Convection phenomena at reduced gravity of importance in space processing of materials

SIMON OSTRACH

Case Western Reserve University, Cleveland, Ohio 44106, USA

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Abstract. The basic aspects of convection processes are delineated. It is shown that even in weak gravitational fields buoyancy can induce fluid motions. Furthermore, at reduced-gravity other non-gravity forces such as surface or interfacial tensions, *g*-jitter, thermal-volume expansions, density differences due to phase changes, and magnetic and electric fields can induce fluid motions.

The various types of flow possible with these various driving forces are described and criteria for determining the extent and nature of the resulting flows and heat transfer are presented. The various physical mechanisms that can occur separately and in combination are indicated and the present state of knowledge of each of the phenomena is outlined.

Keywords. Reduced-gravity convection ; thermal convection ; solutal convection ; thermosolutal convection ; surface-tension convection ; thermoacoustic convection ; phase-change convection ; coupled convection.

1. Introduction

It is a common impression that in the reduced gravity environment, say 10^{-6} g, of an orbiting spacecraft, convection cannot occur and hence such manufacturing processes where convection is inevitable in 1-g environment of earth, is deleterious and can be performed more successfully. Thus, much enthusiasm has been expressed for utilizing spacecraft for such processes. However, initial experiments carried out in Apollo, Skylab and other spacecraft have indicated, to the contrary, that convection is not absent (Grodzka and Bannister 1972; Bannister 1973), and indeed can be present in significant amounts. The basic reason for this is that in the space environment there are a variety of non-gravity forces that can induce fluid motion, which can be further influenced by the reduced *g*-levels encountered in spacecraft (tables 1 and 2). Such non-gravity driving forces which are usually suppressed by gravity include surface or interfacial tensions, thermal volume expansions, magnetic and electric fields and finally *g*-jitter, caused by onboard vibrations from machinery or astronaut movements, attitude control manoeuvres, etc.

Due to all the above complexities it has become necessary for scientists planning materials processing experiments in space to know the extent and nature of convection in space and factors controlling it. This information could be used to minimize the effects of convection or to utilize it to advantage. A rather comprehensive presentation of the various types of natural convection possible in space

manufacturing processes is given by Grodzka (1973). Related existing publications are also indicated therein. In Grodzka and Bannister (1974) some of the convection types are related to space-flight experiments. The present article outlines key aspects related to natural convection of various types and its effects in reduced gravity environment.

2. Nature of convection

Most configurations related to materials processing are ones in which the fluid is confined by rigid boundaries. Internal convection problems are considerably more complex than external ones because the fluid boundary layer and core are closely coupled (Ostrach 1972). This constitutes the main source of difficulty in predicting the resulting flow and heat transfer. More than one core configuration (flow) is sometimes possible and which will actually occur for a given set of conditions cannot be determined *a priori*....Furthermore, the entire flow is sensitive to the configuration geometry and to the imposed thermal boundary conditions.

To add to the complexity there are essentially two basic modes of flow generated by a body force (Ostrach 1964). The first, which will be referred to as conventional convection, occurs whenever a density gradient (due to thermal, concentration, or other effects) is normal to the body force (gravitational) vector. In such a case flow results immediately. The second mode, which will be called unstable convection, results whenever the density gradient is parallel but opposed to the body force. In this situation the fluid remains in a state of unstable equilibrium (due to heavier fluid being above lighter fluid), until a critical density gradient is exceeded. A spontaneous flow then ensues which rather quickly becomes steady. This motion is usually in the form of cells or vortex rolls and, hence, causes more mixing than laminar conventional convection. It must be emphasized that this instability is different from the one that results in laminar flow becoming turbulent. The steady flow obtained after the critical condition is exceeded is laminar; this flow, (as all others due to buoyancy), can also become turbulent under proper conditions. The onset of the unstable motion is highly dependent on the confining boundaries, *i.e.* the motion can be markedly delayed by proper design of the configuration (Ostrach and Pnueli 1963 ; Sherman and Ostrach 1967).

As if all the above were not sufficiently difficult to deal with it should be pointed out that both modes of convection, conventional and unstable, can also occur in a given configuration (for example, see Hart 1971, 1973).

As was indicated above, the space environment further complicates the picture because of the additional driving forces. Further complexities arise in materials processing because the fluid is not homogeneous so that concentration gradients can cause density gradients in addition to temperature gradients. The density gradients due to those two causes can enhance or oppose each other in coupled ways. Relatively little work exists for normal natural convection with multiple coupled driving gradients and, particularly, for the types of geometric configurations that correspond to materials processing methods. It is thus, perhaps not surprising that the effects and nature of natural convection under reduced-gravity conditions are often neglected, misinterpreted, or confused.

From the above discussion it should be clear that, because different modes of convection are possible and they are extremely sensitive to the configuration and boundary conditions, in order to assess convection effects at reduced gravity the following information must be specifically and explicitly known:

- (i) Both the magnitude and direction of accelerations ; the latter to help determine the mode of convection,
- (ii) The geometric configuration,
- (iii) The imposed boundary conditions,
- (iv) The material properties.

Unfortunately, most of the existing literature on this subject is deficient in one or more of these.

3. General considerations

For reasons given above it is necessary to study each problem by itself to obtain detailed information on the transport processes. However, considerable insight into the qualitative nature of the problem can be obtained from dimensional analysis. The first step in the understanding of such a complex phenomenon, therefore, is to obtain the relevant dimensionless parameters. These are best determined from the basic equations and boundary conditions that describe the phenomena (Ostrach 1966).

Parameters — For convection generated by an acceleration acting on a density difference (or gradient) the parameters are:

(a) The Grashof number, Gr , which represents the ratio of buoyancy to viscous forces

$$Gr = g \frac{\Delta \rho d^3}{\rho \nu^2}, \quad (1)$$

where $\Delta \rho$ denotes the density difference, g the acceleration, d a characteristic dimension, ρ a reference density, and ν the kinematic viscosity. If the density difference is due to a temperature difference (or gradient) (1) becomes

$$Gr = \frac{\beta g \Delta T d^3}{\nu^2} = \frac{\beta g (\partial T / \partial x) d^4}{\nu^2}, \quad (1a)$$

where β is the fluid volumetric coefficient, ΔT is the temperature difference, and $(\partial T / \partial x)$ denotes a spatial temperature gradient. Note that for gases $\beta = 1/T$ where T is the absolute reference temperature.

(b) The Rayleigh number

$$Ra = (c_p \mu / k) Gr = Pr Gr, \quad (2)$$

where c_p is the specific heat at constant pressure, μ is the absolute viscosity, k the thermal conductivity coefficient, and Pr is the Prandtl number and is a measure of the ratio of the diffusion of vorticity to heat.

The Grashof number basically appears in the equations of motion and, therefore, the fluid velocities are directly related to it. For large Grashof numbers ($Gr > 1$) the fluid velocities, U can be estimated from

$$U = \sqrt{Gr} \frac{\nu}{d} = (\beta g \Delta T d)^{1/4}, \quad (3a)$$

whereas for small Grashof numbers ($Gr < 1$)

$$U = Gr \frac{\nu}{d} = \frac{\beta g \Delta T d^2}{\nu} \quad (3b)$$

The Rayleigh number, on the other hand, appears in the energy equation so that the heat transfer is related to it.

If the density difference in (1) is due to a difference in concentration, then (1) becomes

$$Gr_c = \alpha g \Delta c d^3 / \nu^2 = \alpha g (\partial c / \partial x) d^4 / \nu^2, \quad (1b)$$

where α is the concentration densification coefficient, Δc is the concentration difference, and $\partial c / \partial x$ represents a spatial concentration gradient. The corresponding solutal Rayleigh number is

$$Ra_s = \alpha g (\partial c / \partial x) d^4 / \nu D, \quad (2a)$$

where D is the diffusion coefficient.

Since fluid motions are of primary concern in most materials processing problems, the procedure to obtain an estimate of the velocities is as follows: From the direction of acceleration and the configuration determine which mode of convection is to be expected. For conventional convection compute the Grashof

Figure 1. Effect of aspect ratio on critical Rayleigh number for vertical cylinders.

number from the appropriate equation (1), then use the corresponding velocity expression (3). If unstable convection is anticipated, the proper critical Rayleigh number for the configuration must be determined to see if such a flow will actually occur. In addition to Ostrach and Pnueli 1963; Sherman and Ostrach 1967 there is an increasing number of papers in which critical Rayleigh numbers are determined for various configurations subject to different conditions. Space limitations preclude a detailed discussion of them (Ostrach 1976). However, the essential physical aspects of the problems can be illustrated by figures 1 and 2. The effect of aspect ratio on the critical Rayleigh number is shown in figure 1 for vertical cylinders of square cross-section with both conducting and insulated vertical boundaries. The solid lines represent theoretical results of Samuels and Churchill (1967), Davis (1967), Catton (1970) and Jennings and Sani (1972) and the experimental data came from Catton and Edwards (1967), Heitz and Westwater (1971) and Edwards and Catton (1969). There is good agreement between theory and experiment regardless of whether the cross-section is rectangular or circular, although the form of the resulting flows may be different. Increasing the aspect ratio (containment) can be seen to be very stabilizing. The critical Rayleigh number is, however, insensitive to the aspect ratio for values of it greater than 5.

Figure 2. Critical Rayleigh number as a function of aspect ratios.

The stability of fluids in rectangular parallelepipeds heated from below was theoretically determined by Catton (1972) for a wide range of thermal boundary conditions on the lateral walls. Some of the results are presented in figure 2 where the critical Rayleigh number is plotted against aspect ratios for various rectangular cross-sections. It is evident that with increasing cross-sectional confinement (large H/W_s) that the configuration is even more stable than for square or circular cross-sections for which H/W_s and H/W_s are equal. This indicates another design option for delaying the onset of unstable convection.

When a rectangular cavity with one wall hotter than the other is rotated with respect to the gravity vector, or *vice versa*, each of the natural convection modes, conventional and unstable, is obtained as limits and for angles in between both modes interact. The types of flow are delineated (Hart 1971, 1972) and a summary of the results is shown in figure 3. The Rayleigh number is based on the distance and the temperature difference between the hot and cold walls of the container. When the hot surface is below ($\delta = 90^\circ$) there is no convection until the classical Benard cells appear at $Ra_c = 1708$. At $\delta = -90^\circ$ the hot surface is on top and the fluid layer is stably stratified and again there will be no convection. However, when the slot is nearly vertical or rotated so that the hot wall is above, a steady circulating two-dimensional unicellular flow occurs with fluid rising along the hot surface and descending near the cold surface. Longitudinal vortex rolls develop when the two basic modes interact or when the Rayleigh number is sufficiently large and wavy flow patterns result.

Other aspects of the combined modes are treated by Unny (1972), Hollands and Konicek (1973) and Clever (1973) for very shallow boxes. The combined effects of aspect ratio and inclination angle on the circulation and heat transfer rate in a

Figure 3. Flow types with combined modes of convection.

finite rectangular region were investigated primarily theoretically by Ozoe *et al* (1974a, b) and experimentally by Ozoe *et al* (1975). It was found that when the angle of inclination from horizontal was zero (unstable configuration) the flow pattern was a series of roll cells with axes parallel to each other and perpendicular to the long axes of the channel. When the inclination angle was increased slightly in steps a series of roll cells persisted with their axes in the upslope but the average Nusselt number (heat transfer) decreased. As the angle was increased further a minimum Nusselt number was attained. Beyond that angle the flow pattern changed to a single roll cell with its axes in the long dimension of the channel and the associated Nusselt number increased. This flow pattern persisted as the angle was increased until the heated surface was horizontal but above the cold one. The Nusselt number passed through a maximum and then decreased to unity. This behaviour was qualitatively the same for channels with aspect ratios from unity to fifteen but the inclination angles corresponding to the Nusselt number extrema depend strongly on the aspect ratio. Comparison of the theoretical and experimental results indicated that the results of Ozoe (1974b) can be utilized up to $Ra = 10^5$ and aspect ratios up to at least 8.4.

Scaling—The dimensionless parameters are extremely useful for reasons in addition to that of obtaining flow estimates. They indicate how to scale a problem, for example, to reduce convection or to study the phenomena in a model. They also indicate possible simplifications for analysis, the minimum number of experiments necessary, and how best to correlate data (see Ostrach 1966).

4. Buoyancy-induced convection

The acceleration due to gravity on earth is essentially constant at a value of 980 cm/sec^2 (one- g). A steady and reduced value of acceleration is inherent in most spacecraft because of atmospheric drag, centripetal force due to vehicle rotation, gravity gradients, solar wind, and solar pressure. Superposed on this background of a uniform but weak acceleration field are temporarily-varying accelerations that are due to engine burns, attitude-control manoeuvres, and onboard vibrations from machinery of astronaut movements.

Steady Micro-Gravity Fields—Some of the steady accelerations associated with several missions are summarized in tables 1 and 2 (taken from Chin *et al* 1969 and Forester 1971 and presented by Grodzka and Bannister 1974).

From the values of the accelerations presented above it would appear that the g -levels are *small* and, therefore, that the environment is one of *zero gravity* and no convection is possible. This is the misconception that is so prevalent in much of the space processing work. However, the basis for estimating both thermal and solutal convection effects was given above. Under the most mundane condition, *e.g.*, temperature differences of 10° K at levels of about 20° C , and a characteristic length of 10 cm the Grashof number (for thermal convection) at one- g (equation 1 (a)) for a gas (like air) is of the order of 10^6 , for a liquid (water) is like 10^7 , and for a liquid metal (mercury) is about 10^9 . Thus, it is clear that even in reduced-gravity levels as indicated in the tables the Grashof number is not negligible. For example, at $10^{-5} g$ velocities of the order of tenths of a millimeter per second would be induced in the liquid and liquid

Table 1. Summary of steady reduced-gravity accelerations.

Source	Type of mission		
	Low-altitude earth orbit	Low altitude lunar orbit	Interplanetary trajectory
Atmospheric drag	$5 \times 10^{-6} g$ and lower	None	None
Centripetal force	$1 \times 10^{-6} g$	$3 \times 10^{-7} g$	$3 \times 10^{-14} g$
Gravity gradient	$3 \times 10^{-9} g/cm$	$2 \times 10^{-9} g/cm$	$4 \times 10^{-17} g/cm$
Venting thrust	All $10^{-4} g$ to $10^{-6} g$, neglecting drag		
Vehicle thrust	All $0.1 g$ to $6 g$		

Table 2. Steady g -levels in Apollo missions.

Apollo flight mode	Typical g -level
Passive thermal control (PTC)	$3 \times 10^{-6} g$
Attitude hold in translunar or transearth orbit	$7 \times 10^{-8} g$
Attitude hold in lunar orbit	$5 \times 10^{-7} g$

metal under the given conditions and about four times that in the gas. Further increases in the temperature (or density) difference and length would lead to even higher fluid velocities. Similar considerations apply for solutal convection. However, since concentration gradients in materials processing can be considerably greater than temperature gradients, for a given g -level solutal convection effects could be significantly larger than those due to thermal convection. It is, thus, clear that the weak steady acceleration fields can lead to fluid motions. These motions occur immediately with no delay in the case of conventional convection. There may, however, be no corresponding immediate change in heat transfer associated with the flows under certain conditions. For example, for conventional convection in a rectangular enclosure it was found by Batchelor (1954) that the heat transfer will differ from that for pure conduction only if $Ra > 500 (l/d)$ where l is the height and d the width of the enclosure.

The nature of conventional convection at reduced gravity will be similar to that at normal gravity as summarized by Ostrach (1972). The essential difference is that in space because the Grashof numbers are significantly reduced the flow will be laminar whereas on earth it may be turbulent. Unstable convection will be less likely in space because the associated lower Rayleigh numbers may be lower than the critical.

Although there is, unfortunately, little experimental data on reduced-gravity convection corroborative evidence is available from studies made for the cryogenic gas storage tanks for the Apollo 14 and subsequent flights. Although these ground-based and space flight studies of reduced-gravity convection are specifically limited to an unusual fluid (supercritical oxygen) and rather complex configurations (the Apollo tanks) the results are, nevertheless, of significance. For example, it was found that the natural-convection in the Apollo tanks was sufficient to obviate the need for forced convection by mixing fans (Rice 1971). Data from Apollo 14 (Fineblum *et al* 1971) indicates increased convection with increases in the vehicle rotation rate (up to 3 RPH) as would be expected.

g-jitter— As contrasted to the non-uniformities of the gravity field, some of which must be accepted as part of the natural environment of an orbital vehicle, there are transient or time-varying perturbations to the gravity field at a point. The unsteady variations which are referred to as *g-jitter* can arise from spacecraft manoeuvres and mechanical vibrations.

Spacecraft manoeuvres can produce *g-jitter* magnitudes of $10^{-4}g$ and higher. This effect can be overcome if the space processing is performed during the drift mode. On the other hand, *g-jitter* caused by mechanical vibrations cannot necessarily be controlled at their sources. Mechanical vibrations that are transmitted to the experiment have the same effect as a time-varying gravity. They can be caused, for example, by astronaut movement, rotating and reciprocating machinery, and extra-vehicular activities. Arm and leg movements and console operations such as flipping switches are all significant in this respect (see Conway 1972). During Skylab experiments the *g-jitter* has been estimated to be as large as $10^{-3}g$ with the frequency spectrum of this random vibration from about one to several thousand hertz. Evidence of *g-jitter* in Apollo flights is presented by Grodzka and Bannister (1972) and Bannister *et al* (1973) and discussed in some detail by Grodzka and Bannister (1974).

Some indications of the effects of *g-jitter* on convection can be obtained by related research such as that of Richardson (1967), Pak *et al* (1970) and Gershuni *et al* (1970). It was found that vibrations can either substantially enhance or retard local heat transfer, significantly increase total heat transfer and drastically affect convection by altering the transitions from quiescent to laminar flow (critical Rayleigh number) and from laminar to turbulent flow. More detailed discussion of related work is presented by Spradley *et al* (1975). In the last reference specific consideration was given to models for evaluating *g-jitter* effects and they will be summarized in a later article in these proceedings.

This phenomenon merits special consideration not only because it represents a convection mode that is suppressed under normal gravitational conditions and which is significant at reduced gravity but also because it is inherent in all spacecraft environments and cannot, therefore, be easily controlled.

5. Surface-tension induced convection

Surface tension on the free surface of a liquid may, under some conditions considerably affect liquid motion. The presence of an interface between two fluid phases can influence the motion of the fluids when either the interface has finite

curvature or when the interfacial tension varies from point to point. In both cases, forces appear in the interfacial region that can affect or generate the fluid motion.

When the motion takes place in a gravitational field the relative importance of surface tension can be estimated from the Bond number, $Bo = \rho g d^2 / \sigma$, which indicates the ratio of gravitational to surface-tension forces, where σ is the surface tension. From the Bond number it is clear that on earth surface tension is important ($Bo < 1$) only in small scale configurations, *i.e.*, where d is very small. Therefore, most existing work on the effect of surface tension deals with flow in capillaries and thin films or the motion of droplets or bubbles or short wavelength water waves. In space, on the other hand, surface tension becomes a significant force whose influence on fluid motion must be assessed and understood.

Surface-tension gradients can arise from gradients in temperature or concentration. These surface-tension gradients can generate conventional convection flows or unstable cellular flows (see, for example Pearson (1958); Nield (1979); Scriven and Sternling 1974) just as gravity induces such convective flows. When the surface-tension gradients and density differences are due to temperature gradients the dimensionless parameter related to gravitational convection is the Rayleigh number, $Ra = \beta g \theta d^3 / \nu \kappa$ and the corresponding one for surface tension induced

flows is the Marangoni number, $Ma = \frac{(\partial \sigma / \partial T) \theta L}{\rho \nu \kappa}$ where β is the fluid volumetric expansion coefficient, θ is a characteristic temperature difference and κ is the thermal diffusivity. Note that the Marangoni number is independent of gravity. The relative magnitude of surface-tension and buoyancy forces is given by the ratio $Ma/Ra = (\partial \sigma / \partial T) / (\rho \beta g d^2)$. Note that this is just the reciprocal of a modified Bond number. Again, it can be seen from this ratio that surface tension becomes orders of magnitude greater (under identical conditions) than the buoyancy in a reduced-gravity environment.

Conventional convection—There are many possible modes of flow and configurations of interest in which surface tension can be significant. Consideration will now be given to a situation in which conventional convection will occur. The flow and heat transfer of a fluid in an open container can be expected to change markedly as gravity is reduced. For example, in a normal gravitational environment the natural convection (due to buoyancy) may be turbulent (see figure 4a). In a somewhat reduced-gravitational field (say $10^{-3} g$) the gravity force might still predominate over the surface tension but the natural convection would be quite different (figure 4b), *i.e.*, it would be laminar with a single cell or double cell. In these situations the free surface can be said to be passive with respect to the convection in the sense that the fluid motion is induced solely by buoyancy. However, as gravity is reduced further (say $10^{-6} g$) the surface tension becomes dominant and will generate the primary fluid motions. In such a case the free surface becomes an active factor in the convection process (figure 4c).

Figure 4. Modes of convection as a function of g -level.

Theoretical studies of related problems are reported by Birikh (1966) and Babitskiy *et al* (1973). An unbounded horizontal layer of fluid with a rigid lower surface and free upper surface is analysed by Birikh (1966). A linear temperature gradient is imposed along both these surfaces. The velocity profiles due to buoyancy alone and surface tension alone are shown in figure 5. It can be seen therein that near the free surface there is a flow due to surface tension from the warm region towards the cooler and a reverse flow occurs near the lower rigid surface. The profile due to buoyancy alone is of somewhat similar shape but less blunt. The flow due to surface tension in a square container with end walls at different temperatures is analyzed by Babitskiy *et al* (1973) and the computed streamlines and isotherms are shown in figure 6. Once again the strong flow near the free surface can be seen with a reverse cell below. Several aspects of this analysis are questionable.

Since there did not appear to be any experimental study of conventional convection due to surface tension alone the present author designed such an experiment to be carried out in the NASA Lewis Research Centre's 500-foot drop tower in which approximately $5\frac{1}{2}$ sec of reduced gravity ($10^{-5}g$) can be obtained. The details of the experiment are given in a later article.

Figure 5. Film velocity distributions.

Figure 6. Surface-tension flow in a square.

The experiment clearly indicates that surface tension at reduced gravity can generate significant flows that are somewhat similar to those due to buoyancy at normal gravity.

Unstable Convection — When a fluid layer is heated from below it is found that a cellular flow pattern develops when the temperature gradient exceeds a critical value. This motion is referred to as Benard cells. Such motions can be obtained merely due to the thermal instability previously described. However, when a free surface is present the motion has been shown by Black (1956) to be due to surface tension. The theory of such surface-tension induced motions was further developed by Pearson (1958).

Experiments performed on the flights of Apollo 14 and 17, (Gradzka and Bannister 1972; Bannister 1973; Bannister *et al* 1973; Grodzka and Bannister 1974) indicated that Benard cells are obtained in reduced-gravity environments and that, as in a normal gravity environment, a critical temperature gradient must first be exceeded.

Some direct reduced-gravity observations have been obtained for the convection phenomena discussed to date. There are, in addition, other mechanisms possible for generating fluid motions under reduced-gravity conditions. These will now be described but not as comprehensively.

6. Thermoacoustic convection

Independent of gravity, thermal volume expansions can act as the driving force for convection. Rapid heating of a confined fluid causes rapid local expansions which, in turn, generate pressure waves. These pressure waves produce a convective motion which can greatly increase heat transfer relative to conduction and can also mass and chemical species transport. This provides a mechanism for enhancing or suppressing convective motion at low gravity by controlling the heating rate. Thermoacoustic convection in a reduced-gravity environment has been theoretically studied by Spradley and Churchill (1975) and Larkin (1967). Significant reduced-gravity thermoacoustic convection in gases is predicted when the heating rates are sufficiently high. For the example treated by Spradley and Churchill (1975) it was found that at normal gravity the gravity-driven convection is so strong as to virtually overshadow the thermoacoustic effects. The two types of convection are of comparable magnitudes at about $10^{-3} g_0$. At this level the temperature profiles are a hybrid between the buoyancy dominated one- g and the thermoacoustic zero- g cases. No experimental evidence of this phenomenon has, as yet, been demonstrated.

7. Phase-change convection

A shrinkage usually occurs during solidification because the density of the solid is usually higher than that of the liquid and, hence, occupies a smaller volume. This volume reduction results in a flow of liquid toward the solidifying interface. Such flows are also generated by non-equimolar reactions as occur in vapour deposition crystal growing. Pressure pulses can accompany such flows and, thereby, influence the nature of the material,

Analyses of this phenomenon are presented by Chambré (1956) and Horvay (1962). Some speculation concerning the influence of phase-change convection on space experiments is presented by Grodzka and Bannister (1974).

8. Thermosolutal convection

If a thermal gradient is imposed on a solution its components will migrate so that a concentration gradient will be established. This is called the Soret effect. Usually the heavier species migrate to the warmer region and the lighter species to the cooler region. If these gradients are normal to the gravitational force (conventional convection) the unusual phenomenon known as salt fingers occurs in which columns of cold fresh water rise and columns of saltier hot water descend (Yih 1970). Other unexpected results are obtained if the gradients are parallel to the gravity vector (unstable convection). The Soret effect has been used for separation processes, but it is relatively inefficient in the absence of natural convection because of back diffusion. Laminar convection improves the separation. On earth, however, to maintain laminar convection the flow passages have to be quite narrow. In a reduced-gravity environment, however, laminar convection could be obtained with larger flow passages and, thus, larger samples could be processed. In such a case the low-gravity environment is used to control rather than eliminate convection. Thus, thermosolutal convection at reduced-gravity appears to be a promising and beneficial phenomenon.

9. Convection due to electric and magnetic fields

Electric and magnetic fields induce body forces (like gravity) so that they can generate convection and phase separation similar to those in a gravitational field. Whereas in a gravitational field convection is generated by density differences, in an electrical field the flow is generated by differences in electrical conductivity and by differences in susceptibility in a magnetic field. The electrical conductivity and magnetic susceptibility are temperature dependent so that temperature differences are usually required to obtain the flows. Both conventional and unstable types of convection are possible with such fields. These phenomena have not been fully explored or exploited in the space programme, but may be important if the electromagnetic interferences within spacecraft are not multified, especially in experiments involving electrically conducting liquids.

10. Coupling phenomena

It should be noted that two or more forces (such as gravity and surface tension) and gradients (such as temperature and concentration) can occur in a given body of fluid. In a sense, thermosolutal phenomena are examples. Their combined action can be such that a given mode of convection is reinforced, annulled, or altered. What little work that has been done on problems of this type pertains to very specific situations and the results are not generalizable or predictable. This topic forms the subject of a later article where possible flow configurations are described and related problems are identified.

11. Conclusion

To summarize, various types of reduced-gravity convection possible in a reduced gravity environment are as follows. (a) acceleration-field dependent (i) thermal convection, (ii) solutal convection, (iii) g-jitter convection and (iv) thermosolutal convection; (b) independent of acceleration field (i) surface-tension convection, (ii) thermoacoustic convection, (iii) phase-change convection and (iv) convection due to electric and magnetic fields; (c) coupled or combined convection.

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