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Boiling under Microgravity Conditions

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Abstract

Boiling is a very efficient mode of heat transfer and is therefore employed in most thermal energy conversion and transport systems as well as in component heating and cooling. Due to the great density difference between the liquid and vapor phase, it is generally assumed that the transport mechanism is strongly influenced by buoyancy forces. Therefore, gravity is seen as an important factor in all physical based or empirical correlations for boiling heat transfer. Only tests in a microgravity environment provide a means to study the real influence of gravity and to isolate gravity dependent from gravity independent factors.

During the last 10 years we were able to carry out boiling experiments at low gravity in ballistic rocket flights within the German TEXUS program and in parabolic flights with aircraft (KC 135) from NASA at Houston. Our findings were surprising that in nucleate boiling over a wide range of fluid states and heat fluxes, the heat transfer coefficient is hardly influenced by low gravity, which is in strong contradiction to the present picture of boiling, and the predictions of extrapolated equations. The critical heat flux, being the maximum heat flux for nucleate boiling, is 100 to 300 % higher than predicted by most currently accepted theories extrapolated to low gravity and even film boiling can be maintained at low gravity. Thus, the boiling process can also be used for space applications as an effective heat transfer mechanism for thermal power generation, cooling devices and other heat exchangers.

At the present stage however, the study of details of the boiling mechanism is much more significant. If gravity is not the primary force to determine boiling heat transfer, what other mechanisms are able to provide these high heat flux rates? What is the role of the internal process of evaporation and condensation within the bubble? How do surface tension and thermocapillary flow effect this process? There are many questions that remain to be solved, whereby the large bubbles generated in a low gravity environment support these studies necessary for the general, physical understanding of bubble formation and generation, and for the heat and mass exchange at the phase interface in non equilibrium two-phase systems.

This report is concerned with the present state of the art on boiling under microgravity at the various modes of heat transfer as nucleate boiling, critical heat flux and film boiling. The microgravity results are compared to data obtained under the same conditions with earth gravity.

The mechanisms of heat transport are discussed and comments are made in respect to further experimental and theoretical studies under microgravity for a better understanding of the complex boiling process.

1. Introduction and Objectives

Since the first boiling curve obtained by Nukiyama (1934), many investigations on boiling and two-phase flow heat transfer have been performed in the past fifty years. Nevertheless, the interest in boiling heat transfer is growing continually, documented by the numerous publications that appear in journals and conference proceedings. Dhir (1990) quoted two reasons for this increasing interest in his keynote presentation at the 9th International Heat Transfer Conference, Jerusalem:

1. Boiling is a very efficient mode of heat transfer and as such is employed in component cooling and in various energy conversion systems. The quest for improvement in the performance of the equipment and the demand imposed by new high density energy systems continue to motivate studies on boiling heat transfer.
2. Boiling is a extremely complex and illusive process, which continues to baffle and challenge inquisitive minds.

We continue with Dhir's comment:

> Unfortunately, for a variety of reasons, fewer studies have focused on the physics of the boiling process than have been tailored to fit the needs of engineering endeavors. As a result, the literature has been flooded with correlations involving several adjustable parameters. These correlations can provide quick input to design/performance/safety issues and hence are attractive on a short-term basis. However, the usefulness of the correlations diminishes very rapidly as parameters of interest start to fall outside the range of physical parameters, for which the correlations are developed. Also, correlations involving several empirical constants tend to cloud the physics. Thus, if we wish to reduce the repetition of experimental effort in response to changes in the physical parameters of interest in an engineering enterprise, it is important to place greater emphasis on fundamental understanding of this process. A persistent effort in this direction will go a long way in transforming studies of boiling heat transfer from an art to a science and would be attractive and exciting to new researchers.

We fully agree with this statement, and our experience in studying the effect of gravity as a variable parameter results in the same: "the usefulness of the correlations diminishes very rapidly" outside the range of earth gravity. This result may indicate that the physics of the boiling process is indeed not properly understood and is poorly represented in most correlations, if they are extrapolated to lower or higher acceleration values than earth gravity can provide.

The boiling process is very complex owing to the interaction of numerous factors and effects, as the interaction between the solid surface of the heater with the liquid and vapor, interaction between liquid and vapor itself, and the transport of liquid and vapor. Thus the microgravity environment offers the unique opportunity to study these interaction processes without, or at least with reduced buoyancy forces. Larger bubbles are generated so that optical observations can be employed to study the fundamental basis of boiling.

Thus, the basic objectives of the studies about boiling heat transfer under microgravity can be summarized in answering the following questions:

- Is boiling a stable process in a low gravity environment?
- Can the process be used for space applications?
- Can the high heat transfer coefficients be maintained and how are they compared to terrestrial values?
- What is the role of buoyancy and the departure diameter of bubbles in boiling?

- What are the dominating mechanisms, which determine the heat transfer?
- Can the correlations developed for boiling heat transfer on earth be extrapolated for applications in low gravity?
- Are these correlations physically well based?

2. Boiling technology

A heat transfer process between a solid surface, heated or cooled, and a fluid is generally described by Newton's law:

$$\dot{Q} = \alpha \cdot A \cdot (T_w - T_\infty) \tag{1}$$

Where $\dot{Q}$ is the transfered heat flux, α is called the heat transfer coefficient, A is the area involved in the heat transfer, T_w is the surface temperature of the solid wall, and T_∞ is the bulk fluid temperature in some distance from the wall. If a certain heat flux $\dot{Q}$ is transferred in technological processes, the area A and the temperature difference $(T_w - T_\infty)$ should be as small as possible; the first one for a smaller design of the heat exchanger and for the reduction of material and investment costs, and the second for higher efficiency of the thermal process. As a result, the heat transfer coefficient α should be as high as possible. Boiling heat transfer coefficients are some orders of magnitude higher than those in single phase flows. Therefore, the boiling process has a great technological significance.

The heat transfer coefficient in boiling is a complex function combining many different interacting parameters. These are: the heater geometry, heater material, surface structure and roughness, nucleate site density, dynamic wetting behavior, thermophysical properties of solid, liquid and vapor, the fluid state (saturated or subcooled), the vapor pressure and the heat flux. Moreover, many of these parameters are temperature dependent. Therefore, the usual manner to describe transport problems in fluid motion by solving the partial differential equations of the conservation laws can not be applied. Boiling heat transfer correlations are therefore based on optical observations and experimental data and can generally only be applied within the range of parameters, for which they are developed. For more general application in heat transfer, dimensionless parameters such as Nu-, Re-, Ra- and Fo-numbers were often formed to make the correlations independent from the applied scale. As a characteristic length scale in boiling, the Laplace coefficient L or the departure diameter D of the bubble, according to Fritz (1935), is used most frequently:

$$L = \left(\frac{\sigma}{g(\rho_l - \rho_g)}\right)^{1/2} \quad or \quad D = C \cdot L \tag{2}$$

where σ is the surface tension, ρ_l and ρ_g are the densities of the liquid index l and vapor index g, g is the earth gravity and C is a factor related to the wetting angle between the solid surface and the liquid. If the actual system acceleration a is a fraction a/g of earth gravity the departure diameter increases as:

$$D = C \cdot L(a/g)^{-1/2} \tag{3}$$

Thus it is evident that even in empirical correlations the actual acceleration is an important factor. Up to the present, no efforts have been made to verify experimentally how the influence of gravity can be correctly modelled in the boiling correlation. Therefore, as it will be shown later, it is not surprising that the existing correlations are quite contradictory in their representation of the influence of gravity.

3. Earlier low gravity studies

In the 1960s, an interest in the performance of boiling in gravity fields other than earth gravity arose in the United States in regard to the design of heat transfer devices for space vehicle applications. As a result, various studies have been initiated to examine both reduced and enhanced gravity effects. The influence of reduced gravity was studied in drop towers with experiment times less than 1 second. Therefore, these results are not be regarded to be representative for steady state conditions. Furthermore, the results have not been unambiguous, nevertheless, it is regrettable that they are not adequately recognized in the literature of boiling heat transfer. Unfortunately these first studies came to an end with a change of interest in the US space program at the end of the 1960s.

A review of these earlier studies of approximately 25 papers and reports is researched by Siegel (1967), especially for cryogenic fluids by Clark (1968), for Soviet research by Verkin and Kirichenko (1976) and a resume of his own studies during the 1960s and 1970s is recently presented by Merte (1989). Our own research of the last ten years is published in : Weinzierl (1982), Zell (1984), Weinzierl (1986), Weinzierl (1984), Straub (1988), Zell (1990), Straub (1990) and Zell (1991).

4. The heat transfer modes in boiling

The various modes of heat transfer in boiling can be demonstrated with the boiling curve or the so-called Nukiyama curve, fig. 1.

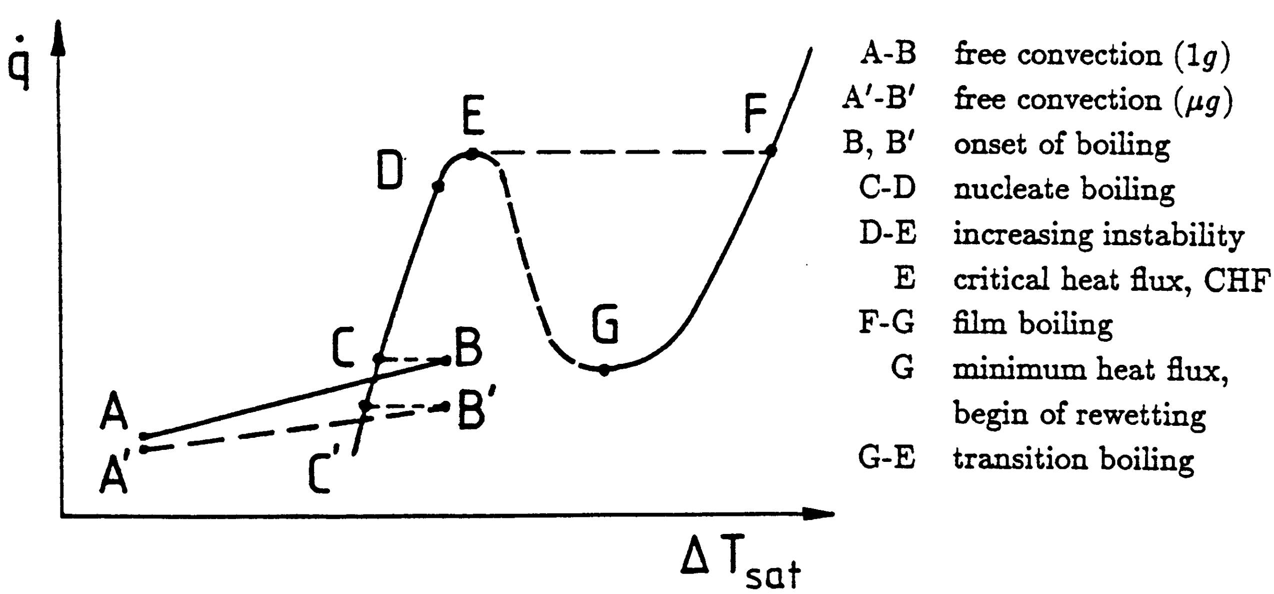

Fig. 1 Sketch of a boiling curve with the various modes of heat transfer

Convection, transient heat conduction

The first mode of heat transfer to a liquid from a heated surface with an increasing heat flux is at 1g-condition convection, A-B. The convection flow is due to a pressure difference either caused by buoyancy, called free convection, or by an imposed pressure difference along or across the surface, called forced convection. In microgravity, if forced convection is excluded, the first mode of heat transfer is transient conduction, A′- B′.

Nucleation

With increasing surface temperature, the liquid boundary layer will exceed saturation temperature and vapor bubbles appear on the heated surface, point B, B′. These bubbles are generated in cavities by heterogenous nucleation or by cavities containing a vapor embryo, called nucleate sites, and activated at a certain superheat of the liquid.

Nucleate boiling

By the inception of boiling, the wall superheat is reduced and single bubbles appear on the surface. With an increase of heat flux, more nucleate sites are activated and bubbles are generated with increasing frequencies. This mode of heat transfer is called nucleate boiling and is the most important one in the technological processes, C-D. In this region, the surface temperature increases only slowly for large changes in the heat flux. This can be expressed by a simple power law relationship:

$$\dot{q} \sim (\Delta T_{sat})^m \tag{4}$$

where $\dot{q} = \dot{Q}/A$ is the heat flux density, $\Delta T_{sat} = T_w - T_{sat}$ is the temperature difference between the surface temperature of the wall T_w and saturation temperature of the liquid T_{sat} corresponding to the saturation pressure. The exponent m depends on the fluid and nucleation properties and is found to be within 2.5 to 4.

Critical heat flux

The nucleation boiling curve in fig. 1 can be obtained in two different manners: by controlling either the temperature of the heated surface, or the heat flux as it is done in most cases. If any attempt is made to increase the value of the heat flux above E, the surface temperature will suddenly jump from E to F, the next stable operating point in the film boiling region. In many practical cases, this large temperature jump is sufficient to cause dangerous situations, like the melting of the heater surface. Hence, the term "burn-out" or "boiling crisis" is frequently used to refer to this phenomenon. The heat flux in point E is called the "critical heat flux", CHF; and D-E is the region where hydrodynamic instabilities occur.

Film boiling

The next stable mode of heat transfer on the curve is called "film boiling", F-G. At large temperature differences a continuous vapor film blankets the heater surface. The major resistance in the heat transfer is confined to this vapor film. This region is the most tractable one for theoretical studies, due to the fact that there is no contact between the liquid and the solid. The heat transfer coefficients of laminar or turbulent films for various geometries can be derived in direct analogy to the relations of filmwise condensation, based on Nusselt's film theory for condensation.

Minimum heat flux

If in a film boiling situation the heat flux, respectively the temperature is reduced, the minimum heat flux G is reached, when the rate of vapor formation reaches a point, where a stable vapor film over the heating surface can just yet be sustained. If the heat flux is a bit less than this amount, an unstable situation occurs, and the liquid vapor interface collapses. Rewetting occurs on the heating surface, cooling it and re-establishing nucleate boiling nearly at the same level of the heat flux.

Transition boiling

The transition boiling mode can be reached, if the temperature of the heater is controlled in a decreasing manner from the minimum heat flux G or an increasing manner from critical heat flux E . The liquid periodically and locally gets in contact with the heating surface with the result that the formation of large amounts of vapor pushes the liquid away from the surface and an unstable vapor film is formed. This film in turn collapses, allowing the liquid to contact the surface once more. Thus, locally the situation oscillates between a wetting and unwetting condition, respectively between nucleate and film boiling, resulting in a local oscillation of the surface temperature. In fig. 1 only the average temperature over the heater surface is represented. On electrically heated wires it is often observed that one part of the wire is in the stable nucleate boiling mode, the other in the stable film boiling mode.

There is no room in this paper to discuss all the correlations, which describe the various modes of boiling heat transfer, however, it may be evident that the buoyancy force and with it, the gravity is an important factor. Therefore, a rigorous test of these correlations and their correct physical description can be reached with experiments under microgravity.

5. Facilities used to compensate earth gravity

The earth gravity force on a body can be compensated either by acceleration in free fall, or by centrifugal force in direct opposition to the gravity force. The first category includes all "free fall" systems like: drop towers, parabolic trajectories of aircraft or ballistic rockets. The second category includes all space systems flying in an orbit around the earth.

In preparation of a shuttle flight for the GAS (Get Away Special) program, scheduled first in 1986, we began to study boiling on wires and flat plates with TEXUS 3 in 1980. It is known that the microgravity environment is as good as $a/g < 10^{-4}$ and the experimental time is 6 minutes. Even TEXUS flights are not so numerous as to study all parameters and modes of boiling heat transfer, therefore we strengthened our boiling program with several campaigns of parabolic aircraft flights KC 135 at the Johnson Space Center in Houston in 1985. During the parabolic trajectory low gravity of about $a/g = \pm 0,03$ over a period of 20 sec can be obtained, followed by a high gravity period with $a/g = 1.8$. Thus in one sequence, a variation from low to high gravity can be researched and a direct comparison between low and high gravity results is possible under the same experimental conditions. During a one day flight, a series of 30 parabolas are flown. In these parabolic flights, the experimenter handles the hard- and software himself, thus insuring the complete experiment control and optimal scientific results.

6. Instrumentation

For TEXUS and parabolic flights different cells with similar design were used as shown in fig. 2. The experimental cell was completely filled with liquid and a metal bellows compensated the volume change during boiling and kept the pressure constant according to the counter-pressure on the opposite side of the bellows. Thus, by control of the counterpressure with compressed air, the liquid state could be changed from saturation to subcooled at a constant liquid bulk temperature.

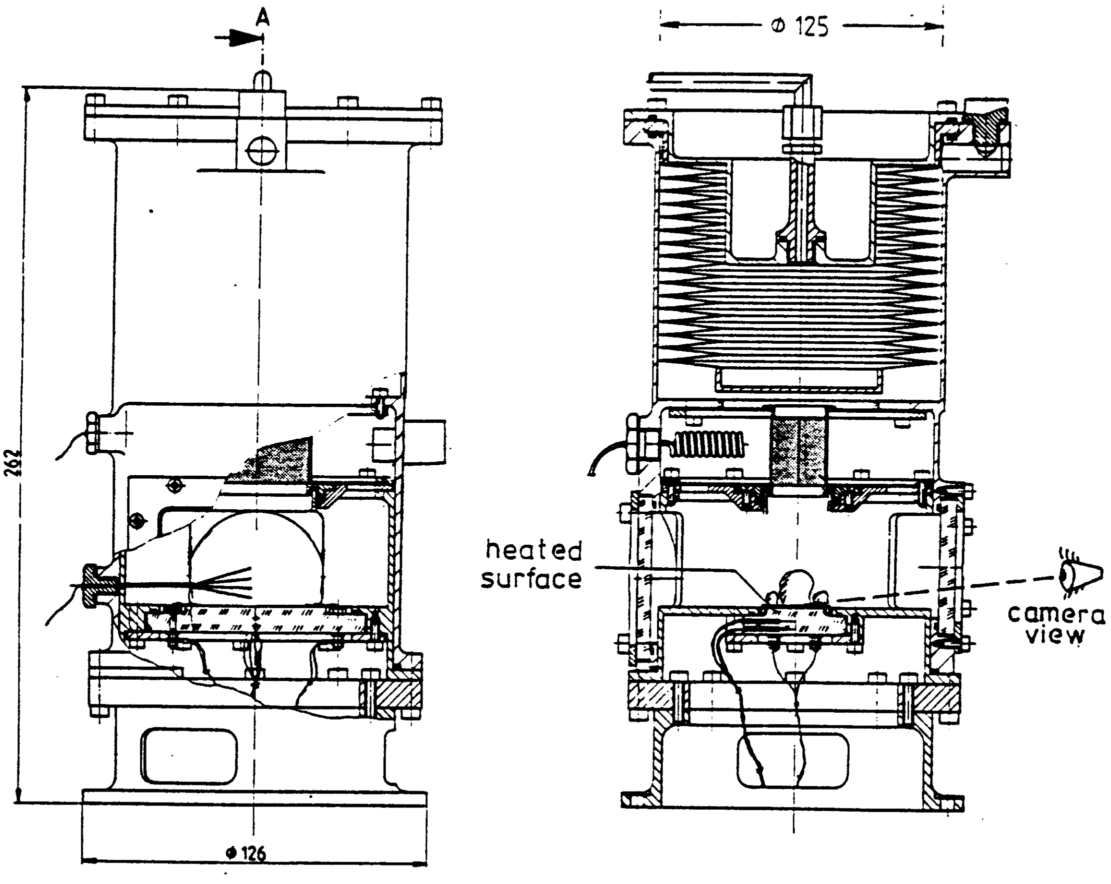

Fig. 2 Experimental cell for TEXUS. For KC 135, a similar design for higher pressure up to 45 bar was used with a larger volume of 2 ltr. The volume compensation was done in a separate cell by a bellows.

While in the TEXUS cell one heater was used at a time (wire or plate), three different heaters were simultaneously installed in the KC 135 and studied one after each other (platinum wire with diameter of 0.05 and 0.2 mm and 50 mm lenght, a gold coated flat plate 40 x 20 mm^2 and in some flights a gold coated glass tube with a diameter of 8 mm and 50 mm lenght instead of one wire). The platinum wires and the gold coatings were simultaneously used as resistance heater and resistance thermometer, measuring heat flux levels and average heater temperatures using voltage and current. The bulk liquid state is measured by several thermocouples and pressure transducer. The cell temperature can be controlled up to 110 °C.

Optical recording was possible through glass windows in the pressure cell by a 16 mm Teledyn film camera with 18 and 100 fps in TEXUS, and by a Arriflex camera synchronized with a stroboscope flash in the parabolic flight set-up.

In the TEXUS arrangement, the experiment was controlled by a timer module in the electronics, the data were transmitted to the ground by telemetry. In the aircraft, modified laboratory hardware and standard commercial equipment were used like: power supplies, digital voltmeter, scanner and a personal computer to control the experiment and record the data. The gravity level was determined by a 3-axis accelerometer. Due to the low maximum pressure of 2 bar of the TEXUS cell, R 113 was studied here at a bulk liquid temperature of about 26 °C and a pressure $p/p_c = 0.013$. To cover a wide range of pressure from $p/p_c = 0.11$ to 0.7, the refrigerant R 12 was used as test fluid in the aircraft flights; p/p_c is the reduced pressure, p the saturation pressure and p_c the critical pressure. The bulk temperature and pressure of the liquid were kept constant and at each parabola only one heater was in operation. After completing one boiling curve with 6 to 8 heat flux levels, one of the other heaters was used at the same fluid state. By changing the bulk pressure, we investigated saturated and subcooled conditions at the same bulk temperature as shown in fig. 3.

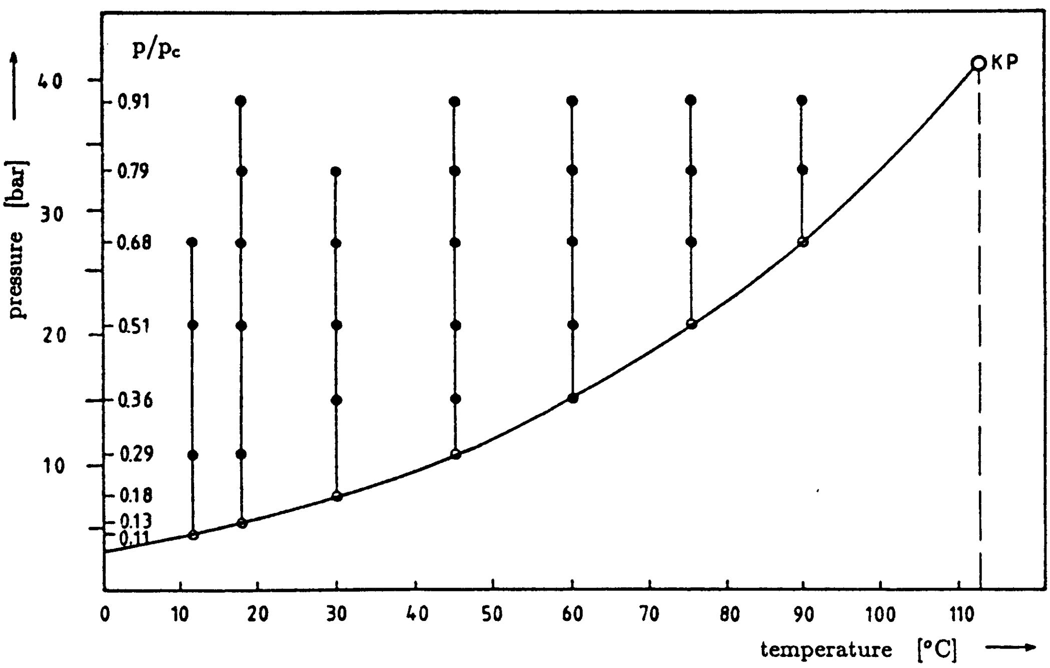

Fig. 3 Investigated fluid states of R 12 in a phase diagram during KC 135 flights

In one sequence during a parabola, low gravity and high gravity levels were obtained. The accuracy of the obtained data is good for boiling experiments and discussed in detail by Zell (1991). The main interest in this study, however, was not to get absolute values of the heat transfer coefficient, but to directly compare low and 1g conditions. In the TEXUS flight 1g data were obtained just before launch and after recovery, in the parabolic flight the data for comparison were always taken from one parabola sequence with low and high gravity at the same fluid condition.

7. Gravity as a parameter in the heat transfer correlations

All correlations for boiling heat transfer are based on physical mechanisms or developed empirically under the conditions of earth gravity; gravity is therefore used as a constant factor and is not considered as a parameter. However, if buoyancy is directly used in the physical models as the driving force for heat transfer, or if the "departure diameter" of the bubbles is introduced in empirical relations, then gravity is raised to a significant physical parameter. A comparison of those relations, extrapolated to lower or higher gravity levels, with experimental data will give a significant indication concerning the interpretation of the physical mechanisms of boiling, and of the correct modelling of the dominating effects. If we assume that gravity is a parameter and that all other parameters are constant, we can analyze the correlation in respect to the effect of gravity, which can be expressed in a power law as:

$$\alpha/\alpha_1 = (a/g)^n \tag{5}$$

where α/α_1 is the ratio of the heat transfer coefficients, with α_1 the value at earth gravity g and a/g is the fraction of the acceleration change. The sign and the value of the exponent n indicates the change of the heat transfer ratio.

8. Nucleate Boiling

8.1 Gravity dependence of correlations

The numerous correlation developed for free convection or pool boiling will not be discussed in detail in the framework of this paper. Briefly stated, they can be classified in 3 categories:

- 1. physically based equations,
- 2. dimensionless group correlations,
- 3. empirical relations.

For the process of nucleate boiling the physically based equations are supported by the following observations: after a bubble is formed in the superheated liquid layer by activation of a nucleate site, the bubble grows by evaporation in the superheated liquid boundary layer. The bubble departs from the surface, when a size is reached, at which the upward forces exceed the adhesive forces. During the departure, a part of the superheated boundary layer follows in the wake as drift flow, transporting the bubbles' enthalpy and superheated liquid into the cooler liquid bulk, while cold liquid flows back into the cavity and is heated by transient heat conduction. At lower heat fluxes, when bubbles do not occupy the entire surface, free convection can also contribute to the heat transfer. Normally, under upward heating conditions, the mean upward force is the buoyancy force, and even drift and free convection flow depend on buoyancy. The very early models, based on this observation from Jakob, Linke (1935) and improved by Rohsenow (1952), result in a strong gravity dependence with $n = 0.5$ in eq. 5. Gravity independent models are founded on the observation that in subcooled liquids, the bubbles did not depart from the heater surface, this results in $n = 0$.

In the second category the correlations are formed on the basis of group properties of the substance supposed to influence the boiling mechanisms significantly, Kutateladse (1963), Stephan (1979, 1980). These relations are valid for several substances or group of substances and are applicable for a wide range of pressure and saturation states. The coefficients and exponents are found by regression analysis and best fit the experimental data. In the dimensionless group parameters and in the Nu-number the departure diameter in eq. 3 is used as a characteristic length for the system; with it gravity is a parameter as well and an analysis of n is shown in table 1 and in fig. 4.

While the theoretical models with $n = 0.5$ indicate a large decrease in the heat transfer coefficient, the dimensionless group correlations shows no uniform behavior. It is of interest to note that measurements at higher gravity levels in centrifuges result in lower heat transfer coefficients, Körner found $n = -0.48$ and Judd and Merte a weaker dependence with $n = -1/6$.

Author	substance	n
Physical model for saturation	—	0.5
Physical model for subcooling	—	0.
Stephan, Abdelsalam (1980)	water	0.4825
	hydrocarbons	- 0.083
	cryogenics	0.143
	refrigerants	0.1275
Stephan, Preußer (1979)	all.substances	- 0.033
Kutateladze (1963)	different fluids	- 0.35

Table 1: Gravity influence according to eq. (5)

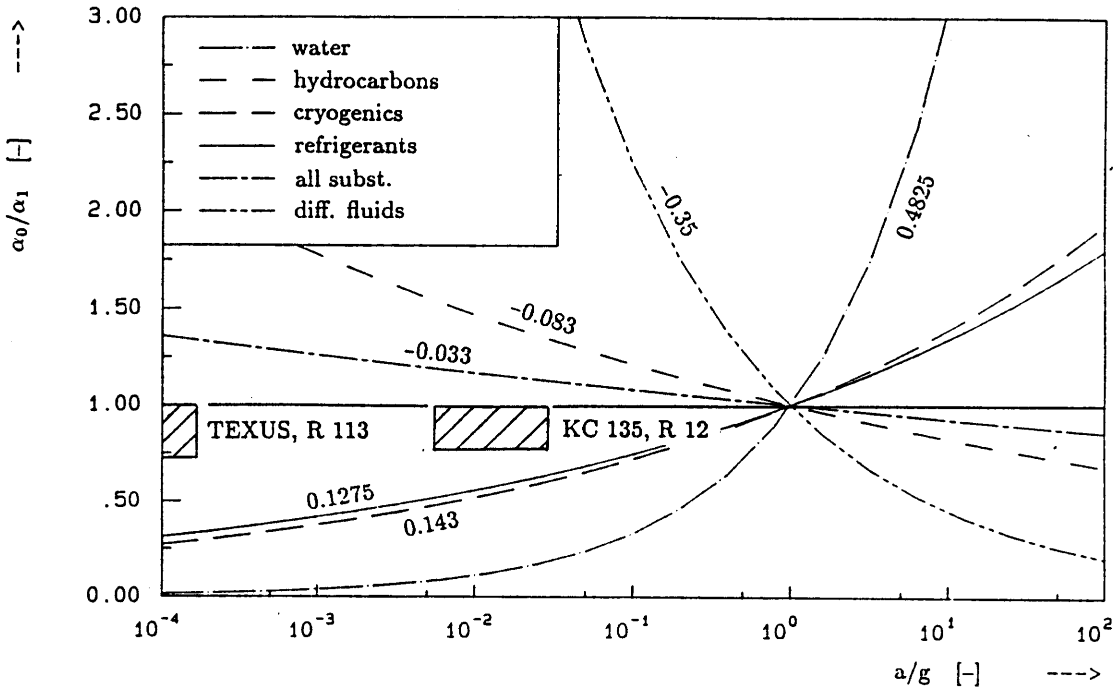

Fig. 4 Variation of heat transport ratio by gravity extrapolation for various correlations of nucleate boiling, compared with the results of this research.

8.2 Results from aircraft flights

Saturated fluid state

A typical parabola sequence of nucleate boiling is shown in fig. 5 on a wire of 0.2 mm dia. at saturation state of R 12 at a reduced pressure $p/p_c = 0.18$. The gravity level a/g, the temperature difference $\Delta T_{sat} = T_w - T_{sat}$ and the power $\dot{q}_w$ of the heater are plotted versus the experimental time. The power was switched on during a low gravity period at 40 sec on the time scale, thus eliminating convection before this stage. Due to the small heat capacity of the wire, the temperature response was very fast after power on and the change of power at 45 sec. At a constant power level from 45 to 94 sec the temperature remains constant even when the acceleration increases from $a/g \approx 0.01$ to 1.8 and decreases to 1 again. The small wiggles in the temperature curve are due to the last digit in the resolution of the temperature. The photographs show the dependence of bubble size on gravity, large bubbles at low gravity and small bubbles at high gravity. Between $a/g = 1.8$ and 1 the average bubble size is barely reduced. It is clearly demonstrated that the heat transfer coefficient is neither influenced by gravity nor by the bubble size at this fluid state. α/α_1 remains nearly constant, but even ratios of $\alpha/\alpha_1 > 1$ have been observed at lower heat flux levels.

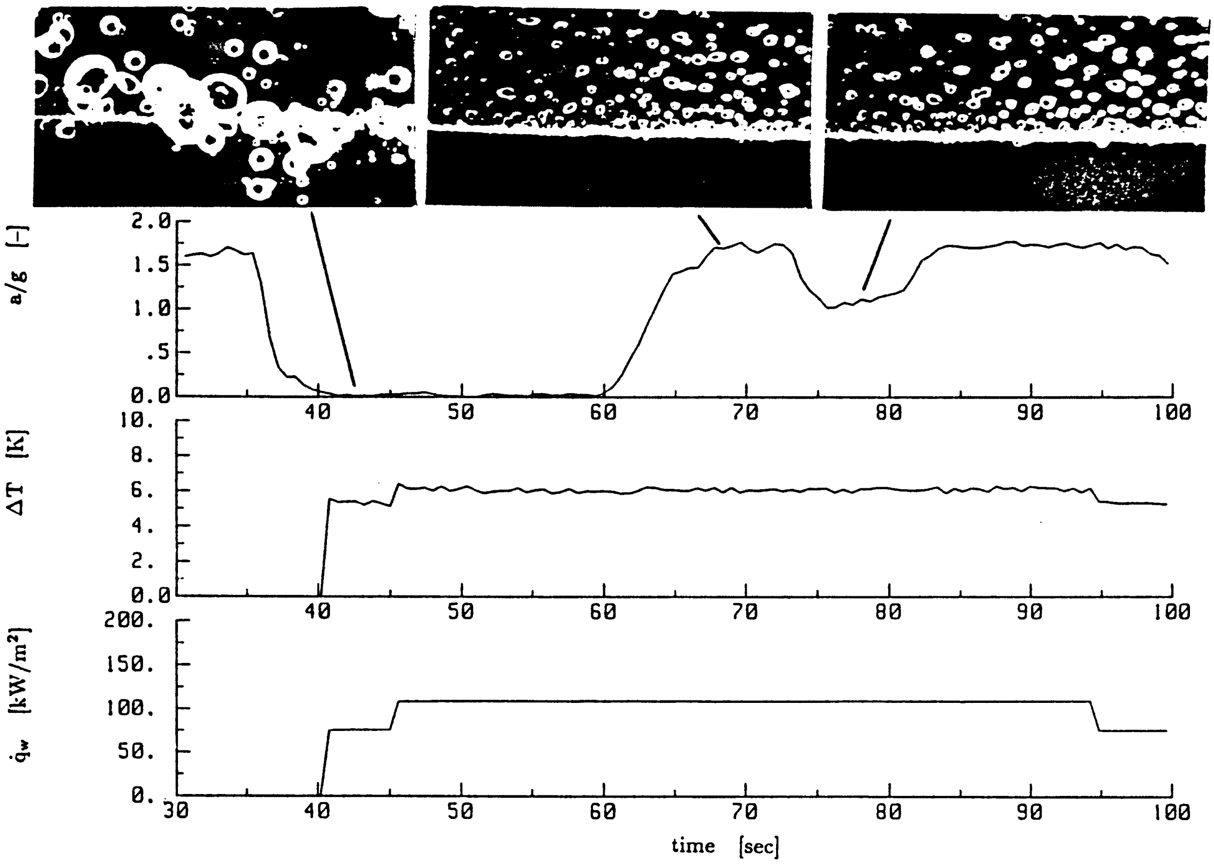

Fig. 5 A parabola sequence, a/g level, wire temperature, heat flux at nucleate boiling $p/p_c = 0.18$, versus time

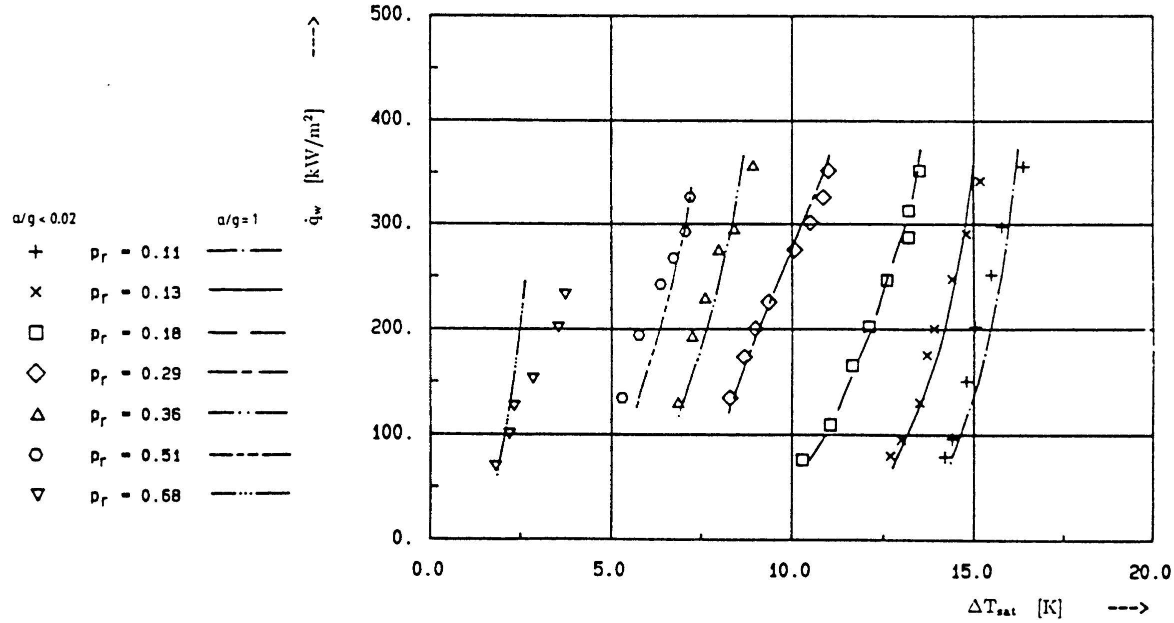

Fig. 6 Nucleate boiling curve for a wire of 0.2 mm dia. in R 12 at various saturated fluid states.

These investigations are carried out for saturated and subcooled fluid states from $0.1 < p/pc_c < 0.7$, see fig. 3 and for four heater configurations: wires with 0.05 mm dia. and 0.2 mm dia., flat plate gold coated surface 40 x 20 mm^2 and tube 8 mm dia. and 50 mm length. The results are evaluated for all heaters by Zell (1991) and plotted as boiling curves with

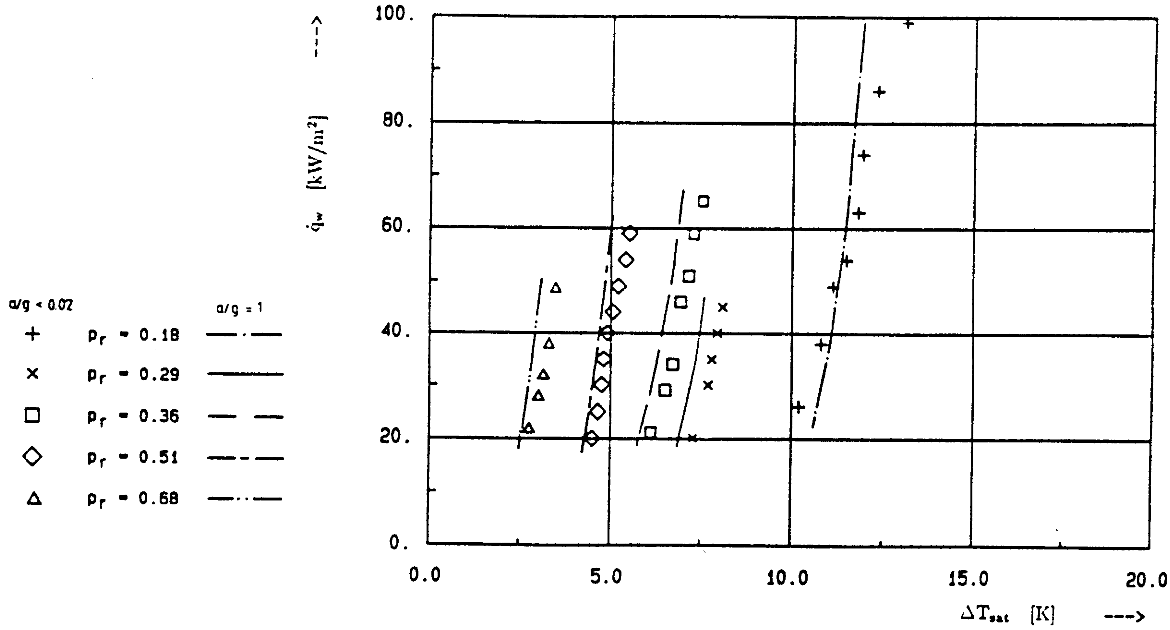

Fig. 7 Nucleate boiling curve for a flat plate in R 12 at various saturated states.

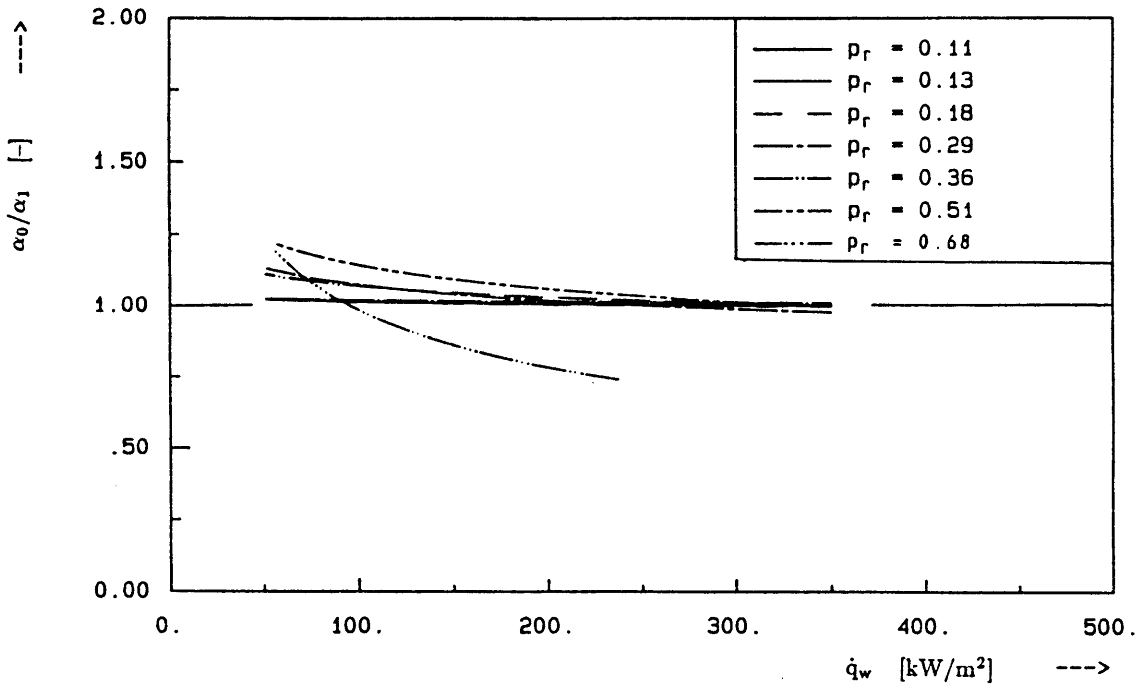

Fig. 8 Heat transfer ratio on the wire dia. 0.2 mm, values from fig. 6

the heat flux density $\dot{q}_w$ versus the temperature difference $\Delta T_{sat} = T_w - T_{sat}$. Only two examples will be shown for the wire 0.2 mm dia. and the flat plate with the bulk liquid being at saturated state for different p/p_c values in fig. 6 and 7. The symbols represent the data obtained at low gravity $a/g = \pm 0.02$, while the lines represent $a/g = 1$ reference data measured immediately after low gravity in the consecutive period of the parabola. The evaluation with respect to the heat transfer ratio α/α_1 versus heat flux density is shown for these two heaters in fig. 8 and 9. From these figures it can be seen that the heat transfer coefficient for wires is even higher than at earth gravity for low heat flux levels. This may be attributed to the fact that at low gravity all nuclei sites around the wire are equally activated. As a result, boiling occurs symmetrically around the wire at low gravity, whereas at 1 g the lower stagnation point is cooled by free convection and only the upper

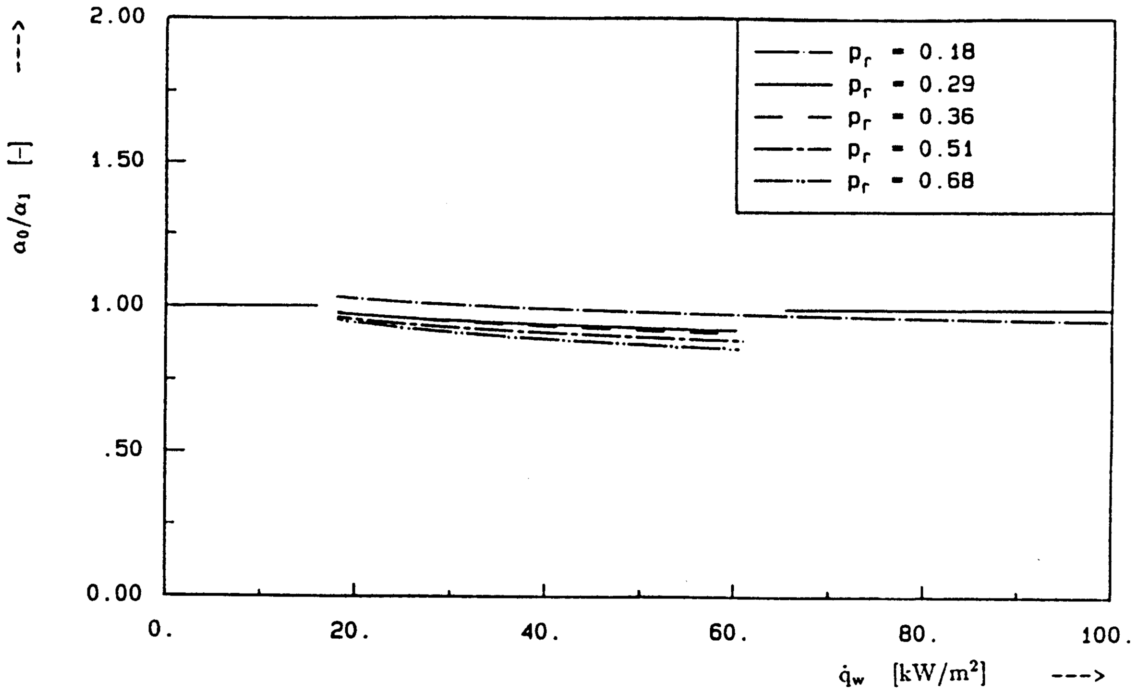

Fig. 9 Heat transfer ration on the plate, values from fig. 7

circumference of the wire is preferred for boiling. Similar behavior can be observed with the other geometries: if convection is eliminated, more nuclei sites are activated at low heat fluxes. The reduction of the heat transfer coefficient at higher heat flux is caused by the larger bubbles and the connected increase of dry areas at the heater below them. At higher system pressure, especially observed on the wires at $p/p_c = 0.68$, α/α_1 decreases by 25% with higher heat flux. This may be due to the small surface tension closer to the critical point. We have observed similar behavior on the tube and on the wire with 0.05 mm diameter.

<u>Subcooled fluid states</u>

As it may be seen in fig. 3, many subcooled fluid states have been investigated. Only one boiling curve at the constant bulk temperature $T_B = 30°C$ on the wire with 0.2 mm dia. is demonstrated here in fig. 10. The temperature difference of subcooling is $\Delta T_{sub} = T_{sat} - T_B$, where T_{sat} corresponds to the actual pressure of the system. It can be seen that the values at low gravity, the symbols in fig. 10, and the values at 1g, expressed by the lines, are nearly identical. Thus the heat transfer coefficient is nearly independent from gravity even in subcooled nucleate boiling.

8.3 Results from TEXUS flights

8.3.1 Boiling on wire

<u>Saturated state</u>

In the TEXUS flights we have used R 113 as a test fluid with bulk temperature about $T_B = T_{sat} = 26$ °C with heat fluxes from 40 to 276 kW/m^2. At low heat fluxes the heat transfer coefficient is the same as in the reference experiment at 1g and is about 4% less at higher heat fluxes. Due to the good quality of the acceleration level $a/g < 10^{-4}$ and no noticeable disturbance in the acceleration, we can observe in the film the following mechanisms:

- single bubbles spring from the surface in all directions

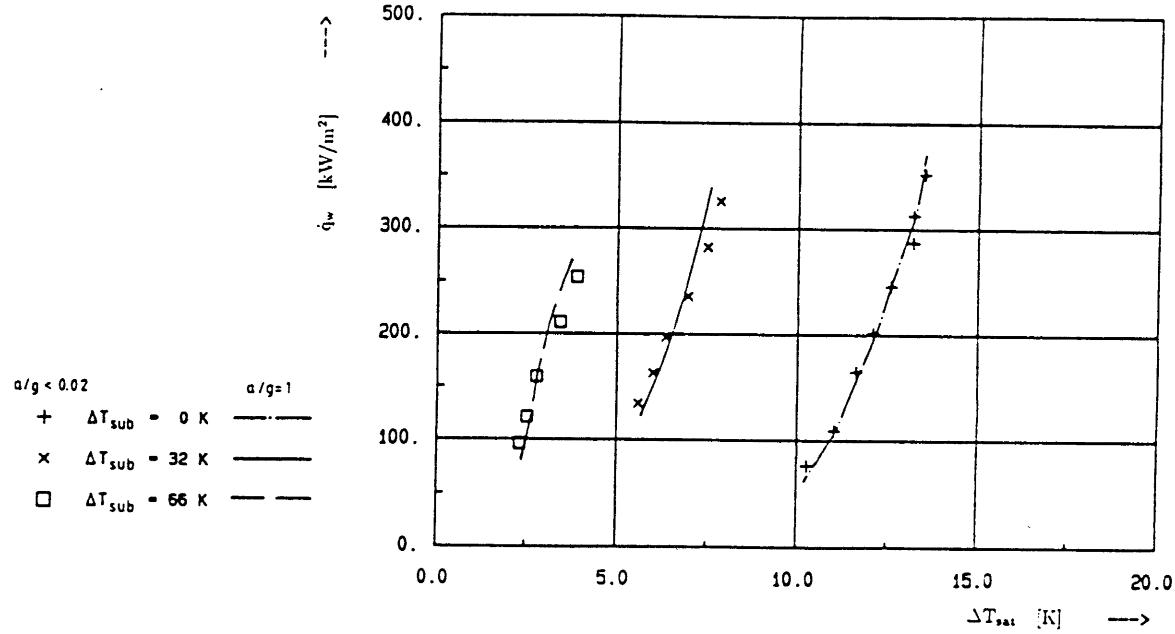

Fig. 10 Nucleate boiling for subcooled states at the wire 0.2 mm dia. with liquid bulk temperature $T_B = 30°C$, symbols are data at low gravity, lines at 1g.

- two or three bubbles coalesce at the wire, and jump from the surface,
- bubbles have various sizes and departure frequencies, the size is two or four times larger than the diameter of the wire,
- the frequency increases with increasing heat flux,
- the bubbles do not condensate, they coalesce in the liquid to larger bubbles,
- convection is induced by the departure of springing bubbles.

Subcooled boiling:

By increasing the pressure to $p = 1$ bar at 26 °C bulk temperature, a subcooling of $\Delta T = 22$ K was established. Between 40 and 441 kW/m^2 steady state nucleate boiling was achieved. At the next step of the heat flux of 450 kW/m^2 film boiling occured, and the power was switched off by an automatic control system. At the $1g$ reference test, which was influenced by convection, boiling begins at a heat flux of 131 kW/m^2. The heat transfer coefficient is the same at lower heat fluxes and 2% less at higher heat fluxes compared to $1g$. We observed the following:

- the bubbles are usually attached to the wire,
- after a lifetime of some tenth of a second they can condense, however, some have a much longer lifetime,
- only a few bubbles depart from the heater surface due to the coalescence process and they condense immediately after departure. At higher heat fluxes, more bubbles depart from the surface, the bubble population density increases as well as the number of coalescing bubbles.
- the main transport mechanism seems to be evaporation and condensation.
- additional convection around the bubbles is observed, which we explain as thermocapillary convection (Marangoni convection).

Similar observations are made in the subcooled $1g$ experiment, here the bubbles remain attached to the surface and the Marangoni convection around the bubbles superimposes the buoyancy convection, which is even strong enough to act against gravity.

8.3.2 Boiling on flat plate

Saturated boiling

Compared to saturated boiling on a wire, the boiling phenomena on a flat plate at very low system pressure of $p/p_c = 0.013$ in R 113 is different. After onset of boiling at a heat flux of 28 kW/m^2, the first bubble grows slowly within in 1 sec to nearly the size of the heater, see fig. 11. In the film, one can observe that small bubbles are formed in the liquid triangle between the heater and vapor, and immediately coalesce with the larger ones. The temperature response of the heater is shown in fig. 12 versus time for μg and $1g$ conditions.

Fig. 11 First growing bubble in R 113 at saturation

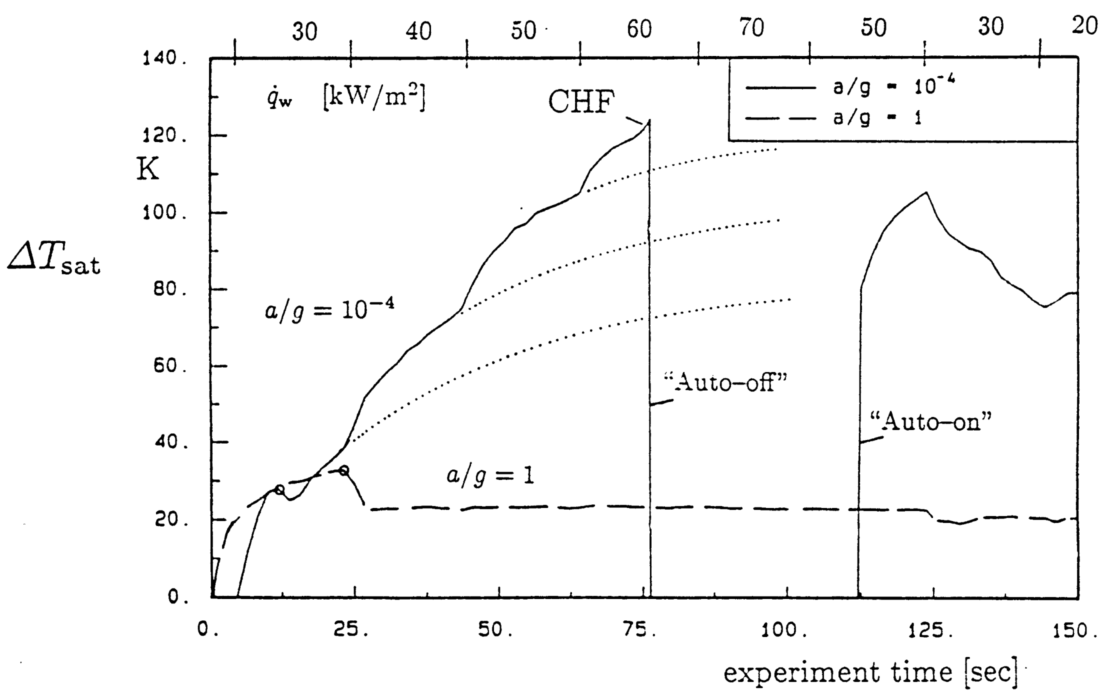

Fig. 12 Temperature response of μg and $1g$ experiment for saturated boiling at low pressure $p/p_c = 0.013$ in R 113

The heat flux is increased in steps of 10 kW/m^2 every 20 seconds. In the μg experiment, the temperature increases after each heat flux step, however, with a decreasing gradient, which indicats a tendency to an asymptotic constant value. It can not be excluded that with a larger heater surface and a longer period of constant heat flux, steady state boiling would have been achieved, however, with heat transfer coefficients much less than at earth conditions. At the 60 kW/m^2 heat flux step the system runs into a burn-out situation with a strong increase of surface temperature and an increasing gradient. An automatic control system switches power off. By reducing the power to 50, 30 and 20 kW/m^2, the surface temperature decreases and it appears that a constant surface temperature can be achieved.

With very large bubbles (30 to 40 mm in diameter) at the low system pressure, a large portion of the heater surface is covered by vapor and this dry area raises the average temperature of the heater.

Transition from saturated to subcooled boiling:

While the heater was nearly covered by one large bubble, the pressure was increased starting from the saturated situation previously described. Thus, the bulk liquid state was suddenly altered to a subcooling of $\Delta T = 25$ K, whereas the heat flux was kept constant at 30 kW/m^2. Fig. 13 demonstrates the immediate thermal stabilization for the μg system.

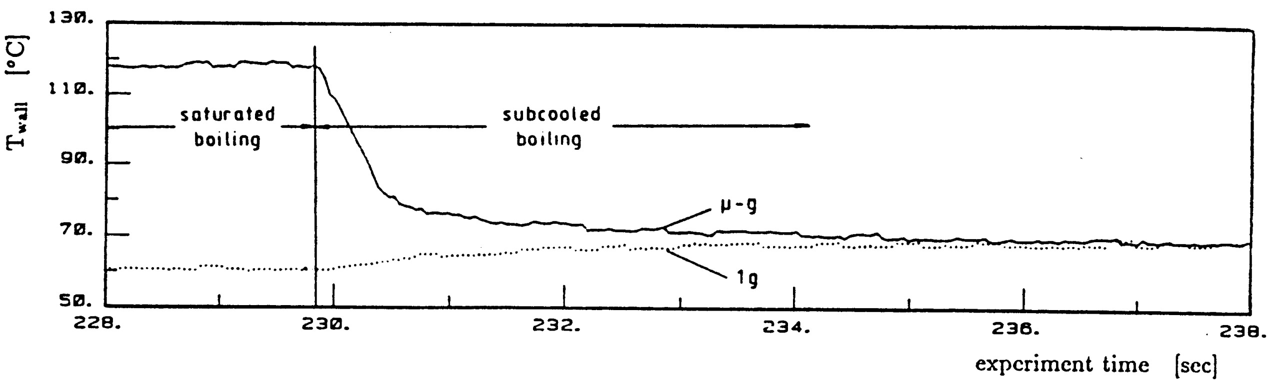

Fig. 13 Transition from saturated to subcooled boiling by pressure increase.

The vapor of the large bubble was condensed and the system returns to nucleate boiling after a few seconds. The heater surface temperature is almost equal to the terrestrial reference experiment.

Subcooled boiling

Some experiments of subcooled boiling are performed at various rates of subcooling by variation of pressure. A typical series of pictures of bubble growth is seen in fig. 14. Boiling is first initiated at a single point in the center of the heater surface, and then begins to spread.

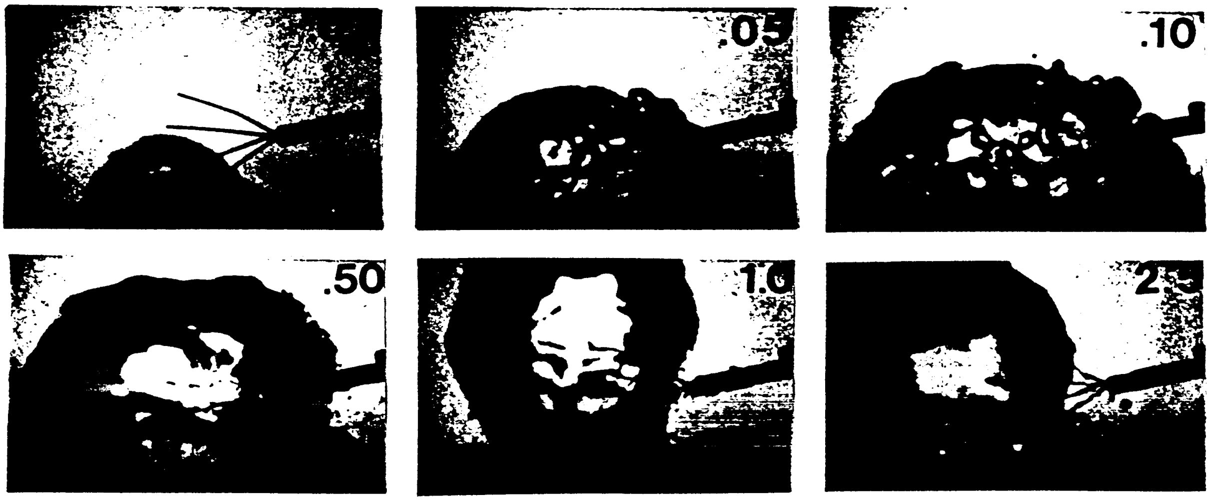

Fig. 14 Development of the first bubble after boiling inception

A bubble of semi-spherical shape covered the heater in less than 0.1 seconds. Bubbles formed at the edge of the bubble, are lifted by the growing bubble, that looks pock-marked. After

1.2 sec the bubble grows large at the base, the smaller bubbles at the base coalesce, or more precisely, feed the larger one. At the top, the bubbles condensate in a very dynamic process. Steady state conditions are reached after about 4 sec. In the series of photographs in fig. 15, steady state boiling is seen up to 42 kW/m^2.

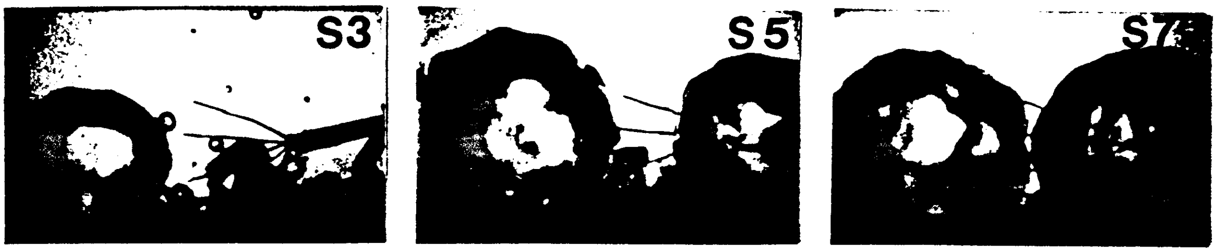

Fig. 15 Steady state subcooled boiling on a plate for various heat fluxes

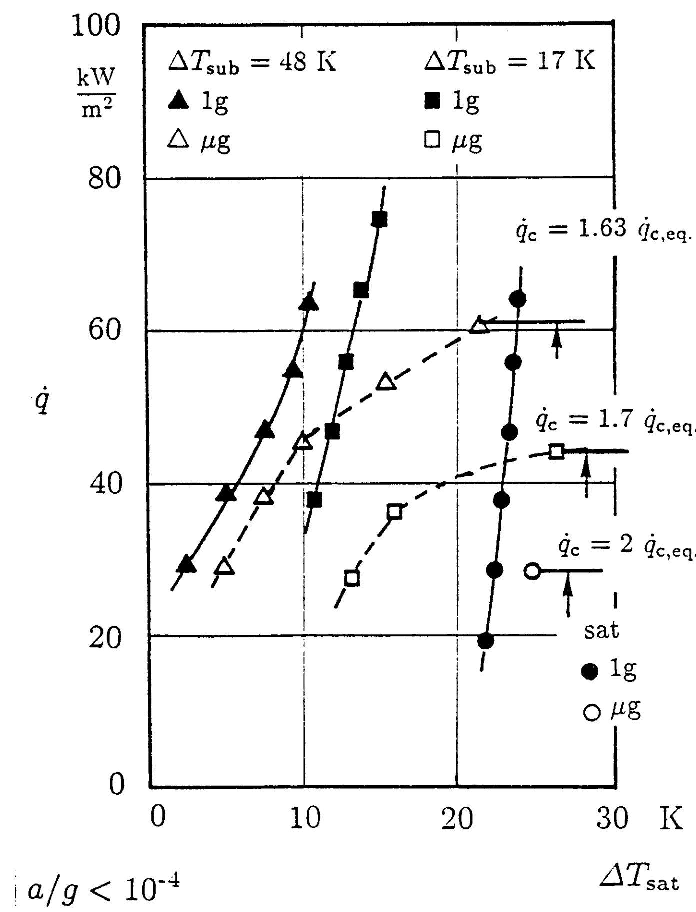

Fig. 16 Boiling curves for the R 113 / flat plate system measured in TEXUS

Very few bubbles depart from the surface, sometimes they are lifted up and replaced by smaller bubbles growing below. At the same time two larger bubbles can be observed, establishing a mass flow through the bubble by coalescence at the base and condensation of vapor at the crown. At 50 kW/m^2 the heater temperature increases, however, with a decreasing gradient. A stationary heater temperature might have been achieved, if the period for one heat flux step could be prolonged. In fig. 16 the boiling curves for saturated and subcooled boiling are plotted. The low gravity curves, in comparison to $1g$, are characterized by higher temperatures and lower heat transfer coefficients.

9. Critical Heat Flux

Theoretical correlations for critical heat flux (CHF) were obtained using the well-known Taylor-Helmhotz instabilities for liquid interfaces. The hydrodynamic instability model by Kutateladse und Zuber for plates predicts the critical heat flux in good agrrement with experimental data and is the widely accepted. The relation of Zuber (1959) for flat horizontal plates of infinite dimensions with an upward facing surface is written as:

$$\dot{q}_{c,\infty} = 0.131 \cdot h_{l,g} \cdot (\sigma \cdot g \cdot (\rho_l - \rho_g))^{1/4} \sqrt{\frac{\rho_g \cdot \rho_l}{\rho_l + \rho_g}} \tag{6}$$

For heaters of finite dimensions the CHF depends on the geometry as well as its characteristic dimensions. A typical dimension of a hydrostatic instability problem is the Laplace coefficient, as seen in eq. (2).

Many papers investigate these geometric effects, see the fundamental summary of Lienhard and Dhir (1973). For small tubes and wires with radius R, a dimensionless radius R' , is formed by

$$R' = \frac{R}{L} = R\sqrt{\frac{g(\rho_l - \rho_v)}{\sigma}} \tag{7}$$

and the Zuber relation was extended by Lienhard and Dhir to

$$\dot{q}_{c,R} = 0.94 \cdot \dot{q}_{c,\infty} \cdot R'^{-0.25} \tag{8}$$

valid for $R' < 1$. This relation predicts an increasing CHF for decreasing R', based on 900 experimental data available at that time, including reduced gravity data. However, it seems to be a limit at $R' \approx 0.1$; with further decrease of R', 60 experimental data of CHF decrease as well. Therefore the validity of eq. (8) is assumed between $0,1 < R' < 1$. From eq. (6) the gravity influences for plates and larger tubes can be developed to the critical heat flux relation:

$$\frac{\dot{q}_{c,\infty}}{\dot{q}_{c,\infty,1}} = (a/g)^{1/4} \tag{9}$$

where the index 1 indicates the CHF value at $1g$. For small tubes and wires from equations (6),(7) and (8) the gravity dependence are derived to be:

$$\frac{\dot{q}_{c,R}}{\dot{q}_{c,\infty,1}} = (a/g)^{1/8} \tag{10}$$

As discussed before, this relation is valid between $0,1 < R' < 1$. Our experiments at low gravity were conducted to primarily study nucleate boiling and only incidentally CHF, therefore we do not have a full set of experimental data for a proper comparison with the theory. We compared, however, the data received to the equation of Zuber (1959), extended for finite geometries and for wires according to Lienhard and Dhir (1973) with the extension from Zuber et al. (1961) for subcooled liquids. In this relation the increasing effect of CHF for subcooling is diminished by $(a/g)^{3/4}$.

A properly defined gravity quality is available in the TEXUS experiments with $a/g < 10^{-4}$ and with a wire of a radius 0.1 mm ($R' = 0.001$) we are outside of the valid region of eq. (8) and (10). According to present knowledge, the CHF is much less than the calculated one by eq. (8). Under the given experimental conditions we calculate with Zuber (1959) and the correction for small wires from Lienhard and Dhir (1973), the value of 75.6 kW/m^2 for saturated state. However, we have obtained in the experiment 276 kW/m^2, this is approximately 3.7 times higher than the calculation. In case of subcooled boiling the calculated value for CHF is 135 kW/m^2, whereas the experimentally obtained one is 450 kW/m^2, respectively 3.3 times higher than the theory predicts. It is surprising that the CHF data for the wire are more than 3 times higher than predicted, if the relations are extrapolated over the range of their present validity. A decrease of CHF, as found in some experiments, could not be observed for $R' < 0.1$

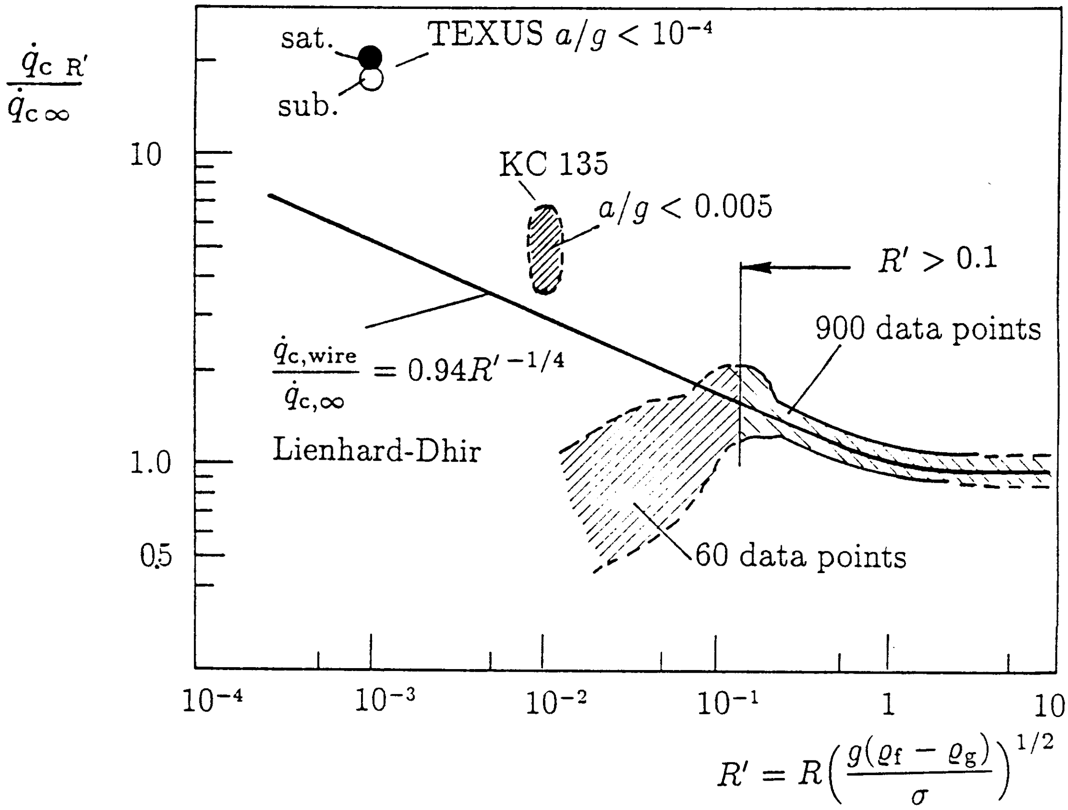

Fig. 17 Critical heat flux for wires similar to a plot of Lienhard and Dhir, extended over two decades in R' and heat flux relation in a logarithmic scale.

In fig. 17 the results for wires are plotted in a similar graph as originally used by Lienhard and Dhir, where the dimensionless radius R' is extended over two decades and the critical heat flux ratio $\dot{q}_{c,R'}/\dot{q}_{c,\infty,1}$ is in a logarithmic scale. The 900 data points which follow the Zuber-Lienhard, Dhir relation are marked as an area and the 60 data points, which miss this relation are also marked. The values obtained in TEXUS for wires at the good low gravity level are about 20 times higher than the predicted values on a flat plate by Zuber and 3.3 to 3.7 times higher than the theory of wires predicts.

The area marked with KC 135 represent about 30 data points from the parabolic flights, which are 1.2 to 2 times higher than the theoretical one on wires. In the parabolic flight experiments the gravity level a/g was alternating between ± 0.03. We have observed that at a high heat flux the transition to film boiling occured on the wires if the acceleration was reduced below $|\, a/g \,| < 0.005$. The dimensionless radii R' for these experiments are about 10^{-2}.

The calculated critical heat flux for the saturated flat plate experiment in TEXUS is about 14 kW/m^2, half the value we observed for the onset of boiling. Carefully estimated, we may say, that the experimental CHF is 2 times higher than the calculated one. The same observation is made in the case of subcooled liquids with a factor of 1.7 for $\Delta T_{sub} = 17$ K and 1.63 for $\Delta T_{sub} = 48$ K . If we assume, that steady state boiling can be obtained after the asymptotic increase of the average plate temperature according to fig 12., the CHF would be even much higher and factors between 3-4 would be obtainable. In fig. 18 the original plot of Siegel (1967) is extended in the ordinate in two decades of a/g. On the abscissa the ratio of the experimental CHF to predictions for wires and plates are shown.

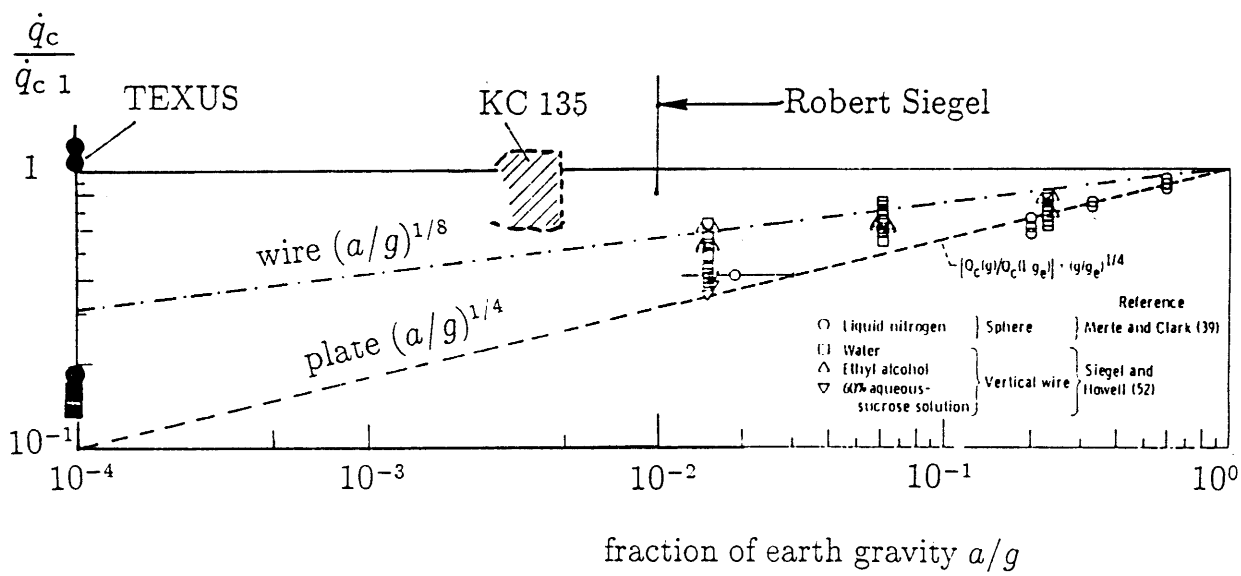

Fig. 18 CHF ratio from Siegel (1967), extended over two decades of a/g

The comparison of experimental data with the theory illustrates that the CHF theory based on hydrodynamic instability of the vapor film can not be applied at low gravity. Because buoyancy is not the driving force even in nucleate boiling, surface tension, coalescence and other effects are more dominating.

10. Film Boiling

Nucleate boiling close to the critical heat flux is a situation of great instability and very difficult to control. By an infinite small increase of the heat flux, the surface is suddenly covered with a vapor film, which yields to a sudden jump of the surface temperature due to the insulation effect of vapor. The transition from nucleate to film boiling is shown in a series of pictures, taken from a parabolic flight sequence, and the corresponding records of the acceleration a/g, the temperature difference ΔT_{sat}, and the power, fig. 19.
At the first and following power steps, nucleate boiling occurs with low wire temperature of about $\Delta T_{sat} = 10$ K. At a heat flux of 300 kW/m^2 the system change to film boiling with an increase of ΔT_{sat} to 300 K. Now small g-variations change the heater temperature, but film boiling is still maintained during 1.8g and 1g periods. The photos show the different behavior of the closed vapor film. It is formed by surface tension into a chain of large and small bubbles with a distance of about the Laplace length. The small bubbles pump the vapor toward the large bubbles by the pressure difference between them and peristaltic motion. The vapor hose is very sensitive to disturbances of the g-level, which can be seen in the temperature record.

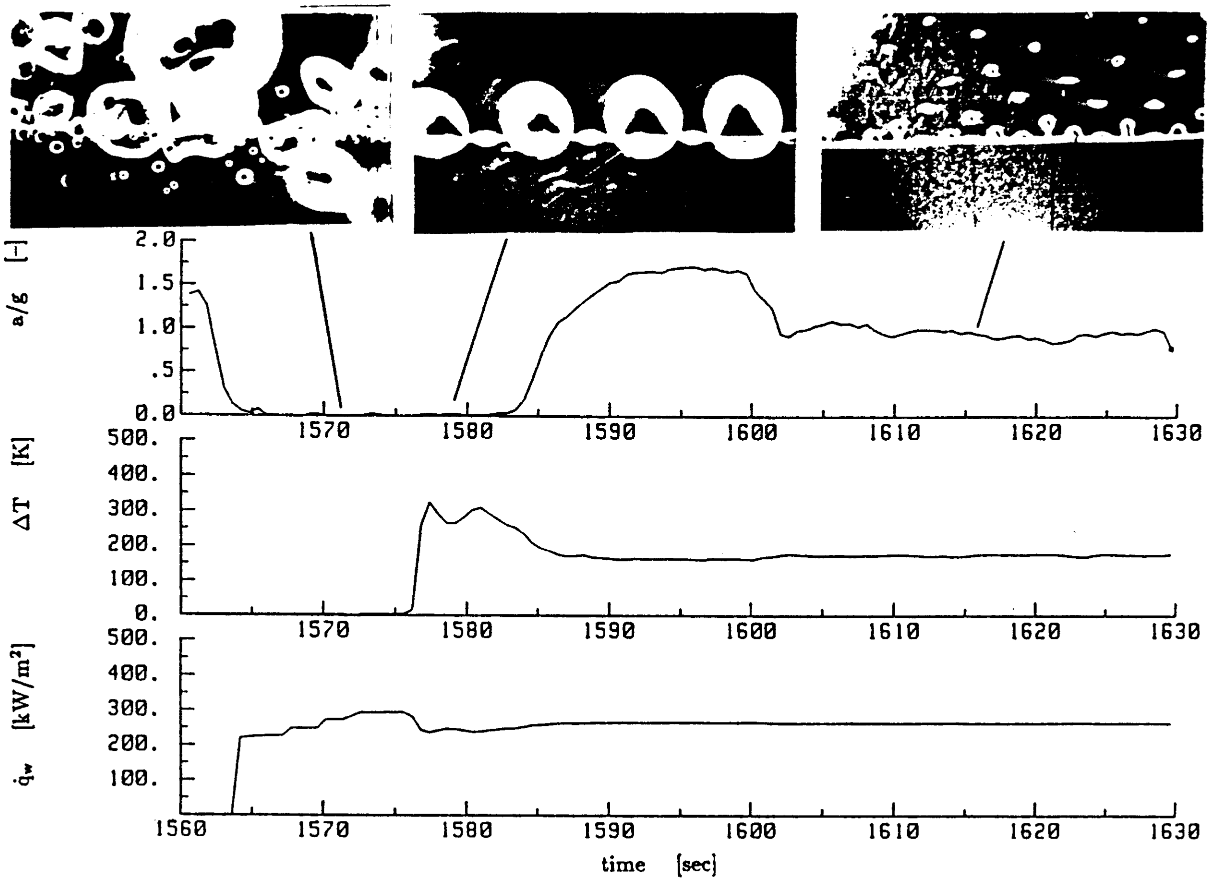

Fig. 19 Sequence of a parabola, with transition to film boiling

Several correlations exist for film boiling, all based on the film theory of Nusselt for condensation. One of the earliest relations is from Bromley (1950), which can be analyzed for its gravity dependence of the heat transfer coefficients according to eq. (5) with the exponent $n = 0.25$.

The film boiling data of Merte and Clark (1962, 1963) on spheres in liquid nitrogen at low gravity down to $a/g = 0.017$, and Freon 113 data at high gravity up to $a/g = 10$, are in agreement with the correlation of Frederking and Clark (1963), which represents the gravity dependence with $n = 1/3$. For smaller cylinders and wires, Pitschmann (1968) extended the relation from Bromley including the influence of radiation and the Smoluchowsky effect for low density gases. Their influence on gravity is given by $n = 0.16$.

The correlations of Pitschmann, Bromley and Frederking and Clark are in agreement with our data on R 12 at saturation, with wires having 0.05 mm and 0.2 mm diameters; Pitschmann is on the upper and Frederking is at the lower limit of the scatter band, see fig. 20. However, it seems that at $a/g = 5 \cdot 10^{-2}$, the heat transfer coefficient is nearly independent of further gravity reduction. This result is confirmed by data obtained during film boiling in TEXUS experiments with $\alpha/\alpha_1 = 0.48$ and 0.38. This is explained by the dominating effect of surface tension as seen in fig 19. A chain of large and small bubbles are formed around the wire, and vapor is pumped from the small bubbles into the large bubbles due to the higher pressure, whereby the smaller bubbles continuously change size. In TEXUS it was observed that a very large bubble of approx. 20 mm in diameter was formed and a chain of small bubbles with decreasing diameters pump the vapor into the large bubble at a high frequency. We therefore assume that correlations derived on the basis of boundary-layer theory may no longer be applied for $a/g < 5 \cdot 10^{-2}$; surface tension, radiation and axial flow of the vapor within the

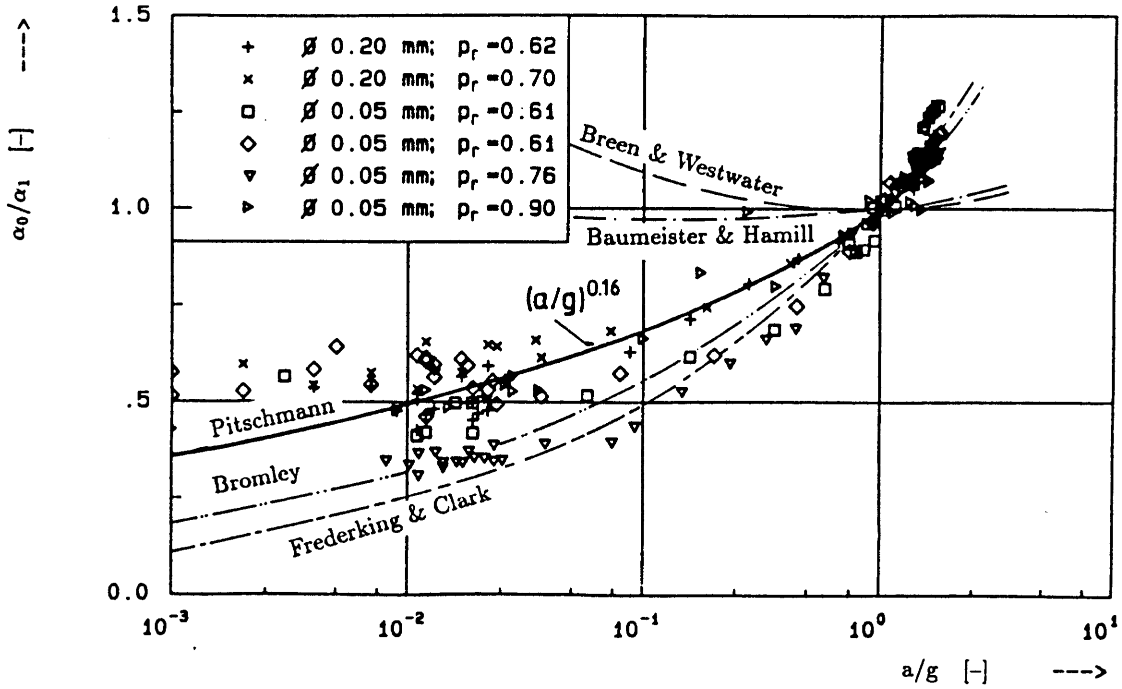

Fig. 20 Measured film boiling data and corresponding correlations

bubble chain is the mechanism dominating the heat transport. However, we also found that small variations in gravity influence the bubble chain. It is no longer arranged symmetrically around the wire as under very low gravity conditions.

The evaluation of subcooled data shows a more distinct gravity dependence with $\alpha/\alpha_1 = (a/g)^{0.25}$. The bubbles around the wire are not as spherical than at saturated state, they are deformed and Marangoni convection around them can be observed.

11. The mechanisms of boiling in the various modes of heat transfer

11.1 Nucleate boiling

Our experimental finding in boiling microgravity research is that nucleate pool boiling heat transfer is more or less nearly independent of the gravity level over a large pressure range of $0.1 < p/p_c < 0.7$. Only at very low and high pressures the influence of gravity is remarkable. At low pressures, the bubbles grow to large size and thus dry areas below them yield to an increase of the observed averaged temperature of the heater due to an insulation effect. At high pressures, the lower surface tension seems to be the limiting factor. However, boiling seems to be nearly independent of buoyancy and the departure size of the bubbles over a wide range of fluid states,, which is in contradiction to most of the present conceptions of boiling.

The question, however, remains: what are the forces and the mechanisms to drive the nucleate boiling heat transfer at reduced gravity, if the dominating buoyancy force is changed to lower neglegible values? Thus we can draw the following conclusions, that the boiling process must be divided into a primary mechanism and several secondary mechanisms.

- The primary mechanism is the formation and the growth of the bubbles themselves by evaporation at their base in the superheated liquid boundary layer. Most important for the heat transfer is the edge at the three phase interface, soild-liquid-vapor on the baseline of the bubbles. In this corner the evaporation rate will be very high. This evaporation is not determined by gravity, but only by the temperature of the heater. We could observe that in the liquid-solid edge below large bubbles continuously new bubbles are formed, which then coalesce and feed the larger ones.

- The secondary process, just as important, is the transport of the latent heat and the superheated liquid of the boundary layer away from the surface, which occurs at earth gravity by buoyancy. At low gravity, however, it is replaced by other mechanisms. Here we have to decide between saturated and subcooled fluid states.

Saturated states

Siegel and Keshock (1964) observed a coalescence mechanism in perpendicular direction to the heated surface, with which they explain the mechanism at saturated boiling:

"After a bubble departs and begins to move upwards, if its rise velocity is small, the next bubble growing at the surface will collide with the rising bubble due to the rapid rate at which the diameter of the attached bubble increases during the early stages of growth. The succeeding bubbles formed at the nucleation site that contact the detached bubble and merge with it are thereby pulled from the surface before they can grow very large."

Through this process of coalescence, the newly attached bubble is sucked from the surface. The coalescence itself promotes movement in the liquid, which pulls the bubble from the heater surface and draws liquid in its wake, with inertia effects propelling the bubble further upward. Bubbles and patterns of them hover at a certain distance over the heater surface.

In our experiments, we have observed this effect sporadicly, however, that does not help to explain the high heat fluxes. We observed in the low pressure experiments especially on the wire, that bubbles spring from the heater surface by two ways: single, small bubbles are released from the surface by inertia force during growth, and larger bubbles formed by the coalescence of two or three bubbles parallel to the heater surface. The movement of coalescence and the inertia of fluid motion push the bubbles away from the surface. At reduced pressures between 0.1 to 0.7, we observed large bubbles attached to the heater surface. Between the larger bubbles, smaller bubbles are continuously formed and coalesce with the larger ones, or, more correctly, feed the larger bubbles. Smaller bubbles, growing below the larger ones, lift these bubbles up from the surface and replace the larger ones. Our summary the mechanism of bubble departure at saturation is as follows:

- inertia force at low system pressure on wires,
- vertical coalescence,
- horizontal coalescence,
- coalescence to form larger bubbles and the formation of new bubbles below them,
- the lifting and replacement of the larger bubbles by fast growing smaller ones below them.

Subcooled states

In subcooled liquids the bubbles are generally attached to the surface, this well-known observation is even made under earth gravity conditions. The heat transfer mechanism is explained by the periodic growth and condensation of the bubbles at high frequency. The resulting pumping effects the liquid exchange at the heater surface. In low gravity this effect does not seem to be so important, because the temperature of the liquid layer close to the heater soon reaches saturation temperature.

At the wires the bubbles grow up to a larger size than at $a/g = 1$ with evaporation at the base and condensation at the crown acting as a small "heat pipe" between the superheated boundary layer and the subcooled liquid. We also observed the development of very strong convection around the bubbles, enabling them to pump hot liquid from the boundary layer to the bulk liquid. This effect, known as Marangoni convection, is driven by the surface tension gradients around the bubbles. The kinetic mechanism of evaporation and condensation requires only very small temperature differences which will normally not drive surface tension convection. However, even if the liquid is very pure, a small amount of solved gases, in the order of some ppm, is released by evaporation. This gas, however, will not condense at the crown, it concentrates here quickly and increases the condensation resistance, thus increasing the temperature difference on the bubble between the top and the base and thereby inducing thermocapillary flow. The surface tension convection strengthens the holding forces of the bubbles which also explains the general observation that the bubbles stick to the wall more tightly in subcoolded than in saturated liquids.

This convection could not be observed in saturated liquids. The liquid-vapor interface will be close to saturation temperature except at the bubble base, where the temperature is slightly higher to maintain evaporation. This observation may strengthen the explanation of surface tension convection described above.

We have even observed bubble detachment due to inertia by fast bubble growth at low pressures and large bubbles being lifted up and replaced by the growth of smaller bubbles below them.

On a plate the mechanism is different. The surface is covered by large bubbles of characterictic size, which is lower at a high degree of subcooling. Dynamic movement at the crown is caused by partial condensation. We could not observe an entire bubble collapse by condensation. Smaller bubbles are formed in the space between the large bubbles that coalesce, or feed the larger ones. With an increase in heat flux, one or two larger bubbles are formed and a dynamic motion at the top, caused by partial condensation, could be observed. This bubble increases to a size, where the subcooled liquid can maintain condensation. The dynamic process of condensation at the top of the bubble provides strong movement in the liquid, as a result, the heating surface is supplied with fresh liquid. Summarizing the effects:

- bubbles can depart by inertia force at low liquid temperature;
- bubbles can depart by coalescence parallel to the surface, by lift up and replacement;
- pumping by high frequency growth and condensation, called microconvection, with short bubble lifetimes seems not to be a dominant mechanism
- at low gravity, bubble lifetime is longer. Evaporation at the bubble base and condensation at the crown, dominates the heat transfer in combination with surface driven convection;
- plates are covered with large bubbles, smaller bubbles are formed between the larger ones, coalescence at the bubble base and condensation at the top, and large bubbles grow up to the regions where the liquid is stilled subcooled for condensation indicating dynamic movement.

11.2 Critical heat flux

If nucleate boiling can be maintained at high heat flux values even at low gravity conditions, the hydrodynamic theory of liquid film instability can no longer be applied for CHF. The mechanism can be explained as follows: Near the CHF the bubble population is very high, bubbles coalesce and form local clusters. They coalesce and form local areas covered with vapor film. This area expands rapidly over the entire heater surface. This mechanism will even occur under earth gravity, however, up to now, no theory properly explains it.

11.3 Film boiling

It was previously discussed that even film boiling can be stabilized. This also appears to apply to plates and tubes with larger diameters. A chain of bubbles with large and small diameters is formed around the wire by surface tension. The vapor produced is pumped by contracting and expanding of smaller bubbles in a peristaltic motion. Vapor flow and the increasing surface temperature intensify the heat transfer by radiation, maintaining the heat transfer coefficient lower than at $1g$, however, nearly constant at lower g values. The existing theories based on Nusselt film theories can only partially explain the heat transfer coefficient.

12. Summary and General Outlook

In this report we have presented a short survey of the latest developments in the field of pool boiling heat transfer under microgravity conditions. It is of interest to note that buoyancy acting on the bubbles and buoyancy free convection are not the only dominating mechanisms controlling the heat transfer. The buoyancy can be replaced by other powerful mechanisms that maintain boiling and keep the heat transfer at nearly the same level during nucleate boiling. Most important are the effects caused by the surface tension at the interface, however, the physical reasons behind the process are not yet completely understood and our interpretations must be regarded as preliminary. This is due to the present limitations in microgravity research such as limited flight opportunities, limited experimental time, limited quality of gravity and time in the parabolic flights, as well as the limited number of experiments to study the numerous parameters and finally the restrictions by the facility in size, weight, power, optical and data recording capacity. Many questions are still open and require more study to enlarge our understanding of boiling. Some of the questions that require additional study are:

- Nucleate boiling:
  - Are saturated and subcooled nucleate boiling steady state processes at a high quality of microgravity?
  - What are the mechanisms which determine the heat transfer?
  - Is evaporation at the interface solid-liquid-vapor the primary process of heat transfer?
  - What are the most important secondary mechanisms for the vapor transport: coalescence, lift-up, evaporation-condensation, thermocapillary flow?
  - What is the influence of the temperature field around and below the bubbles?
  - What is role of the microlayer?
  - What is the influence of additional thermocapillary flow at subcooled boiling? Is this flow dependent on the content of solved gases?

- Critical heat flux:
  - What are the mechanisms of critical heat flux, if the hydrodynamic instabilities caused by gravity are diminished and disappear?
  - What is the influence of geometry like wires, tubes, plates and of fluid states?
  - How can the CHF model be improved according to the physical process?

- Film boiling:
  - Is stable film boiling possible on wires, tubes, plates? Will the vapor film grow continuously, or will a final thickness be reached?
  - What is the influence of surface tension on the Kelvin-Helmholtz instability?
  - Can film boiling at microgravity be described by a single correlation for all geometries?

- Technical and enhanced heat transfer surfaces:
  - What is the mechanism of the enhanced heat transfer? Can it be maintained in microgravity?
  - What is the influence of higher nucleate sites densities?

- Minimum heat flux:
  - How will the vapor film collapse, if the Rayleigh-Taylor instability can be ignored?
  - What is the mechanism of rewetting and the influence of gravity on the Leidenfrost temperature?

- Transition boiling:
  - Can transition boiling be generated at microgravity, stable or oscillating?

- Flow boiling:
  - What is the influence on boiling when the process at the various modes of heat transfer is overlapped by a cross flow at low or high mass flow rates of variable quality?

The benefit of solving these questions will result in correlation that properly describe these processes on a much more physical and fundamental base as the correlations used today. These relations will not lose their usefulness, if the parameters are used outside the regions, for which they have been developed. The benefits will be in earth and space application, however, basic fluid physics will benefit the most. We will be able to learn more about the complex and difficult interaction effects at phase interfaces in non equilibrium states and about the effects of surface tension forces.

Up to now, boiling phenomena are disregarded in fluid physics and even in engineering due to their complexity and empirical character. However, it is indeed one of the most challenging problems in the field of hydrodynamic fluid physics and engineering. And microgravity can help solve many of the open unanswered problems.

Acknowledgments

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