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# POOL BOILING UNDER MICROGRAVITY

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**Abstract**—Microgravity is a very good means to prove theoretical developed correlations for pool boiling in respect to their gravity dependence. As our measurements with FREON 12 and FREON 113 show, pool boiling is gravity independent, which is contradictory to many model laws. The main heat transport mechanism involved is the evaporation process.

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## 1. INTRODUCTION

In the mid 1970s, the German Department of Research and Technology (BMFT) was offering opportunities for experiments in space aboard the space shuttle, free floating units, Get Away Special containers (GAS) and sounding rockets. One of the research fields our institute was dealing with at that time, was pool boiling, which is not yet understood well enough. Some interesting questions, that require additional study, should be looked at in space either in the field of basic research or for technical applications in the future (e.g. heat transfer problems aboard the space station, scheduled to go into operation at the end of this century). Is pool boiling still a stable process in space as it is on earth? What are the heat transfer coefficients compared to terrestrial values? What is the main heat transport mechanism in boiling?

The first question, which determined the future of our project, could be affirmed in the early 1980s in sounding rocket flights, using a simple set-up of a test vessel filled with FREON 113 and a platinum wire as the heating device. Already at that stage, we had some astonishing results concerning the second question. However, we started a series of boiling experiments using a NASA aircraft (KC 135) to assure these results over a wide range of thermodynamic properties, and using different fluids and heater geometries. The limiting factor in KC 135 flights, the short duration of the reduced gravity period, could be overcome by introducing heaters with low heat capacities, which respond to changes in the heat transfer conditions very quickly. This second question will be analyzed later on in the paper. The third question appears to be very simple and consequently easy to answer. There are, however, several theories—sometimes quite contradictory—concerning the process of pool boiling, but none of them adequately describe all the effects involved. Microgravity is a very good means to eliminate all gravity driven effects and so reduce the number of parameters. By cross checking our heat transfer measurements with the corresponding theories, we were able to obtain results that can help solve the third question. But nevertheless, this problem complex requires further attention in the future.

## 2. EXPERIMENTAL DETAILS

### 2.1. *Reduced gravity conditions*

A reduction in gravity conditions can be achieved in two different ways. It is possible to compensate the gravity force by a second body force, e.g. the centrifugal force. This is carried out in shuttle flights in an orbit of about 320 km above ground. The second possibility is to conduct free falling experiments. Everything inside the test vessel is falling at exactly the same speed, so components don't act upon each other any more. The two facilities presented below belong to this category.

*TEXUS ballistic rocket.* TEXUS (Technologische Experimente unter Schwerelosigkeit—technological experiments under microgravity) is a German space research program sponsored by the BMFT and managed by the German space administration DLR (DFVLR). The small rockets (450 mm dia.), capable of carrying up to a 400 kg payload, are launched near Kiruna, Sweden. The experiment modules, with a typical weight of 60 kg, are controlled by computers; data recording is done by a telemetry system, allowing a maximum measuring speed of 100 Hz per channel. The acceleration level is less than $10^{-4}\ g$ (guaranteed! $g = 9.81\ \mathrm{m\ s^{-2}}$), the $\mu g$ period lasts up to 6 min. Due to weight and power considerations, we used FREON 113 in this facility (no pressure vessel required at room temperatures).

KC 135 *aircraft.* In another part of the German microgravity program NASA offers to use a KC 135 aircraft, similar to a Boeing 707, to carry out parabolic flights. The duration of reduced gravity periods is about 20 s per parabola, the gravity level changes between 1.8 $g$ and $\pm 0.02\ g$. During one flight, up to 30–40 parabolas may be reached, thus obtaining an experiment time of approximately 500 s. In this facility laboratory hardware can be implemented, the experiments are controlled by the investigators themselves, which is unique for microgravity experimentation. Here, we conducted experiments with FREON 12 and additional boiling experiments with FREON 113 and water.

### 2.2. *System parameters*

*Fluid FREON* 113. Due to space and weight considerations, we decided to start with a very simple set-up using FREON 113 and a platinum wire. This fluid has a saturation temperature of 47°C at ambient pressure and as a result no heavy pressure vessels are required for this experiment. After two successful flights with this system, we changed the heater geometry, now using a flat plate which is closer to technical applications than the employed wires. An overview of the TEXUS experiments is presented in Table 1. During the flight, measurements of the heat flux, the heater temperature, the system pressure and the temperature in the bulk were made with data recording rates up to 100 Hz. Simultaneously, a movie camera recorded the process with film speeds of 18 and 100 fps. These experiments were the basis for the test series with FREON 12 aboard the KC 135. Comparing the results of TEXUS with the very low $g$-jitter level ($<10^{-4}g$) with those of KC 135 ($<0.02\ g$), we recognized only minor differences, maintaining that the experiments in the KC are a good simulation for microgravity experiments in boiling. A detailed discussion of the TEXUS results are presented in Weinzierl (1984) for the wire experiments and in Zell (1989) for the flat plate.

*FREON* 12. The main part of the experiment was conducted with FREON 12 in the KC 135 supplied by NASA in Houston. This facility offers the unique opportunity of having not only reduced gravity ($<0.02\ g$), but also 1 $g$ and enhanced gravity (up to 1.8 $g$). The experimental set-up consisted of laboratory hardware mounted to solid racks which were bolted down to the floor of the KC 135. Figure 1 gives an impression of the flight hardware: the left rack contains all the power supply units, and one test unit on the top. A second test cell is mounted on a platform inside a metal frame. This facility provides a semi-free-floating

Table 1. Experiment parameters of the TEXUS flights

| | $T_{\mathrm{sat}}$ [°C] | $T_{\mathrm{sat}} - T_\infty$ [K] | $p/p_c$ [−] | $\dot{q}_{\max}$ [kW m$^{-2}$] |
|---|---|---|---|---|
| Platinum wire | 30 | 0 | 0.015 | 300 |
| 0.2 mm dia. | 47 | 17 | 0.03 | 500 |
| Flat plate | 30 | 0 | 0.015 | 30 |
| 20 × 40 mm | 47 | 17 | 0.03 | 70 |
| | 77 | 47 | 0.06 | 70 |

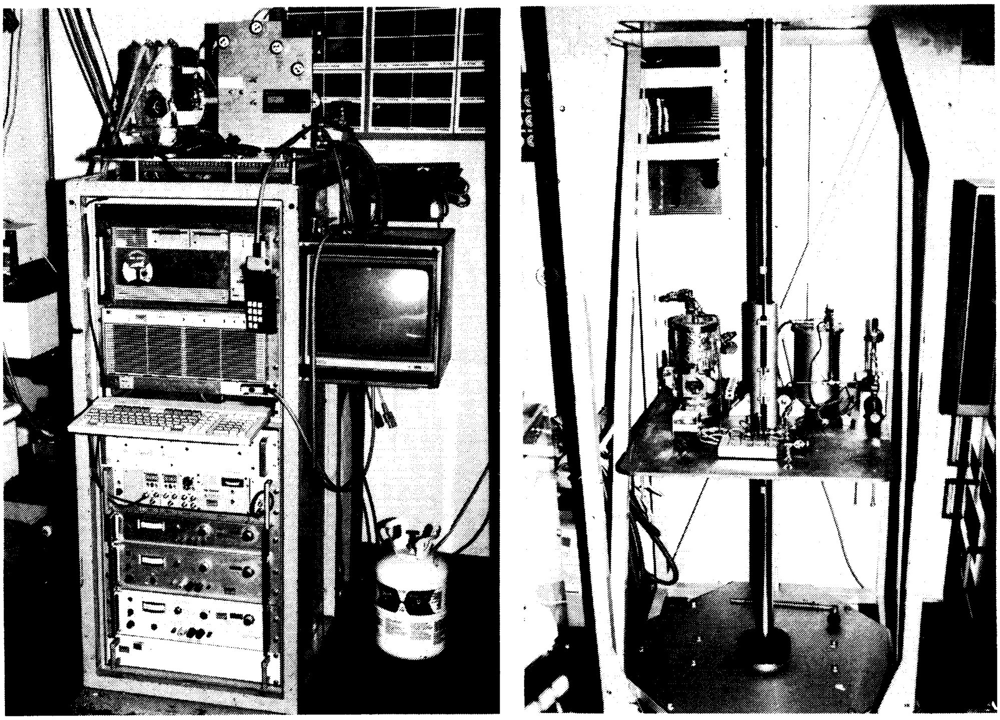

Fig. 1. Hardware used in KC 135 flights.

platform for compensation of the $g$-jitter effects in the direction perpendicular to the floor. A small rack not shown here, consists of a personal computer and measuring devices for data acquisition.

In our experiment, heaters with low heat capacities were used to obtain a thermal system with a very low response time, thus allowing reference measurements to be made in one

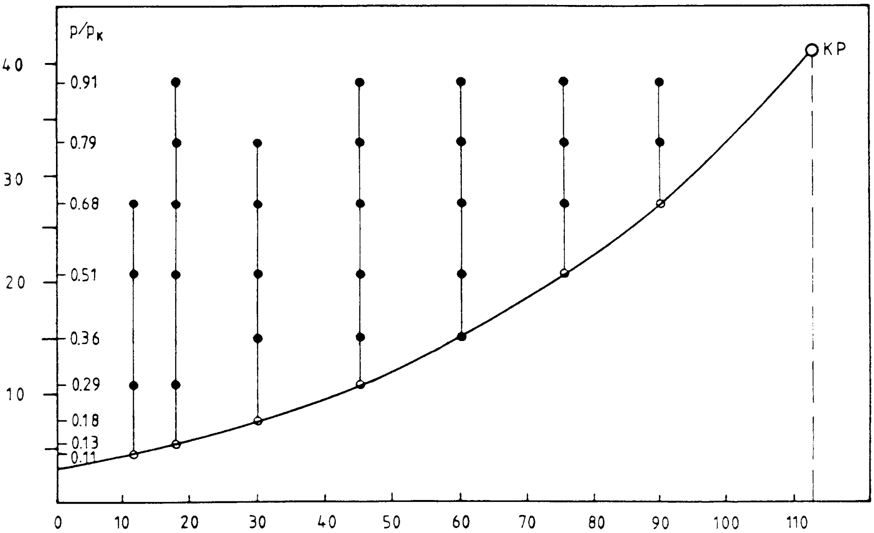

Fig. 2. Fluid state of the FREON 12 experiments.

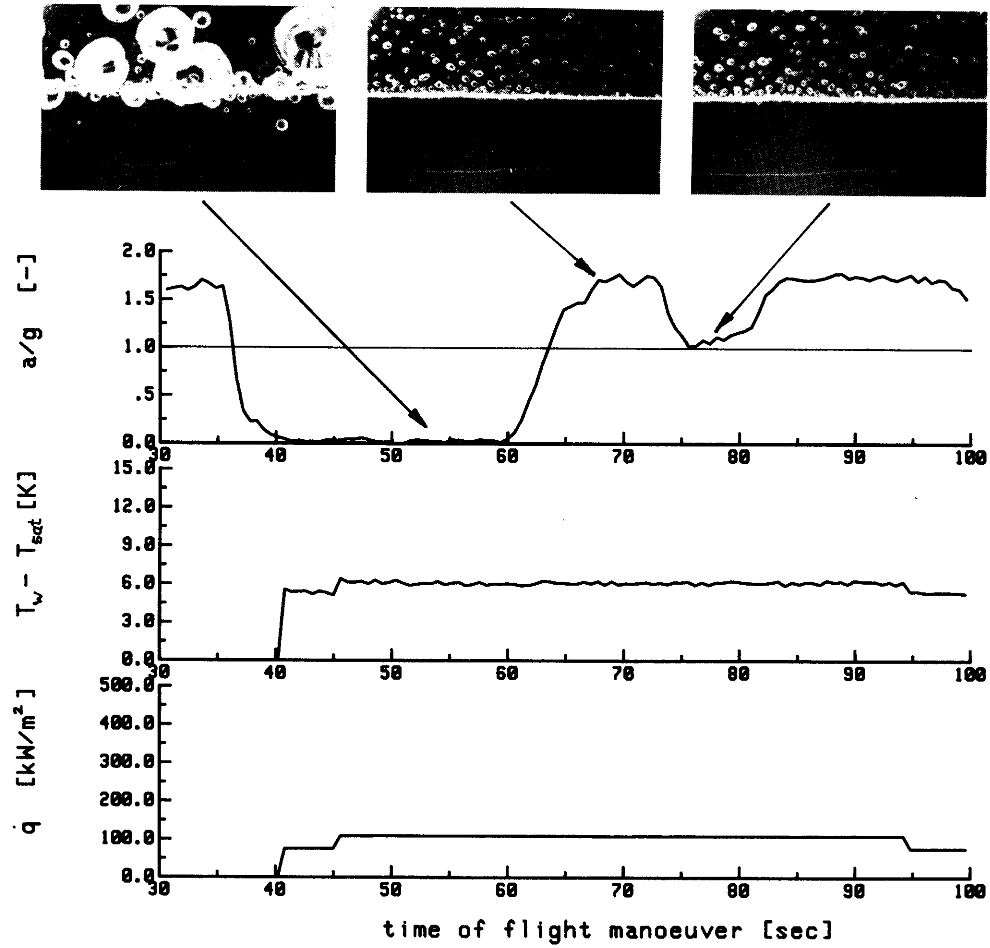

Fig. 3. Heater temperature response to variation of gravity. Platinum wire 0.2 mm dia., saturated plate, $p/p_c = 0.18$.

parabola cycle. In Fig. 2 an overview of the fluid states is given at which we measured boiling curves with four different heater types (platinum wire 0.2 mm dia., platinum wire 0.05 mm dia., flat plate 20 × 40 mm, cylinder 8 mm dia. × 50 mm).

## 3. THE BOILING REGIME UNDER MICROGRAVITY

During parabolic flight dramatic changes in the boiling regime occurred when the reduced gravity period was reached. Instead of many tiny bubbles rising due to buoyancy forces, only a few, now much larger bubbles are located near the heater. Bubble population decreases to approx. 5% compared to earth values, and simultaneously the mean bubble diameter increases by a factor of 3–8. The large bubbles stay near the heater and are fed by smaller bubbles generated at the heater wall that coalesce with the larger ones.

The most interesting factor is that the heater temperature (and consequently the heat transfer coefficient) remains nearly constant regardless of the system acceleration. One example of this behavior can be seen in Fig. 3: the values represent an experiment with a platinum wire of 0.2 mm dia. in R12 at saturated state, $p/p_c = 0.18$. The first plot shows the $g$-level of the plane vs time. Beginning with the pull-up maneuver, the acceleration

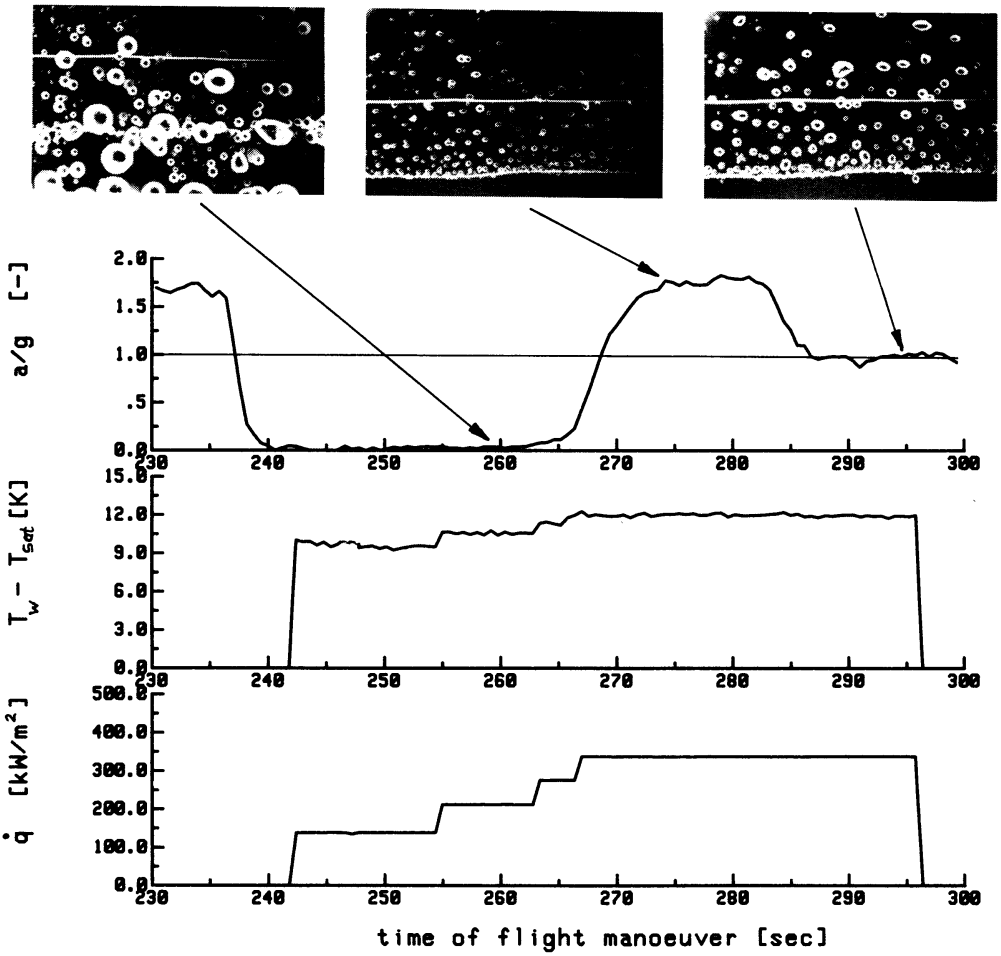

Fig. 4. Heater temperature response to variation of gravity. Platinum wire 0.05 mm dia., saturated state, $p/p_c = 0.18$.

reaches values of 1.5–1.8 *g*, then drops rapidly to "zero *g*" and increases after the parabola again. Between two parabolas, there are short breaks for reference measurements. The third plot shows the heater flux imposed on the system and the second one provides the system answer, the heater temperature. As one can clearly see, only the change of the heat flux influences the temperature significantly, but not the acceleration level during the pull-out maneuver. The pictures above the plots give an impression of the boiling regime at different experiment phases. Under $\mu g$ the bubbles may reach a size of a few millimeters. This is dependent on the heater geometry (bubbles generated at thin wires are smaller compared with the ones generated at a flat plate), the pressure ratio $p/p_c$ (decreasing bubble diameters for increasing $p/p_c$) and the fluid state (with increased subcooling, smaller bubbles as it is under terrestrial conditions). For higher gravity values the bubble departure diameters decrease in comparison to earth gravity. But the heat transfer conditions do not change, because the bubble departure frequency increases at the same time.

This is basically also true with the other heater geometries (flat plate and cylinder), although there is generally a small increase in the heater temperature for the $\mu g$ system. A second example of the boiling regime under $\mu g$ is given in Fig. 4 to show the influence of the wire thickness.

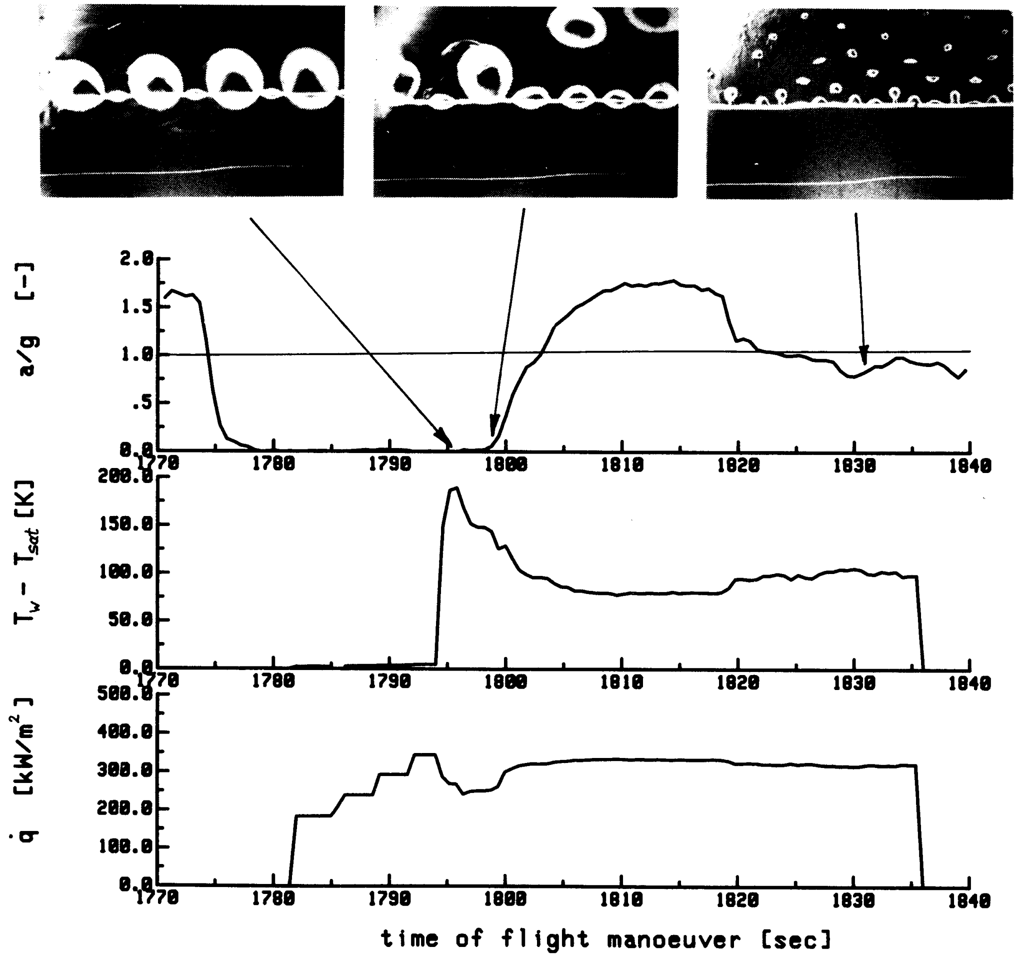

Fig. 5. Film boiling at a platinum wire 0.2 mm dia., saturated state, $p/p_c = 0.18$.

For subcooled states, the system answer is very similar to the saturated state: the $g$-level only has a slight influence, but it also dramatically alters the boiling regime. This applies to all heater types investigated.

An interesting detail in boiling research is film boiling. Especially at higher pressures and high heat fluxes, the system of pool boiling is unstable and tends to jump into the film boiling regime. This was also observed under reduced gravity conditions, although it is not one of the main scientific goals, due to the danger of damaging the heater and losing parabolas for measurements. One example is shown in Fig. 5 with three data plots and the corresponding pictures. During the reduced gravity period, the heater temperature suddenly increases by a value of over 100 K. The vapor film around the wire is regularly formed by large and small bubbles. After the transition to higher $g$-levels the temperature decreases slightly, and increases again when reaching 1 $g$. This behavior clearly demonstrates that film boiling is gravity dependent. The explanation for this behavior is, that the departing bubbles break up the vapor film. During this time, cool liquid is evaporated at the heater to form a new vapor film. This process is connected firmly with the bubble detachment frequency, which increases for increasing acceleration. Consequently the heater temperatures during the high $g$ maneuvers are lower than during $\mu g$.

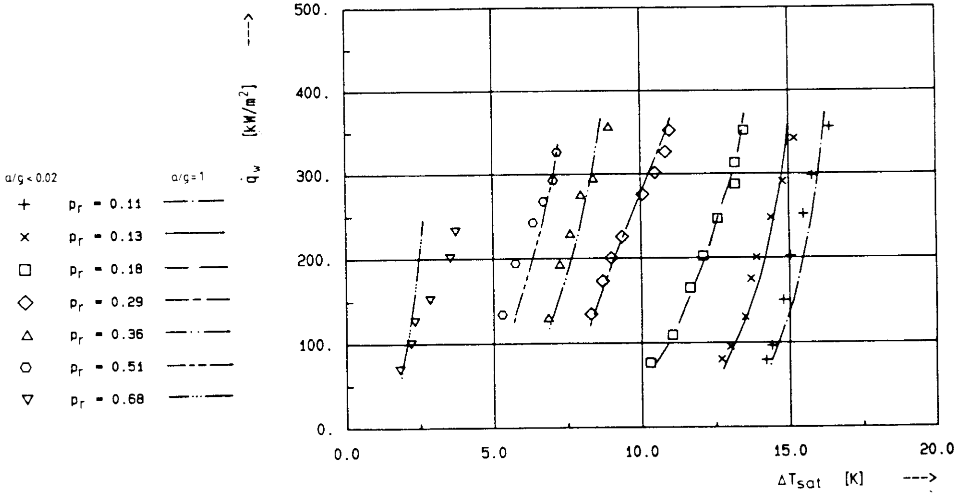

Fig. 6. Boiling curves for the platinum wire 0.2 mm dia. at saturated states, $0.11 < p/p_c < 0.68$.

## 4. BOILING CURVES

All measurements of heat transfer can be summarized in boiling curves for different heaters at the individual fluid states. Here, only a few examples should be presented to give an impression of the general tendencies in pool boiling heat transfer under microgravity. In Fig. 6 one can see the results of the platinum wire, 0.2 mm dia., for saturated fluid state ranging from low pressure ratios $p/p_c = 0.11$ up to $p/p_c = 0.68$. The symbols mark the values for reduced gravity, where as the values for 1 *g* at the same heat flux levels each are shown as lines. The measurement for "zero *g*" and 1 *g* were following each other consecutively, but not all data points are recorded with the same heater. These measurements were taken during three flight campaigns, using different wires and different FREON fillings. So a systematic error coming from a single set-up may be excluded. This also applies to the other heater geometries.

For low heat flux values, heat transfer rates are slightly higher under reduced gravity. This may be explained by the fact that natural convection influences the lower segments of the wire. Under $\mu g$ conditions boiling may act symmetrically around the wire. This fact is also the reason that at higher heat fluxes the earth system works more effectively: the natural convection here does not influence the wire itself, but it carries away the vapor volumes from the heater.

Similar behavior also occurs when looking at the results of the flat plate at saturated states (Fig. 7). The boiling curves are parallel for medium heat flux, meet at low heat fluxes and diverge after reaching critical values. The reason for the general increase in heater wall temperature is that the bubbles under $\mu g$ required more space at the wall. These "hot spots" will lead to a general increase in heater temperature. The reason for the general high wall temperature superheat (range of 3–10 K) for zero-*g* and 1 *g* is that our heaters are made of thin gold layers on very smooth glass substates. These surfaces do not provide a large number of nucleation sites as technical surfaces do by their increased roughness.

For subcooled liquid states, there is a significant change in the physics of the system. Now we have not only evaporation at the heater wall, but also condensation at the bubble

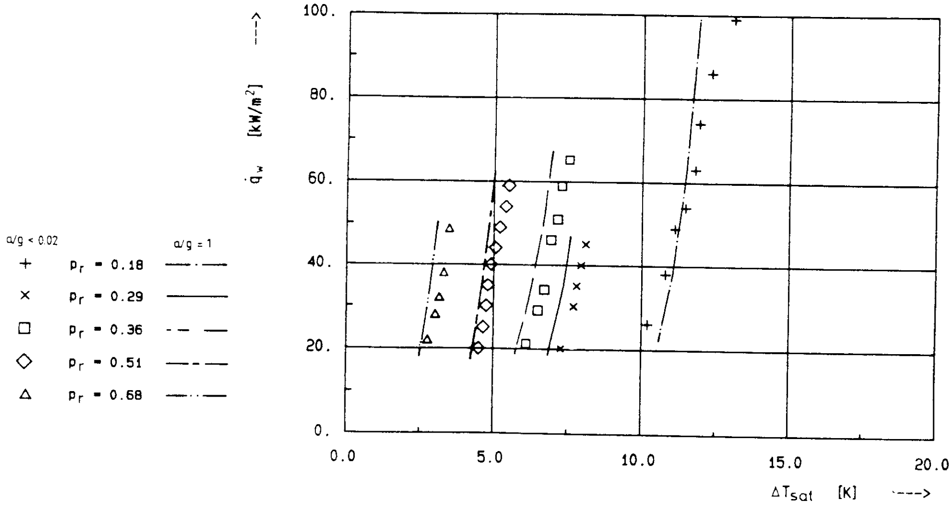

Fig. 7. Boiling curves for the flat plate at saturated states, $0.18 < p/p_c < 0.68$.

crowns. Consequently we get smaller bubbles compared to saturated fluid state, which sizes are limited by the thermal boundary layer of the heater. This, however, does not have a significant influence on the heat transfer coefficients, when compared to either the terrestrial reference point or the saturation point at the same pressure level. One interesting aspect in these experiments is the fact that the transport of enthalpy, coming out of the condensation at the bubble crowns, can't be managed by diffusion alone. But there is a new transport mechanism helping to transport this energy further on into the bulk liquid: surface tension convection, or so-called Marangoni convection on the bubbles. The liquid vapor interface close to the heater is in the superheated boundary layer; the bubble crown is at the saturation temperature or very close to it. This temperature difference induces a surface tension gradient resulting in a movement of the interface toward the bubble crown. Shear stress now moves fluid volumes next to the interface also in the direction of the bubble crown. Thus a flow is induced that is strong enough to transport this energy. If we look at pool boiling under microgravity in respect to the reduced pressure ratio, it can be stated, that fluid states (either saturated or subcooled) in the low and in the high ranges should be avoided. In the low range the limiting factor is the large density difference between the liquid and the vapor phase. Frankly stated, there isn't enough space for all vapor volumes needed to transfer high heat fluxes. In the high range the bubbles tend to form a vapor film due to decreasing surface tension. Film boiling is reached earlier at lower heat flux levels.

When comparing saturated and subcooled boiling under $\mu g$, subcooled boiling provides a more stable system behavior, because vapor is condensed directly. For saturated states the vapor volumes must be moved away from the heater and condensated separately (especially for the flat plate), otherwise the heater will turn into film boiling.

## 5. COMPARISON WITH THE THEORY

Many theoretical models of pool boiling introduce gravity as a system parameter directly or indirectly via the bubble detachment diameter. All these models fail in describing all these measurements recorded under $\mu g$. The same applies for many empirical models, consisting of terms containing gravity dependent parameters. One of them was published by Stephan *et al.* (1980):

$$Nu = \frac{\alpha \cdot d_A}{\lambda_l} = a_0 \cdot \left(\frac{\dot{q} \cdot d_A}{\lambda_l \cdot T_{\text{sat}}}\right)^{a_1} \cdot \left(\frac{c_{p,l} \cdot T_{\text{sat}} \cdot d_A^2}{a_l^2}\right)^{a_2} \cdot \left(\frac{h_{lg} \cdot d_A^2}{a_l^2}\right)^{a_3} \cdot \left(\frac{\rho_g}{\rho_l}\right)^{a_4} \cdot Pr_l^{a_5} \cdot \left(\frac{(\rho \cdot c_p \cdot \lambda)_{\text{wall}}}{(\rho \cdot c_p \cdot \lambda)_l}\right)^{a_6} \cdot \left(\frac{\rho_l - \rho_g}{\rho_l}\right)^{a_7} \quad (1)$$

with the bubble departure diameter

$$d_A = 0.851 \cdot \beta_0 \cdot \sqrt{\frac{2\sigma}{g \cdot (\rho' - \rho'')}} \quad (2)$$

the contact angle $\beta_0$ and the parameters $a_i$, which were found by a regressional analysis of data points of several authors for different fluid types. The dependency on gravity can be seen in Fig. 8, which is strongly dependent on the fluid type. According to this model, even enhanced heat transfer for $\mu g$ can be postulated for special fluids.

Our measurements can also be summarized for the different heaters, all showing the same tendencies as the ones for the platinum wire and the flat plate for saturated states. The heat transfer is slightly enhanced for low heat fluxes and slightly decreased for high heat fluxes. This trend intensifies the increasing pressure up to the critical values (see Fig. 9).

The empirical equation is only based on the data form "normal" 1 $g$ measurements. So it might be regarded unfair to extrapolate over decades of $g$. The fact remains that, if the models behind the factors in this equation are in accordance with the physics of boiling, the results should present a correct trend. This, however, is not the case here (gravity is always introduced as a variable in the model, and then held as a constant).

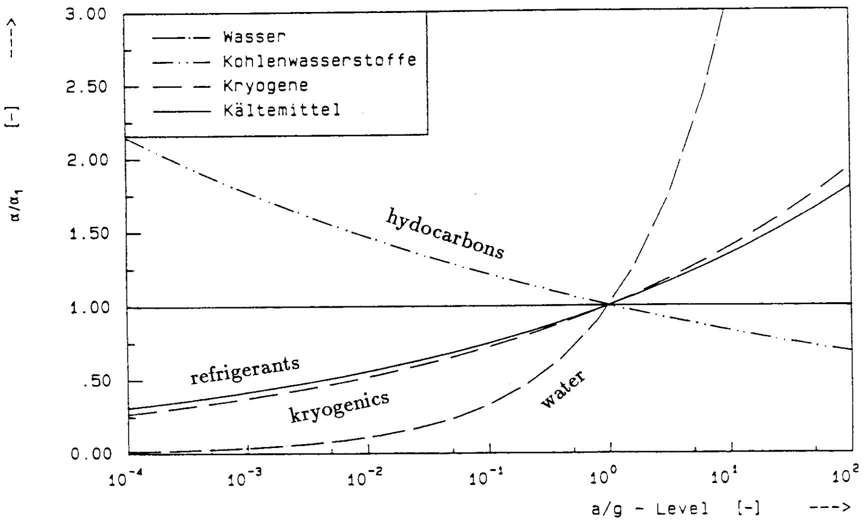

Fig. 8. Gravity dependency of the empirical model by Stephan, equation (1).

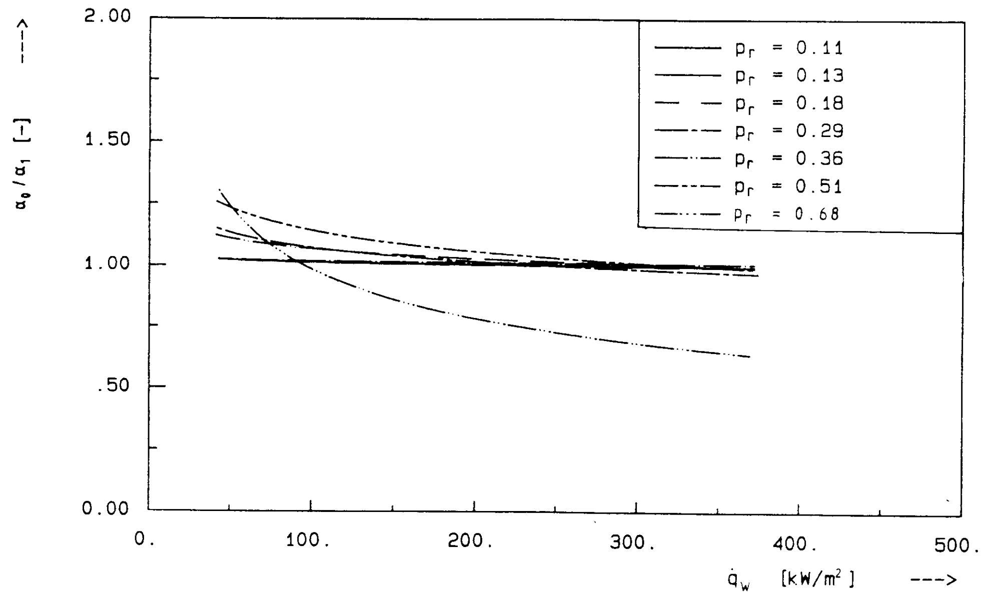

Fig. 9. Gravity dependency of the heat transfer coefficient ratio $\alpha_{\mu g}/\alpha_{1g}$ for the platinum wire, 0.2 mm dia.

As a consequence one should focus on the process of boiling in greater detail, returning to the starting point to find out what the main heat transfer mechanisms are, and how much they contribute to the entire heat transfer process. Looking at our measurements, it should be a gravity independent mechanism.

## 6. CONCLUSIONS

The process of boiling is not gravity dependent as postulated in many models of pool boiling heat transfer. The dependency is only of minor importance, and itself dependent on the reduced pressure ratio. This can be confirmed for the two refrigerants (R113, R12) as well as for water (measurement evaluation is still in progress) and for different heater geometries.

As a consequence the main heater transport mechanism must be gravity independent. At the same time, "significant parameter" as the bubble detachment diameter must be questioned strongly to be the correct physical parameter to describe boiling. All the measurements give a strong indication that the most important factor in boiling is evaporation itself, which sets the limits of this process. There are many secondary mechanisms that take over some parts of heat transfer under certain conditions, but as can be seen under $\mu g$, where most mechanisms vanish, evaporation takes over the part, often in combination with other secondary mechanisms as e.g. Marangoni convection.

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