An experimental study of surface-tension induced convection at reduced gravity

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Abstract. Fluid motions are induced by surface-tension gradients on the free surface of a liquid in a cylindrical container which is in free fall in a drop tower. Identical experiments are conducted in a normal gravitational environment. The motion in that case is due to natural convection. The ratio of surface-tension to buoyancy forces in the tests is of the order of 10^4 at reduced gravity conditions and 0.13 under normal gravity. In each case a two way flow occurs throughout most of the liquid. Comparison of the results from the two types of experiments is made in order to indicate differences in the flow details.

Keywords. Thermocapillary flow; reduced gravity.

1. Introduction

This article discusses details of an experiment to study the surface-tension induced convection under reduced gravity and to compare it with normal gravity convection with all other conditions identical. The intensities of such flows and their penetration depth below the free surface are also determined. In this way the dominant role of a free surface in a reduced gravity environment is indicated.

In two earlier papers by the author in these *proceedings*, one on the convection phenomena at reduced gravity and the other on motion induced by capillarity, the convection induced by surface or interfacial tension gradients has been discussed in detail. These gradients, which can arise due to gradients in temperature or concentration at the surface or interface, can generate conventional convection flows or unstable cellular flows just as gravity induces these two types of natural convection flows in the presence of density difference. When caused by temperature gradients, the dimensionless parameters related to gravitational convection is the Grashof number, Gr , and that corresponding to surface-tension induced convection is the Marangoni number, Ma . It is noted that the Marangoni number is independent of gravity and the Grashof number is independent of surface tension. Thus, the relative magnitude of surface tension and buoyancy forces is given by the ratio $Ma/Gr = \nu(\partial\sigma/\partial T)/\rho\beta gL^2 k$. The quantities appearing in the relation have been defined in the earlier papers. The experiment being discussed here was designed so that this ratio Ma/Gr takes on values from about 0.13 to 1.5×10^4 in normal and reduced gravity environments, respectively.

Many possible modes of flow and configurations of interest in which the surface tension can be significant have also been discussed earlier, in particular the role

of free surface on reduced gravity convection. The latter is also of particular interest in the present experiment.

Among the existing publications related to this problem are the ones reported in Babitskiy *et al* (1973), Birikh (1966), Levich (1962) and Yih (1968). Babitskiy *et al* (1973) consider the steady flow generated by the free surface in a rectangular enclosure in which the two opposite walls that bound the free surface are at different temperatures. It is indicated that the solutions are valid for *sufficiently small* Marangoni numbers (~ 1.0) yet results are presented for values of the parameters of 5 and 500. An exact solution is found by Birikh (1966) for the equations for free convection and surface tension in an infinite plane-parallel horizontal layer of liquid with a constant temperature gradient in the horizontal direction. Here also the steady state has been considered. Levich (1962) has discussed purely capillary convection. Yih (1968) has pointed out many inconsistencies in his solution and has given a corrected solution of the Levich problem.

The only reduced gravity experiments on surface-tension driven flows are those induced by a thermal instability (Grodzka and Bannister 1972) (heating from below) and, thus, are different from the configuration of interest herein. Since there did not appear to be any experimental study of conventional convection due to surface tension alone, the present experiments were developed to be conducted in the NASA Lewis Research Centre's 500-ft drop tower in which approximately 5.5 sec of reduced gravity (about $10^{-5} g_0$) can be obtained. From an order of magnitude analysis (Pradhan and Ostrach 1976) it was estimated that it would take somewhat less than 3 sec for the surface boundary layer to reach steady state. Thus, worthwhile data could be obtained in that facility.

2. Experimental set-up

The drop tower facility imposed a number of constraints on the test apparatus. The size is limited by that of the drop module and the instrumentation and power supply have to conform to the capsule capacity. In addition, it must be able to withstand the impact of a 40-g deceleration. The test apparatus mounted in a plexiglass leakproof chamber that is maintained at a pressure of 1 atm, even when the drop-tower pressure is 100 μ of mercury, is shown in figure 1. The liquid container is a cylindrical plexiglass dish with a 10 cm i.d. and 3 mm thick vertical walls of 3.16 cm height. The inner wall of the dish is covered with a teflon tape to yield a 90° contact angle with distilled water at 25° C. Considerable preliminary testing (Pradhan and Ostrach 1976) was required to determine this method of maintaining a flat interface and preventing creeping of liquid up the walls at reduced gravity.

Distilled water is chosen as the test fluid because it has the following properties : (a) large surface-tension variation with temperature ; (b) low viscosity ; (c) small density variation with temperature ; (d) transparency ; and (e) easy accessibility. The temperature gradient is imposed by an infrared heat source located above the free surface (see figure 1).

The heat source is positioned vertically above the liquid at the centre of the dish with its bottom $2.5 \text{ mm} \pm 0.05 \text{ mm}$ above the free surface. With such a heating from above configuration, convection due to buoyancy is minimized

Figure 1. Test container.

and the temperature gradient on the free surface is imposed faster than by heating the side wall.

Methylene blue dye is used to make the flow patterns visible. Four 40-mesh dye particles and $\frac{1}{2}$ mg of fine ground (400-mesh) dye are placed on top of a knurled spoon which, when vibrated by means of a 24-V d.c. motor, sprinkles the dye on the liquid free surface about 10 sec before the start of the test. Some of the finely ground dye spreads over the free surface and larger dye particles penetrate into the liquid and form vertical strands. When the fluid is completely stationary and there are no temperature gradients, the dye strands maintain their position and do not diffuse for about a minute. When the test starts and the liquid moves, the dye strands also move and thereby indicate the velocity profiles. Top and side views of the dish are recorded on a movie film by two 16 mm high speed Melikon cameras.

To measure the radial surface temperature gradient imposed by the heat source, five thermistor probes (accuracy $\pm 1^\circ\text{C}$) are placed so that their beads just touch the free surface. To avoid any disturbance on the free surface due to other than 90° contact angle between probes and water, a shrinkable teflon tube is slipped over the probes.

Some disturbances due to thermistor probes however remain. To correct for these, some velocity data are taken without the thermistors in place. The previous temperature profile readings are considered to be applicable for these tests as well. The temperature measurements are made once the waves subsided about 1 sec after the release of the module in the drop tower.

Two electronic clocks, which are visible in the films, are used to record time. Further details of the experimental set-up can be seen in Ostrach and Pradhan (1978).

3. Experimental procedure

The dish is first cleaned by a special process (Pradhan and Ostrach 1976) to eliminate any possible contamination. The inner wall of the dish is then covered with a single layer of transparent teflon tape. The dish is cleaned again with methyl alcohol and distilled water. The dish is then taped into place. The distilled water is added up to the thermistor beads. The heater is adjusted so that when it comes to position, its bottom is 2.5 mm from the free surface.

The particles of methylene blue are carefully placed on the vibrator spoon. The test apparatus is then placed in the leak-proof tank which was hydrostatically tested for leaks and found to be good up to a pressure difference of 13 psi, which is considered sufficient for these tests. The entire apparatus is then assembled in the capsule for the drop-tower test. The drop module is hung in the drop tower for 45 min so that the fluid can become stationary before the test.

The following tests are run in the drop tower :

(i) The heat source starts heating the free surface 1 sec after the package is released.

(ii) The free surface is preheated for 10 sec before the drop.

(iii) The free surface is preheated for 40 sec before the drop.

Test (i) is performed to see how the flow starts with surface tension gradients being dominant. This might also give some idea as to what kind of steady-state flow pattern can be expected for high reciprocal modified Bond number (greater than 10^4) cases. Tests (ii) and (iii) show any abrupt changes in flows as the gravity level is dropped to $10^{-5} g_0$. All of the tests are performed at normal gravity also, with all initial conditions identical.

Test conditions are : initial temperature, 23°C , surface-tension temperature, $da/dT = 0.16 \text{ dyn/cm}/^\circ\text{C}$, characteristic length of 4.5 cm . The heater is initially heated for about 2 min, 35 sec far from the free surface. In this time interval the steady state of the heater is achieved, and it is in this state that the heater is used to heat the free surface. This steady-state time of the heater is measured by means of a thermocouple attached to its lip. Once the calibrations are over, the thermocouple is removed and the heater is heated in all experiments for the same time period (2 min, 35 sec). The relevant dimensionless parameters are indicated in table 1.

4. Results

The results of the various experiments are presented in the order in which they were described previously.

Test (i) : The heat source starts heating the free surface 1 sec after the package is released. This 1-sec time interval is given to eliminate any small disturbances that are produced by the release mechanism. A previous test under identical conditions has shown that the disturbance caused by release is very small and lasts for about 0.5 sec.

The surface tension gradient induced motion starts soon after the heater starts to heat the surface as can be seen from the movie frames. The flow starts from the centre close to the heater and spreads outward as the temperature gradient is established (see figure 2). The temperature profiles in figure 2 are for a single run and are drawn assuming that the free surface temperature close to the side wall remains the same as the initial liquid temperature in the time interval of 5 sec. This is done to get some idea of the characteristic temperature difference. The temperature profiles in figure 2 are for a test where the heating starts with the release of the package in the drop tower.

Looking at the movie films, it appears that a very thin film on the surface is pulled away from the heater at considerable speeds because of the induced surface-tension gradient. Very little or no motion could be observed around 3 cm away from the centre of the dish, where the surface tension gradient is also found to be small. The free surface velocities are shown in figure 3 and represent the velocities measured by tracking the dye particles on the surface, for small velocities like 2 mm/sec , the dye particle displacement is measured at intervals of 1 sec. Thus the velocities shown in figure 3 are those measured from a time interval of 2 to 3 sec after heating.

As soon as heating starts, the dye movement is observed around the heater, but after 2 sec of heating all the free surface is not active. The dye movement is observed only up to a radius of about 2 cm from the centre because temperature gradients are established in that region only. However, after 3 sec of heating

Table 1. Average values of relevant dimensionless parameters^a.

	Reduced gravity			Normal gravity	
	After 3 sec of heating	After 5 sec of heating	After 3 sec of heating	After 5 sec of heating	
Ma	$6.43 \times 10^4 (1.57 \times 10^5)$	$1.66 \times 10^5 (3.61 \times 10^5)$	$6.05 \times 10^4 (3.43 \times 10^5)$	$1.116 \times 10^5 (7.52 \times 10^5)$	
Gr	4.497 (11.0)	2.54 (27.3)	$4.097 \times 10^5 (2.33 \times 10^6)$	$8.58 \times 10^5 (5.78 \times 10^6)$	
Ra	24.40 (59.68)	65.77 (143.18)	$2.26 \times 10^6 (1.285 \times 10^7)$	$4.5 \times 10^6 (3.03 \times 10^7)$	
Ma/Gr	1.48×10^4	1.32×10^4	0.1476	0.130	

^a Values in parentheses are the maximum values. The average values are calculated using the average surface temperature and temperature differences. The maximum values are calculated using the maximum surface temperatures and maximum temperature differences. All values are for a 80-W infrared heating source.

almost all of the dye has moved out from the centre and no measurements can be made there. Velocities measured about 2.5 cm away from the centre are seen to be the same as those shown in figure 3.

In the interior of the liquid a two-way motion is observed, *i.e.*, flow away from the heater close to the free surface and the rest of the fluid moving in the reverse direction because of continuity. Dye strand displacements with time as determined from the films are given in figure 4. Before the heat is imposed the dye strands are stationary, although they are not necessarily straight and vertical. If vertical velocities are assumed to be negligible, the dye strand displacements can be used to calculate internal fluid velocities. From these figures it can be seen that a boundary layer forms close to the free surface. Outside this free-surface boundary layer the fluid moves toward the centre with a velocity of 1.0 ± 0.2 mm/sec.

The $(Ma/Gr)_{avg}$ ratio is found to be around 10^4 (see table 1) for a given test. The ratio is a function of average liquid temperature and the gravity level. During a specific test its value does not change too much (max 10%) as the average liquid temperature changes by no more than 10°F in the 5-sec time period. The initial liquid temperature being about 80°F , this change in liquid temperature gives rise to only small changes in the constants which form $(Ma/Gr)_{avg}$ ratio. The average liquid temperature at different time intervals is calculated using the surface temperature profiles given in figure 2 and making use of the following formula

$$T_{avg} = \frac{2}{R^2} \int_0^R T(r) r dr,$$

where R is the dish radius.

The average temperature difference used in the calculation of Marangoni, Grashof, and Rayleigh numbers is as follows :

$$(\Delta T)_{avg} = T_{avg} - T_w.$$

From the values of dimensionless parameters that are given in table 1 we see that the Marangoni number which represents surface-tension gradient-induced flow is about 10^4 times larger under reduced gravity than the Grashof number which represents buoyancy-induced flow. This indicates that the flow due to surface-tension gradient is dominant.

As the heating is continued we see that the value of $(Ma/Gr)_{avg}$ ratio reduced from 1.48×10^4 (at 3 sec) to 1.32×10^4 (at 5 sec after heating) as the average surface temperature increases. Though the change in the value of $(Ma/Gr)_{avg}$ is small, it shows the trend that the buoyancy effects keep increasing as heat continue but in the 5 sec of drop time they are still negligible.

The average Marangoni number is found to increase with time— 6.43×10^4 (at 3 sec) to 1.66×10^5 (at 5 sec after heating)—which means the free surface boundary layer does not reach steady state in 5 sec of reduced gravity period and the flow is still developing. The free surface boundary layer steady state could not be achieved in 2.81 sec, as estimated from an order-of-magnitude analysis because of the reverse flow created by the side wall, which was not considered in the order-of-magnitude analysis. Moreover, in the order-of-magnitude analysis the effect of heat transfer through the boundaries and vapor-

Figure 2. Surface temperature profiles at reduced gravity.

Figure 3. Surface velocity vs distance from centre of dish. Taken 2 sec after heating.

Figure 4. Dye displacement with time-reduced gravity.

zation of liquid from the free surface are not considered though they are present in reality and affect the occurrence of steady state.

The two-way motion in the interior of the liquid and the decrease in surface velocities away from the heater can be explained as follows. The two-way motion in the interior of the liquid can be easily explained by means of continuity. If we consider that the free surface remains close to horizontal with time, as is observed

in the tests, for mass conservation a given mass flow in one direction has to be compensated for by an equal mass flow in the opposite direction for a contained fluid. In order to understand the decrease in surface velocity with radius, we next look at the fluid element inside the free surface. Let us consider a fluid element of r thickness, at a distance r from the centre and located between the free surface and the zero horizontal velocity region as shown in figure 5. The zero horizontal velocity region is created by the appearance of the two-way flow as mentioned previously. The depth of the zero velocity region from the free surface is L_r and $L_r + \Delta_r$, and the free surface velocities are U_r and $U_r + \Delta_r$, at a distance of r and $r + \Delta_r$, from the centre, respectively.

Assuming small vertical velocities in the region, as has been found in the order-of-magnitude analysis, we obtain a relation between $U_r + \Delta_r$, using mass continuity,

$$2\pi(U_r)(L_r) = 2\pi(r + \Delta_r)(U_r + \Delta_r)(L_r + \Delta_r), \quad (1a)$$

$$U_r + \Delta_r = \left(\frac{r}{r + \Delta_r}\right) \left(\frac{L_r}{L_r + \Delta_r}\right) U_r.$$

It is observed from the experiments that the distance of the zero horizontal velocity region from the free surface increases as one goes away from the centre because of the diffusion of momentum from the free surface to the interior of the liquid. So, $L_r + \Delta_r > L_r$ for all r . Therefore, $U_r + \Delta_r < U_r$. This shows that the continuity itself would lead to a decrease in surface velocity with radius, as is observed in figure 4.

Test (ii): The free surface is preheated for 10 sec before the drop. In the first 10 sec during which the free surface is preheated at normal gravity, the surface motion away from the centre is slower than that expected under reduced gravity conditions. As the experimental package enters the reduced gravity environment the surface velocities are seen to increase.

Comparing the temperature profiles in figures 3 and 9 we see that the temperature difference between the given points and at a given time are larger under normal gravity than in reduced gravity. This means that more heat is being transferred by convection under reduced gravity than in normal gravity because both

Figure 5. Schematic of fluid element inside the free surface.

of the tests are performed under identical initial conditions. This supports the aforementioned observation of higher surface velocities under reduced gravity.

Test (iii) : The free surface is preheated for 40 sec before the drop so that a steady state thermal boundary layer seems to be established during this preheat time under normal gravity environment. Except for the free surface effect, such as is observed in the preceding experiment (test ii), no change in the flow pattern is observed during the 5 sec of reduced gravity. The two-way flow in the interior of the liquid remains the same.

The three experiments just described are repeated for identical initial condition in a normal gravity environment. Dye displacement curves at different time intervals are given in figures 6 and 7. The temperature profiles for this case are presented in figure 8. The values of relevant dimensionless parameters are given in table 1.

Figure 6. Dye displacement with time—normal gravity.

Figure 7. Dye displacement with time—normal gravity.

The temperature profiles up to 10 sec after heating are drawn assuming the side wall temperature unchanged due to heating and are used to compare the results with the reduced gravity temperature profiles in figure 2. The temperature profiles between 10 sec and 33 sec after heating are used to get some idea of the temperature gradients present when the experimental package is dropped as in tests (ii) and (iii).

Comparison of the results (see figure 3) indicates that surface velocities are considerably higher under reduced gravity conditions than in normal gravity for the same initial conditions. In figure 3 the normal gravity curve is drawn from a single run by tracking the dye particles as they move on the free surface. The velocities are calculated starting at 2 sec after heating in a manner similar to the ones in the reduced gravity test (i). The velocities calculated between 2 and 4 sec seem to remain the same.

It is observed that in the interior of the liquid the boundary layer near the free surface is thicker at 1 g than at reduced gravity. At normal gravity the Grashof numbers are found to be an order of magnitude larger than the Marangoni

Figure 8. Surface temperature profiles—normal gravity.

Figure 9.

numbers, and so the flow due to density differences and buoyancy is dominant. This gives rise to large internal flows close to the free surface and directed away from the centre of the dish. This flow is large close to the free surface because that is where the temperature gradients are present. But as heating continues, the heat diffuses downward and increases the Grashof number (see table 1) and ultimately the mass flow, boundary-layer thickness and internal velocities.

Thus we see that though the free surface velocities are smaller the overall mass flow rate away from the centre is quite large due to the large density gradient induced flow. This gives rise to large reverse flow due to continuity requirements.

Although none of the existing work (Babskiy *et al* 1973; Birikh 1966; Levich 1962; Yih 1968) deals with the identical configuration studied herein in that either the configuration or thermal boundary conditions are different and also it all deals with steady flows, the flow profiles (figures 4, 6 and 7) are qualitatively similar.

5. Conclusions

The present experiments have indicated that surface tension gradients at reduced gravity can be dominant and can generate flows as large as buoyancy at normal gravity.

Under normal gravity the free surface can be said to be passive with respect to the heat-transfer process in the sense that the fluid motion is induced by buoyancy. The buoyancy effects are dominant in the form of a thicker free surface boundary layer produced by larger flow due to density gradients. Moreover, the free surface velocities at normal gravity are smaller than those under reduced gravity for the identical initial conditions.

As the gravity level is reduced ($10^{-5} g_0$) the surface tension gradient force becomes dominant ($Ma \sim 10^5$ and $Gr \simeq 20$) and there is negligible gravity-induced convection. In this case, the free surface plays an active role in the heat-transfer process. Surface-tension gradient driven convection is seen to produce a thin boundary layer (~ 3 mm) near the free surface within a period of 5 sec and a two-way flow is observed inside the liquid. Free surface velocities as high as $3 \text{ cm/sec} \pm 0.1 \text{ cm/sec}$ and internal velocities of the order of $1 \text{ mm/sec} \pm 0.2 \text{ mm/sec}$ in the reverse flow are observed. The foregoing velocities are obtained for the reduced gravity case with an 80-W heater.

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