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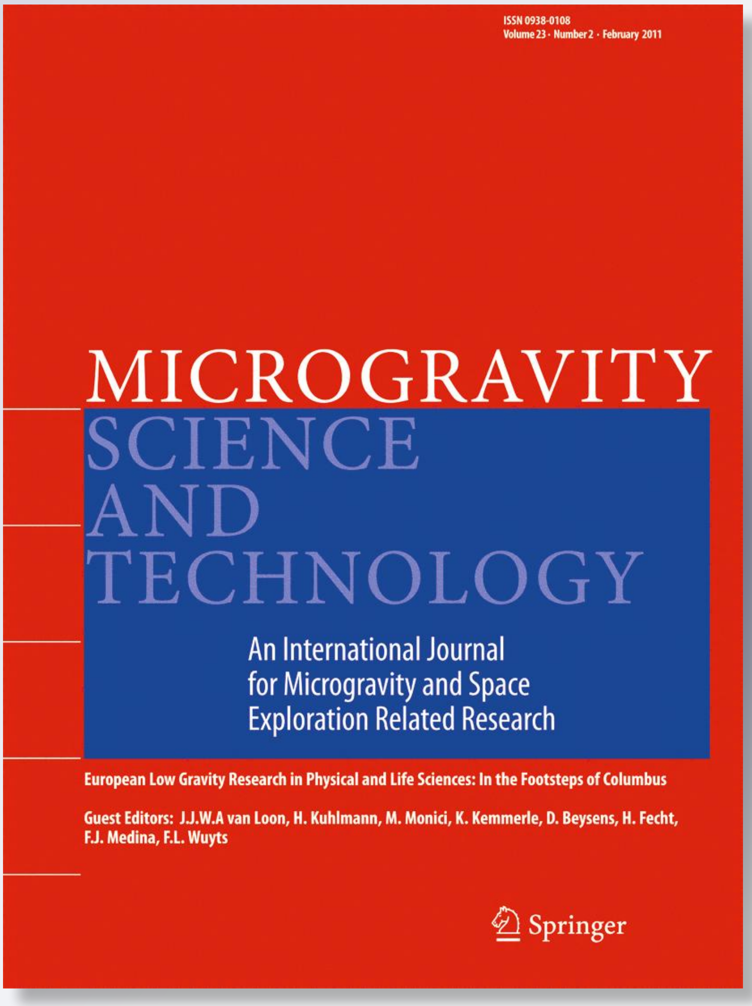

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ORIGINAL ARTICLE

Effect of Liquid Properties on Heat Transfer from Miniature Heaters at Different Gravity Conditions

Sotiris P. Evgenidis · Konstantinos A. Zacharias · Thodoris D. Karapantsios · Margaritis Kostoglou

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Abstract This work presents experiments for the estimation of heat transfer from sub-millimeter spheroidal heaters at varying gravity conditions. Experiments were performed during the 50th Parabolic Flight Campaign of European Space Agency (May 2009). Heat pulses of varying strength were given to a miniature heater submerged in the liquid while its thermal response was registered during heating. Tests were conducted in water and FC-72, two liquids with distinctly different thermophysical properties. Runs were also conducted with packed beds and dense suspensions of two size classes of polystyrene particles in water. The contribution of natural convection in heat transfer was estimated from differences observed when the acceleration varied from 0g to 1.8g. Although the analysis of data is not finished yet, it is evident that natural convection is more profound in FC-72 than water. In addition, closely packed particles suppress entirely natural convection but this is not so for dense particle suspensions.

Keywords Natural convection · Microgravity · Conduction · Rayleigh number · Spheroidal heater

Introduction

Heat transfer over sub-millimeter spheroidal solids submerged in fluids is of interest in many engineering processes such as manufacturing systems, packed beds and many electronic components of nearly spherical shape (Gebhart et al. 1988). Apart from heat conduction (molecular thermal diffusion) another important mechanism of heat transfer in the above processes is natural convection which calls for the macroscopic buoyant transport of fluid due to local density differences: hotter regions move against gravity whereas colder regions move along gravity. The presence of natural convection can lead to heat transfer rates many times larger than that of pure heat conduction.

Over the last years, we have been investigating thermal degassing of liquids (e.g. Divinis et al. 2004, 2006; Karapantsios et al. 2008; Kostoglou and Karapantsios 2007). In particular, we have examined the growth of bubbles from different liquids saturated with dissolved gas when their temperature was locally raised above the saturation value, yet below their boiling temperature. We did several experiments in the low gravity environment of parabolic flights (25th, 26th, 35th, 38th and 49th ESA Parabolic Flight Campaigns PFC) in order to decouple bubble growth from buoyancy effects and study the combined thermal and mass diffusion dominating the process. However, results from those experiments displayed a significant deviation from theoretical predictions indicating a possible contribution from residual natural convection probably due to the poor low-g conditions in parabolic flights (Shafie and Amin 2005; Shafie et al. 2005).

Despite the huge literature devoted to natural convection heat transfer rates over spheres (and to a smaller extent over spheroids) there is not a generally accepted correlation especially for small Rayleigh numbers. Existing correlations for external (open domain) geometries predict a continuous progressively

S. P. Evgenidis · K. A. Zacharias ·
T. D. Karapantsios (✉) · M. Kostoglou
Department of Chemistry,
Aristotle University of Thessaloniki,
University Box 116, 541 24 Thessaloniki, Greece
e-mail: karapant@chem.auth.gr

increasing contribution of natural convection to heat transfer with respect to gravity starting from zero gravity. This means that at the common residual gravity level during parabolas (g-jitters) it is possible to have a measurable effect of natural convection.

To test this hypothesis, during the 49th ESA PFC (November 2008) we conducted heat transfer experiments in degassed water and glycerol aiming to investigate the effect of residual natural convection on the development of a thermal boundary layer around heating points. Runs were performed with different heating powers and durations during low gravity periods but also during normal gravity and hyper gravity periods. Clearly, there was an effect of two basic parameters on the appearance of natural convection: gravity level and liquid thermophysical properties. Evidence was provided that during parabolas there was no natural convection in both liquids. Natural convection appeared in water during normal gravity and, more distinctly, during hypergravity periods with an intensity scaling with the value of the thermal driving force (difference between bulk liquid temperature and heater temperature). Interestingly, however, natural convection was not progressively increasing from zero gravity but instead a lower threshold value of the heater temperature (in fact, of the thermal driving force) was found below which no natural convection was witnessed. In glycerol there was absolutely no sign of natural convection in all the examined gravity conditions, because of glycerol's high viscosity value (Kostoglou et al. 2009).

In an effort to discriminate between the effects of gravity level and liquid properties, in this work we performed experiments in the 50th ESA PFC (May 2009) with different test liquids. First, we did tests with water as a reference and also as a reproducibility check with prior PFCs. Then, we did tests with FC-72 (a liquid refrigerant) because of its much lower kinematic viscosity than water which allows more profound appearance of natural convection during different g-levels. Finally, we did tests with solid microparticles dispersed in water in two forms: as a packed bed and as a dense suspension. We used two separate size classes of particles in order to introduce different degrees of heterogeneity in the liquid phase and therefore examine in another way whether liquid conditions are strong enough to create natural convection currents.

Materials and Methods

The experimental set up and procedures were described in detail by Kostoglou et al. (2009) regarding the 49th ESA (European Space Agency) Parabolic Flight Campaign. Only some brief information are presented here.

The present experiments were conducted during the 50th ESA (European Space Agency) Parabolic Flight Campaign. Each parabola provided a sequence of normal-high-low-high-normal gravity phases. Data of onboard gravitational acceleration provided by ESA showed that during the low gravity phases the gravity value fluctuated randomly (g-jitters) within $\pm 2.6 \times 10^{-2}$g whereas during the high gravity phases reached a peak value of about 1.6–1.8g. The low gravity duration is slightly different among parabolas but on the average lasted approx. 22 s. Each parabola was used to conduct a separate run.

The examined test liquids were de-ionized water, FC-72 (3M, Belgium) and packed beds or suspensions of polystyrene particles crosslinked with divinylbenzene (Micropore Technologies Ltd, UK) in water. Particles had specific gravity 1.05 g/cm^3 at 20°C and thermal conductivity ~0.1 W/mK. Two size classes of particles were employed in separate runs. One class had an average size of 0.330 mm (order of size of the heater; see below) and the other of 0.033 mm, respectively. Values of average particle sizes exhibit 15% coefficient of variation, as estimated by the manufacturer. Particles were employed either as a packed bed or as a 16% *v*/*v* suspension in water. Test liquids were initially degassed by boiling at low pressure for 1 h. Next, the degassed liquids were used to fill the sample cells.

The core of the equipment was a thermostat unit, a CPF-2 type, into which an exchangeable sample cell was inserted. A sample cell was essentially a sealed glass tube with an internal diameter of 1.5 cm. The cells were specially designed to stay completely full with liquid so as to prevent free float of the liquid in microgravity. Three different cells, filled with a different liquid each day of the campaign, were used in the present experiments. Packed beds of different particle sizes were formed inside different sample cells just before take-off. Special care was taken when filling the cells with particles to achieve uniformly close-packed conditions. On the contrary, particles suspensions were achieved by loose packing conditions in a sample cell before take-off, which by manually shaking the cell between parabolas and also during the hypergravity period before a parabola allowed re-suspension of particles (uniform visually). This was feasible with the 0.330 mm particles but not with the 0.033 mm particles. Evidently, the latter being of much smaller size have settled stably enough during the ~2 h period between filling the cell on the ground and the first parabola of the flight and were not possible to disturb effectively by hand shaking.

Heating runs were conducted with a spheroid miniature heater (NTC thermistor, Thermometrics, Inc., 0.125 mm nominal diameter) placed at the center axis of sample cells. More specifically, the heater was an axisymmetric ellipsoid with a small-to-large radii ratio of 1:2; the value of the nominal radius represents the two small, approximately equal, radii. A prescribed voltage value, V_o, was applied to the heater through a special electrical network. This voltage was constant through each run but different among runs. Registering the voltage drop across the heater allowed the delivered power, Q, and temperature of the heater to be calculated. The uncertainty in power and temperature readings was 0.1°C and 0.05 mW, respectively. These values were below the noise of measurements. The thermal performance of the equipment was supervised by a custom-made software.

A brief outline of the experimental scenario was as follows. An exchangeable test cell was inserted in the thermostat and was left to equilibrate at a temperature a few tenths of a degree below 32°C. Then the temperature of the liquid was raised locally by energizing the heater at a preset voltage level and for a duration of 35 s. This was done about 7 s after the onset of the low gravity phase during a parabola to ensure that the experiment would start at good low gravity conditions. Since the low gravity period during a parabola lasted about 22 s, in all runs heating extended inside the succeeding hypergravity period. Each test cell was exchanged with a new one after five or ten consecutive parabolas.

Results and Discussion

Figures 1 and 2 display heater temperatures versus heating time in water and FC-72, respectively, at different applied powers. Repeatability runs practically coincide so only single runs are presented. Furthermore, as a stringent consistency check, three earlier runs in water are also shown in Fig. 1 from the previous 49th PFC (at 23.9 mW, 33 mW and 42.6 mW). In all runs, heating starts from the low gravity phase of a parabola and continues for ~17 s to ~20 s inside the subsequent high gravity phase.

The evolution of the heater temperature is a result of the competition between generation of heat on it by ohmic heating and removal of heat from it to the surrounding liquid by conduction and natural convection. A common pattern is found in all curves in both liquids. Temperature climbs very fast at the beginning but only gradually later towards a plateau value. With

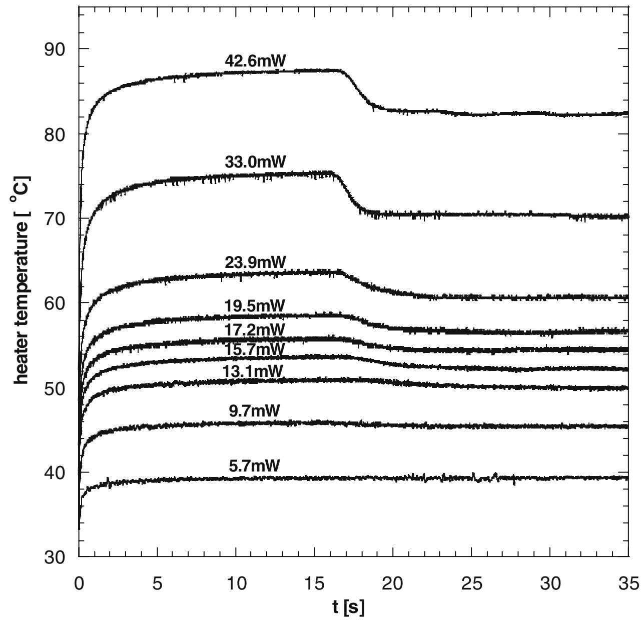

Fig. 1 Heater temperature vs heating time measured in water at different applied powers

FC-72 the heater temperature was kept below 51°C to avoid boiling.

In all runs, except those with the lowest power, the heater temperature was sensitive to changes in gravity level. In particular, going from the nearly zero gravity during a parabola to hypergravity the heater temperature drops. The extent of this drop and the rate it is

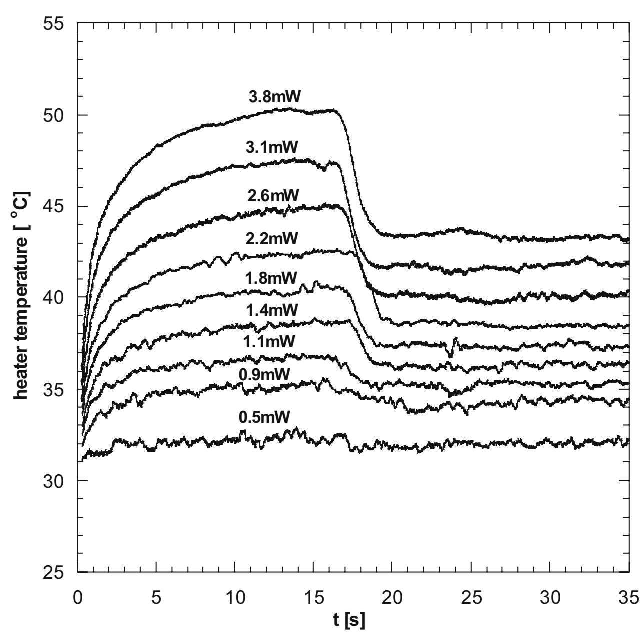

Fig. 2 Heater temperature vs heating time measured in FC-72 at different applied powers

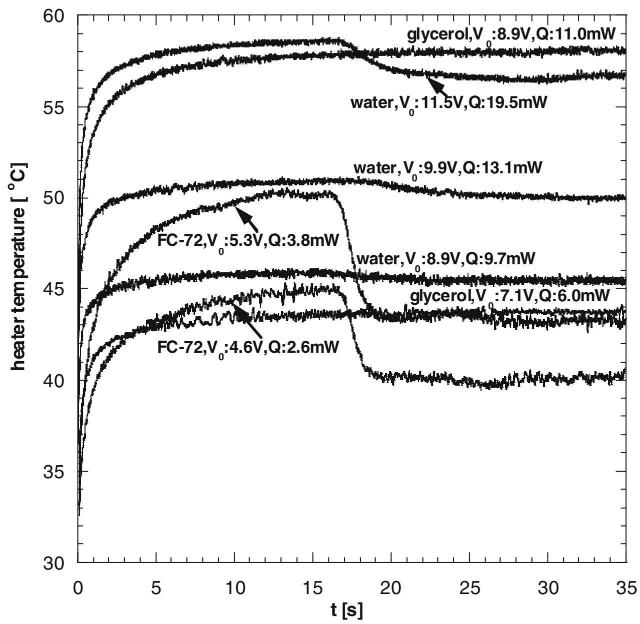

Fig. 3 Comparison among selected runs in water, FC-72 and glycerol

done depends on heating power and, therefore, heater temperature. At higher power (and heater temperature) the drop is larger and faster. For the runs with the lowest power in both liquids there is virtually no effect of gravity level on the heater temperature. Therefore, it seems that there is a threshold for the onset of natural convection. This is in agreement with other recent results (Kostoglou et al. 2009).

Figure 3 presents an interesting comparison among selected runs in water, FC-72 and glycerol (the latter from the 49th PFC). Natural convection is strongest in FC-72 where the observed temperature drop when going to hypergravity is higher. On the other hand, glycerol shows no sign of natural convection even at the most elevated temperatures, chiefly due to its high viscosity. The behavior of water is intermediate between the other two liquids. What is also interesting is that the required applied powers to attain similar heater temperatures are different among liquids. FC-72 needs only a small amount, whereas water the largest of all. This is a result of the higher heat capacity of water. All the above, is a manifestation that the thermophysical properties of the liquid can play a role on heat transfer over and above the effect of gravity.

According to existing correlations for natural convection, there should be an observable contribution of natural convection due to g-jitters. On the contrary, the present experiments indicate the existence of a threshold only above which natural convection occurs. Kostoglou et al. (2009) using just a few experimental runs estimated the value of this threshold as a critical Rayleigh number ($Ra_{crit} \approx 70$) and showed that in low gravity conditions heat transfer occurred solely by conduction. The present more systematic and denser dataset will allow a more accurate determination of Ra_{crit} when the analysis is completed. Detailed analysis of the experimental results and comparison with approximate and numerical solutions of the heat transfer problem will follow in the future. But it is stressed that any kind of mathematical analysis based on the conventional theory predicts (as the correlations also do) that natural convection exists for any value of Rayleigh number. So, the threshold Rayleigh number for the onset of natural convections which is directly observable in the present experimental results sets a fundamental question to the current understanding of the problem and for this reason, it constitutes a major outcome of the present work.

Figures 4 and 5 present heater temperatures versus time at different powers applied in packed beds with particles 0.033 mm and 0.330 mm, respectively. Note that different sample cells were used for the 0.033 mm and 0.330 mm particles which, furthermore, were different from the cell used for water. Qualitatively, the shape of curves was similar to previous ones. No sign of natural convection was observed in any run. This is rather expected if one considers that a packed bed hampers the onset of convective currents since only narrow interstices are available for liquid flow. In the absence of natural convection, the experimental

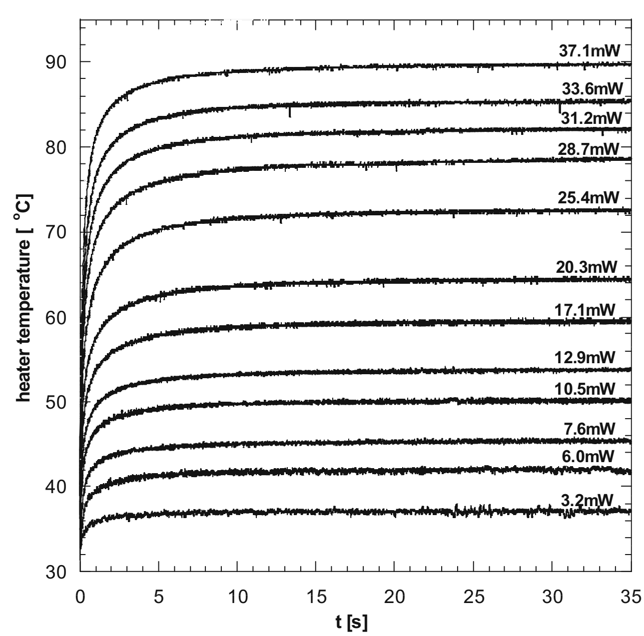

Fig. 4 Heater temperature versus time measured in packed beds with particles 0.033 mm in water at different applied powers

thermal response curves can be successfully described by approximating solutions of the transient heat conduction equation for the spheroidal geometry of the heater. Work in this direction is underway.

Before each run, sample cells with particles were shaked by hand for about half a minute in order to introduce different arrangement of particles (heterogeneity) in the neighborhood of the heater. This procedure did not affect the behavior of the 0.033 mm bed but affected some higher power runs of the 0.330 mm bed. This can be seen in Fig. 5 as closely neighboring curves which, however, correspond to not so close power values. It is necessary to analyze quantitatively these results before making conclusive arguments.

Figure 6 displays heater temperatures versus time at different powers applied in a 16% *v*/*v* suspension of 0.330 mm particles in water. For comparison, curves obtained with the packed bed of 0.330 mm particles in water are shown, measured at the same sample cell. The latter curves were created by applying exactly the same voltage V_o but as can be seen their heater temperatures and applied powers were noticeably larger, this being more so as temperature and power rises. Comparison between the uppermost pair of curves in Fig. 6 shows that higher heater temperatures can be created in the packed bed than in the suspension even with a lower power in the packed bed (38.0 mW) than in the suspension (42.6 mW). Furthermore, initial fluctuations of the heater temperature in the suspension are more intense as temperature escalates and accordingly take more time before they fade out. The origin of these fluctuations is the initial hand shaking of the cell to re-suspend particles combined with the fact that the size of particles is comparable to the size of the heater. Therefore, the effective conductivity of the dispersion—as the heater senses it—depends on the relative position between particles and heater so the motion of particles creates fluctuations. As already mentioned, for the small particles it was not possible to achieve an effective re-suspension in the sample cell by hand shaking. In principle, however, if this were possible then we would not expect to see strong temperature fluctuations—if any—even with the particles in motion because in this case the heater senses a homogeneous suspension with a conductivity that does not depend on the relative position of particles. The above observations support the notion that natural convection currents emerge in the suspension not only increasing heat transfer rates from the heater to the liquid but also creating dynamic conditions that need time to die away and reach steady state. More work is needed to clarify this issue.

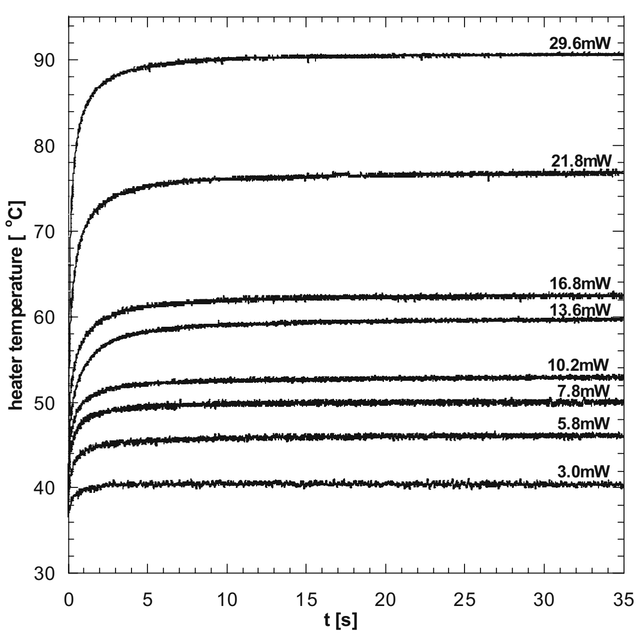

Fig. 5 Heater temperature versus time measured in packed beds with particles 0.330 mm in water at different applied powers

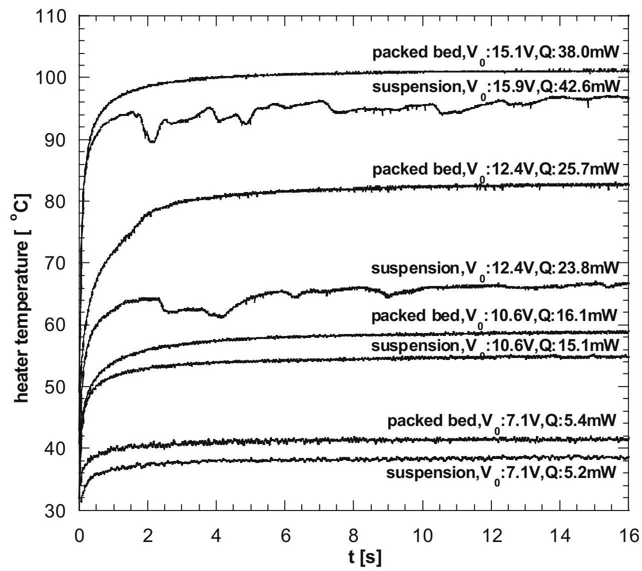

Fig. 6 Heater temperature versus time measured in 16% *v*/*v* suspensions with particles 0.330 mm in water at different applied powers

Conclusions

Experiments were performed in different liquids where the temperature evolution of a sub-millimeter size spheroid heater was recorded at varying gravity conditions with a constant voltage applied across the heater. The different thermophysical properties of the examined liquids appeared to influence heat transfer from the heater to an extent comparable to the effect of different gravity levels. Moreover, the experiments in water and FC-72 showed that there was a threshold before natural convection appears. Although the analysis of the data is still in progress, it appears that heat transfer during parabolas is rather governed by heat conduction. Apparently, additional research is needed regarding the natural convection around sub-millimeter objects for relatively small Rayleigh numbers.

References

Divinis, N., Karapantsios, T.D., Kostoglou, M., Panoutsos, C.S., Bontozoglou, V., Michels, A.C., Sneep, M.C., de Bruijn, R., Lotz, H.: Bubbles growing in supersaturated solutions at reduced gravity. AIChE J. **50**(10), 2369–2382 (2004)

Divinis, N., Karapantsios, T.D., de Bruijn, R., Kostoglou, M., Bontozoglou, V., Legros, J.C.: Lateral motion and interaction of gas bubbles growing over spherical and plate heaters. Microgravity Sci. Technol. **XVIII-3/4**, 204–209 (2006)

Gebhart, B., Jaluria, Y., Mahajan, R.L., Sammakia, B.: Buoyancy Induced Flow and Transport. Hemisphere Publishing Corporation, New York (1988)

Karapantsios, T.D., Kostoglou, M., Divinis, N., Bontozoglou, V.: Nucleation, growth and detachment of neighboring bubbles over miniature heaters. Chem. Eng. Sci. **63**, 3438–3448 (2008)

Kostoglou, M., Karapantsios, T.D.: Bubble dynamics during the non-isothermal degassing of liquids. Exploiting microgravity conditions. Adv. Col. Surf. Sci. **134–135**, 125–137 (2007)

Kostoglou, M., Evgenidis, S.P., Zacharias, K.A., Karapantsios, T.D.: Heat transfer from small objects in microgravity: experiments and analysis. Int. J. Heat Mass Transfer (2009, submitted)

Shafie, S., Amin, N.: g-Jitter induced free convection boundary layer on heat transfer from a sphere with constant heat flux. Journal of Fundamental Sciences **1**, 44–54 (2005)

Shafie, S., Amin, N., Pop, I.: The effect of g-jitter on double diffusion by natural convection from a sphere. Int. J. Heat Mass Transfer **48**, 4526–4540 (2005)