Investiagtion of Free Surface Heat Transfer Effect and Oscillation Mechanisms for Thermocapillary Flow of High Prandtl Number Fluid

By

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Abstract: The effect of free surface heat transfer on oscillatory thermocapillary flow in liquid bridges of high Prandtl number (Pr) fluids is investigated experimentally as well as numerically. It has been found that the critical condition is very sensitive to the free surface heat transfer under certain conditions but relatively insensitive under other conditions. In this work it is shown that this sensitivity difference may be related to the difference in the oscillation mechanism. Several oscillation mechanisms have been proposed in the past for oscillatory thermocapillary flows in liquid bridges of high Prandtl fluids, mainly hydrothermal wave type instability and a non-linear mechanism involving dynamic free surface deformation. It is discussed here that the range of Marangoni number, where the flow is found to become oscillatory in many experiments for high Pr fluids, is too low for the flow to become unstable by the hydrothermal wave instability mechanism, or any linear instability mechanism. Instead, we need non-linear mechanisms where the driving force is altered continuously by some means. In order to get this conclusion, our past work is summarized and some new results are presented herein.

1. INTRODUCTION

Thermocapillary flows in liquid bridges are known to become oscillatory for a wide range of Prandtl number. Despite the fact that much work has been done in the past, the transition mechanism for high Pr fluid is not yet well understood. The present work is motivated to clarify the oscillation mechanism. In the process of obtaining more experimental data on the subject, we have found that the heat transfer at the free surface has an appreciable effect on the transition in room temperature tests. Generally, heat is lost from the liquid free surface to the surroundings in room temperature tests. The surrounding air motion caused by the heating-cooling arrangement of the experiment is mainly responsible for the heat transfer, so the heat transfer rate is small compared to the total heat transferred through the liquid. We have shown that the critical Marangoni number (Ma_{cr}) changes by several factors by simply changing this heat transfer condition. This sensitivity is found only when the free surface loses heat.

Recently we have obtained more data under heat gain conditions. For this, we increased the surrounding air temperature by placing the experimental setup in an oven. It is found that under the heat gain condition the free surface heat transfer has no appreciable effect on Ma_{cr}. It is not possible to explain the observed large difference in the sensitivity to the free surface heat transfer between the loss and gain cases by one oscillation mechanism.

It is known that Ma_{cr} depends strongly on the shape of the liquid bridge. Thermocapillary flows in nearly straight liquid bridges and those in concave bridges seem to behave differently under the heat loss condition. We have shown that the aforementioned sensitivity to the free surface heat transfer is true for nearly straight bridges, but the critical conditions for concave liquid bridges are much less sensitive to it. In fact, the critical condition for

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concave bridges is not sensitive to either heat loss or gain. Again, it seems difficult to explain this difference in the nearly flat and concave bridge behaviors unless we assume that something is fundamentally different in these two situations.

As in our past work, numerical simulations are performed in order to study the surrounding air motion and compute the resultant heat transfer rate at the free surface. All of our past data and more recent data are put together in order to discuss the relation between the oscillation mechanism and the sensitivity to the free surface heat transfer.

2. EXPERIMENT

The experimental apparatus is described in our previous work [1,2], so it is not repeated herein. It is a standard arrangement in which liquid is suspended between a heated top cylindrical rod and a cooled bottom rod. The liquid bridge diameters are D = 2 and 3 mm. Silicone oils with 2 and 5 centistokes kinematic viscosity are used as the test fluids. The static free surface shape is varied from flat to concave. Most of the tests are conducted in an oven. In a typical test, we fix the cold wall temperature (T_C) and air temperature (T_R) at specified values and increase the hot wall temperature until the flow becomes oscillatory.

3. NUMERICAL SIMULATION OF AIR MOTION

In the simulation study the airflow and the liquid flow are solved simultaneously because they are coupled through the boundary conditions at the free surface. The computational domain for the airflow analysis is consistent with the experimental conditions [3-5]. We mainly analyze the airflow for the experimentally found critical conditions in order do relate the critical conditions to the free surface heat transfer. The local heat flux (q) is non-dimensionalized as $qR/(k\Delta T)$, which is called the local Biot number ($Bi_{,loc}$), where k is the liquid thermal conductivity and R is the liquid bridge radius. The total free surface heat transfer rate (Q) is non-dimensionalized as $Q/(2\pi Lk\Delta T)$, which is called the average Biot number (Bi). Conventionally, Biot number represents heat transfer coefficient so that the net heat transfer depends on the Bi and the temperature difference between the liquid surface and the surrounding air. Instead of specifying both, the current Bi represents, by itself, the net heat transfer from the free surface.

4. IMPORTANT DIMENSIONLSS PARAMETERS

The important dimensionless parameters for the thermocapillary flow in the liquid bridge configuration in the absence of gravity are: Marangoni number $Ma = \sigma_T \Delta TL/\mu\alpha$, Prandtl number $Pr = \nu/\alpha$, and aspect ratio $Ar = L/D$, where σ_T is the temperature coefficient of surface tension, μ is the dynamic viscosity of the liquid, ν is the liquid kinematic viscosity, and α is the liquid thermal diffusivity. L is the liquid column length and D is the liquid column diameter. Additionally, Kamotani and Ostrach [2] introduced the aforementioned 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 $S = (\sigma_T\ \Delta T/\sigma)/PrMa^{3/14}$, where σ is the surface tension at the free surface. In order to describe the shape of the liquid bridge, diameter ratio, Dr, is used, which is defined as $Dr = D_{min}/D$, where D_{min} is the diameter of the liquid at the neck (Dr = 1 for straight bridge). The thermal effect of the surrounding airflow is represented by the local and average Biot numbers as explained above. The following parametric ranges are covered in the present work: $Ma < 5.0 \times 10^4$, $24 < Pr < 50$, $Ar = 0.65\text{-}0.7$, and $0.4 = Dr = 1.0$. 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 Nearly Straight Liquid Bridge with Free Surface Heat Loss

In a typical room temperature experiment, T_H (at the critical condition) is higher than T_R, so heat is lost from the free surface. The results with nearly straight liquid bridges have already been reported [3-6]. In summary, the critical condition is very sensitive to the heat transfer and, contrary to what some theoretical studies have shown, the flow is destabilized with increasing heat loss. After computing the Biot number for each critical condition, Ma_{cr} is plotted against Bi for fixed Pr and Ar, which is reproduced in Fig. 1. The figure shows that the critical condition cannot be described by Ma_{cr} and Bi alone. The figure also shows that Ma_{cr} changes substantially over a relatively narrow range of Bi, or even when the basic flow is not substantially altered. It seems that the heat loss effect cannot be explained by a linear stability concept.

For this reason the critical results are in the form of S vs. Bi (or modified Biot number $Bi/Pr^{0.5}$), as shown Fig. 2. It shows that the critical conditions for all of our tests can be correlated reasonably well by S and $Bi/Pr^{0.5}$. The reason why Bi is modified as $Bi/Pr^{0.5}$ is discussed in [6]. We have also conducted the heat loss experiment under the condition in which forced airflow removes heat from the free surface. It was shown that the data from the forced cooling tests also agree well with the trend of Fig. 2 [5].

As shown by Kamotani and Ostrach [2], the flow is viscous dominated even when the Reynolds number (Re = Ma/Pr) is as large as 1000 in the case of high Pr fluids. The flow is viscous dominated because the main driving force exists in a relatively small region near the hot wall called the hot corner. The hot corner shrinks as Ma (or Re) increases, which tends to keep the flow viscous dominated. The S-parameter model is based on the viscous flow. If Re becomes larger than about 1000, the inertia forces will become important, so the situation will be different. As Fig. 1 shows, Ma_{cr} can be as large as $(3 - 5) \times 10^4$ (or Re is about 1000) when the heat loss is minimized, which is about the limit of the S-parameter model. It is interesting that with decreasing heat loss the S-parameter increases up to the limit of its validity.

The value of Ma_{cr} when the heat loss is minimized (around 4×10^4) is near the critical values predicted numerically for Pr ~ 25 in the past without dynamic free surface deformation. For example, Savino and Monti [7] predict $Ma_{cr} = 4.2 \times 10^4$ for Pr = 30 and Ar = 1. In the current JAXA project, Kawamura et al. are conducting extensive numerical simulations for high Pr fluids with and without dynamic free surface deformation. Their prediction of Ma_{cr} is 3.25×10^4 for Pr = 28.1 and Ar = 0.5 [8]. We are also conducting 3-D numerical simulations with undeformable free surface to investigate the free surface heat transfer effects (to be reported in the future). Ma_{cr} in our work is also near these predicted values ($Ma_{cr} = 4.2 \times 10^4$ for Ar = 0.7 with insulated free surface). One important feature of the computed instability is that the inertia forces play an important role since Re is large. In fact, in our numerical simulations the flow will not oscillate if we do not include the inertia terms in the equations. Recently, Sim and Zebib [9] analyzed oscillatory thermocapillary flow of Pr = 27 numerically. They tried to simulate the experiments by Masud et al. [1], including concave bridges. The predicted Ma_{cr} = 5,700 for insulted free surface by Sim and Zebib seems too low (the inertia forces and convection are too weak to cause any instability). In any case, their results show that Ma_{cr} is sensitive to the free surface heat transfer and Ma_{cr} is shown to increase with increasing heat loss. In contrast, our simulations show that the heat loss decreases Ma_{cr} up to about Bi = 0.5 and then increases Ma_{cr} with further increase in Bi. The reduction of Ma_{cr} is due to the fact that the overall liquid velocity increases with increasing heat loss. However, the effect is not strong: Ma_{cr} changes from 4.2×10^4 to 3.0×10^4 when Bi is changed from 0 to 0.5. Then, when Bi is increased further, the heat loss shrinks the hot corner so that the inertia forces in the bulk region decreases, resulting in Ma_{cr} increase. Therefore, it is not possible to predict oscillations around experimentally found $Ma_{cr} = 1.5 \times 10^4$ in room temperature tests (heat loss tests) in which Bi = 0.5. Ma_{cr} becomes as low as 7,000 in the large heat loss tests (Bi ~ 1, see Fig. 1). All in all, the instability shown numerically for high Pr fluids does not seem to be the same phenomenon as the one we observe experimentally.

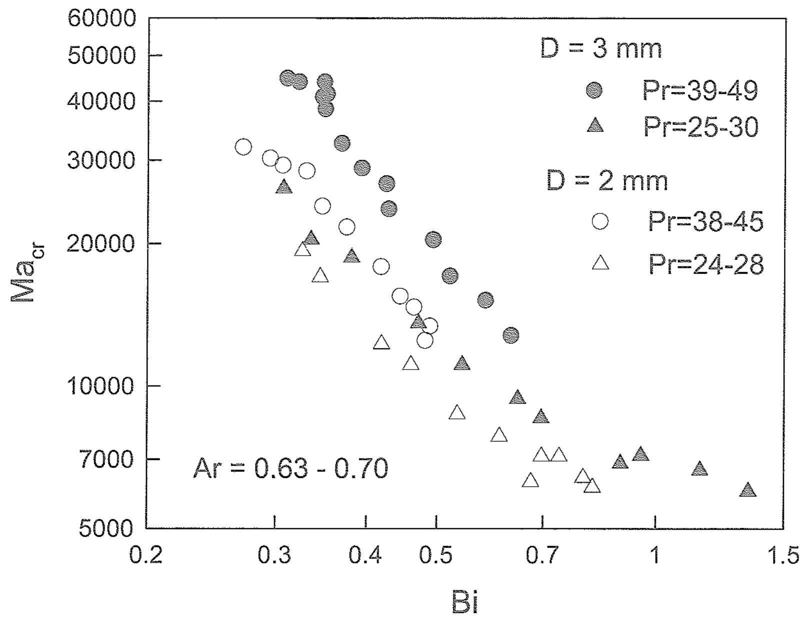


Fig. 1 Correlation of critical Marangoni number with average Biot number

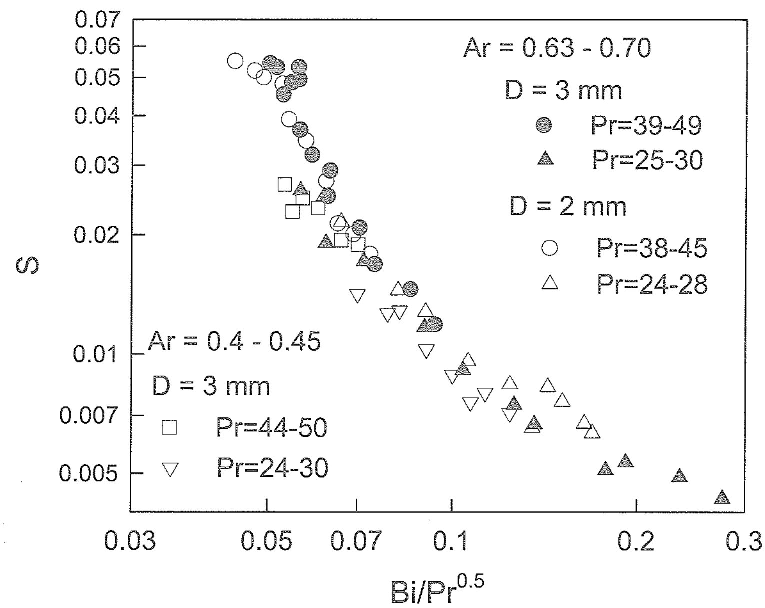


Fig. 2 Correlation of S-parameter at critical condition with modified Biot number

Typical streamlines and isotherms with free surface heat loss are presented in Fig. 3. Since the flow is driven in the hot corner, the center of the recirculating flow is situated near the hot wall. As a result, the recirculating flow pattern generates a relatively large region where the flow moves radially inward. This radial convection tends to make the bulk fluid temperature distribution rather uniform near the free surface. As will be discussed later, uniform radial temperature distribution in the surface flow region is not conducive to the hydrothermal wave instability.

From these observations, our conclusion is that it is not possible to make the flow unstable around Ma = 10^4 by the hydrothermal wave instability mechanism. It seems that the only way to make the flow time-dependent near this low Ma is to change the driving force in the hot corner by non-linear means. Based on the S-parameter correlation of Fig. 2, the dynamic free surface deformation in the hot corner is indeed changing the driving force during oscillations.

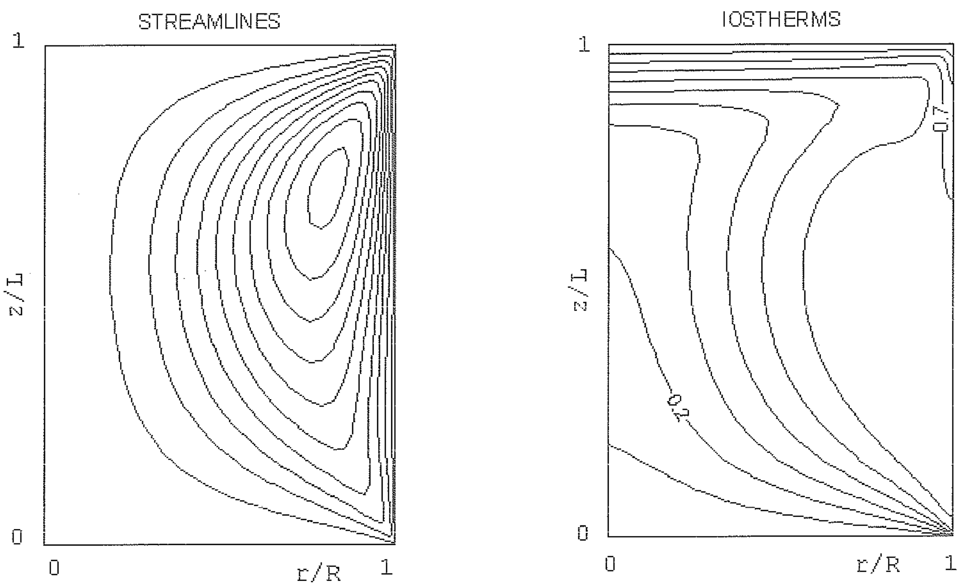


Fig. 3 Computed streamlines and isotherms of liquid flow
(Ma=1.2×10^4, Pr=28, D=3 mm, Ar=0.7, Dr=1.0, Bi=0.38)

5.2 Nearly Straight Liquid Bridge with Free Surface Heat Gain

As we increase T_R in the oven, T_R becomes eventually greater than T_H at the critical condition. In this situation the liquid bridge gains heat form the environment. Fig. 4 shows how ΔT_{cr} changes with increasing T_R (or, more appropriately, T_R-T_C) for nearly flat free surface shape. For the reason to be discussed later, we cannot take data for Dr = 1 with heat gain, so the data in Fig. 4 for the heat gain case are for Dr slightly less than unity. As the figure shows, ΔT_{cr} increases up to a certain T_R-T_C but drops suddenly beyond this T_R-T_C. It appears that there are two different branches in Fig. 4. The changeover temperature difference depends on the liquid diameter. The same data are plotted in terms of the computed Bi and presented in Fig. 5. Bi is positive for net heat loss and negative for net heat gain. Figure 5 shows that the sudden change in Ma_{cr} occurs when the free surface heat transfer changes from net loss to gain. Once we get into the heat gain situation, Ma_{cr} becomes relatively insensitive to Bi (Ma_{cr} ~ 1.4×10^4) . Also, Ma_{cr} does not depend on the diameter. Therefore, it seems that Ma_{cr} is the proper parameter to specify the critical condition in the case of heat gain. Apparently, the oscillation mechanism changes suddenly once we get into the heat gain range.

Before we discuss the oscillation mechanism, it is important to know how the liquid flow is affected by the net heat gain. Typical streamlines and isotherms with heat gain are shown in Fig. 6. With heat gain, the bulk fluid temperature increases so that the temperature gradient in the hot corner decreases. On the other hand, the surface temperature gradient in the cold corner increases. Consequently, the hot corner becomes less active and the cold corner becomes more active with the free surface heat gain, which makes much of the surface flow originating from the hot corner go into the cold corner (see Fig. 6). However, the main driving force is still in the hot corner in the range of Bi investigated herein. Therefore, the oscillations still originate from the hot corner. One visible feature of the oscillatory flow with heat gain is an increased activity in the cold corner. Apparently, the cold corner is assisting the oscillation mechanism in some way. Our numerical simulations for Dr = 1 show that the flow is stable around Ma = 1.4×10^4 even when the heat gain is large (Bi = -1). Therefore, the oscillation mechanism for the observed oscillations with heat gain must also include the free surface curvature.

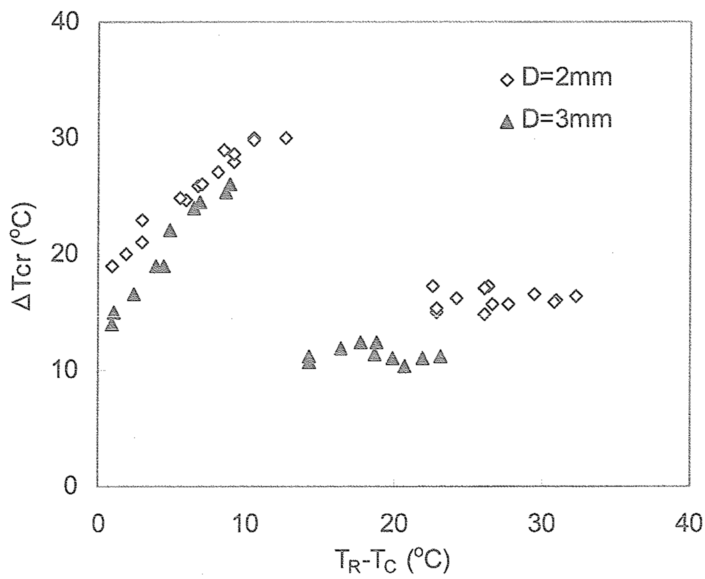


Fig. 4 Critical ΔT for nearly straight liquid bridge with heat gain and loss

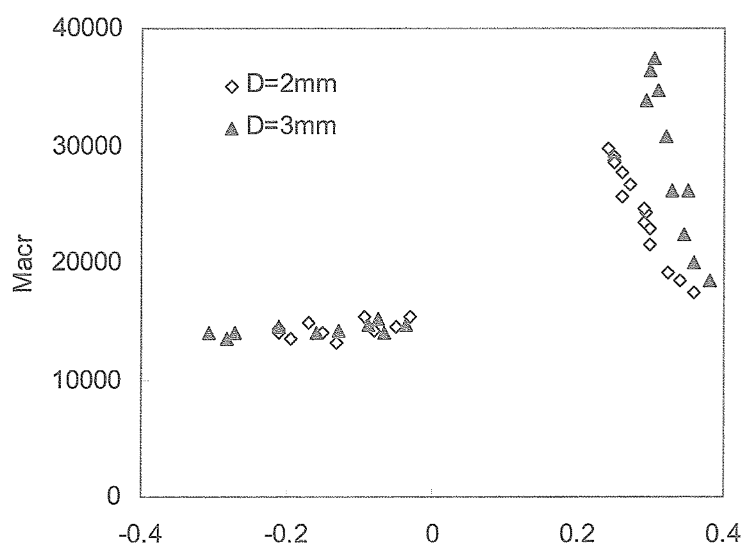


Fig. 5 Critical Ma vs. Bi for nearly straight liquid bridge with heat gain and loss

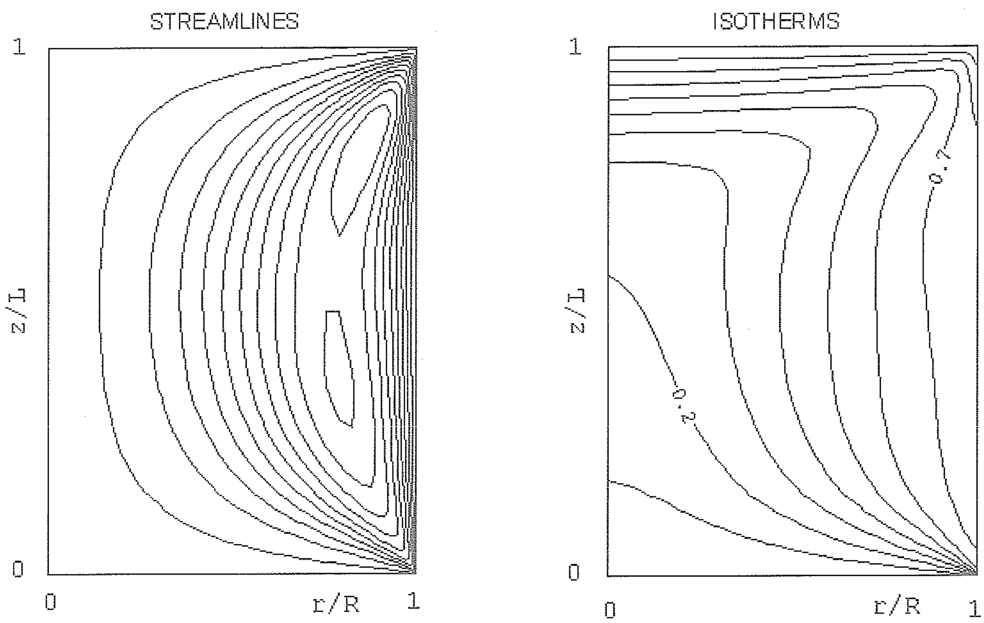


Fig. 6 Computed streamlines and isotherms of liquid flow
($Ma=1.2\times10^4$, Pr=28, D=3 mm, Ar=0.7, Dr=1.0, Bi=-0.38)

5.3 Concave Liquid Bridge with Free Surface Heat Loss or Gain

Tests with concave free surfaces are commonly done near room temperature. Typical results of room temperature tests for concave free bridges are shown in Fig. 7. It is well known that the Ma_{cr}-Dr curve has two branches: one for nearly flat surface (called the fat branch) where Ma_{cr} increases with decreasing Dr, and the other branch for concave surface (the slender branch) where Ma_{cr} is relatively unaffected by Dr. The changeover occurs suddenly across a certain Dr (Dr of about 0.8 for Ar=0.7 as seen in Fig. 7). This sudden change is similar to that found for the case of nearly flat free surface when the net heat transfer changes from loss to gain. As will be discussed later, this changeover for the concave free surface case is also due to a change in the oscillation mechanism. Although the so-called shape effect is usually shown in a graph similar to Fig. 7, it does not give a complete picture because it does not contain free surface heat transfer information except that the tests are done under the heat loss conditions.

Some results from the heat loss tests (room temperature tests with variable T_C) are presented in Fig. 8. As discussed above, Ma_{cr} increases with decreasing heat loss (decreasing Bi) for nearly flat free surface. Figure 8 shows that this trend holds for the fat branch (Dr > 0.8). Ma_{cr} for D r= 0.9 is larger than that for Dr = 1.0 until they become nearly equal beyond Bi of about 0.5. However, Ma_{cr} is not affected appreciably by the heat transfer in the case of concave free surface (slender branch). This trend for the slender branch remains the same even when the heat transfer changes to net gain, as shown in Fig. 9.

The only important effect of free surface heat transfer is that the slender branch extends to larger value of Dr as the surface heat transfer changes to net gain, as shown in Fig. 10. It is not possible to perform heat gain tests in the fat branch because T_R becomes too large. The vapor of the test liquid tends to condense on the cold wall when T_R-T_C becomes large, which can destroy the bridge if the condensation is too much. Our data indicate that the transition to the fat branch occurs around Dr = 1 in the heat gain tests. This is the reason we do not have heat gain data for exactly Dr = 1 in Figs. 4 and 5.

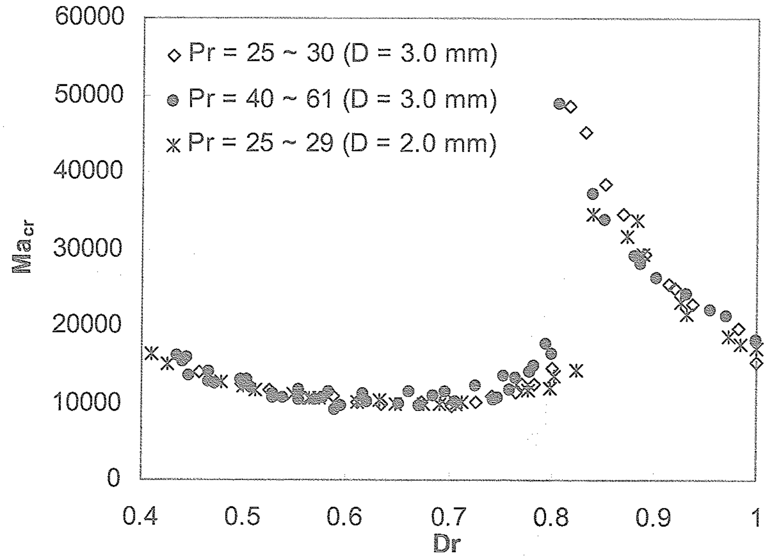


Fig. 7 Ma$_{cr}$ vs. Dr (Ar ~ 0.7) for heat loss tests

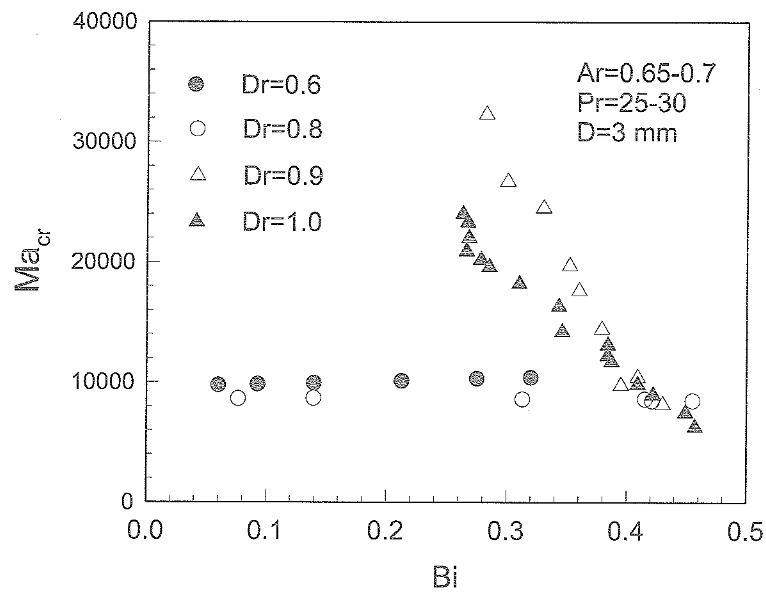


Fig. 8 Ma$_{cr}$ vs. Bi for heat loss tests with various Dr (D=3 mm, Ar=0.67, T_R=23°C))

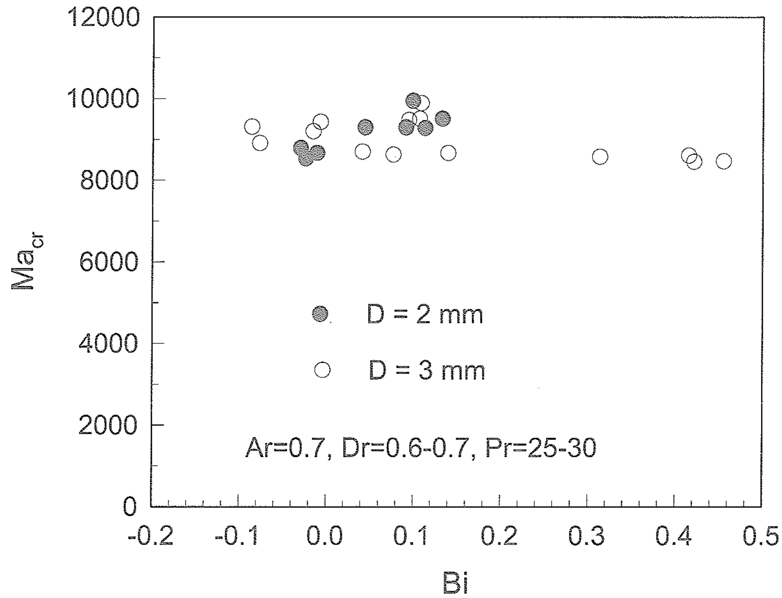


Fig. 9 Ma_{cr} vs. Bi for concave liquid bridge with heat gain and loss

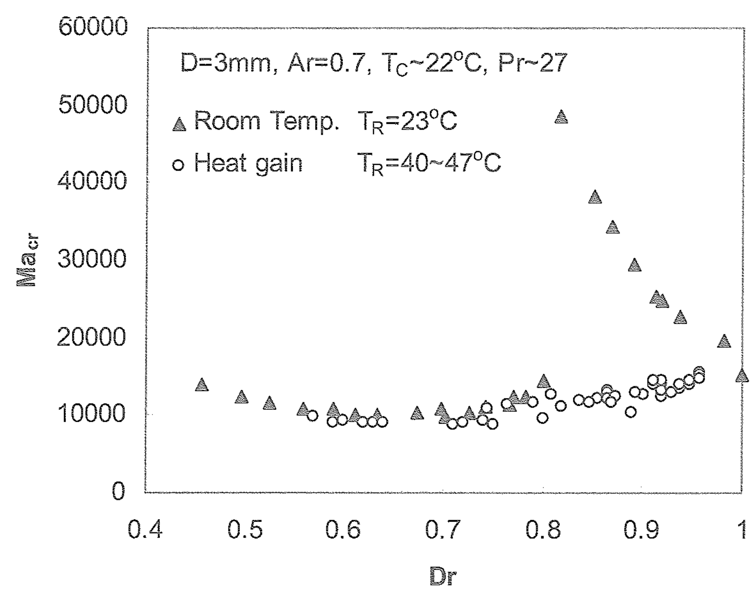
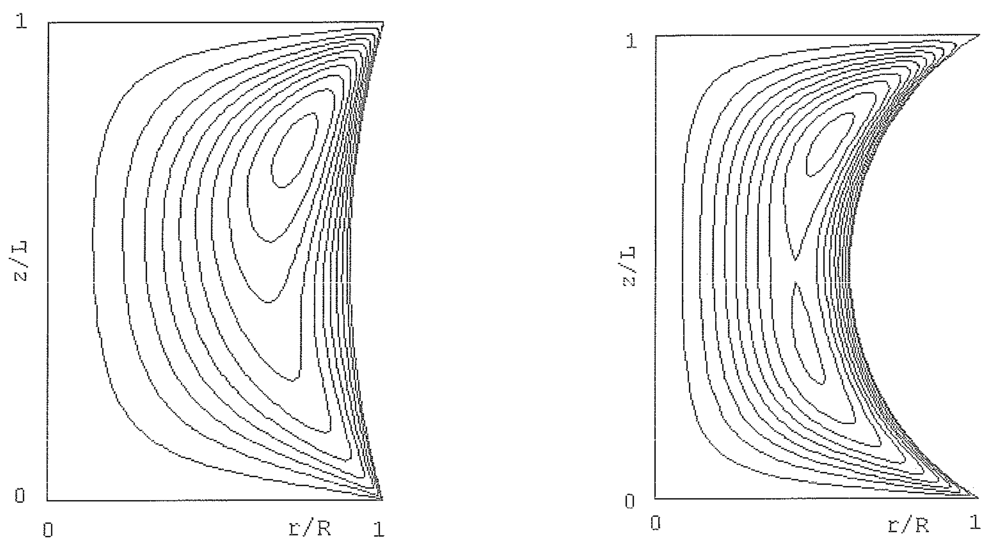


Fig. 10 Ma_{cr} vs. Dr with heat loss and gain

In order to see how the liquid flow structure changes with the shape, the computed streamlines are shown in Fig. 11 for the insulated free surface case. As the surface becomes more concave, the hot and cold corners become increasing narrow zones. Consequently, the flows in the corners are increasingly suppressed. The free surface velocity distributions for the conditions of Fig. 11 are given in Fig. 12, which shows this trend. In order to show this trend from a different angle, the ratio of the free surface temperature gradient (along the free surface direction) at the mid-height, $(dT/ds)_{L/2}$), to that at the location where the surface velocity becomes a maximum near the hot wal, $(dT/ds)_{hot}$), is computed for various Dr. The former location represents the bulk region and the latter location represents the hot corner. The ratio is given in Fig. 13. As the figure shows, the ratio increases, meaning that the driving force in the bulk region becomes more important, as Dr is decreased. Knowing that the bulk region has more surface area than the hot corner, the main driving force region clearly shifts from the hot corner to the bulk region below a certain Dr. Figure 13 shows that the ratio begins to increase sharply below about Dr of 0.8. As discussed above (Fig. 7), Ma_{cr} changes appreciably across the value of D $\sim$ 0.8 for Ar = 0.7. Apparently, this change coincides with the shift of the main driving force from the hot corner to the bulk region. This suggests that there is a shift from the S-parameter mechanism to a different mechanism below Dr of 0.8. With decreasing Dr, the flow is squeezed in the neck region, so the overall flow slows. When the surface is highly concave, the return flow from the cold region (region below the neck) to the hot region is partially blocked by the neck. As a result, a secondary cell appears in the cold region, as seen Fig. 11.



Dr=0.9 Dr=0.6

Fig. 11 Computed streamlines of liquid flow with insulated free surface
($Ma=1.0\times10^4$, Pr=28, D=3 mm, Ar=0.7)

As in the heat gain case for nearly flat free surface, Ma_{cr} is rather low, less than 10^4, so that the hydrothermal waves cannot occur with highly concave surface. The S-parameter mechanism is not important either since the flow is not driven in the hot corner. The only known other mechanism is the one we investigated earlier based on two-dimensional simulations [10]. Since the flow is squeezed at the neck, the return flow below the neck has difficulty to pass the neck region together. This slowing of the flow in the neck region increases the surface temperature gradient in the region. This situation is unstable against three-dimensional disturbances. Eventually, when Ma becomes large enough, the return flow begins to take turn to pass the region in a three-dimensional manner. For example, in the case of oscillation pattern of mode number one, half of the return flow passes through the neck and the remaining half is blocked from the passage. After the passage, the surface temperature gradient decreases as the hot and cold regions mix, but the gradient increases in the region where the return flow is blocked. Eventually, the flow pattern is reversed, resulting in oscillations with rotating temperature and velocity patterns.

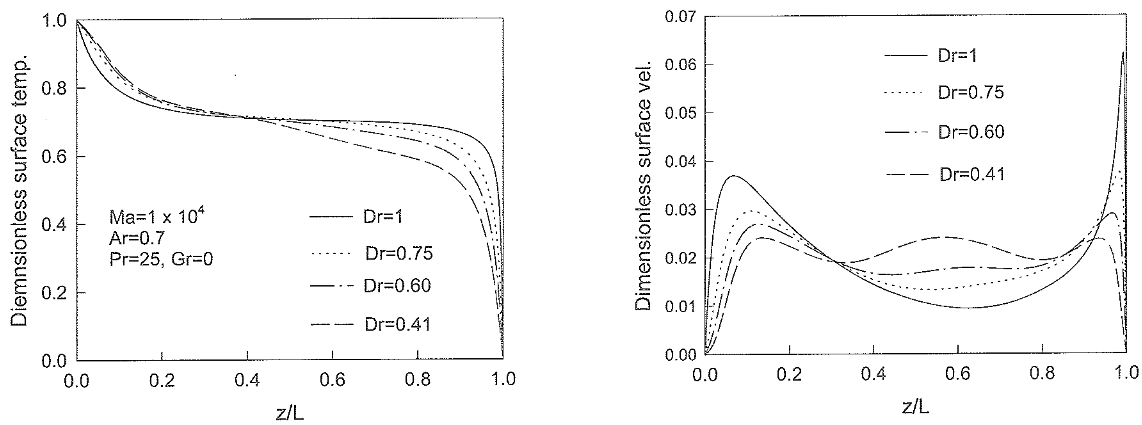


Fig. 12 Surface temperature and velocity variations with diameter ratio for Bi=0

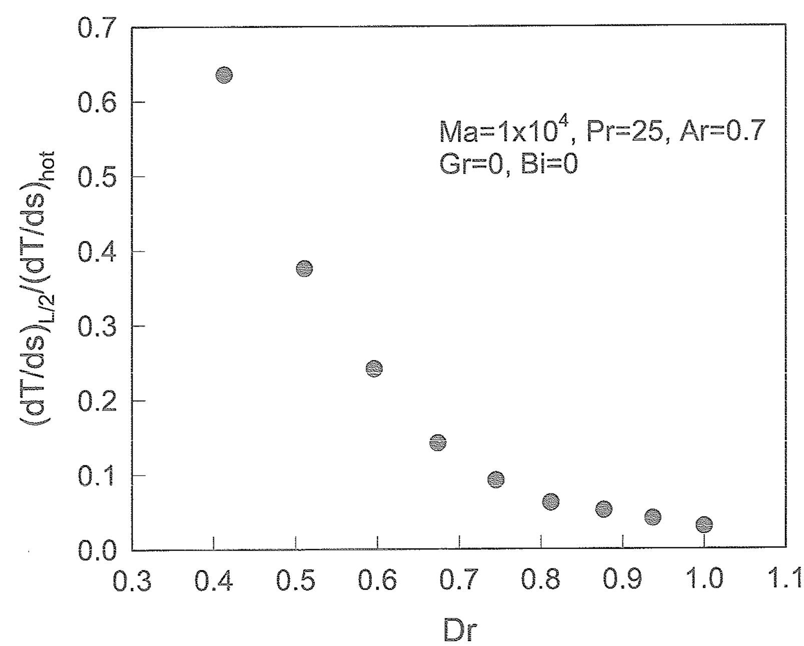


Fig. 13 Surface temperature gradient ratio as a function of Dr

The above oscillation mechanism depends on the existence of the neck region, so it does not apply to fat bridges. However, the data in Fig. 10 show that the trend of Ma_{cr} for concave bridges continues smoothly to that for slightly concave bridges with heat gain. Actually, a close examination of the data show that Ma_{cr} begins to increase slightly with increasing Dr beyond about Dr = 0.8. Therefore, the oscillation mechanism for concave bridges is somewhat modified but still applicable even to a slightly concave bridge in the presence of heat gain. The heat gain activates the cold corner in the case of nearly flat bridge, as discussed above. This situation is similar to the activation of the flow in the cold region due to the neck in the case concave bridge. Although more work is needed, this similarity may explain the trend of Ma_{cr} for slightly concave bridge with heat gain.

5.4. Discussion of Oscillation Mechanisms

Much has been discussed in the past concerning the mechanism of thermocapillary oscillation phenomenon in liquid bridges. The mechanism for low Prandtl number fluids (Pr ~ 0.01) is well understood; a result of hydrodynamic instability as the Reynolds number (or inertia forces) becomes sufficiently large. On the other hand, the oscillation mechanism for high Pr fluids (Pr > 15) is still being debated. Two models have been proposed in the past for high Pr fluids. One is the S-parameter model by Kamotani and Ostrach [2] and the other is a linear stability model. In the S-parameter model, the fact that the flow is mainly driven in the hot corner is taken into account and the dynamic free surface deformation in the hot corner plays an important role. In contrast, no dynamic free surface deformation is considered in the linear stability model, which predicts the appearance of hydrothermal waves.

Since the hydrothermal wave instability is often cited as the only cause of the various oscillatory thermocapillary flows of high Pr fluids, it is important to know under what conditions the hydrothermal wave-type instability occurs. Based on the linear stability analyses by Smith and Davis for thin liquid layers [11] and Wanschura et al. for liquid bridges [12], the following conditions are important for the appearance of hydrothermal waves in high Prandtl number liquids.

(i) The basic flow is driven by the axial temperature gradients along the free surface. The Marangoni number of the flow is sufficiently large so that convection heat transfer is important.

(ii) Temperature gradients also exist in the radial direction (or in the direction normal to the free surface). These radial temperature gradients are produced by the main axial convection. In particular, the radial temperature gradients near the free surface are due to the convection by the main free surface flow.

(iii) The axial dimension of the hydrothermal waves predicted for liquid bridges scales with the bridge length. Also, the disturbance flow in the axial direction is relatively small.

The observed oscillation phenomenon in room temperature experiments has some features that are different from the above features of the hydrothermal waves.

(i) The disturbance flow in the axial flow direction is quite prominent.

(ii) Since the radial convection by the disturbance flow must be uniformly important over the bridge length and since the end wall tends to generate axial disturbance flow in the corner region, the only region where such waves could be generated is the bulk region, not the hot corner.

(iii) When heat is lost at the free surface, the radial temperature gradient in the surface flow region is reduced (see Fig. 3). Such a condition is not conducive to the hydrothermal wave instability.

(iv) As discussed earlier, numerical simulations show that it is not possible to have hydrothermal wave type instability at a Ma as low as about 10^4.

(v) The work by Wanschura et al. [12] is up to Pr of about 4, and no accurate linear stability work exists for the Prandtl number range of current interest, namely Pr > 15.

Therefore, the observed oscillatory flows of high Pr fluids are not due to the hydrothermal wave instability. From our earlier studies together with the present investigation of free surface heat transfer effects, we have identified two oscillation mechanisms that are not based on linear stability theory. Our S-parameter model holds if (i) the free surface is nearly flat, and (ii) the free surface is thermally insulated or it loses heat to the environment. Note that many experiments performed in the past belong to this case. The correlation of the critical conditions shows that the oscillation mechanism represented by the S-parameter is responsible for the transition. The oscillations are a result of dynamic free surface deformation altering the main driving force in the hot corner periodically. The condition for the onset of oscillations is very sensitive to the free surface heat loss in the S-parameter range, because it is coupled with very small free surface deformation.

In the case of curved free surface, the driving force in the bulk region becomes increasingly important as the shape becomes more concave. As a result, the oscillation mechanism shifts from the S-parameter to an oscillation mechanism associated with the bulk region, as Dr is decreased. The oscillations are a result of the flow passing through the neck region in a three-dimensional and time-dependent manner. Since no small quantities are involved in this case, such as the dynamic free surface deformation, the critical condition is not very sensitive to the free surface heat transfer. With heat gain, a similar mechanism holds even for slightly concave bridge.

6. CONCLUSIONS

The effects of free surface heat loss and gain on the conditions for the onset of oscillatory thermocapillary flow are investigated experimentally in liquid bridges of high Prandtl fluids. Both straight and concave liquid bridges are investigated. The free surface heat transfer rate is computed numerically. Nearly straight liquid bridges are very sensitive to the free surface heat loss, the flow being destabilized with increasing heat loss. However, they are not sensitive to free surface heat gain. Concave liquid bridges are not sensitive to gain or loss. It is discussed that for nearly straight bridges with heat loss (including insulated free surface), the onset of oscillations is specified by the S-parameter. On the other hand, for concave bridges with heat gain or loss and for nearly straight bridges with heat gain, the oscillation mechanism is associated with the convection in the bulk region so that Ma_{cr} can specify the critical condition.

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