NUCLEATE POOL BOILING IN SUBCOOLED LIQUID UNDER MICROGRAVITY – RESULTS OF TEXUS EXPERIMENTAL INVESTIGATIONS

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Abstract

An experimental investigation of subcooled nucleate pool boiling in microgravity has been carried out in order to separate gravity driven effects on heat transfer within the boiling process. A ballistic trajectory by sounding rocket flight (TEXUS 5 and 10) has been used to achieve a gravity level of $a/g = 10^{-4}$ for 360 seconds. For determination of geometrical effects on heat transport two different experimental configurations (platinum wire and flat plate) have been employed. Boiling curves for both experiments and also bubble dynamics recorded by cinematography lead to gravity independent modelling of the boiling phenomena. The results ensure the applicability and high efficiency of nucleate pool boiling for heat exchangers also in space laboratories.

Keywords: Nucleation, heat flux, vapor bubble, heat transport mechanism, evaporation, condensation, Marangoni convection, Nukiyama curve

1. Introduction

Nucleate boiling, with or without forced convection, provides high heat transfer rates compared to natural convection or film boiling. Most models describe heat transfer in pool boiling including gravity driven forces (buoyancy). For example Han and Griffith (bulk-convection model), Mikic and Rhosenow /2/ (bulk convection), Cooper and Lloyd /3/ (micro-layer) or Judd and Hwang /4/ (combined model).

Models without the influence of gravity had been presented by Forster and Zuber /5/ (micro-convection) or Robin and Snyder /6/. They showed, that within a bubble lifetime a multiple quantity of the vapor mass can be transported through itself by evaporation of the microlayer beneath it with simultaneous condensation at the top of the bubble. Nevertheless, this boiling model demands forced convection at the top of the bubble in order to provide condensation conditions. Without forced convection, this should lead to a transient behaviour of the system. Taking in account the models for heat transfer in pool boiling (/1/ - /4/), one expects the influence of a microgravity environment to result in lower levels of heat flux for a given ΔT_{sat}. On the other hand, /5/and /6/ indicate the possibility of boiling heat transfer without gravity forces using different models.

Some investigators (e.g. /9/, /10/, /4/) have studied pool boiling using low gravity in order to eliminate buoyancy effects within the boiling regime in a physical way. The variety of results may be due to the short microgravity period of 1 - 4 seconds. Therefore, two subcooled pool boiling experiments in microgravity have been conducted, which allowed measurements of the attainable heat flux in a steady state and investigation of the dominating boiling mechanisms free of gravitational effects.

2. Scientific Objective

In spite of tremendous scientific efforts in classifying the portions of the different heat transport mechanisms being concatenated in the very complex boiling process, there remain a lot of obscure questions:

- which transport phenomenon is the dominant effect in the boiling regime (in µ-g <u>and</u> on earth).
- are there gravity independent mechanisms providing steady state boiling also in microgravity
- applicability of pool boiling for heat exchange facilities in space laboratories

- bubble dynamics in microgravity (bubble growth, maximum size, population, frequency, departure from the heater?)

Therefore two boiling experiments have been carried out in microgravity to measure the attainable heat fluxes, and bubble behaviour only controlled by forces like surface tension, surface tension gradients, momentum and the evaporation/condensation mechanism, but not by gravity driven effects. Subcooling of the liquid as a function of $T_{sat} - T_{bulk} > 0$ permits investigation of condensation effects at the bubble surface.

3. Measurements in Microgravity Environment: Boiling Behavior : Platinum Wire / Subcooled Freon 113

3.1. Experimental Apparatus

A schematic outline of the experimental apparatus is given in fig. 1 . The testfluid, R113 (triclorotrifluro-ethane) was destilled and degassed by freezing several times before filled into the evacuated test chamber . The chamber was completely filled up to atmospheric pressure. For compensation of changes in volume due to

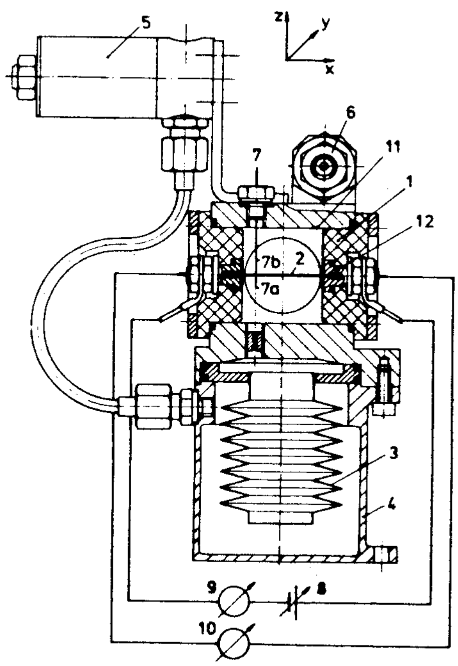

Fig. 1: Experimental apparatus (schem.)
1- VA chamber, 2- platinum wire, 3- VA bellows, 4- expansion volume, 5- magnetic valve, 6- pressure sensor and filling valve, 7a,b- thermocouples in liquid, 8- constant voltage (9 levels), 9- current meter, 10- voltmeter, 11- temperature bulk liquid, 12- temperature wire clamp

evaporation and thermal expansion of the fluid, a metal bellows (3) was used. The heater consists of a platinum wire (2) with a length of 25 mm and 0.2 mm in diameter. During the µ-g period, nine discrete levels of constant voltage can be supplied. The heater temperature can be determined by measurement of heater-current and voltage (9,10). Also fluid temperature near the heater (7a,b) and the bulk liquid (11) were measured. The measuring frequency was 4 Hz, but 107 Hz for heater current and voltage.

3.2. Results: Platinum Wire / Subcooled Bulk Liquid

3.2.1. Onset of Nucleate Boiling (ONB)

Nucleation occurs within the thermal and velocity boundary layer of the liquid. Since the velocities in the liquid vanish in the immediate vicinity of the wall and heat transport takes place by conduction only the nucleation temperature difference $\Delta T_{ONB} = T_{ONB} - T_{sat}(p)$:

$\Delta T_{ONB}(a/g = 1) = 39.6$ K $\qquad q_{ONB} = 10.4$ W/cm²

$\Delta T_{ONB}(a/g = 10^{-4}) = 49.4$ K $\qquad q_{ONB} = 3.6$ W/cm²

Nonuniformity of heater temperature in µ-g caused by the boundary effects of the heater clamp at the ends of the wire could be computed to about 5%. The difference in ΔT_{ONB} of 25% (compared to earth) is due to the transient fluid temperature in the vicinity of the wire in µ-g, while the terrestrial experiment reaches steady state (by natural convection) long before ONB. (fig. 2).

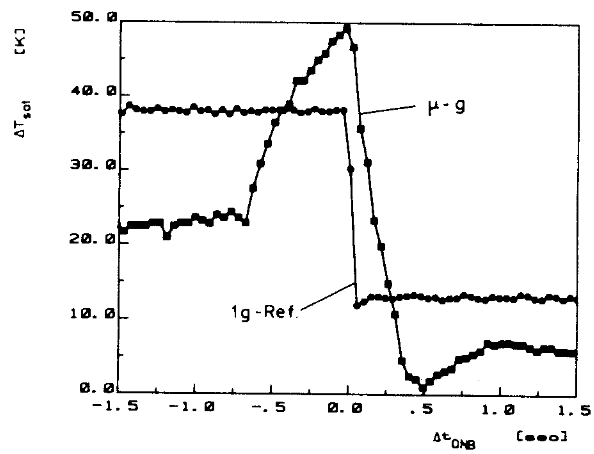

Fig. 2: Course of ΔT_{sat} versus time after ONB

The significant drop of ΔT_{sat} after the departure of the first oscillating bubble from the wire is due to the beginning of steady state boiling and not caused by the first bubble (taking evaporation enthalpy from the superheated liquid around the wire), because the generation of first bubble (vapor tube) takes only 0.02 seconds.

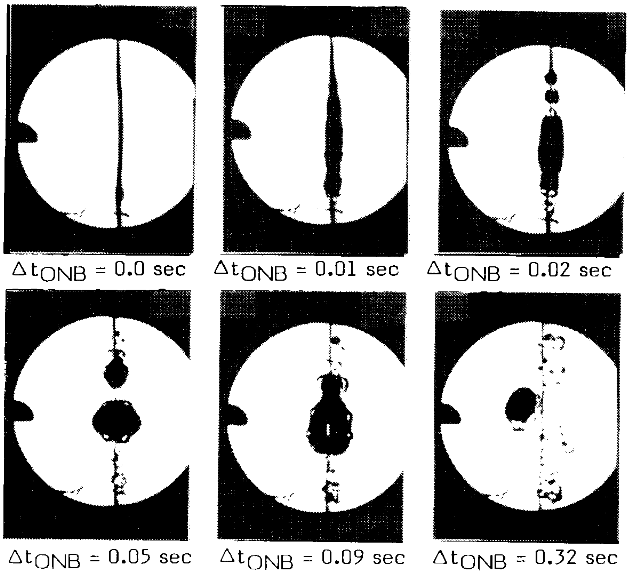

Fig.3: Onset of nucleate boiling (ONB) in microgravity

Nearly $\Delta T_{sat} = 0$ can be achieved 0.5 seconds after ONB, that means the number of activated sites is much larger than necessary for causing the partly deactivation of sites after some tenths of a second.

3.2.2. Steady State Boiling

The electrical and thermal measurements combined with visual observation by the movie of the μ-g experiment show the following bubble behaviour:

- generated vapour bubbles condense at the wire after a life-time of some tenths of a second
- the vapor bubbles formed do not leave the wire, except when coalescence occurred between bubbles moving towards each other
- bubble population decreases by stepwise increase of heat flux
- time delay of thermal response of the heater temperature to increased heat flux in the range of 0.5 seconds
- bubble population and size very similar to terrestrial conditons
- the bubbles induce a motion of the fluid at their curved surface (Marangoni convection), causing the acceleration of their own fluid boundaries towards lower temperatures. This is a typical charactaristic for convection on the bubble surface caused by surface tension gradients.

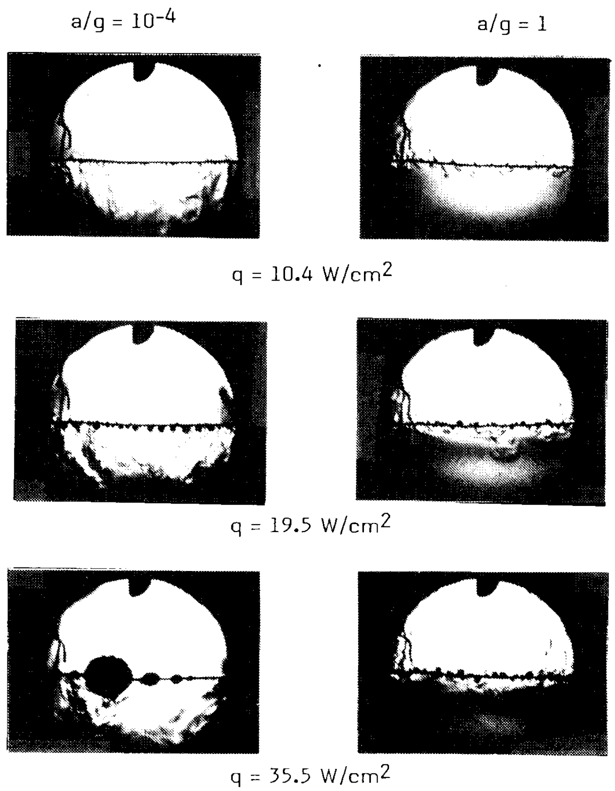

Fig. 4: Steady state boiling (real size)

The bulk convection of the experiment in microgravity is caused by surface tension gradients along the interface bubble-liquid. Resulting velocities of the bulk liquid both for μ-g and a/g = 1 (Marangoni and buoyancy forces) have been evaluated in figure 5.

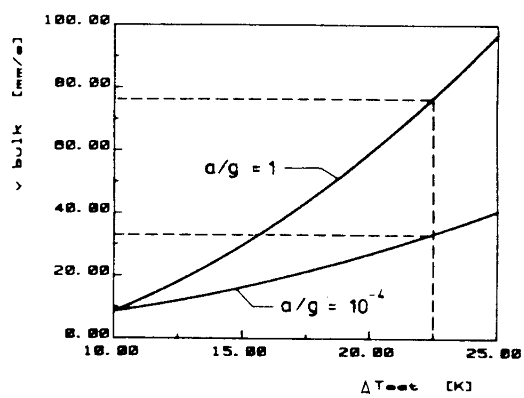

Fig. 5 : Bulk velocities for μ-g and a/g = 1

The driving force of the Marangoni convection only acts along the surface of the bubbles and then the liquid calms down . On earth there are buoyancy forces causing convection until the hot liquid stream from the heater gets in thermal equilibrium with the colder bulk liquid.

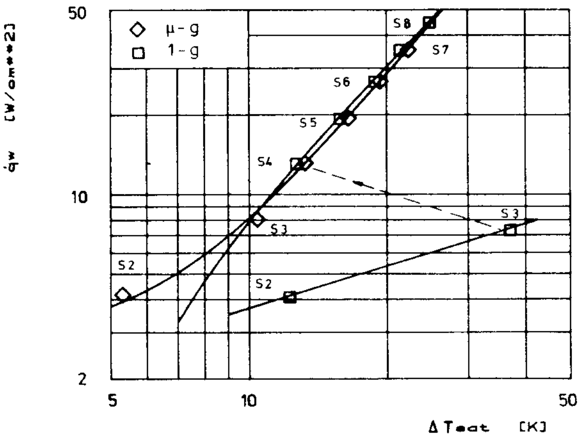

Fig. 6 : Heat flux versus T_{sat} in subcooled R113 ($p = 1$ bar, $T_{bulk} = 25$ °C, $T_{sat} = 47.5$ °C)

The boiling curve for discrete heat flux levels (S1 - S9), especially comparison of the μ-g and 1-g experiment yields the efficiency of the heat transport mechanisms. Heat transfer coefficients for level S2 and S3 are higher for the micro-g system, because it already works in the boiling regime while the terrestrial experiment has not yet reached nucleation temperature (natural convection). The critical heat flux decreases under μ-g in the range of 20 % (heat flux level S8 already in film boiling regime). Supported by further laboratory investigations (single gas bubble on a heated wire in R113 doubles Nusselt number compared to natural convection without bubble) and computations (unsteady Marangoni flow by surface tension gradient) the new boiling correlation valid for μ-g and $a/g = 1$ uses the dimensionless Marangoni number to represents the relevant heat transport mechanisms.

$$Ma = \frac{\frac{d\sigma}{dT} \cdot (2R\frac{dT}{dz}) \cdot (2R)}{a_f \cdot \eta_f} \qquad (1)$$

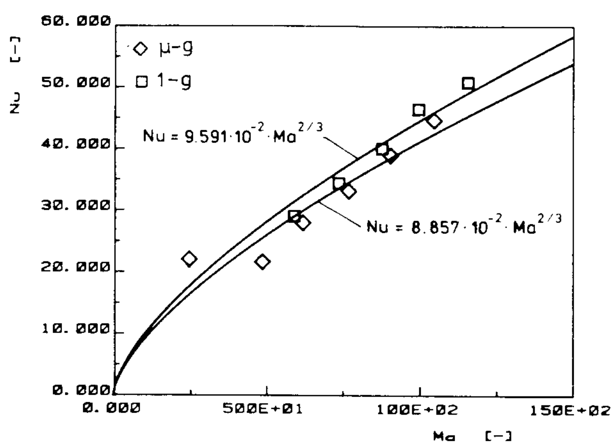

Fig. 7 : Boiling correlations for subcooled pool boiling

In fact, three mechanisms contribute to heat transport in subcooled pool boiling under microgravity :

- conduction q_λ
- kinetic heat transport through the vapor phase q_{kin}
- heat transfer by Marangoni convection q_{Mc}

$$q_{total} = q_\lambda + q_{kin} + q_{Mc} \qquad (2)$$

Because the experimental results prove the dominating role of Marangoni driven heat transport, q and q_{kin} can be added into the Marangoni term by the characteristic temperature difference for all heat transport processes

$$q_{total} = f(\Delta T) = f(T_w - T_{sat}) = f(Ma) \qquad (3)$$

4. Nucleate Pool Boiling on a Flat Plate

4.1 Scientific Objective

Nucleate pool boiling on plane surfaces is used in a variety of technical facilities (e.g. heat exchangers in reactors) where enormous quantities of energy have to be transferred from solid surfaces to liquids. For this purpose, the nucleate boiling mechanisms guarantee constant wall temperature near to saturation up to critical heat flux. By physical separation of gravity driven effects the μ-g experiment should yield the influence of convection terms on the efficiency and stability of the boiling mechanisms. Two dimensional bubble population on a plate (bubbles grow in symmetric thermal conditions because of neigbouring bubbles at all sides) varies significantly from one dimensional bubble distribution on a heated wire (bubble position on the wire according to the direction of bulk convection). For this reason thermal and kinetic interaction of the vapor bubbles on a plate will affect heat transport within the microlayer.

The space experiment has been conducted to investigate:

- surface superheat at the inception of boiling
- thermal response of the heater
- attainable heat flux in steady state boiling (for technical use in space laboratories)
- bubble dynamics
- influence of Marangoni effects
- determination of the heat transport mechanisms in space
- effects of heater geometry on heat transport in nucleate pool boiling under microgravity

The results should lead to improved understanding of the very complex boiling mechanisms also for earth conditions.

4.2 Experimental Setup

A thin gold film on a cerodur glass substrate, properly calibrated, was used simultanously as a heater and resistance thermometer in the range of 20 °C to 200 °C with better than ± 1 K accuracy and producing heat flux levels up to burnout in subcooled R113 (ΔT_{sat} = 17 K).

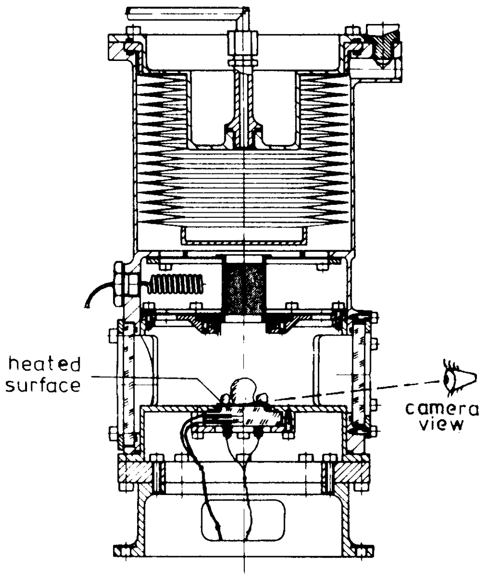

Fig. 8: Experimental apparatus : boiling on a plate

By this measurement technique eight discrete heat flux levels could be provided and five thermocouples were installed to measure liquid/vapor temperature profiles. Four thermocouples in the cerodur glass substrate of the heater enabled the calculation of deficit heat flux.

4.3 Results : Subcooled Boiling on a Flat Plate

4.3.1 Onset of Nucleate Pool Boiling

Boiling initiated first at a single point in the center of the heater and then spread over the surface.

ΔT_{ONB} (a/g=1) = 25.0 K $\quad$ q_{ONB} = 3.0 W/cm²
and
ΔT_{ONB} (μ-g) = 40.3 K $\quad$ q_{ONB} = 1.35 W/cm²

Compared to terrestrial conditions the superheat of the surface increased , whereas activation of the first site required only 45 % of heat flux. A bubble of spherical shape covered the heater within 0.04 seconds taking most of the evaporation enthalpy from the superheated thermal boundary layer (fig. 9). This rapid spreading of nucleation is a consequence of differences in the boundary layer temperature levels between pure conduction (μ-g) and convection regime. Inception of boiling over the entire surface takes 0.8 sec for the 1-g reference experiment.

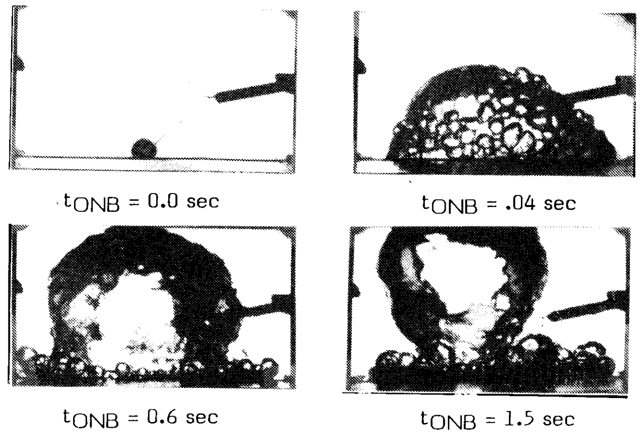

Fig. 9: ONB in microgravity (real size)

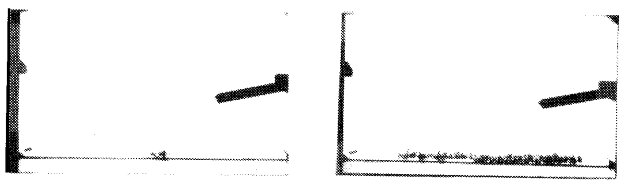

Fig. 10: ONB on earth (real size)

Without gravity the first bubble at ONB raises the thermal boundary layer causing single bubbles to grow within the superheated liquid missing any contact to the heater. Because of the quantity of energy in the thermal boundary layer it takes 1.5 seconds until first volume decrease of the first bubble can be noticed, but the bubbles on the activated sites around have already reached steady size.

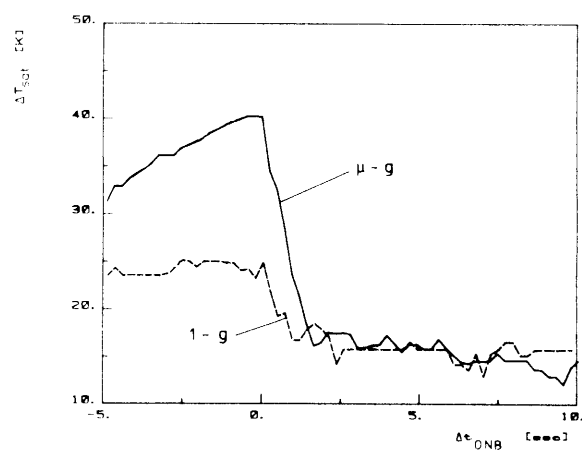

Fig. 11: Course of ΔT_{sat} at onset of nucleate boiling

The preceding plot yields the thermal response of the wall to inception of nucleate boiling. Although spreading velocity of boiling over the surface in the μ-g system exceeds the terrestrial one by a factor of twenty, the time delay for steady surface temperature of the heater increased to ten seconds after ONB because of very different liquid superheat profile within the thermal boundary layer.

4.3.2 Steady State Boiling

By analysation of the data concerning heat flux as a function of ΔT_{sat}, the boiling curve both for microgravity and the terrestrial reference experiment (heater surface horizontal up) can be calculated (fig. 12).

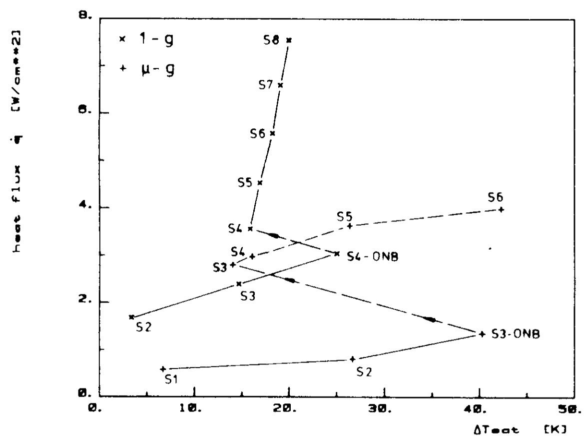

Fig. 12: Boiling curve in subcooled R113 : μ-g and 1-g

The thermal measurements can be interpreted by the evaluation of the movie which shows the behavior of the vapor phase depending on heat flux (fig. 13).

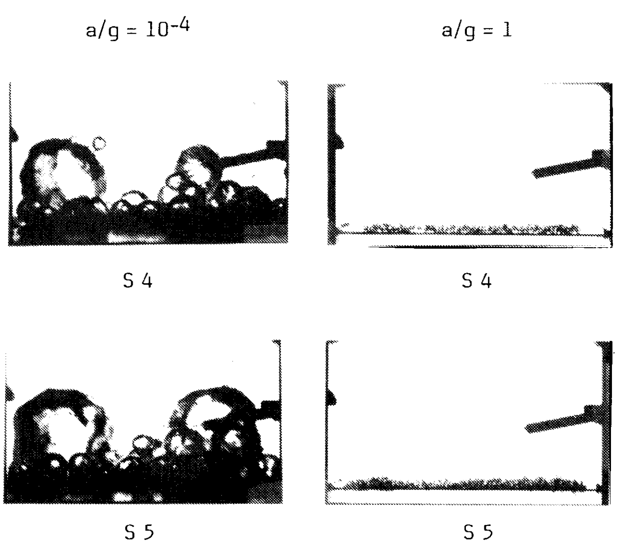

Fig. 13: Steady state boiling on a plate for different heat flux levels (fig. 12)

Concerning the boiling curves supported by visual impressions of the boiling regime, the following statements can be postulated for characterisation of heat transfer in boiling without gravity :

- the heat transfer coefficient for heat flux level S3 exceeds the terrestrial value
- bubble population on the heater decreases due to increasing bubble size
- vapor bubbles are generated in the superheated microlayer with a frequency of 0.5 - 2 Hz transferring their vapor enthalpy by coalescence to larger ones
- larger bubbles take the condensation part of the system on their cap in the subcooled bulk liquid
- enthalpy transport by departure of the bubbles from the heater can be neglected
- Marangoni effects seem to vanish because of small temperature gradients along the bubble surface

4.4 Kinetic Heat Transport Model

The observations on the behavior of the vapor phase enhance the theory that heat transport in nucleate pool boiling under μ-g is due to evaporation in the superheated microlayer and condensation on the cap of the bubbles guaranteeing energetic balance for the bubbles (fig. 14).
The massflux per unit area through the bubble can be expressed by

$$\frac{\dot m}{A} = \alpha \cdot \left[\frac{R_0}{2\pi M}\right]^{1/2} \left[\frac{T_f^{1/2}}{v'(T_f)} - \frac{T_g^{1/2}}{v_g}\right] \qquad (4)$$

Equation (4) leads to $\dot m/A > 0$ for evaporation and $\dot m/A < 0$ for condensation.

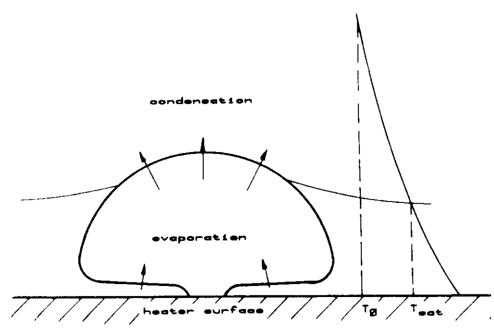

Fig. 14: Kinetic heat and mass transport through a bubble by evaporation/condensation

When solving equation (4) using the estimated area of condensation on the bubble cap, the condensing temperature difference $T_f - T_g$ necessary to produce the massflux (corresponding to heat flux by evaporation enthalpy) is only a fraction of 1 K.
Further experiments in space with variation of the

thermodynamical fluid state in comparison with laboratory investigations have to be done in order to fit this theory of kinetic heat and mass transport responsible for heat transfer in μ-g boiling.

5. Summary

Under the sponsorship of the German "TEXUS" program, two subcooled nucleate pool boiling experiments have been carried out in order to study effects of missing buoyancy on heat transfer. Boiling on a platinum wire demonstrated the efficiency of Marangoni forces caused by surface tension gradients along the curved surface of the bubbles. The investigations yield the equality of heat transport coefficients up to 80% of terrestrial critical heat flux.

Nucleate pool boiling on a plane disc, demonstrates the interaction of vapor bubbles generated on a two dimensional surface. By means of kinetic mass transfer (evaporation/condensation mechanism) supported by agitation of the vapor bubbles the boiling system is able to fit on changed thermal conditions under microgravity.

6. Acknowledgement

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7. Nomenclature

a	acceleration
a_f	thermal diffusivity of the fluid
A	bubble surface area
g	terrestrial gravity
M	molecular weight
Nu	Nusselt number
q	heat flux
S1...Sx	constant heat flux levels
R	bubble radius
R_0	gas constant
t	time
T	temperature
ΔT_{sat}	$T_{wall} - T_{sat}$
z	characteristic length (bubble diameter)
Δ	delta, difference
η_f	dynamic viscosity of the fluid
λ	thermal conductivity
σ	surface tension

Indices :

bulk	bulk liquid
kin	kinetic heat and mass transfer
Mc	Marangoni convection
ONB	onset of nucleate boiling
sat	saturation of liquid as a function of pressure
wall	heater surface

8. References

1. Han,C.H., and Griffith, P., "The Mechanism of Heat Transfer in Nucleate Pool Boiling - Part II", Int. J. Heat Transfer, 8, pp. 905-914, 1965
2. Mikic, B.B., and Rohsenow, W.M., "A New Correlation of Pool Boiling Data Including the Effect of Heating Surface Characteristics", J. Heat Transfer, C 91, pp. 245-250, 1969.
3. Cooper, M.G., and Lloyd, A.J.P., "the Microlayer in Nucleate Pool Boiling", Int. J. Heat Mass Transfer, 12, pp. 895-913, 1969.
4. Judd, R.L., and Hwang, K.S., "A Comprehensive Model for Nucleate Pool Boiling Heat Transfer Including Microlayer Evaporation", J. Heat Transfer, C 98, pp. 623-629, 1976.
5. Forster, H.K., and Zuber, N., "Dynamics of Vapour Bubbles and Boiling Heat Transfer", AICHE J., 1, pp. 531-535, 1955.
6. Robin, T.T., and Snyder, N.W., "Theoretical Analysis of Bubble Dynamics for an Artificially Produced Vapour Bubble in a Turbulent Stream", Int. J. Heat Mass Transfer, 13, pp. 523-536, 1970.
7. Stralen, S. van, and Cole, R., "Boiling Phenomena I, II", Hemisphere Publishing Corporation, Washington, New York, London, 1979.
8. Roache, P.J., "Computational Fluid Dynamics", Hermosa Publishers, Albuquerque, 1972.
9. Merte jr., H., and Clark, H.B., "Boiling Heat Transfer with Cyrogenic Fluids at Standard, Fractional and Near-Zero Gravity", Transactions ASME, pp. 351, 1964.
10. Littles, and Walls, "Nucleate Pool Boiling of Freon 113 at Reduced Gravity Levels", ASME, 70-HT-12.
11. Weinzierl, A.,"Untersuchung des Wärmeübergangs und seiner Transportmechanismen bei Siedevorgängen unter Mikro-Gravitation", Dissertation Technische Universität München, 1984.