1. Investigations for High Prandtl Fluid

1.1 Investigation of Free Surface Heat Transfer effect on Oscillatory Thermocapillary Flow of High Prandtl Number Fluid

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

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The effect of heat transfer at the free surface on oscillatory thermocapillary flow in liquid bridges of high Prandtl number fluids is investigated experimentally as well as numerically. Both net heat loss and gain conditions are studied. The air motion is simulated numerically in order to compute the free surface heat transfer rates for given experimental conditions. We have shown earlier that the critical Marangoni number (Ma_{cr}) decreases substantially with increasing free surface heat loss. It is shown in the present work that the critical conditions for various heat loss cases can be correlated by a surface deformation parameter (S-parameter) and the modified Biot number. When the free surface gains heat from the surrounding air, the situation changes substantially. Ma_{cr} decreases sharply when the free surface heat transfer changes to a net gain. The oscillatory flow structure also changes. It is discussed that dynamic free surface deformation near the cold wall is important in the oscillation phenomenon with net heat gain and that dynamical interactions between the liquid and air flows near the cold wall modify this deformation effect. The main objective of the present work is to understand the physical mechanism of transition to oscillatory flow for high Prandtl number fluid.

1. INTRODUCTION

We have been investigating oscillatory thermocapillary flow in liquid bridges of high Prandtl number (Pr) fluids in order to clarify the transition mechanism that is not yet fully understood. One prevailing concept is that the transition is due to a hydro-thermal wave type instability, so that the flow becomes oscillatory when Ma is increased beyond a certain Ma_{cr} for given Pr and liquid bridge aspect ratio (Ar = bridge length/diameter ratio). However, available experimental data taken over a wide range of liquid bridge diameters show that Ma_{cr}, for given Pr and Ar, varies strongly with the diameter, which should not occur if Ma_{cr} alone could specify the transition [1]. For this as well as for other reasons, we have postulated a non-linear dynamical mechanism involving dynamic free surface deformation and proposed a parameter called S-parameter, which is valid only for high Pr fluids [2]. More work is needed to determine the cause of oscillations conclusively.

Recently we have shown that the transition is sensitive to the heat transfer at the free surface. Usually in room temperature tests, the liquid bridge loses heat from the free surface to the surrounding air. The amount of free surface heat loss is relatively small compared to the total heat transferred through the liquid, since the surface heat transfer is caused by weak natural convection in the air associated with the cooling-heating arrangement of the experimental apparatus. For this reason, it has been neglected in the past. However, we have shown that one can change Ma_{cr} by several factors simply by varying the airflow natural convection [3]. In some situations, even when the heat loss is so small that the basic flow is hardly altered, its effect on Ma_{cr} is important. Again this result is not consistent with the linear stability concept in which the heat loss effect is felt by way of the basic flow change. It suggests that a non-linear thermal interaction between the liquid flow and the airflow at the free surface is responsible for the heat loss effect on the critical condition, which is consistent with our model of the oscillation mechanism. Therefore, we analyze our data based on this concept and then explain the relation between the oscillation mechanism and the heat loss in the present report.

We also report some results for the free surface heat gain case. The heat gain effect is shown to be much different from the heat loss effect. We will discuss how the heat gain might affect the critical condition.

2. EXPERIMENT

The experimental apparatus is described in our previous work [1-3], so it is not repeated herein. The basic liquid bridge configuration is illustrated in Fig.1. 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 nearly flat but slightly concave surfaces are used in some tests. The tests are conducted in an oven. The cover of the oven is replaced by a transparent plexiglass board so that the inside can be seen to observe the test section. 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.

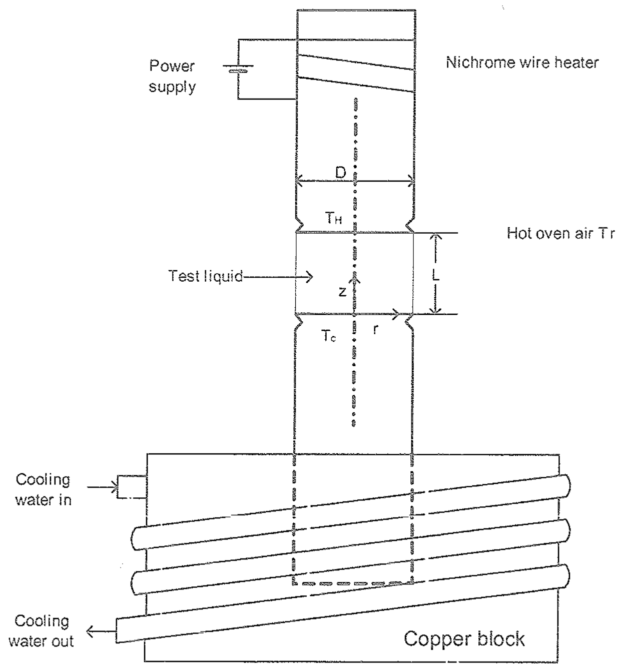

Fig. 1 Liquid bridge configuration

3. NUMERICAL SIMULATION OF AIR MOTION

The heat transfer rate at the liquid free surface 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 [4]. The computational domain for the airflow analysis is consistent with the experimental conditions. Experimentally, we vary the surface heat transfer rate mainly by varying the temperature difference $T_R - T_C$ and determine the critical temperature difference ($\Delta T = T_H - T_C$) for the liquid flow for each case. Then, we simulate the airflow for this condition and compute the free surface heat transfer rate. 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).

4. IMPORTANT DIMENSIONLSS PARAMETERS

The important dimensionless parameters for the thermocapillary flow in the liquid bridge configuration 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 afore-mentioned 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.

The thermal effect of the surrounding airflow is represented by the local and average Biot numbers as explained above. The hydrodynamic interaction between the liquid and air flows is neglected because the viscosity of air is only less than 1% of the test fluid viscosities.

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 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. 2. 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.

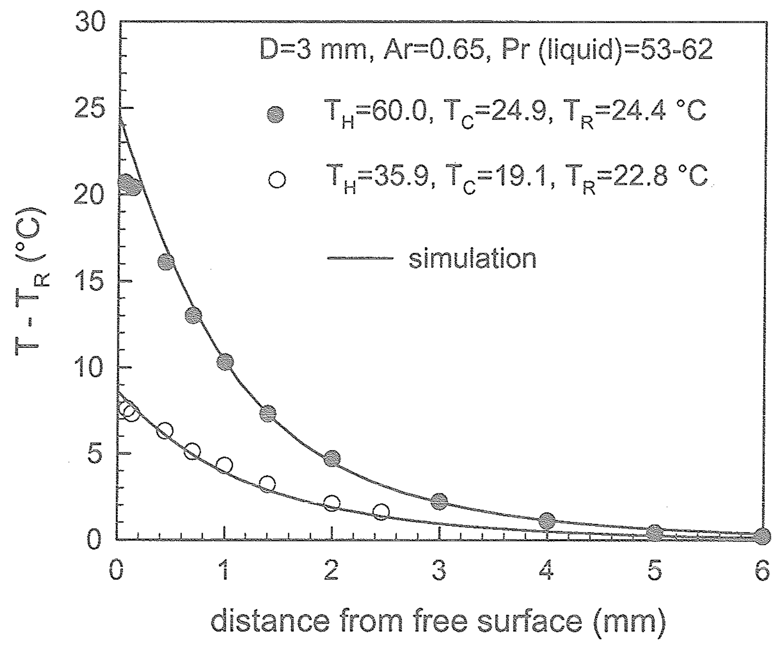

Fig. 2 Comparison of measured and computed temperature distributions at liquid mid-height

5.2 Case of Free Surface Heat Loss

In the present experiment we vary the amount of free surface heat loss by varying the temperature difference $T_R - T_C$. Since our main interest is the critical condition for the onset of oscillations, when we say heat loss or gain at the free surface, it is near the critical condition. In the case of free surface heat loss, T_H (at the critical condition) is always greater than T_R. We have conducted the heat loss experiments under two conditions, one in which the airflow is due to natural convection induced by the heating and cooling arrangement of the experimental setup, and the other condition in which forced airflow removes heat from the free surface.

5.2.1 Heat loss due to natural convection

The critical conditions determined under various conditions have been reported in our last year's report [5]. We have obtained more new data since then. First, we correlate all of the data for a fixed Ar in terms of Ma_{cr} and Bi. The result is shown in Fig. 3. Overall, the correlation is not satisfactory. Especially, the data taken with different diameters do not follow one curve for a given Pr, as they should if Ma and Bi were the only parameters to specify the critical condition. The general trend of Fig. 3 is that it becomes easier for the flow to become oscillatory (or Ma_{cr} decreases) with increasing surface heat loss (or increasing Bi). However, Fig. 3 suggests that Ma_{cr} cannot go below about 6000 because convection effects in the liquid flow then become too weak for the oscillations to occur. Fig. 3 also shows that (i) Bi must be smaller than about 0.3 for negligible heat loss effect and (ii) the heat loss effect changes Ma_{cr} substantially in a relatively small range of Bi, between 0.3 and 0.7. As discussed in our last year's report [5], the basic flow is not strongly affected by Bi in this range so that such a large change in Ma_{cr} cannot be attributed to the basic flow change. This and other facts [5] imply that the heat loss effect cannot be explained by the linear stability concept. This means that the effect is a result of a non-liner interaction with the air. This interaction must be thermal in nature, because the thermal conductivity of air is only about one-fourth of that of the test liquids.

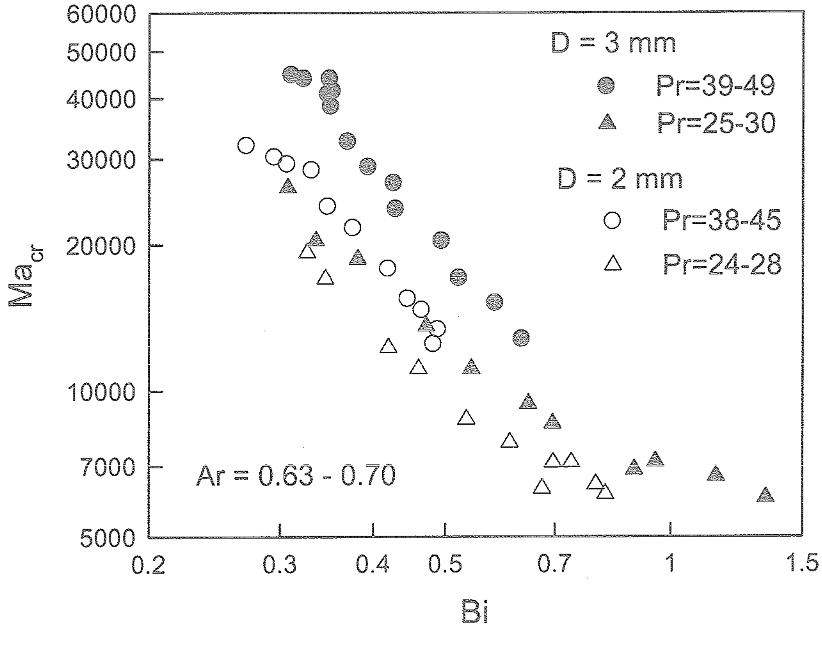

Fig. 3 Correlation of critical Marangoni number with average Biot number

Therefore, we correlate the same data now in terms of the S-parameter and Bi in Fig. 4. The correlation now is better in the sense that the data now follow one curve for each Pr. Fig. 4 tells us that the heat loss effect on the S-parameter depends on Pr. In order to understand the heat loss effect better, we try to find a parameter that includes Pr. It is found that if Bi is modified as $Bi/Pr^{0.5}$, all of the present data, including the data taken with different Ar, follow just one curve, as shown in Fig. 5. The figure shows that under negligible heat loss condition the S-parameter is about 0.05 for the present range of Ar, but it is reduced sharply by the heat loss.

The next question is what this modified Biot number $Bi/Pr^{0.5}$ means. It is already discussed that the heat loss effect is important mainly in the hot corner where the dynamic free surface deformation effect is also important [5]. Moreover, both effects are important only near the free surface. Therefore, both effects are expected to interact. The dynamic free surface deformation is relatively small but its effect on the oscillation mechanism is considered to be important in our oscillation model [2]. The heat loss is also relatively small, but it could have a significant effect if it somehow affects the dynamic deformation effect. Therefore, the parameter $Bi/Pr^{0.5}$ must represent this interaction between the two effects. Since the flow oscillates even when the surface heat loss is negligible, the surface deformation effect is the main effect and the heat loss effect, when it is important, modifies this main effect. In a dynamical situation where both velocity and temperature fields vary with time, the ratio of viscous to thermal diffusion speeds is represented by $Pr^{0.5}$. Since this diffusion speed ratio is the most obvious parameter related to $Pr^{0.5}$, and probably the only parameter considering the conditions under which the oscillations are observed, the $Pr^{0.5}$ part of $Bi/Pr^{0.5}$ is considered to represent this diffusion speed ratio. Then, the present result shows that if this ratio of diffusion speeds is large (or if $Pr^{0.5}$ is large), the effective heat loss is reduced.

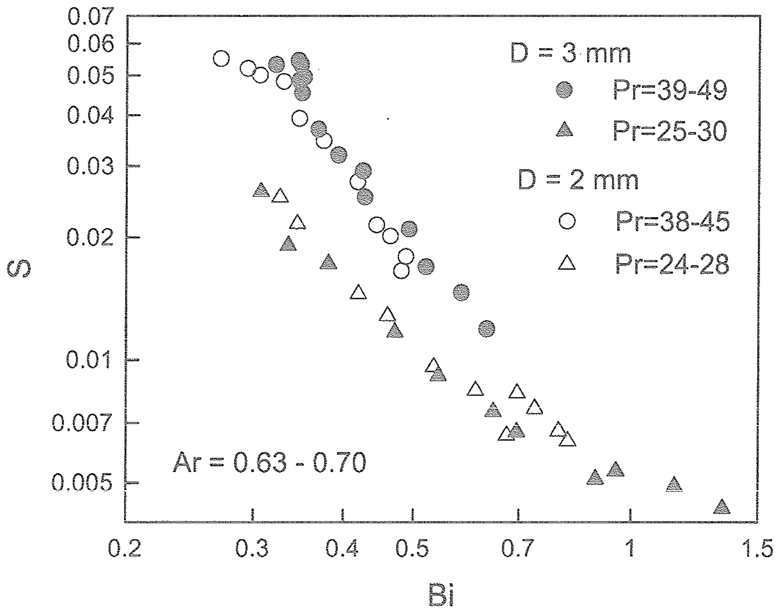

Fig. 4 Correlation of S-parameter at critical condition with average Biot number

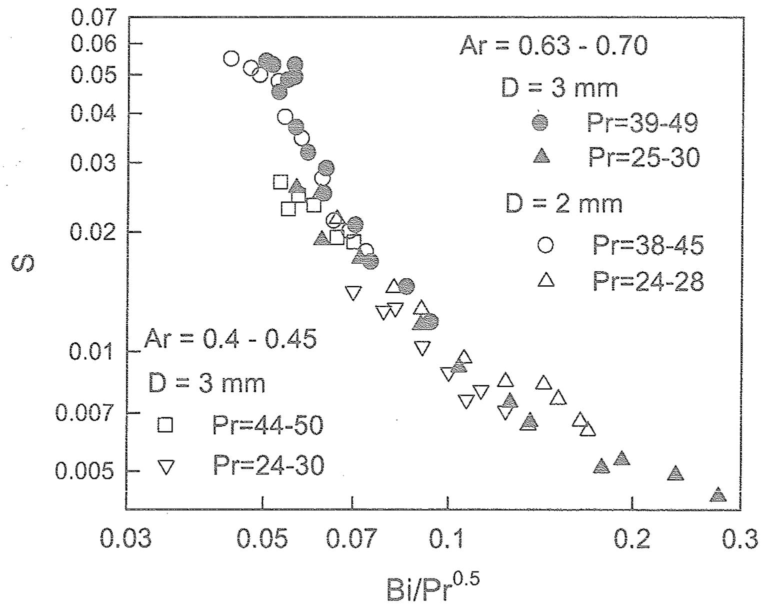

Fig. 5 Correlation of S-parameter at critical condition with modified Biot number

From the above observations, we can postulate the following oscillation process in which the dynamic free surface deformation and the free surface heat loss interact strongly. In our oscillation model, when the surface flow accelerates in the hot corner, the free surface depresses by transporting some fluid near the surface out of the region [2]. The additional convection associated with this fluid transport along the free surface initiates the so-called active period. The free surface deformation in the hot corner is associated with the viscous diffusion process perpendicular to the free surface [2]. As a result, it can alter the thermal boundary layer along the free surface in a transient period, because the deformation proceeds faster than the thermal boundary layer development in the case of high Pr, which is the reason the small deformation can change the driving force significantly. Now, in the presence of surface heat loss, the fluid near the free surface is somewhat cooler than the interior fluid just below the surface. Consequently, when some fluid is removed from the free surface, it exposes warmer fluid, which helps to increase the convection along the free surface with increasing time. For this reason, the heat loss augments the free surface deformation effect. In a transient situation, both the surface deformation and heat loss effects propagate from the free surface to the interior, and in this process, if the deformation effect propagates very fast (large Pr), the heat loss effect (or the temperature gradient normal to the free surface caused by it) would be confined to a very small layer near the surface. Therefore, the heat loss effect is reduced when Pr, or more accurately $Pr^{0.5}$, is large, which seems to explain why the parameter $Bi/Pr^{0.5}$ represents the effective heat loss effect.

The work related to the heat loss effect has been submitted for publication [6].

5.2.2 Heat loss due to forced convection of air

The above data analysis is done for the case in which the heat loss is caused by the air natural convection. Just to check anything special about this heat loss, it is interesting to see whether the same correlation works when the loss is caused by the forced convection of the surrounding air. The experimental setup for the forced convection experiment is sketched in Fig. 6. The liquid bridge is placed in a plastic tube through which air flows. The air is injected from the cold wall side and its temperature is the same as the cold wall temperature (both at room temperature). In this way, the air temperature is uniform before it contacts the liquid bridge. The air also goes through a fiberglass filter to make the incoming airflow uniform. In this configuration, the airflow opposes the liquid free surface flow, and heat is lost from the free surface. When the air speed is high (above about 10 cm/s), we can observe that the liquid flow is slowed by the air shear. Since this situation is not our interest herein, our tests are conducted below this air speed. Again, the airflow around the liquid bridge is simulated numerically for given test conditions in order to compute the free surface heat transfer rate (Bi).

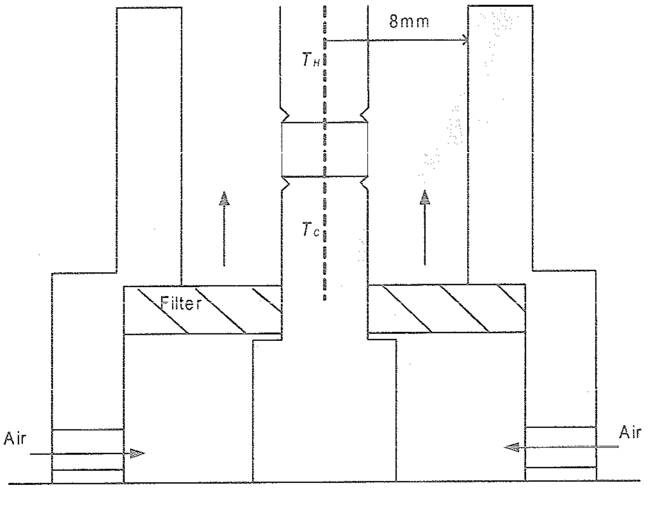

Fig. 6 Setup for forced airflow experiment

Some typical data are presented in Fig. 7, where Ma_{cr} is plotted against Bi. Ma_{cr} decreases with increasing Bi (or increasing air speed), which is consistent with the natural convection tests. Since small liquid bridges are used in our tests, convection relative to conduction is not very strong in the present air velocity range. Besides, as discussed above, we cannot make the airflow too fast. Consequently, one can cover only a limited range of Bi in this forced airflow test, so one does not observe a large Ma_{cr} variation as in the natural convection tests where T_R is varied over a wide range. Probably for this reason, although forced airflow experiments have been conducted in the past by other investigators, this flow destabilization in a small velocity range has not been reported. All of the forced airflow data are compared with the natural convection data in the S vs. $Bi/Pr^{0.5}$ of Fig. 8. All of our data are consistent within the experimental error. Therefore, one can conclude that the present heat loss effect does not depend on how the loss is induced.

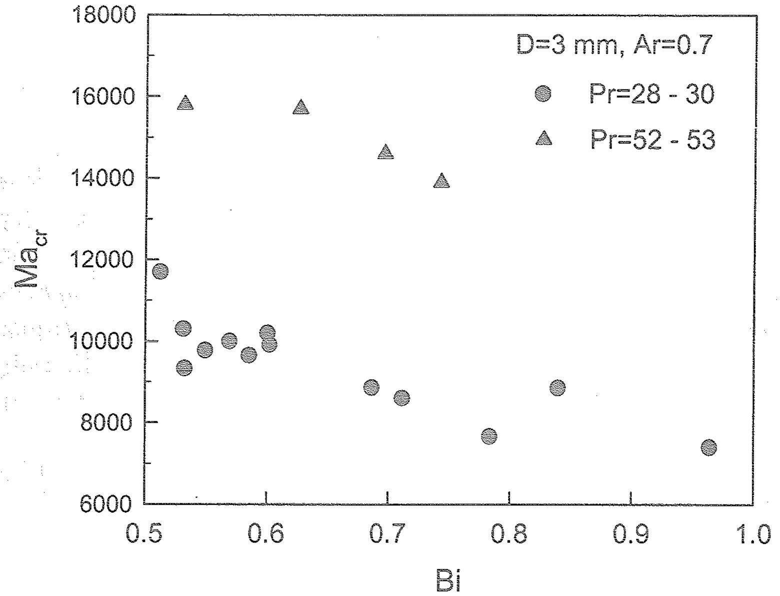

Fig. 7 Critical Marangoni number vs. Bi for forced airflow tests

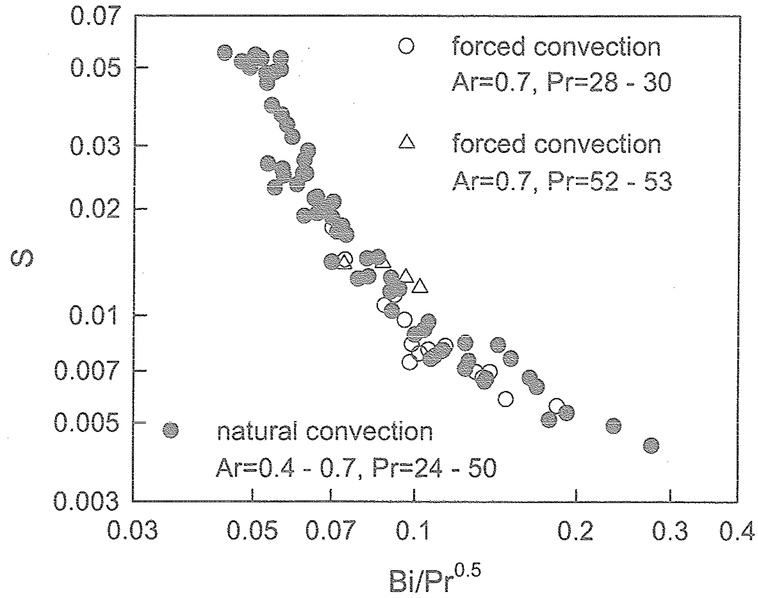

Fig. 8 Correlation of critical conditions for both forced and natural convection airflows

5.3 Case of Free Surface Heat Gain

Next, we discuss the case of heat gain. In this situation, T_R is always greater than T_H. Since the oven air heats the hot wall, the top wall must be cooled by cooling water in some situations to control the wall temperature. A few preliminary data were presented in our last year's report, but we now have more data. For a given T_C, if we keep increasing T_R, the heat loss becomes smaller and eventually changes to gain. Ma_{cr} as a function of T_R is shown in Fig. 9 for D = 3 mm. As seen in the figure, one observes a sudden reduction in Ma_{cr} above a certain T_R. When the same data are plotted against Bi in Fig. 10, it is clear that the sudden change in Ma_{cr} occurs when the heat loss (Bi > 0 in the present convention) changes to gain (Bi < 0). Notice in Fig. 10 that how sensitive Ma_{cr} is to the heat loss. On the other hand Ma_{cr} is not so sensitive to Bi with heat gain. Moreover, the oscillatory flow structure with heat gain is different from the well-known structure in room temperature and heat loss tests. At present, we cannot describe the oscillatory flow structure accurately but the heat gain case exhibits more activities near the cold wall than the heat loss case. Therefore, there are significant differences between the heat loss and gain effects. The same trend is also observed for D = 2 mm, as Fig. 11 shows. However, the oscillations in the 2 mm bridge are more intermittent compared to the 3 mm case where the oscillations are continuous once the flow becomes unstable. As will be discussed later, the oscillations are not observed when the free surface is flat for D = 2 mm, so the data in Fig. 11 for heat gain is the diameter ratio of between 0.93 to 0.97. We investigate this oscillation phenomenon with heat gain in more detail below. Note that in our experiment we usually increase T_H, for fixed T_C and T_R, until the flow becomes oscillatory. Now, if we keep increasing T_H beyond the critical condition in a heat gain test, the heat transfer at the free surface eventually changes to loss. Then the oscillations disappear, because the critical ΔT is much larger with heat loss.

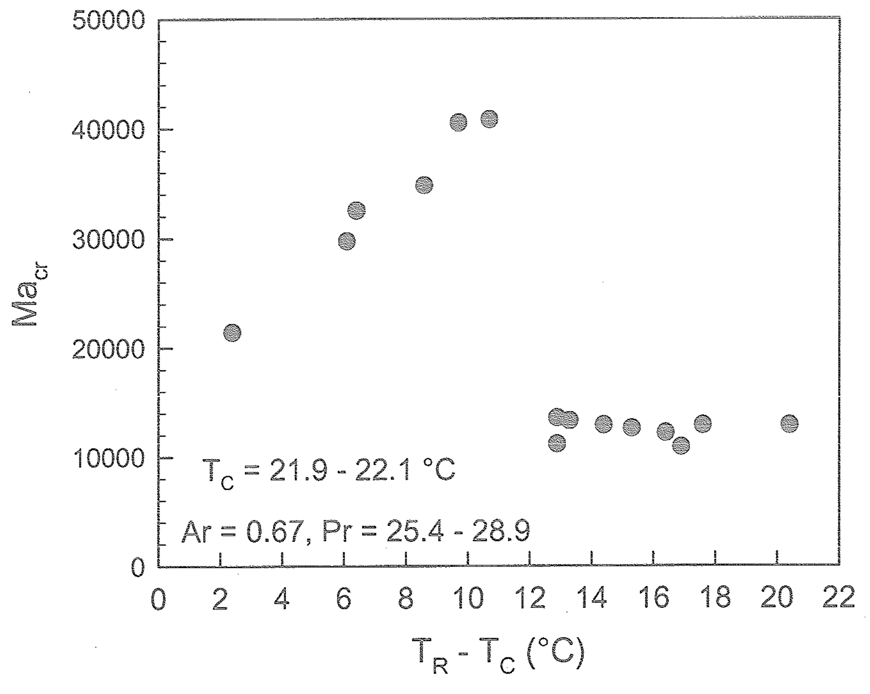

Fig. 9 Critical Marangoni number as a function of ambient air temperature for D = 3 mm

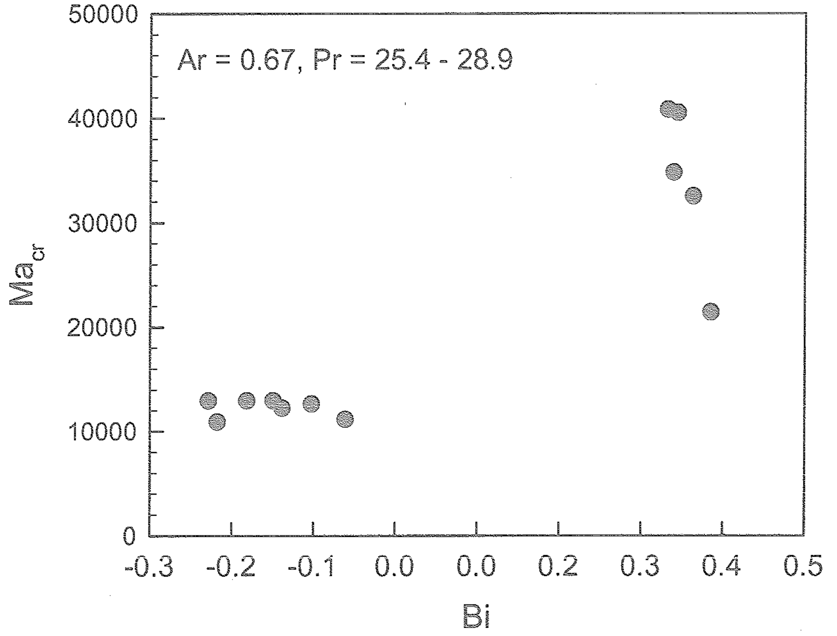

Fig. 10 Critical Marangoni number vs. Bi for heat loss and gain tests for D = 3 mm

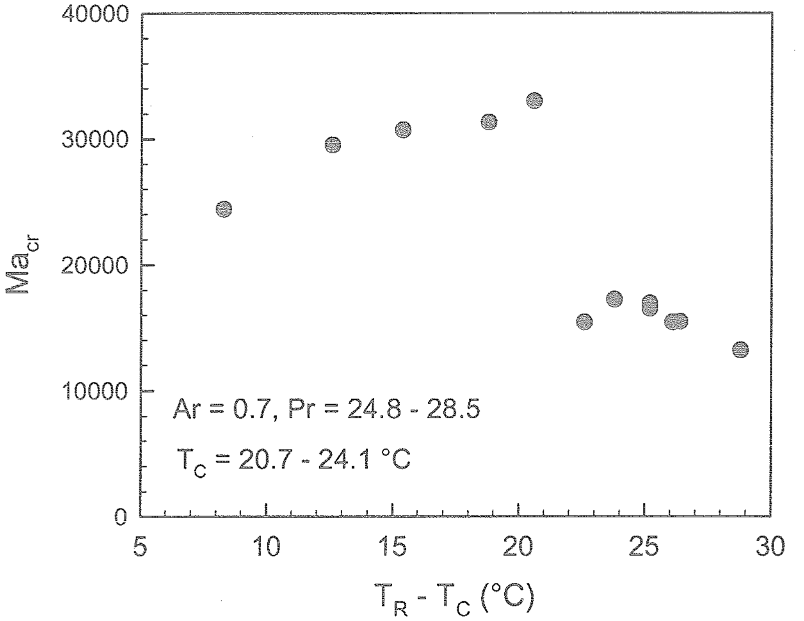

Fig. 11 Critical Marangoni numbers for D = 2 mm

The overall airflow structure is shown in Fig. 12 for a heat gain case. The airflow is downward everywhere, which is different from the heat loss cases. The thermal boundary layer that develops along the hot wall becomes thicker than the liquid radius when it gets contact with the liquid column. Therefore, convection heat transfer in the airflow is not very strong compared to conduction due to relatively weak airflow. The local Biot number distribution for this case is shown in Fig. 13. $Bi_{,loc}$ is negative (heat gain) over a large part of the free surface, but it is positive (heat loss) near the cold wall because of heat transfer from the liquid surface to the cold wall through the thermal boundary layer in the air (see the isotherms in Fig. 12). Note that since this large heat gain near the cold wall always exists, even when the average Biot number is nearly zero, most of the free surface experiences heat gain.

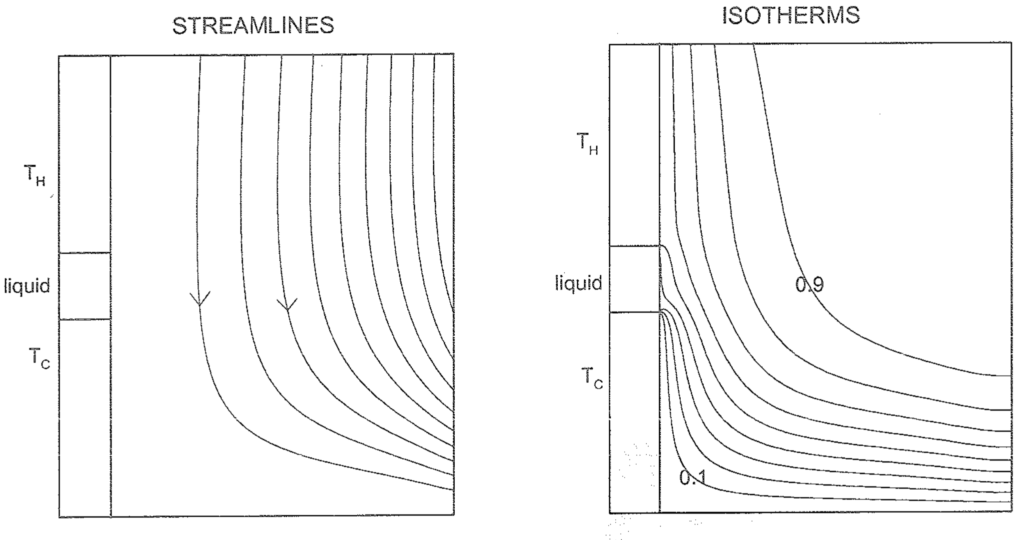

Fig. 12 Airflow structure in heat gain test (Ma = 1.3 x 10^4, Pr = 29, Ar = 0.7, Bi = -0.24)

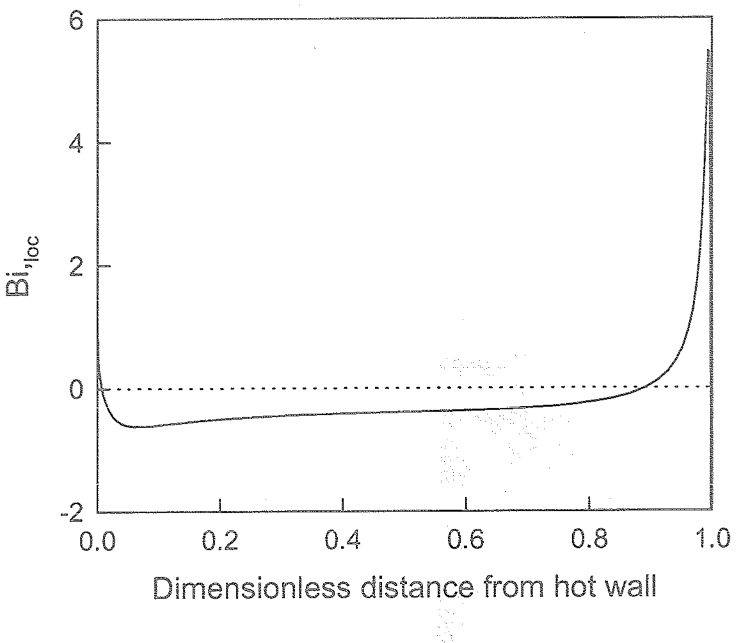

Fig. 13 Local Biot number distribution for the condition of Fig. 12

The flow structure of the liquid flow corresponding to the above airflow condition is shown in Fig. 14. As the streamline pattern shows, it has two cells. This two-cell structure is also observed experimentally. For comparison, the flow structure with no heat transfer at the free surface is shown in Fig. 15. With no heat gain, the flow structure is unicellular. Comparison of the isotherm patterns with and without heat gain shows that the heat gain makes the fluid near the free surface warmer. As a result, the radial temperature gradient near the free surface is increased by the gain. The buoyancy associated with this radial temperature gradient opposes the main recirculation flow due to thermocapillarity. Therefore, when the buoyancy is non-negligible, the overall flow becomes slower with heat gain, as the values of the maximum stream function, given in the streamline figures, show. The heat gain and loss near the bottom part of the liquid bridge increase the free surface temperature gradient, which makes the flow active near the cold wall. However, some of the fluid cannot flow all the way back to the hot wall region because of opposing buoyancy and thus recirculates near the cold wall. To show that this two-cell structure is a combined effect of heat gain and buoyancy, we artificially eliminate buoyancy in the liquid flow (but not in the airflow). The resultant streamline pattern is given in Fig. 16, which shows a unicellular structure even though heat is gained at the free surface. The two-cell structure is also observed for D = 2 mm even though buoyancy effect is smaller. It is noted that when Bi is relatively small (but still negative), the flow structure is unicellular during oscillations, so the two-cell structure is not a necessary condition for the transition. Therefore, even with the heat gain, the main driving force of the overall flow exists mainly near the hot wall.

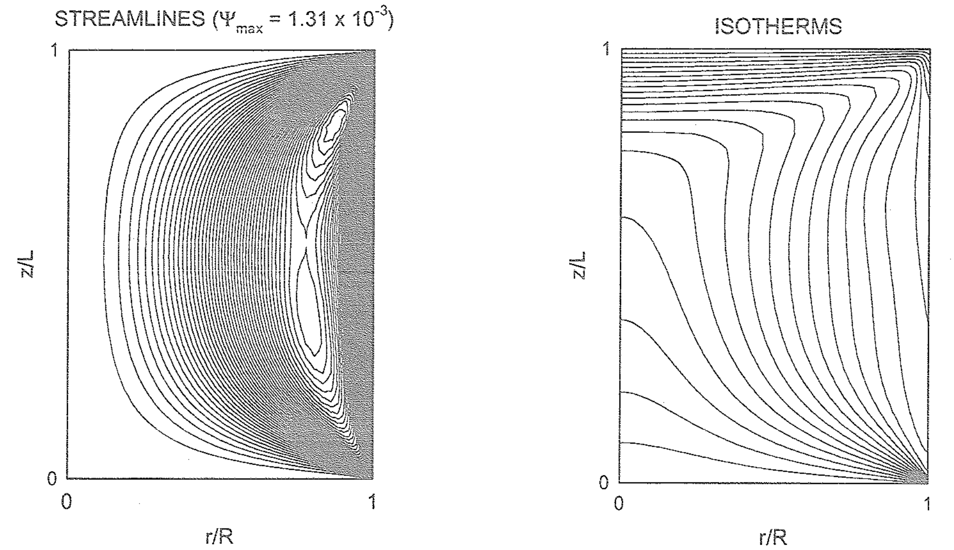

Fig. 14 Liquid flow structure for the condition of Fig. 12

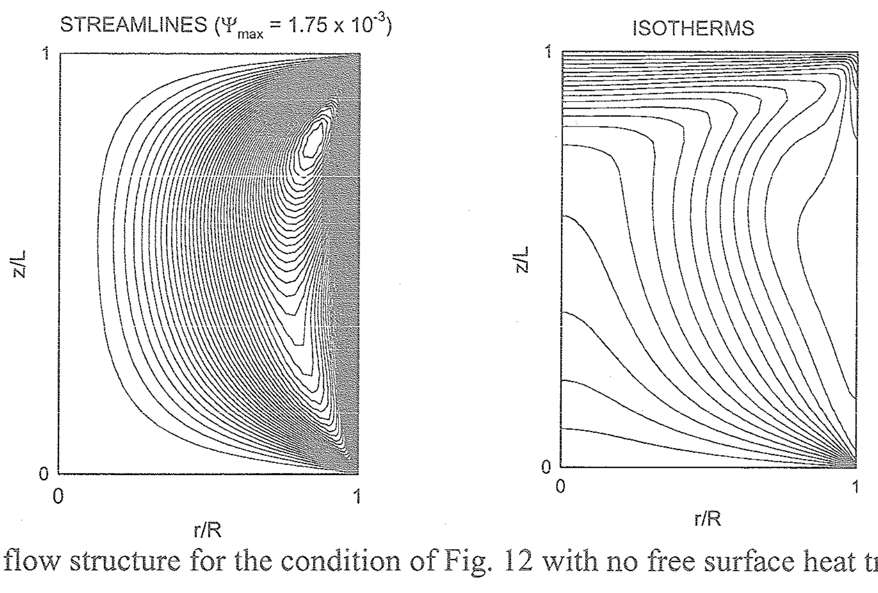

Fig. 15 Liquid flow structure for the condition of Fig. 12 with no free surface heat transfer

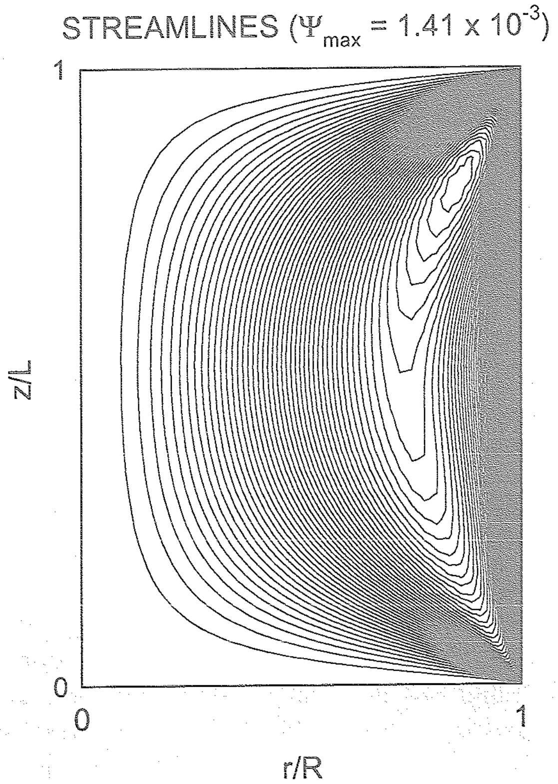

Fig. 16 Liquid flow structure for the condition of Fig. 12 without buoyancy in liquid flow

The surface velocity and temperature distributions are shown in Fig. 17 at the critical condition for a case in which Bi is very small. This condition is obtained when only the oven air heats the top wall. T_H is smaller than T_R in this situation because the top wall is also cooled by the bottom wall through the liquid, so this results in a small heat gain. These distributions are compared with those with zero free surface heat transfer in the same figure. They are almost unchanged by the surface heat transfer. Based on this comparison, one might say that this transition has nothing to do with the surface heat transfer. Before we address this question, let us consider a test with T_R slightly smaller than that of Fig. 17 with the top wall being heated only by the oven air. This is also a small heat gain condition that is very similar to that of Fig. 16. However, the flow of Fig. 16 results in oscillations but this test with a smaller T_R does not in this situation. Apparently, the difference is ΔT. In a test in which the top wall is heated only by the oven air, T_H decreases with decreasing T_R. Consequently, the Ma of this lower T_R test is slightly smaller than that of the test of Fig. 17 in this situation. Suppose that in this test with a smaller T_R, we then increase T_H (by the heating wire while T_R is fixed) to increase ΔT slightly so that ΔT in this test is now the same as that of Fig. 17. But, the flow still does not oscillate because we are now in a heat loss situation and move to a different branch of Fig. 9. Therefore, although the basics flows are very similar at this ΔT, whether we have heat loss or gain, both of which are relatively small, determines which branch of Fig. 9 the test follows This means that even such a small heat transfer rate influences the transition strongly near the dividing conditions of two branches.

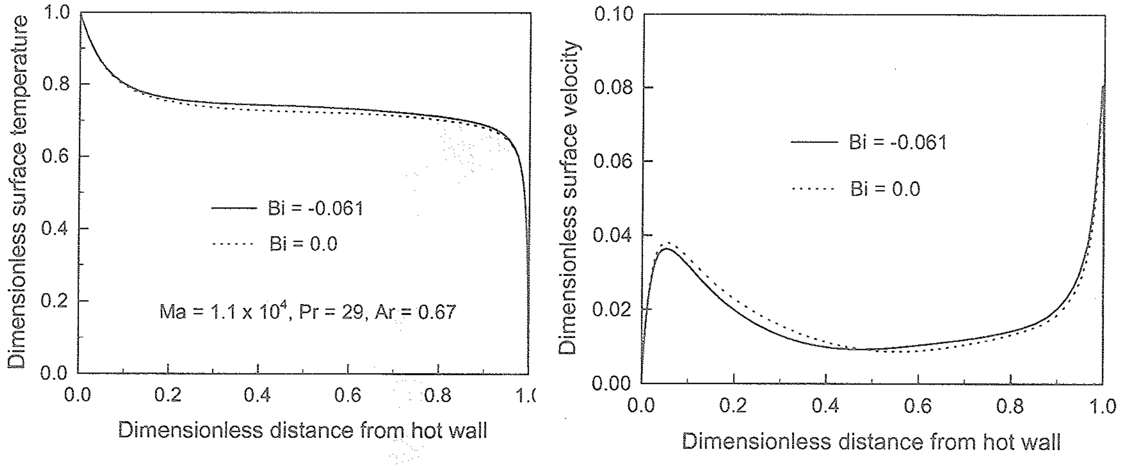

Fig.17 Surface temperature and velocity distributions with and without small surface heat gain

Moreover, even for the condition of Fig. 17 where the average Bi is small, $Bi_{,loc}$ is not necessary small everywhere, as shown in Fig 18. Therefore, although the basic flow is not much altered when the heat gain and loss are nearly balanced as in Fig. 17, it will change if the balance is broken for some reason. This could happen if the liquid and air flows interact dynamically. If the liquid surface temperature is to be altered by this interaction, it should happen in the location where the air temperature changes sharply, namely near the cold wall (see Fig. 12). It is noted that if we change the experimental arrangement such that the liquid bridge is heated from below, the liquid surface flow and the main airflow now opposes each other, so the interaction near the cold wall is different from the heated-from-above configuration. Experimentally we indeed observe that the oscillation phenomenon is somewhat different in the heated-from-below configuration: The transition seems to be delayed but it is difficult to identify the onset of oscillations cleanly probably because buoyancy makes the liquid flow somewhat unsteady most of the time.

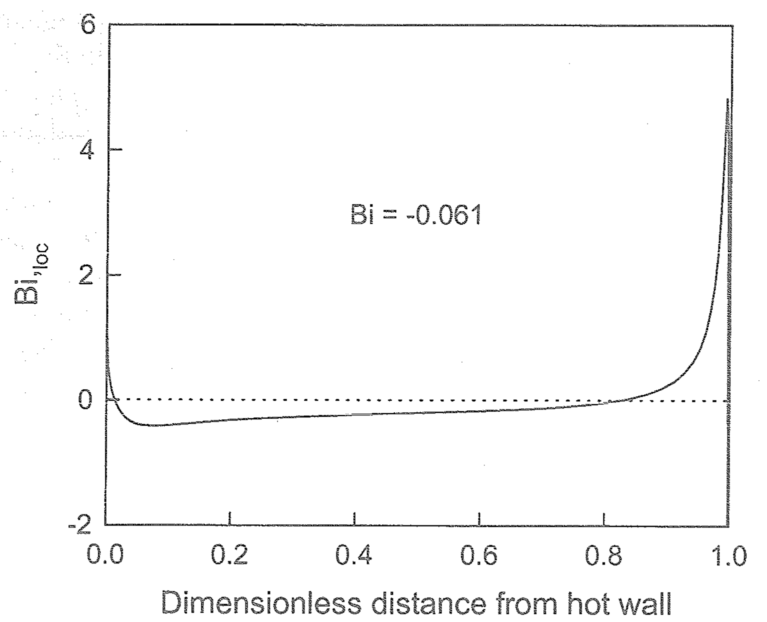

Fig. 18 Local Biot number distribution for the condition of Fig. 17

Based on the above discussions, one can conclude that in the oscillatory flows with heat gain the liquid flow is affected by the airflow even when Bi is small and that the oscillation phenomenon is a result of a non-linear dynamical interaction between the liquid and air flows, not through a change in the basic flow.

It is important to know the nature of the liquid-air interaction, especially near the cold wall. Several interesting facts are found, which are related to this interaction. As mentioned in the last year's annual report [5], the liquid flow in the heat gain tests, where $T_H < T_R$, appears to be disturbed intermittently and randomly even when ΔT is small. These disturbances not only make it difficult to identify the transition but they also affect the oscillatory flow. This type of disturbance was not observed in the heat loss experiment where the air moves up along the hot wall since $T_H > T_R$. In contrast, the air moves down along the heater in the heat gain experiment, which may indicate that some type of disturbances already exists in the airflow along the hot wall, but the airflow is too weak to become unstable in the present configuration. An interesting fact is that when the liquid column shape is made slightly concave, the disturbance is much reduced and the oscillatory flow after the transition becomes well organized. On the other hand, the situation gets worse when the surface is convex. It is found that the flow disturbance can be much reduced, even when the liquid surface is nearly flat, by placing a plastic plate around the cold wall near the liquid-cold wall interface (about 0.3 mm from the interface), as illustrated in Fig. 19. It can be shown numerically that even when we have a very short cooling wall, we still have sharp temperature gradients near the cold wall in steady flow. Therefore, the fact that the liquid flow is less disturbed when the plate is used may be due to the fact that the air motion is more constricted near the cold wall because of the plate.

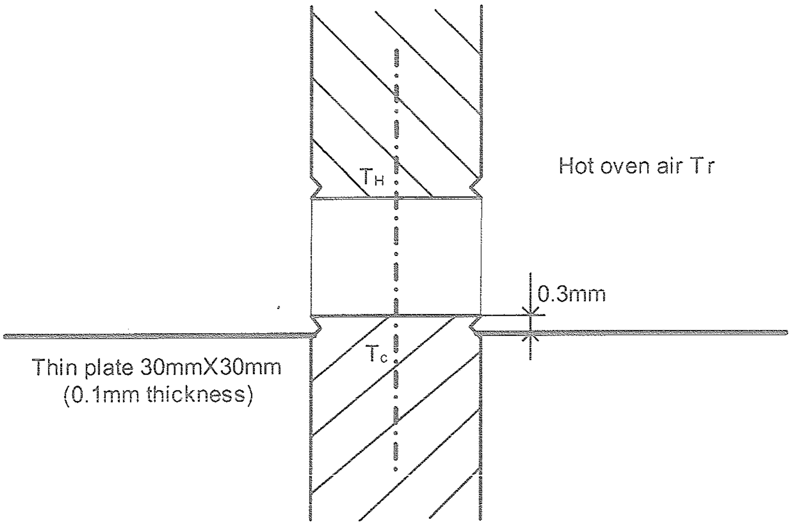

Fig. 19 Illustration of plate placed near cold wall

Apparently, a complex phenomenon is taking place near the cold wall. At present, we think the following is happening. Since the liquid flow along the free surface impinges on the cold wall, it is difficult to maintain a well-defined contact line at the cold wall experimentally, especially when the surface is nearly flat or slightly convex. The effect of this contact-line problem is observed to become worse as the liquid bridge diameter becomes smaller, probably because the contact-line region becomes relatively more important. This somewhat unstable contact line, coupled with the afore-mentioned important air-liquid interaction near the contact line, may be responsible for the observed liquid flow disturbance. Note that the air and the liquid do not interact strongly near the cold wall when a plate is placed near the cold wall. The contact line becomes more stable when the free surface is concave, so the liquid flow is less disturbed, with or without the plate. This contact-line effect may explain why the oscillations for D = 2 mm are intermittent compared to those for D = 3 mm.

Therefore, it is easier to perform experiment with slightly concave free surfaces, especially with D = 2 mm. Ma_{cr} is plotted against Dr (the diameter ratio) for D = 3 mm in Fig. 20 and for D = 2 mm in Fig. 21. It is known that in room temperature tests Ma_{cr} is affected strongly by the liquid bridge shape and that there exist two branches, fat and slender branches, in the Ma_{cr}-Dr plot [1]. Our interest here is nearly flat surfaces, so tests are performed only in the fat branch. The tests are done with and without the plate near the cold wall. As seen in Figs. 20 and 21, Ma_{cr} generally decreases with decreasing Dr. This trend is exactly opposite to that in room temperature tests [1]. This result shows again that the oscillation phenomenon with heat gain is different from that with heat loss. The data for D = 2 mm in Fig. 21 scatters, especially when Dr become close to unity and no oscillations are observed when the surface is nearly flat. In comparison, the data for D = 3 mm in Fig. 20 is more consistent, and the oscillations are observed even when the surface is convex. This data trend seems to be related to the aforementioned wetting condition at the cold wall. For D = 2 mm, the cold wall contact line affects the oscillations adversely, except when the surface is concave. Therefore, the cold wall wetting condition causes two things when the free surface is nearly flat. It introduces disturbances to the liquid flow when coupled with the airflow. It also delays or elliminates the onset of oscillations. As discussed earlier, the disturbances are reduced when the plate is placed near the cold wall. Fig. 21 shows that Ma_{cr} increases when the plate is used, especially when the surface is nearly flat. Since the plate alters the airflow near the cold wall, so this difference in Ma_{cr} is due to this airflow change. No oscillations are observed for Dr =1 even with the plate for D = 2 mm, indicating that the wetting condition is not affected by the plate.

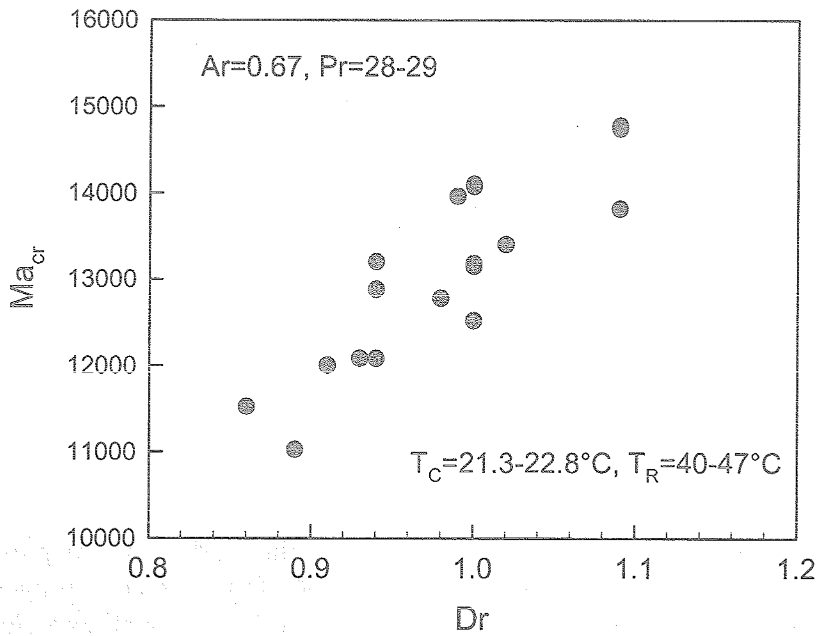

Fig. 20 Ma_{cr} vs. Dr for D = 3 mm

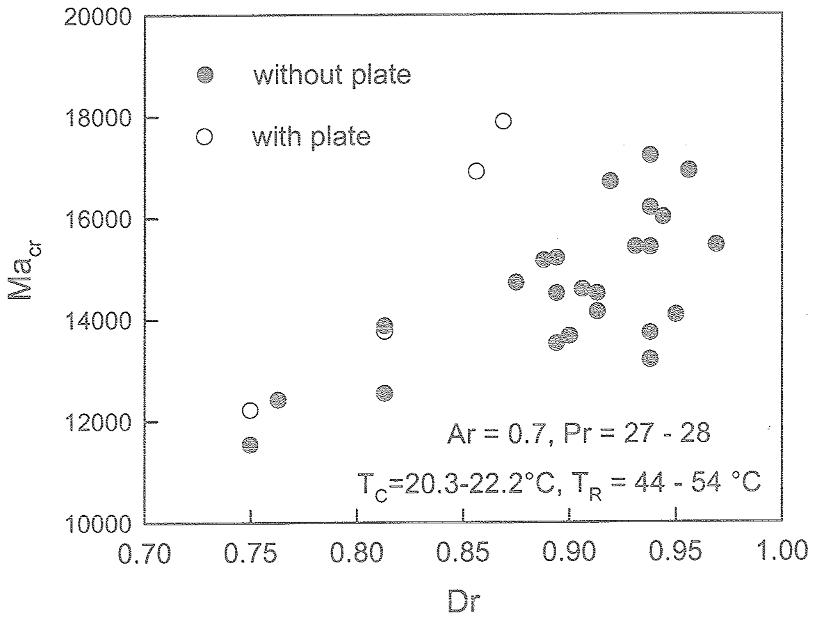

Fig. 21 Ma_{cr} vs. Dr for D = 2 mm with and without plate near cold wall

From the above observations and discussions, one can conclude that the free surface heat transfer near the cold wall is important for the oscillation phenomenon with net heat gain. As in the S-parameter, a question arises regarding the role of dynamic free surface deformation. Can the above dynamic interaction alone cause the transition? We can test this in our numerical analysis. Since we compute the liquid and air fields simultaneously, a transient flow analysis includes this dynamic interaction (but not the dynamic free surface deformation effect). For this reason, we perform the following numerical analysis. We start with a steady solution with heat gain. Then, we disturb the flow field by increasing the thermocapillarity by 100% for 0.2s and observe the subsequent flow variation with time. One result is shown in Fig. 22, where the maximum stream function is plotted against time. As the figure shows, the initial disturbance decays quickly only with a few oscillations. In this Reynolds number range, the viscous effects are relatively strong so that any disturbances are damped quickly. Although the present analysis is a 2-D (or axisymmetric) simulation, it seems very unlikely that the flow becomes oscillatory even in a 3-D simulation at this Reynolds number. Therefore, we must conclude that we need more than the dynamic interaction to explain the oscillation phenomenon with heat gain. Actually, Fig. 22 suggests that the dynamic interaction itself may not even be the main cause.

One feature we were originally concerned with is the effect of oven temperature variation. Unlike in room temperature tests, the air temperature in the oven is not very steady. As reported in the last year's report [5], the oven temperature variation is ±2°C. However, the temperature variation is the same whether the oscillations are weak or strong. We find no correlation between the oven temperature fluctuation level and the oscillation phenomenon. It is important to note that since the liquid bridge is much smaller than the oven dimension, the air temperature around the liquid bridge is quite uniform. As seen in Figs. 10 and 11, Ma_{cr} is not sensitive to Bi. Therefore, we can conclude that although the oven temperature variation affects Bi, it has no appreciable effect on Ma_{cr}, as long as the temperature changes uniformly around the liquid bridge.

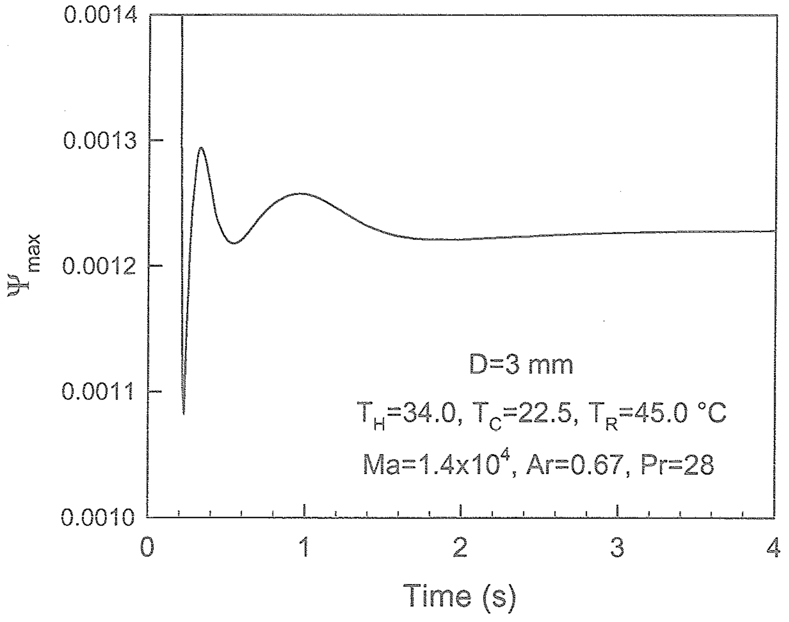

Fig. 22 Variation of maximum stream function with time after thermocapillarity is increased by 100% for 0.2s

Then as in the case of S-parameter, only other feature, which could affect the critical condition significantly, is the dynamic free surface deformation. Since we expect an interaction between the heat gain effect and the free surface deformation, we are now dealing with the deformation near the cold wall. In the tests with the plate near the cold wall in Fig. 21, since the afore-mentioned air-liquid dynamic interaction is much reduced, one can say that the dynamic free surface deformation effect is mainly responsible for the transition. On the other hand, without the plate, both deformation and dynamic interaction effects are important, and as a result, Ma_{cr} decreases. The free surface near the cold wall must deform by a certain amount to create sufficient pressure gradients for the flow to move away from the region (return flow). In a transient situation where the surface flow changes continuously, the return flow response is delayed by this free surface deformation. The mechanism seems to be similar to that in the hot corner with heat loss.

As for the important parameters for the oscillation phenomenon with net heat gain, we must a find a parameter similar to the S-parameter. Since the heat transfer near the cold wall is important, $Bi_{,loc}$ must also be considered. The heat gain enhances the effect of buoyancy in the liquid flow, as shown earlier, so the effect may not be negligible even in the present experiment with small liquid bridges. Although Ma_{cr} appear to be constant in the present heat gain tests, this maybe due to limited conditions in the present experiment. We continue to investigate this subject.

6. CONCLUSIONS

The conditions for the onset of oscillatory thermocapillary flow are investigated experimentally in liquid bridges of high Prandtl fluids. The effects of free surface heat loss and gain on the transition are studied. Both have significant influence on the transition but we cannot explain the effects unless we include the effect of dynamic free surface deformation. In fact, the deformation effect is the main effect, and the heat loss and gain effects modify the main effect by interacting with the deformation in dynamic ways. In the case of heat loss, the interaction occurs in the hot corner, while the interaction is in the cold corner in the heat gain case.

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