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〈小特集：熱交換器の高性能化―先進技術とその応用―〉

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〈第30回日本伝熱シンポジウム記念講演会〉

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How Microgravity Supports Research in Heat Transfer

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Congratulation to the 30th anniversary and best wishes for the next 30 years !

First I like to express my congratulation to the Heat Transfer Society of Japan to her 30th anniversary and for her successful work in the past period on national and international level. The success of research both fundamental and applied is expressed in the high standard of the industrial and economic development of Japan. Nearly all technological processes are strongly involved with heat transfer, like: material processing, energy conversion, heating and cooling devices, environmental technologies, even in electronics and computer technology enhanced cooling systems enable the use of micro components to high efficiency. Thus heat and mass transfer is a basic science in modern technology, and its contribution to the development of it is incalculable. Your society and their individual members, the researchers in industry and on universities have contributed to this development, and with that to the welfare of the nation and its people. Today science is international. and is not limited by borders, and it is tax free if it crosses the national borders, therefore not only your nation much more the whole science benefits from your work.

I wish your society and all its individual members a fruitful continuation of their successful work and furtheron the continuation of good international cooperation.

Last, however, not least I like to express my personal thanks for the invitation which enables me to take part in your symposium and to present this lecture with the title "How microgravity supports the research in heat and mass transfer".

1 Abstract

In the past years microgravity has been developed to an environment for applied and basic research. In the beginning and up to now materials processing has been in the foreground with respect to industrial application. For the processing itself heat and mass transfer is the basic science to describe the heat and mass exchange at the solidification front or the growth of crystals properly. However, in many fields of heat transfer itself the interaction of many parameters is so complex that simple solutions are not possible and the conservation equation can't be applied. This is especially the case in two phase heat transfer, where under earth conditions the buoyancy caused by the large differences in the density between the phases are

so dominant that the weeker forces substantially contributing to heat transfer are suppressed. Often this leads to an incorrect physical view of the process itself, and an inadequate mathematical description. In this presentation some examples will be demonstrated, where experiments in microgravity reinforce our basic knowledge on in principle "wellknown" processes in heat transfer.

2 Introduction

About 15 years ago the possibility for research was offered to perform experiments in an environment which first was called weighlessness, low or reduced gravity, now the term microgravity is commonly established for it. This environment is now widly used in various fields of research mainly in Material Science and Life Science. The first one includes fluid physics, heat transfer, material processing, solidification, crystal growth, and the second is mainly human physiology and biology. As an example about the interest of the various research areas their participation on the recent D2 mission [1], from April 26th to May 6th, 1993 will be counted up as followed:

fluid physics	20 %
material processing	22 %
human physiology	22 %
biology	16 %
earth observation, astronomy and space technology	20%

Our interest here is mainly focused on material science and fluid physics. In material processing the involvement of heat and mass transfer is dominant during the processing. The processing of material by melting and solidification, and the process of crystal growth are completely governed by heat and mass transfer and can be described by the conservation equations of mass, energy and momentum. In microgravity buoyancy convection, sedimentation and stratification can be suppressed, and in absence of a free interface these processes are determined by heat conduction and/or diffusion alone with moving boundary conditions. In absence of convection a more homogenous structure in the solid phase is expected with different or even better properties.

The knowledge of heat and mass transfer and the possibility of the numerical solution of the conservation equations supports nowadays the control during processing to avoid inhomogenous structures. In these cases heat and mass transfer has a service function. On the other hand experiments in microgravity enlarge our horizon and give answers to questions not solved up today, especially in the cases of two phase and interfacial heat transfer, and systems being not in equilibrium, whereby under earth condition the dominating buoyancy force suppresses other weaker forces. They become more evident in microgravity, and their interaction can be studied. In this lecture some examples will be discussed.

3 How to provide microgravity?

Gravity is a natural and universal force of attraction between any two masses. Such on earth any body is attracted by the earth mass with the gravity value or acceleration g. To provide microgravity, there is no other way as to compensate the gravity force. One way is by acceleration and deceleration, the other is by centrifugal force directed in opposit to gravity. The first category includes all free fall systems like drop towers and drop shafts, parabolic trajectories of aircraft or ballistic rockets. The second category includes all space systems flying in an orbit arround the earth in manned vehicles likes the Space Shuttle or the MIR station, as well as unmanned systems like the satellites, the russian system Foton, Eurokosmos or Express. We have to recognize that at the usual altitude of these orbits of 300 to 400 km, the gravity itself is only a little reduced compared to the value on the earth surface, thus microgravity is provided by the centrifugal force with the high velocity of 27.819 km/h (shuttle D2). The space vehicles in the orbit provide microgravity for days and even years as we learn from the space shuttle system, the russian MIR station and the planned US space station Freedom on which an European and a Japanese modul will be linked up. One of the less expensive possibilities are parabolic flights with aircraft, which provide microgravity of about 20 sec, however, the quality of the microgravity level is not very high, and it is alternating between $\pm 5 \cdot 10^{-2} g$. It is interesting to note that in the last years with the increasing request for microgravity research new drop facilities have been commenced to operate. The largest is now the JAMIC drop shaft in Hokkaido with a free fall altitude of about 500 m. He provides a high microgravity level of better than $10^{-4} g$ over a duration of 10 sec. Last autumn I have been invited by Dr. Y. Abe, ETL, to take part on a campaign, and we could use this facility sucessfully to study interfacial heat and mass transfer.

4 What is expected from microgravity?

Microgravity allows a remarkable reduction of the buoyancy force, thus in material science and fluid physics it affects and suppresses:

- the buoyancy in two phase systems,
- the thermal buoyancy convection,
- the sedimentation of materials of different densities,
- the stratification of liquids,
- the hydrostatic pressure difference.

The influence of buoyancy is expressed in the dimensionless numbers: Archimedes, Grashof, Rayleigh, Bond, Weber, which are proportional to gravity and strongly reduced in microgravity by the order of 10^{-4} depending on the quality of the gravity level.

Thus microgravity allows to study without being influenced by buoyancy convection: interfacial heat and mass transfer, boiling, thermocapillary convection, capillarity, two phase systems, critical fluids with its diverging properties etc.

The benefit of microgravity for science and its application will first be demonstrated in few short examples:
In measurements of thermal conductivity buoyancy convection often bothers the results and can hardly be avoided. This is especially true for melts of metals and materials for semiconductors at high temperatures. Therefore Hibiya et al. [2] from NEC have performed conductivity measurements at high temperature in InSb melts using ballistic rocket flight TEXUS first, and later the JAMIC drop shaft. They receive very good results, and can demonstrate that earlier measurements are often influenced by convection.

Fig. 1 shows the computer simulation of a fractal aggregate consisting of 50 millions of particles after P. Ossadnik, KFA Jülich, Germany. The characteristic feature of the object under realistic conditions is its fragility due to the small forces holding the structure together. In microgravity it would be possible to study the growth of large fractal aggregates, important for the galvanic deposition of metals, for tertiary oil recovery from pores of host rocks or for understanding of the formation of snowflakes. On earth relevant experiments are only possible for two-dimensional structures on a fluid surface.

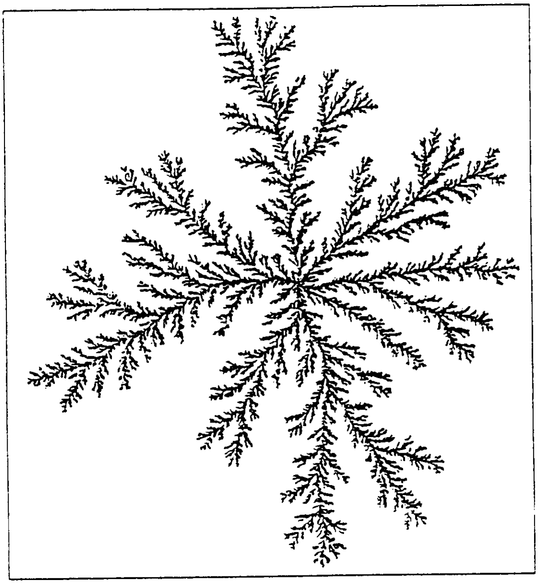

Figure 1: Computer simulation of a fractal aggregate consisting of 50 millions of particles after P. Ossadnik

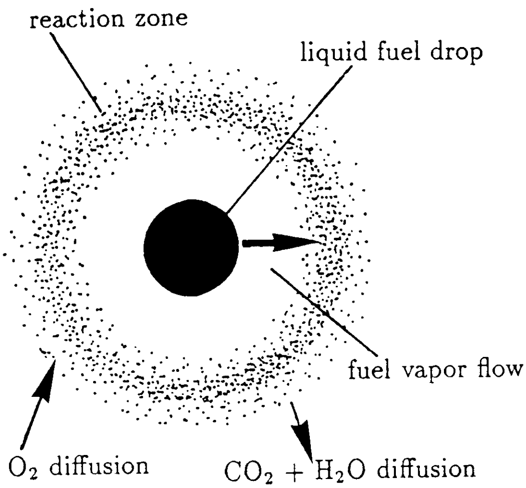

Figure 2: Sketch of droplet combustion

Similar fragile is the structure of dendritic crystals, which are easily destroyed by the buoyancy convection created by the heat and mass transport during its own growth. A significant progress has been reported in the past two years in protein crystallization. Larger crystals grow up in microgravity due to the fact that temperature induced convection could be minimized.

An interesting example for the benefit in using microgravity environment is the study of heat and mass transfer problems in combustion, Fig. 2. Especially the combustion of droplets is studied intensively in Japan by a research group of the Tokyo University and IHI. If the droplets are small the short time of drop towers or shafts are enough for the investigation of combustion. Without buoyancy convection the fuel drop evaporates at its surface by the heat from the combustion zone transfered mostly by radiation. The fuel vapor flows by its volume expansion during evaporation and diffusion to the reaction zone, reacts with the oxygen transported by diffusion from outside. The exhausted gases CO_2 and H_2O diffuse in the opposite direction away from the combustion zone. As long as the heat and mass flow is balanced to maintain the reaction, the upper and lower stability limit can be studied, and with enhanced measuring techniques the reaction zone itself can be analysed with respect to the chemical processes itself.

Only few examples are enumerated here to demonstrate the wide field of microgravity research whereby the classical areas for using microgravity like crystal growth, solidification are not refered to. In more details I will now describe some examples of my own research fields, with which I like to show you the useful support of microgravity to solve questions in the research of thermodynamic and heat transfer.

5 Critical fluid

5.1 Observations

A fluid near its critical gas-liquid point is characterized by extreme values of the thermodynamic properties. Thermodynamic and transport properties diverge, which has the following consequences:

- The high compressibility compresses the fluid on earth by the hydrostatic pressure under its own weight. The critical state itself is realized in a very small layer only.
- The high volume expansion leads to high Gr-number, additional with the diverging Pr-number, Fig. 3 [4], to a strong increasing Ra-number, thus the critical fluid is very sensitive to buoyancy convection.
- Due to the high isobaric specific heat the thermal diffusivity, Fig. 4 [5] tends towards zero approaching the critical point, with the consequence that up to recent it was assumed that

in microgravity the heat transport by conduction is completely slowed down. However, the first experiment performed in microgravity indicated the opposite.

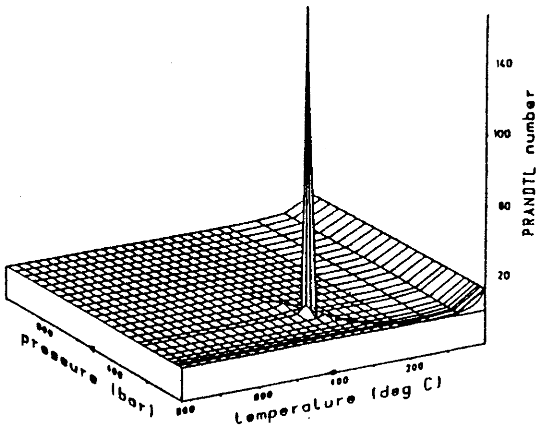

Figure 3: The Prandtl Obelisk for water

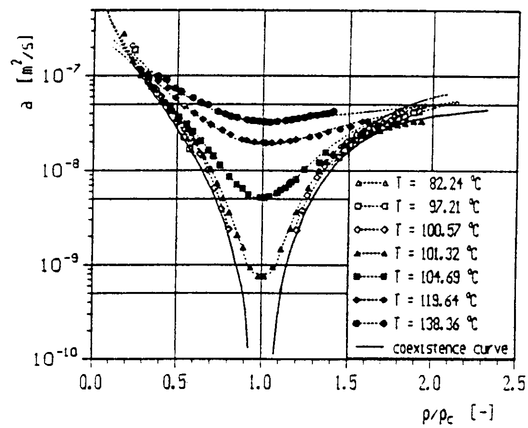

Figure 4: Thermal diffusivity of R134

In a microgravity experiment carried out during a ballistic rocket flight of TEXUS 8 (1984), a cylindrical cell of 25 mm in diameter and 1.5 cm long was heated up with a constant temperature ramp from $T - T_c = -0.4$ K to $+0.4$ K within the 6 minutes of microgravity. With a thermistor at the wall and in the center of the cell the thermal response was measured. On earth an almost constant temperature difference of 0.1 K between the center and the wall was maintained throughout the ramp. The heat transfer is enhanced by strong convection, as it was observed through the cell windows. In microgravity no convection was observed, however, it was surprising, that the temperature in the center of the fluid followed the wall with nearly the same constant temperature difference as under earth conditions. This phenomenon was also measured in a parallel cooling run with a second cell of the same design.

These measurements and the observations indicate that the heat transport and the temperature equilibration was much faster as expected, even without convection, which was contradictionary to the comprehension until now. In early studies of density profiles near the critical point [6] we have observed a very slow density equilibration, which is confirmed by the observations in the Critical Point Facility (CPF) during the IML 1-mission in 1992 and confirms the interpretation of our results of the D1 mission [7].

5.2 Isobaric and isochoric processes

For the theoretical description of the heat and mass transport in microgravity we assume, that there exists no gravity force, and the mass flow generated by the local difference in the chemical potential only is very slow, thus the momentum equation can be neglected. The energy equation can be expressed either with the enthalpy: $h = h(T,p)$ or the internal energy: $u = u(T,\varrho)$. If heat is transfered by conduction only, and using the Fourier formulation, we receive identical relations:

$$\frac{\partial T}{\partial t} + \frac{T}{\varrho^2 c_p}\left(\frac{\partial \varrho}{\partial T}\right)_p \frac{\partial p}{\partial t} = \frac{1}{\varrho c_p}\left(\frac{\partial}{\partial x}\lambda\frac{\partial T}{\partial x}\right) \tag{1}$$

and

$$\frac{\partial T}{\partial t} - \frac{T}{\varrho^2 c_v}\left(\frac{\partial p}{\partial T}\right)_\varrho \frac{\partial \varrho}{\partial t} = \frac{1}{\varrho c_v}\left(\frac{\partial}{\partial x}\lambda\frac{\partial T}{\partial x}\right) \tag{2}$$

The identity is given by the thermodynamic relation between the heat capacity of constant pressure and constant volume:

$$c_p - c_v = -\frac{T}{\varrho^2}\left(\frac{\partial p}{\partial t}\right)_\varrho \left(\frac{\partial \varrho}{\partial T}\right)_p \tag{3}$$

Using equation (1) with $\frac{\partial p}{\partial t} = 0$ the usual Fourier equation is achieved with the thermal diffusivity $a = \frac{\lambda}{\varrho c_p}$, which tends to zero approaching the critical point thus generally a "critical slowing down" of the temperature conduction process was expected at microgravity. Using, however, equation (2) and assuming that $\frac{\partial \varrho}{\partial t} \approx 0$, as observed in experiments, the temperature change is now following an isochoric process with $\frac{\lambda}{\varrho c_v}$. This isochoric diffusivity is increasing and diverging approaching the critical point, thus thermal equilibration is enhanced. An other model for fast temperature equilibration was presented the first time by Onuki (1989) [8] and is called the piston model.

5.3 The piston model

If a cell filled with a fluid of near critical state is heated or cooled, the boundary layer changes its volume due to the high thermal expansion coefficient and the bulk liquid is immediately compressed or expanded, and changes its temperature by this adiabatic volume change. Therefore this model is called the "piston effect" because the volume change of the boundary layer acts like a piston for the bulk liquid itself. This model was first developed by Onuki (1989) [8] and results in a very fast temperature equilibration of the order of milliseconds. During the recent D2 mission, we although have conducted dynamic experiments. First evaluations of 10 mK temperature steps at the wall of the sherical cell of 20 mm diameter, filled with SF_6 of critical density, shows, that closer to the critical temperature, the differences between the wall temperature and three thermistors at three different radial positions from the wall to the center are getting smaller and are zero close to the critical temperature. Most experiments carried out till now follow in the bulk very fast to a temperature change at the wall, however, not as fast that this model is rigorously confirmed [9].

5.4 Heat conduction and mass diffusion

The other description of equilibration in temperature and density is given with equation (2) as mentioned briefly before.

From our experimental experience we know that the temperature equilibrates fast, and the density very slowly. Therefore for the first approach we consider that

$$\frac{\partial \varrho}{\partial t} \approx 0 \tag{4}$$

than we get for the temperature equilibration:

$$\frac{\partial T}{\partial t} = \frac{1}{\varrho c_v} \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) \tag{5}$$

In this case the temperature change is now determined by the isochoric thermal diffusivity $\frac{\lambda}{\varrho c_v}$, and $\frac{\lambda}{\varrho c_v} \gg \frac{\lambda}{\varrho c_p}$ and is increasing approaching the critical point. Experiments which we have conducted in TEXUS and experiments from other authors indicate that the temperature change with time can be described by this isochoric conduction model.

The second term of equation (2) describes the mass equilibration at nearly a constant temperature:

$$-\frac{T}{\varrho} \left(\frac{\partial p}{\partial T} \right)_\varrho \frac{\partial \varrho}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right) \tag{6}$$

For the mass transport energy is still necessary expressed by the right term. By thermodynamic relations the temperature gradient can be written as:

$$\frac{\partial T}{\partial x} = \left(\frac{\partial T}{\partial p} \right)_\varrho \cdot \frac{\partial p}{\partial x} + \left(\frac{\partial T}{\partial \varrho} \right)_p \frac{\partial \varrho}{\partial x} \tag{7}$$

Assuming that at earth gravity only the hydrostatic pressure gradient $\frac{\partial p}{\partial x} = -\varrho g$ exists in the direction of the x-axis, and convection terms are negligible, the mass transport can be written as a mass diffusion as:

$$\frac{\partial \varrho}{\partial t} = \frac{\partial}{\partial x} \left[\frac{\lambda}{\varrho (c_p - c_v)} \left(\frac{\partial \varrho}{\partial x} + \varrho^2 g \chi_T \right) \right] \tag{8}$$

with the mass diffusion coefficient:

$$D_m = \frac{\lambda}{\varrho (c_p - c_v)} \tag{9}$$

Close to the critical point $c_p \gg c_v$ the mass diffusion coefficient is nearly equal to the thermal diffusivity and tends to zero approaching the critical point.

With the above the observation is explained, that the temperature is fast equilibrated, while the mass equilibration is very slow [7].

6 Marangoni Convection

When a liquid-liquid or a liquid-gas interface is exposed to a temperature or concentration gradient, a flow termed Marangoni, surface tension-driven convection or, in the case of a temperature gradient, thermocapillary convection is induced in the liquid in direction of higher surface tension. In most fluids, surface tension decreases with increasing temperature, thus, a convective flow is induced from higher to lower temperature thus supporting the heat transfer. Due to the dominance of buoyancy over thermocapillary convection on earth, this form of natural convection was not paid much attention to for a long time. In addition, it is impossible to separate the effects evoked simultaneously by both buoyancy and surface tension convection in experiments on earth. However, with the technical feasibility of experiments on board of orbiting spacecrafts, on ballistic rockets or in drop towers, an increasing interest has been directed towards the research of Marangoni flows. Under microgravity, containerless processing methods, such as floating zone melting and solidification, and Czochralski crystal growth have been focused on. Any kind of convection is undesired in those processes. Buoyancy convection can be suppressed, while Marangoni convection can hardly be avoided in case of a free surface subjected to a temperature gradient. From the viewpoint of heat and mass transport, however, thermocapillary convection enhances the heat transferred through the liquid.

6.1 Experimental Studies

To demonstrate the effect of thermocapillary flow, the heat transfer around a single steam bubble is studied. A plate heater is mounted upside down in subcooled R113. A single bubble is created (Fig. 5) and observed by holographic interferometry. In some distance from the bubble, the interferometer fringes show a temperature profile due to pure conduction, as the density stratification is stable, and no buoyancy convection occurs. On both sides of the bubble, strong convection is induced by thermocapillary forces and this flow is strong enough to act against the buoyancy force.

The enhancement of heat transfer is investigated in various liquids by the arrangement sketched in Fig. 6. A platinum wire of 0.02 mm in diameter and 3 mm in length immersed in the liquid serves both as heater and resistance thermometer. The heat flux through the wire is kept low enough so that only free convection occurs. By a special holder, a semi-spherical air bubble of 2.5 mm in diameter is positioned in a way that the wire is just touched by the bubble.

The flow around the bubble is observed by tracer particles, while the heat transfer is measured by the change of the temperature and resistance of the wire, respectively. Immediately when the air bubble touches the wire surface, thermocapillary flow sets in and the wire temperature is reduced. In Fig. 7, the increase of the heat transfer is represented by the Nu number

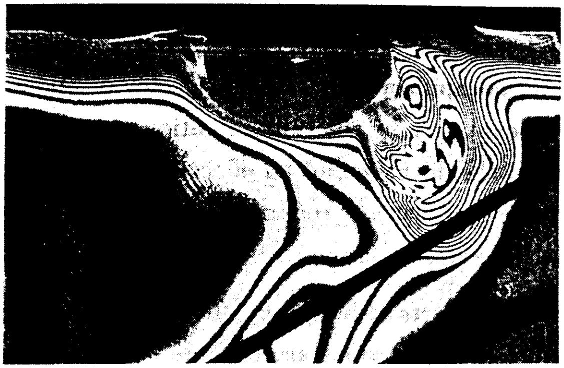

Figure 5: Thermocapillary flow in subcooled R113 observed by holographic interferometry. The bubble is in upside-down position

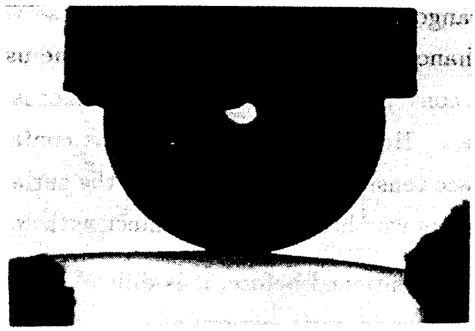

Figure 6: Air bubble of 2.5 mm in diameter on a heated platinum wire

as a function of the Marangoni number, which is defined as:

$$Ma = \frac{d\sigma}{dT} \cdot \frac{\Delta T D}{a\eta} \tag{10}$$

with σ as the surface tension, D the diameter of the wire, a the thermal diffusivity, η the dynamic viscosity, and ΔT the temperature difference between the wire and the bulk liquid.

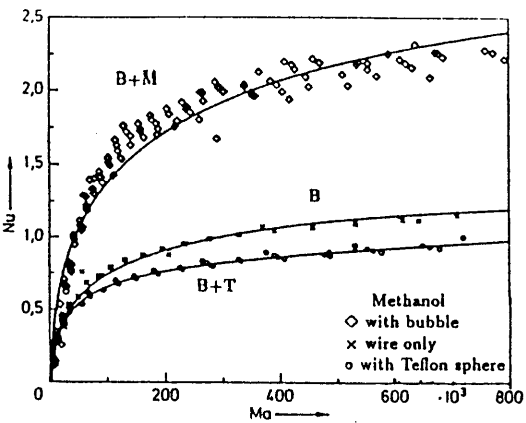

Figure 7: Enhancement of heat transfer by thermocapillary flow on a wire submerged in methanol

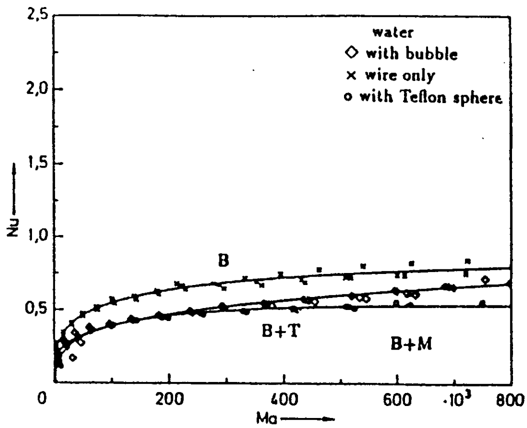

Figure 8: Reduction of heat transfer on an air bubble in water

To prove that the enhanced heat transfer is due to Marangoni convection, a solid Teflon sphere of diameter D is brought in the same position on the wire. As expected, the heat transfer is reduced because of the obstacle to the flow. This is a clear evidence that thermocapillary flow contributes to heat transport very efficiently.

For this experiment we used various liquids, like methanol, propanol, ethanol, R113, water, and mixtures of water and methanol. In case of pure water, it should be mentioned that

Marangoni convection could not be observed for a longer period. Contrary, a mixture of 20 % methanol and 80 % water exhibited the usual thermocapillary flow. The deficiency of Marangoni convection in the case of pure water is usually explained by the contamination of the water surface. However, if this is true, the contamination should have had an effect not only on the surface tension itself, but also on the surface tension gradient and reduce this gradient to zero. It seems worth to study this effect with water in more details (Fig. 8).

As mentioned before, it is difficult to separate the effects of buoyancy and thermocapillary convection in earth experiments. Therefore, numerical simulations are decisive tools to study them. They also help to support the planning of space experiments, to facilitate the design of new equipment and to reduce the number of expensive space experiments.

6.2 Numerical Studies

Transient Marangoni convection is simulated around a gas bubble floating in a rectangular cavity filled with liquid. The side walls are adiabatic, while the bottom and the top walls are maintained at different temperatures. Two 2-dimensional numerical methods are employed, a finite difference scheme with explicit time steps and a fully implicit control-volume finite element method. To simplify the calculations, the bubble is fixed in the middle of the container neglecting buoyancy effects and the force exerted on the bubble by the thermocapillary flow around it. The magnitude of this force is calculated. It can be regarded as the holding force necessary to keep the bubble in place, otherwise it would migrate in the direction to the higher temperature. Variable gravity conditions make it possible to study the interaction of buoyancy and surface tension-driven convection. The system under consideration is governed by the conservation laws for mass, momentum, and energy. As fluid properties the values of water are used, because they are easily available and for the principle study it is of secondary interest that with water thermocapillary convection can not be maintained stationary. In a first approximation, the 3-dimensional problem is reduced to 2 dimensions by considering only a cross-section of the bubble. The special combination of circular and rectangular geometry excludes the use of regular grids. Special elements are used to approach the curved surface of the bubble. For details of the numerical methods we refer to [12] and [13]. The temperature field around the bubble without buoyancy is closely connected with the flow field (Fig. 9).

When the temperature difference between bottom and top walls of the container or the Marangoni number, respectively, is increased, the heat transfer is enhanced and the isotherms accumulate near the heated and cooled walls. The number of isotherms originating from the bubble surface decreases with increasing Marangoni number. With an increasing gradient of surface tension around the bubble, two vortices develop due to the recirculating flow. In Fig. 10, the influence of earth-gravity acting in either parallel or opposite direction of the thermocapillary flow is obvious. In the case of Marangoni convection acting against buoyancy (**M–B**),

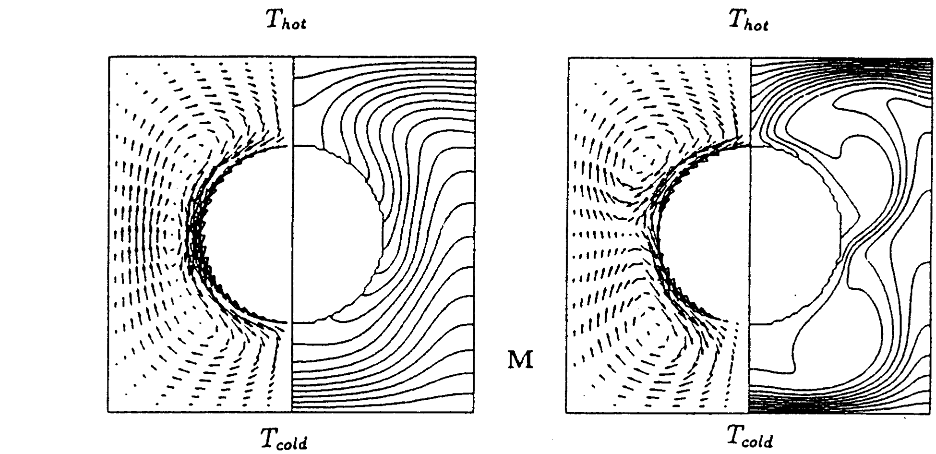

Figure 9: Predicted velocity fields (left) and isotherms (right) for increasing Marangoni numbers under micro-gravity $Ma = 5000$ (left), and $Ma = 100000$ (right)

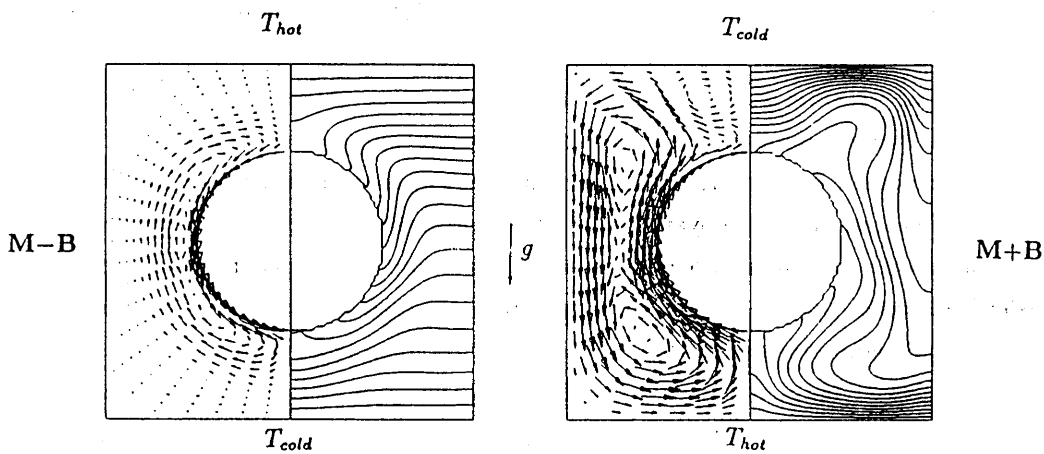

Figure 10: Interaction between thermocapillary flow and buoyancy. **M-B** ($Ma = 10000$) denotes the case of counteraction, **M+B** ($Ma = 5000$) the case of cooperation

the initial temperature field causes a stable vertical density stratification. The displacement of the isotherms accounts for the effect of the thermocapillary flow being in opposite direction of buoyancy. Compared to microgravity conditions, buoyancy pushes the recirculating flow closer to the bubble surface. With **M+B**, an unstable density stratification is chosen as initial condition in the cavity so that thermocapillary flow and buoyancy convection augment each other. Now, the recirculating flow is governed by one large vortex filling up the whole cavity. The influence of thermocapillary convection can be demonstrated quantitatively in the enhanced heat transfer, as in the plot of the *Nu* number versus the *Ma* number (Fig. 11).

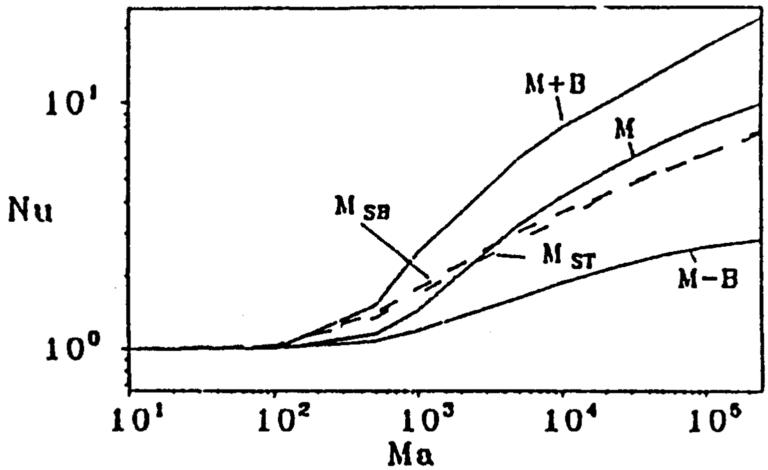

Figure 11: Heat transfer depending on the Marangoni number for the various cases investigated

Pure conduction inside the cavity with inactive bubble is defined as $Nu = 1$; it should be emphasized that in this case the bubble has an insulating effect, the heat transfer is 67.5 % lower as in the case of a cavity completely filled with liquid. The steady-state Nu number increases significantly, when a Marangoni number of $Ma = 10^2$ is exceeded. In a range of $1 \leq Ma \leq 10^2$, convection is still existent, however, its contribution to heat transfer can be neglected. The behavior that a certain Marangoni number is necessary for an observable increase in the Nusselt number is already known from buoyancy convection. As expected, the biggest enhancement of heat transfer is the buoyancy supported thermocapillary flow (**M+B**) in Fig. 10. The case, where buoyancy convection acts against Marangoni flow (**M−B**), has the lowest increase in the Nu number. However, it must be recognized that even here the heat transfer is enlarged, i.e. the thermocapillary flow is strong enough to exceed the buoyancy flow. For pure Marangoni convection, the heat transfer is about eight times higher than for pure heat conduction at $Ma = 10^5$. In Fig. 11 the heat transfer of a semi-spherical bubble attached either to the bottom (M_{SB}) or to the top (M_{ST}) of the enclosure, is included additionally. In both cases, the heat transfer is little less than that of a spherical bubble of the same diameter. At higher Ma numbers, the strong increase of the Nu number is reduced. This is due to the reduction of the isotherms on the bubble surface.

The experiments and the numerical calculation demonstrates that the Marangoni flow contributes in a reasonable quantity, and enhances the heat transfer. We observed first time Marangoni convection during subcooled boiling in microgravity. This stimulated us to investigate the contribution of it alone. The experiments on earth can only be conducted in a way that buoyancy convection supports or suppresses the Marangoni convection. For the examination of the theoretical studies microgravity experiments are an essential tool for comparison and to develop a relationship between the heat transfer, the Nu-number, and the Marangoni number. Additional effects as observed with water should even be studied, because it seems that contamination is not the exclusive reason that Marangoni convection does not develop well.

7 Nucleate Boiling

7.1 Results from experiments

Due to the great differences in the densities between the surrounding liquid and the vapor bubbles, it is generally assumed that the heat transport in pool boiling is highly influenced by buoyancy forces. Thus, gravity is regarded as an important factor in all physically based or empirical correlations for pool boiling heat transfer. Tests in a microgravity environment provide a means to study the real influence of gravity and to separate gravity-related to gravity-independent factors.

In the first stage of our experimental studies in microgravity, the most important question was, whether nucleate pool boiling can be maintained without buoyancy forces. Furthermore, what mechanisms are able to provide similar high heat flux rates as high as on earth, and which forces can replace the effect of gravity.

The boiling process is very complex because of the interdependence of numerous factors and effects, such as the interaction between the solid surface of the heater with the liquid and vapor, the interaction between the liquid and vapor itself, and the transport of liquid and vapor from the heater surface. This complex behavior is the reason that – despite of nearly 6 decades of boiling research – the physics of the boiling process itself is not properly understood and is poorly represented in most correlations. This becomes evident from the fact that the usefulness of most correlations diminishes very rapidly, if they are used outside the range of the physical parameters for which they were developed [14]. Thus, a microgravity environment offers the unique opportunity to study these complex interaction processes without or, at least, with reduced buoyancy forces.

Saturated and subcooled pool boiling have been investigated in parabolic aircraft flights and in TEXUS rocket. The fluid used was R12, the pressure ranges from $0.1 < p/p_c < 0.7$, with p_c the critical pressure. Platinum wires of 0.2 and 0.05 mm diameter, a gold-coated tube of 8 mm diameter, and a gold-coated plate of 40 mm × 20 mm are used as heaters. The platinum wire and the gold coating served as heaters and resistance thermometers simultaneously to determine the surface temperature of the heater. During a parabola sequence the gravity level a/g, the temperature difference $\Delta T_{sat} = T_w - T_{sat}$, and the power q_w supplied to the heater was measured versus the experimental time. The power was switched on during the low-gravity period, eliminating thus convection before the microgravity state was reached. Due to the small heat capacity of the wire, the temperature responded immediately after the power was turned on. The power was increased stepwise, the wire temperature reacted without delay. The duration of the low-gravity period was about 20 s. After that, the acceleration increased from about $a/g \approx 0.01$ to 1.8, and decreased to earth-gravity $a/g = 1$ again. Thus, in one parabola sequence the boiling behavior at microgravity and at higher accelerations could be studied. The low-gravity period of 20 s was long enough to achieve steady-state boiling conditions. The temperature record reveals that the temperature of the heater remains constant even when the acceleration changes from microgravity to $1.8\,g$. The bubble size, however, is gravity-dependent.

With that it is clearly demonstrated that the heat transfer coefficient is neither influenced by gravity nor by the bubble size at this fluid state. The results are summarized for the wire in the boiling curves at saturated states for various pressures in Fig. 12. The symbols represent the data obtained under microgravity, while the lines represent the 1-g-data measured immediately after the low-gravity in the consecutive period of the parabola. The evaluation of the heat transfer coefficient ratio α/α_1 versus heat flux density is shown in Fig. 13.

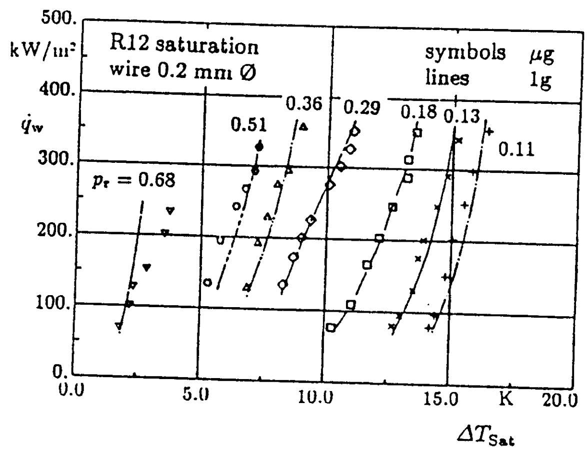

Figure 12: Boiling curves for R12 at saturation and various pressures $p_r = p/p_c$. Symbols at μg, lines at 1g.

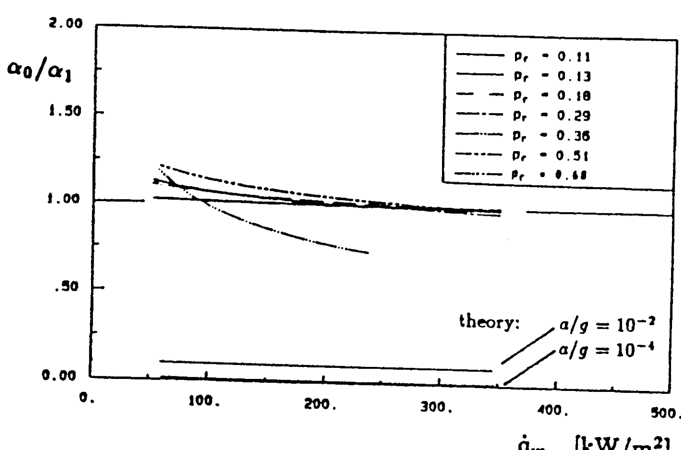

Figure 13: Heat transfer ratio, microgravity values related to 1g values, compared to theory at a/g=10^{-2} and a/g=10^{-4}.

α is the heat transfer coefficient under microgravity, α_1 at 1-g. It becomes obvious that the heat transfer coefficient for low heat flux loads, especially for wires, is even higher than at earth-gravity. This may be contributed to the fact that in low-gravity all nuclei sites on the wire are equally activated. As a result, boiling occurs symmetrically around the wire in low-gravity, whereas in 1-g, the lower stagnation point is cooled by free convection, and only the upper circumference of the wire is preferred for boiling. The reduction of the heat transfer coefficient at higher heat fluxes is caused by the higher bubble density and the appearance of larger bubbles due to bubble coalescence connected with the increase of dry areas below the bubbles. For lower pressures, $p/p_c < 0.1$, experiments conducted in TEXUS flights, not shown here, the bubbles are large due to the small density of the vapor. Below the large bubbles dry areas are formed, which reduce the heat transfer, however, much less as predicted by theory. These dry spots are not circular, they are locally instable the wetting line is moving forward and backward wetting and non-wetting. This movement is very dynamically as observed by Ervin [10] and Oka [11], too, by a view from below through the transparent heating surface. At higher system pressures $p/p_c \geq 0.7$, the reduction in the heat transfer coefficient may be caused by the smaller surface tension, which is responsible for the wetting and the departure of the bubbles as discussed later.

In most correlations from literature for saturated nucleate boiling gravity is an important parameter, their extrapolation to lower acceleration level a/g are not in agreement with our experimental findings. Some relations for subcooled boiling are independent from gravity, however, their physical view of the boiling process is not corresponding with our observations. Indeed, all these correlations were developed under earth-gravity conditions and are valid for $a/g = 1$ only. However, if the physics of the boiling process is described correctly, an extrapolation to lower or higher acceleration values should be implicitly possible without too large deviations from the experimental findings. The great deviations, however, support the statement given above that the physics of the boiling process is not properly represented in most correlations. If under microgravity the nucleate boiling can be maintained up to much higher heat fluxes than expected, it is obvious that even the critical heat flux is shifted to higher values than predicted by the generally accepted hydrodynamic theory of vapor film instability. About 2 to 3 times higher values of CHF are observed in both saturated and subcooled boiling on wires and flat plates. The hydrodynamic theory describes a situation where a vapor film on the heaters surface still exists, and get unstable, but not the formation of this vapor film, which causes the CHF.

7.2 Mechanism of Nucleate Boiling

Finally, the question arises, what are the physical mechanisms of nucleate boiling, and how can the transport of energy be explained in the absence of buoyancy. For a better understanding, it is useful to divide the mechanism of the boiling process into a primary and some secondary mechanisms:

Primary mechanism:

The primary mechanism is the formation and the growth of the bubbles in the superheated liquid boundary layer by evaporation at the liquid-vapor interface. Most important for the heat transfer are the transport mechanisms in the microwedge at the solid-liquid-vapor interface on the baseline of the bubbles. In this region, the evaporation rate is very high and not influenced by gravity but only by the temperature at the interface.

After nucleation a microlayer will be formed and evaporates into the bubble, further bubble growing occurs on the bubble base at the microwedge, Fig. 14, formed by the solid-liquid-vapor interfaces. At the liquid vapor interface the vapor evaporates if the liquid surface temperature is higher than the saturation temperature. This temperature depends on the size of the bubble, and is decreasing with increasing bubble size. By capillary pressure difference caused by the evaporation liquid flows parallel to the heater into the wedge. The thickness of the gap between heater and surface of the bubble determines the heat flow to the bubble. At 1g the bubble depart at a certain size determined by the buoyancy, inducing wake flow. In microgravity the contribution by the wake flow is very small and will be negligible. The capillary flow into the wedge is confirmed by the observation that smaller bubbles migrate along the heater surface and coalesce with larger bubbles. By this migration and the coalescence additional flow is induced, more or less parallel to the heater surface.

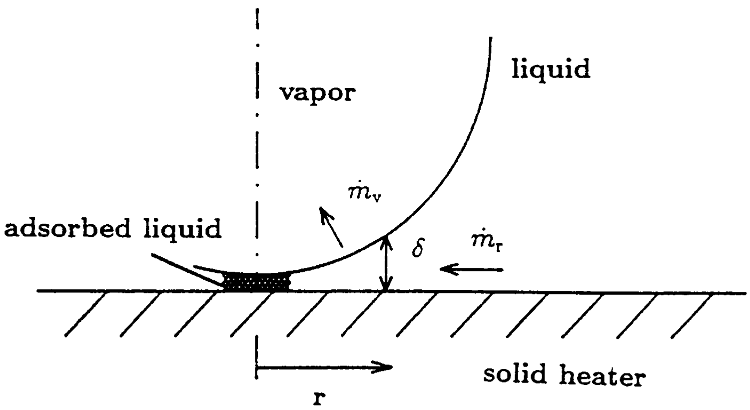

Figure 14: The microwedge modell. $\dot{m}_v$ is the evaporating mass flow, $\dot{m}_r$ is the liquid mass flow to the interface. $\dot{m}_v > \dot{m}_r$ unstable CHF.

If at high heat fluxes a dry spot below a bubble is formed, and the evaporating mass flow is getting larger than the liquid mass flow to the bubble in the wedge the dry area is further increasing, and the situation gets unstable, because the capillary force is reduced, and with that the liquid mass flow, dry up is enforced, first below one bubble than neighbouring bubbles follow, they coalesce, form a film, which leads to the critical heat flux.

Secondary mechanism:

The secondary mechanisms are responsible for the heat transport from the heater surface to the bulk liquid. This occurs by the departing bubbles carrying away latent heat, additional, by the wake-flow following the bubbles, and by convection.

In forced convection boiling, the bubbles and the liquid are carried away by the flow, and in pool boiling under earth-gravity, they are carried away by buoyancy. In microgravity, the various effects observed are mostly caused by surface tension, they are shortly summarized:

- inertia forces during rapid growth; this was observed in boiling of subcooled water on a wire;
- vertical and horizontal bubble coalescence, followed by the inertia of the liquid lifting the bubbles and supplying cool liquid to the heater;
- coalescence of small bubbles into larger bubbles;
- lifting and replacement of large bubbles by the growth of smaller ones below them.

In subcooled liquids, additional effects are observed:

- pumping by high frequency growth and condensation, called micro-convection, observed with small bubbles on earth;
- in microgravity, large bubbles are formed with evaporation at the bubble base and condensation at the crown; acting like small heat pipes, this process is selfcontrolled. The bubble grows up to a size that their crowns reaches the subcooled liquid for condensation
- thermocapillary convection;
- coalescence of small bubbles with large bubbles and condensation at the top. The large bubbles grow into regions, where the liquid is still subcooled. Partial condensation of large bubbles at the top occurs with dynamic fluid motion.

It is interresting to note, that the overall heat transfer coefficient is only less dependent on these secondary mechanisms.

8 Summary

In this paper some examples are presented how microgravity supports research in heat transfer, and it is expressed that heat transfer can support other fields of research, especially material processing because these processes are completely governed by heat and mass transfer. In the example of heat transport near the critical point of fluids we learned with the aim of microgravity experiments that simplified transport equations can not be applied to systems distinguished by extreme values of thermophysical properties.

Thermocapillary flow is much more important for heat transport than it was estimated before. The enhancement of heat transfer is remarkable, however, at higher Marangoni numbers the influence is weakened, because the strong flow at the interface itself reduces the driving temperature gradients.

Boiling, as the most efficient heat transfer mechanism, can be maintained in microgravity, too. Buoyancy does not play the role it has been attributed to until now, nearly the same heat transfer values as on earth are observed in microgravity. The dominating effect for boiling is the evaporation at the wedge formed by the interfaces solid-liquid-vapor on the bubble base and the flow driven by the capillary forces due to the evaporation. The energy transport from the heater surface to the bulk liquid is governed by mechanisms in which surface tension is most important such as bubble coalescence, liquid inertia, and replacement of bubbles. In subcooled liquids, evaporation at the base, and condensation at the top of the bubble induce a highly dynamic liquid motion, and transport cooler liquid to the heater surface.

Regarding the fact that after 60 years of research in boiling heat transfer many open and basic questions exist, we can not expect that by the few experiments which have been conducted in microgravity till now by Japanes, American and German researchers all problems are solved. We are just at the beginning to get familiar with this new environment for solving unsolved research problems. Microgravity is an excellent environment to study transport processes without buoyancy for a better understanding of the physics behind them, and to improve our knowledge for its application. However, to go to this environment is very costly, therefore a closer international cooperation is very desirable.

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10 Nomenclature

a	thermal diffusivity [m^2/s]
a	actual system acceleration [m/s^2]
c_p	isobaric specific heat capacity [J/kg K]
c_v	isochoric specific heat capacity [J/kg K]
D	diameter of the wire [m]
D_m	mass diffusion coefficient [m/s^2]
g	gravitational acceleration [m/s^2]
Gr	Grashof number [-]

h	specific enthalpy [J/kg]
Ma	Marangoni number [-]
Nu	Nusselt number [-]
p	pressure [Pa]
Pr	Prandtl number [-]
q_w	specific heater power [W/m^2]
Ra	Rayleigh number [-]
t	time [s]
T	temperature [K]
u	internal energy [J/kg]
x	coordinate [m]
α	heat transfer coefficient under microgravity [W/m^2 K]
α_1	heat transfer coefficient at 1g [W/m^2 K]
η	dynamic viscosity [Pa s]
λ	thermal conductivity [W/m K]
ϱ	density [kg/m^3]
σ	surface tension [N/m]
χ_T	isothermal compressibility [1/Pa]
$\frac{a}{g}$	gravity level [-]
$\frac{\alpha}{\alpha_1}$	heat transfer coefficient ratio [-]
ΔT	temperature difference between the wire and the bulk liquid [K]

subscripts:

c	critical
p	pressure
sat	saturated
T	temperature
w	wall
1	at 1g

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