_R - T_H$. In the heat loss tests discussed above, T_H is always above T_R, so that the natural convection is upward along the hot wall. Since the air moves downward along the liquid free surface, a recirculating cell appears next to the liquid surface, as shown in Fig. 13a. In contrast, the flow along the heater surface is downward in the heat gain tests. This downward motion along the heater surface continues along the liquid surface, so no flow recirculation occurs in this case, as shown in Fig. 13b. Consequently, the disturbances generated in the airflow along the heater are transported to the liquid region, and some large thermal disturbances are apparently causing the liquid flow unsteadiness. Even in the heat loss tests, we sometimes perform tests with the heater placed at the bottom, the heater temperature being above T_R. In this configuration, the air continues to move upward along the heater and liquid surface. Then, when the temperature difference $T_H - T_R$ becomes large enough, we observe the same kind of disturbed liquid flow [4]. With this kind of disturbed liquid flow, it is not possible to identify the onset of oscillations, if any. Therefore, as we did in the heated-from-below tests [4], we place a thin plate just above the liquid-hot wall interface in order to minimize the airflow into the liquid region from the heater region, as illustrated in Fig. 14. This plate eliminates any visible disturbances in the liquid flow. Therefore, we perform the heat gain tests with this plate.



(a) (b)

Fig. 13 Streamline patterns with heat loss (a) and gain (b) ((a): $T_H = 60.0$ °C, $T_C = T_R = 25.0$ °C; (b): $T_H = 50.0$ °C, $T_C = 24.6$ °C, $T_R = 62.3$ °C)

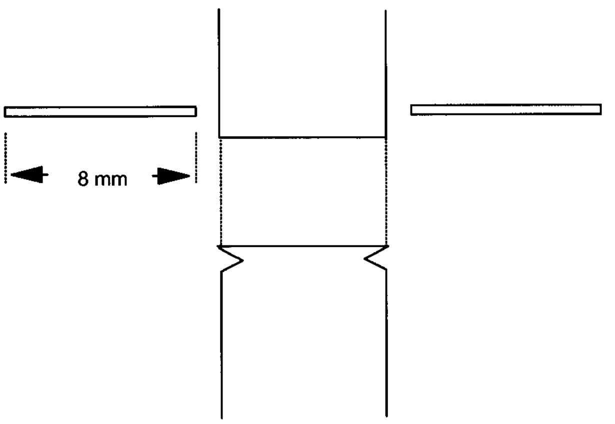


Fig. 14 Thin plastic plate placed around hot wall

The critical Ma determined with the plate is presented in Fig. 15 for both heat loss and gain conditions. The data shown earlier without the plate is shown also for comparison. We have already reported for the heat loss configuration that the critical condition is affected significantly by this kind of plate [1]. The plate slows the airflow near the liquid and reduces the surface heat loss, resulting in a greater Ma_{cr}, as seen in Fig. 15. Since the heat loss is reduced by the plate, we get into the heat gain situation with a smaller temperature difference $T_R - T_C$ than in the tests without the plate. In Fig. 15, the heat loss situation changes to the heat gain situation around $T_R - T_C = 10$ °C. ΔT_{cr} increases sharply in the transition (we could not find oscillations in our tests). Once we get into the heat gain situation, Ma_{cr} (or ΔT_{cr}) decreases with increasing $T_R - T_C$, namely it becomes easier for the flow to become oscillatory with increasing heat gain. This trend is the exact opposite of that found in the heat loss situation.

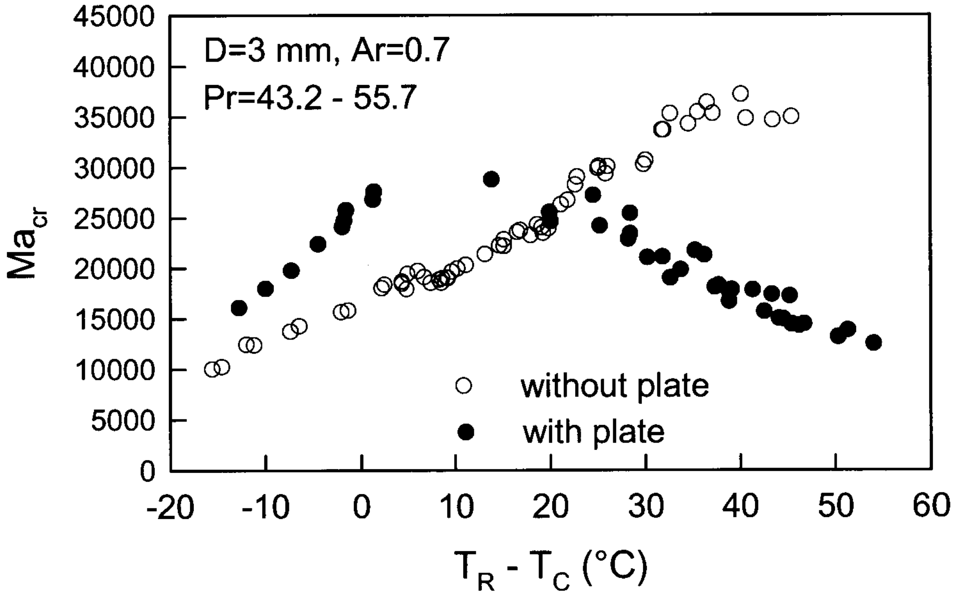


Fig. 15 Effect of plate on Ma_{cr}

The local Biot number distribution for a heat gain case is shown in Fig. 16, with and without the plate. The plate does not change Bi^*_{loc} much. Heat gain occurs over most of the free surface, but there still exists a large heat loss near the cold wall.

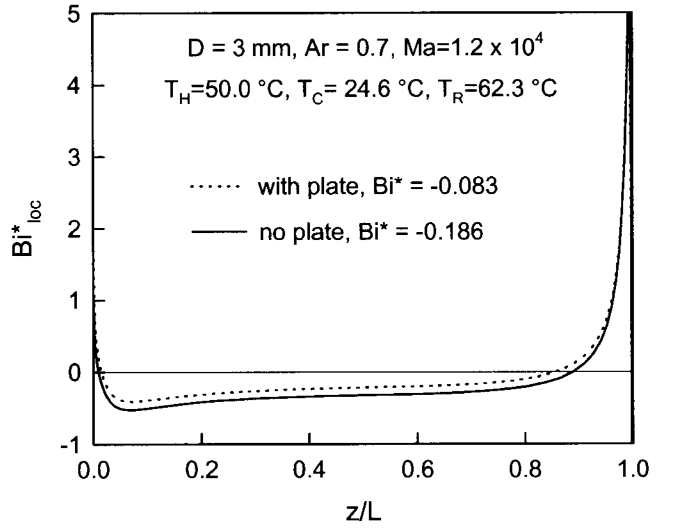


Fig. 16 Local Biot number distribution with net free surface heat gain

The heat gain over most of the free surface decreases the surface temperature gradient. The computed surface temperature and velocity distributions with the plate are shown in Fig. 17. The overall surface temperature gradient decreases, and thus the velocity decreases over a large of the surface compared to the situation with no heat loss, but the effect is small for this condition. On the other hand, the cold wall region becomes more active as the surface temperature gradient in this region increases because of the net heat gain. Experimentally, we observe that the flow near the cold wall is more active during oscillations with net heat gain, compared to the situation with net heat loss. For a given ΔT, the flow near the cold wall becomes faster with increasing heat gain (or increasing $T_R - T_C$). Therefore, it seems that this increased activity near the cold wall is responsible for the observed heat gain effect.

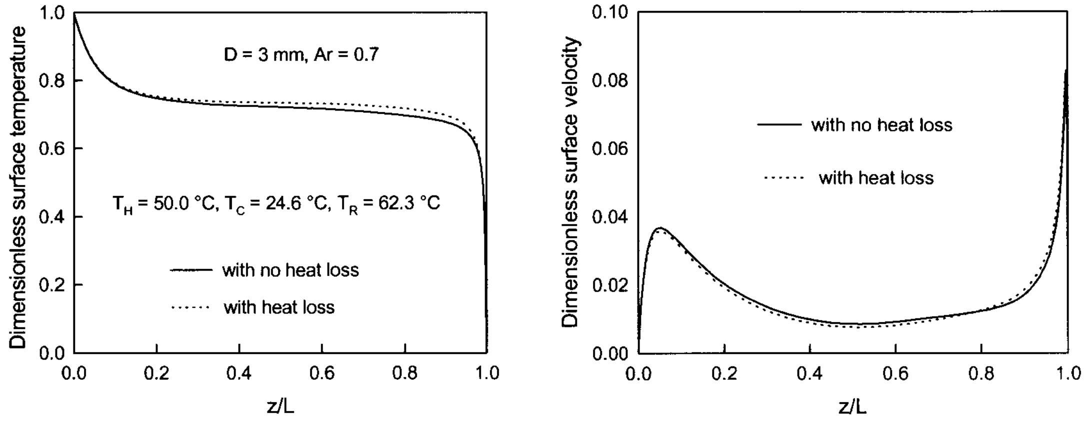


Fig. 17 Surface temperature and velocity distributions for heat gain condition with plate

5.4. Relation between Surface Heat Transfer and Oscillation Mechanism

We have learned above that even a very small change in the surface heat loss can cause the flow to become oscillatory. This suggests that a parameter that is important for the onset of oscillations must be very sensitive to the heat loss. The S-parameter represents the dynamic free surface deformation. It is known that the dynamic free surface deformation is very small. Then, if an effect associated with the dynamic free surface deformation plays an important role in the oscillation mechanism, the oscillation phenomenon is controlled by a small parameter. Since the dynamic deformation is very small, the free surface heat loss, even when it is small, could change the deformation effect significantly.

The basic oscillation mechanism is discussed in [6]. It can be summarized as follows. Since the flow is mainly driven in the hot corner, we have to focus on the changes in this region during oscillations. One oscillation period consists of an active period and a slow period. In the active period, the hot corner expands and, as a result, the viscous effect of the hot wall on the hot corner flow decreases. Consequently, the overall flow in the liquid bridge becomes stronger, and eventually the return flow brings more cold fluid to the hot corner and begins to cool this region, which ends the active period. In the slow period, the hot corner shrinks and the viscous effect increases, which makes the overall flow slower. Since less fluid goes to the cold wall in the slow period, the return flow becomes warmer and eventually begins to heat the hot corner, which ends the slow period. This is a non-linear dynamical process where the temperature and velocity fields are continuously altered by non-linear interactions. It can be shown numerically that this process decays with time, after the flow is disturbed, in the range of Ma in which oscillations have been observed. Therefore, we need an extra feature to sustain the process. In the above process, the overall flow grows in the active period because the viscous retardation is reduced as the hot corner expands. At the same time, however, the thermocapillary driving force decreases because the surface temperature gradient decreases when the hot corner expands. Therefore, we need an extra feature that makes the driving force larger in the active period, especially near the beginning when the viscous retardation is largest.

We think that dynamic free surface deformation is the extra feature. The main effect of dynamic free surface deformation is that it causes a time lag between the surface flow and return flow in a transient situation. After the surface flow is altered for some reason, the return flow response is slightly delayed because the free surface must deform first. Another important fact is that in the case of transient flow of high Prandtl number fluid, the viscous effect propagates faster than the thermal effect. Therefore, the dynamic free surface deformation, which is associated with the viscous effect in the present problem, can interfere with the thermal boundary layer development near the free surface significantly.

Based on our past work, the dynamic free surface deformation affects the oscillation process in the following way. As discussed above, the most important time in the oscillation cycle is the beginning of each active period. Near the beginning of the active period, the surface flow grows rapidly in the hot corner, but the return flow lags behind this surface flow change slightly. Note that the time lag is relatively large at this time because the flow is accelerating rapidly. As a result, a small amount of fluid is removed from the free surface in the hot corner and transported downstream, causing the free surface to depress. In the meantime, the hot corner is made warmer by the warmer return flow, as explained earlier. The flow along the hot wall turns in the hot corner to the free surface direction. The return flow warms the flow along the hot wall first, and then the free surface region is made warmer by the turning flow. Therefore, this warming up process of the free surface region of the hot corner is a transient thermal boundary layer development starting from the free surface. Now, this thermal boundary layer development is hindered by the free surface depression since Pr is large. The result is that the free surface temperature increases more slowly or the surface temperature remains cooler, compared to the situation without the free surface deformation. Reduced free surface temperature in the hot corner means increased temperature gradient and thus increased thermocapillary driving force. Thus, the dynamic free surface deformation can increase the driving force near the beginning of each active period. Moreover, as the surface flow becomes faster, the deformation becomes larger, so the deformation effect can amplify the growth process. Therefore, the flow in the hot corner including this deformation effect could overcome the strong viscous retardation during this time and make the oscillation process going. The surface deformation is important only for a short time, but it is the most important time in the oscillation cycle to determine whether the oscillation process decays or grows because the viscous effect is largest.

It is known that the free surface deformation is usually very small during oscillations. The deformation is very small compared to the overall dimension of the liquid bridge, but the most important length scale for the flow is the hot corner extent, which is also small. The ratio of the free surface deformation to the hot corner extent is the S-parameter. However, the deformation is observed to be on the order of a μm, while the hot corner extent is on the order of 100 μm for the 3-mm diameter liquid column, so the deformation is still much smaller than the hot corner extent. The extent of the hot corner is also the thermal boundary layer thickness in the hot corner [5]. As is clear in the above discussion of the dynamic deformation effect, the deformation is not changing the whole field. The changing of the whole flow field requires a substantial change in the thermal boundary layer thickness of the basic flow, which can be done only by large surface deformation. Instead, the deformation affects only the transient thermal boundary layer development near the beginning of each active period. The time where the deformation is important is very short, compared to the oscillation period, so that the transient thermal boundary layer thickness is much thinner than the boundary layer thickness of the basic flow. However, assuming that the duration of important surface deformation scales with the oscillation period, it can be shown that the transient boundary layer thickness scales with the basic flow boundary layer thickness. Therefore, the expression of the S-parameter is unchanged whether it is compared to the latter or the former.

Now, with the free surface heat loss, the above deformation effect can be augmented in the following way. Near the beginning of an active period, the hot corner temperature is rising. As seen in Fig. 12, when the liquid temperature rises away from the hot wall, the heat loss decreases very near the hot wall but it increases away from this region. Therefore, in the transient warm-up process of the hot corner discussed above, the fluid becomes warmer very near hot wall and cooler away from the region due to this heat loss variation, which increases the surface temperature gradient and thus augments the surface deformation effect. The heat loss is small compared to the total amount of heat transferred through the liquid column, but the surface deformation effect causes only a small change in the overall heat transfer near the free surface, which can be changed significantly by small surface heat loss. We are still investigating this subject.

As for the net heat gain situation, the destabilization of the flow with increasing heat gain must be associated with the activity near the cold wall. We continue to work on this subject to clarify the relation between the basic oscillation mechanism and the cold region activity.

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