Round Table Discussion

8 - 1

Mechanism of Boiling Heat Transfer

Contribution:

Bubble Formation in Sub-cooled Boiling

F. Mayinger

Sub-cooled boiling plays an important role not only in nuclear pressurized water reactors but also in fossil fired steam boilers and in evaporators of high power density. In the literature there are several models /1,2,3,4/ to predict void fraction in forced convection with sub-cooled boiling but they commonly are involved with the uncertainities of

1. onset of boiling and
2. bubble growth and collaps.

To overcome these uncertainities more experimental work is necessary. Theoretical predictions for bubble formation as well as for bubble recondensation in sub-cooled boiling diverge to a large extend depending which phenomenon in the given conditions is prevailing for the bubble formation mechanism: heat transfer or inertia forces.

In the Institute for Verfahrenstechnik of the Technical University Hannover some measurements /5/ were done to get a little more insight into the mechanism of sub-cooled boiling. The experiments were carried out with high speed cinematography and holographic interferometry in water of atmospheric and sub-atmospheric pressure and pool boiling. The bubble growth usually is much faster than the condensation and takes only a small part of the time of the whole bubble history as shown in fig. 1. In the upper part of this figure the bubble diameter versus the life time of a bubble is plotted. The measurements seem to show an oscillatory behaviour of the bubble but this impression could also be given by a rotation of the bubble not having a full spherical form. In the lower parts of this figure the growth- and collapsing velocities and the acceleration of the steam water phase boundary are plotted. One can see that the acceleration is several times changing in sign and value and that the whole bubble formation process has a very dynamic character and probably there is not always thermodynamic equalibrium between the phases.

To get more insight into the physical process interferometric measurements were done giving the temperature distribution round the bubble. In the figures 2, 3 and 4 examples for the temperature conditions in the boundary layer around the bubble and the heating element are given. The bubbles were growing on an electrically heated wire of 0.4 mm diameter. The black and white fringes of the interferometric pattern are not quantitatively identical with isotherms because the temperature field is not two but three-dimensional, in this case spherical symmetric. We have to use here a special evaluation method, the so-called Abel-correction /6/. But qualitatively the temperature distribution can be clearly seen from this figures.

In fig. 2 the temperature conditions round the first detaching bubble after switching on the electrical power input to the heated wire are shown. This first bubble has during its growth an undisturbed laminar boundary round the wire. There are pretty high temperature gradients at the lower part of the bubble, i.e. near the wire. The whole upper part of the bubble is covered with a thin liquid layer of saturation temperature. Due to differences in the surface tension caused by the high temperature gradient at the lower part of the bubble a circulating flow in form of small eddies may start such enhancing the heat transfer process. This phenomenon, the so-called Marangoni-effect was already mentioned by Beer /7/. If we look to the second and the following bubbles starting from the same nucleation point the conditions are quite different as shown in fig. 3. These "following bubbles" now are growing into the drift flow of the preceeding bubble which - due to sub-cooled boiling - already may be condensed. The isotherms at the lower part of the bubbles are now strongly bended and at the top of the bubble there is a thick boundary layer which has to be penetrated by the bubble before recondensation starts.

- 3 -

The conditions at the beginning of this recondensation are shown in fig. 4. The closely spaced fringe fields on the top and on the right side of the bubble indicate the start of the recondensation. From these first recondensation-spots in the next moment starts a very intensive convection around the bubble which brings cold fluid to the lower part of the bubble and such continuing the condensation at the bottom of the bubble while the top of the bubble then is covered with a thin layer of saturated liquid.

In another experiment the temperature distribution above a horizontal flat plate with sub-cooled pool boiling was measured. An example for this is given in fig. 5. The measurements were taken by a microthermocouple with a nearest distance from the wall of 0,04 mm. There is a very strong fluctuation of the temperature in the liquid near the wall as shown in the right upper part of fig. 5. If one draws the envelope curves of these oscillations one gets a minimum and a maximum curve also given in fig. 5. Due to the fact that the temperature maxima are usually very short the curve for the mean temperature lays a little bit nearer to the minimum curve. Finally in addition there is plotted in this figure the difference between the minimum and the maximum values of the temperature fluctuations. The distance from the heated surface, where this temperature oscillation reaches its maximum is depending from the sub-cooling and from the heat flux density. With decreasing sub-cooling it approaches the heated surface. This is easily to be understood because at saturated boiling only the bubble growth - in immediate neighbourhood of the heated surface - has an influence on the temperature oscillations. With high sub-cooling the temperature fluctuation is mainly caused by the recondensing of the bubble which takes place in a distance of 0.2 to 0.5 mm from the heated wall.

As shown in fig. 6 the temperature profile of the liquid in the boundary layer near the heated wall is almost linear. The gradient here is only depending from the heat flux density not from the sub-cooling. This is probably due to the fact that the heat transfer process is partly - in the periods between the bubble formation - done by heat conduction. But from this we cannot deduce that the heat transfer coefficients with sub-cooled and with saturated boiling are identical. Sub-cooling has a strong influence on the heat transfer coefficient as shown in fig. 7, where the values reach from pure free convection up to saturated boiling.

With forced convection the conditions in sub-cooled boiling are even more complicated. Experiments to measure the onset of sub-cooled boiling were done some time ago together with D. Hein /8/. These measurements were done in four rod clusters at pressures round 100 bar. The onset of sub-cooled boiling is a function as shown in fig. 8 of the flow velocity and of the heat flux density. At low velocities and low sub-cooling boiling starts already at values of small heat input which are well within the conditions of technical heat exchangers like boilers and pressurized water reactors.

There is a cosin distribution of the boiling boundary around the rod surface in the cluster. In the area opposite to the neighbour-rod boiling starts earlier than in the more open spaced region diagonal to the cooling sub-channel. This is due to the flow distribution in the sub-channel. These differences in the boundary of first bubble formation decrease with lower mass flow rate and greater pitch to diameter ratio of the cluster.(fig.9)

These short comments in the round table discussion naturally cannot give a complete analytical description of the bubble formation and heat transfer process during sub-cooled boiling. Such an attempt would be quite impossible, regarding the very complex physical mechanism. Moreover it was only intended to give a little more insight into some details of the physics of sub-cooled boiling and such perhaps to improve the understanding of this phenomenon.

L i t e r a t u r e:

/1/ R.W. Bowring:
HPR-29, Institutt of Atomenergi Halden, Norway

/2/ S. Levy:
AEC Research and Development Report, GEAP-5157
General Electric, San José, California, April 1966

/3/ P. Lavinge: Rapport G.E.A. No. 2365

/4/ S.Z. Rouhani:
Symposium on Two-Phase Flow, University of Exeter, June 1965

/5/ F. Mayinger, D. Nordmann, W. Panknin:
Holographische Untersuchungen zum unterkühlten Sieden
Chemie-Ing. Technik, 46 (1974), 5, S. 209, Synopse 022/74

/6/ W. Hauf, U. Grigull:
Optical Methods in Heat Transfer
Advances in Heat Transfer 6, 133 (1970)

/7/ H. Beer:
Progress in Heat and Mass Transfer 2, 311/370 (1969)

/8/ F. Mayinger, D. Hein:
Bubble Formation and Departure with Sub-cooled Boiling
in Water-cooled Channels of High Heat Flux Density,
Panel on Heat and Mass Transfer in Nuclear Power Plants,
IAEA-135, Vienna 1971, p. 87/108

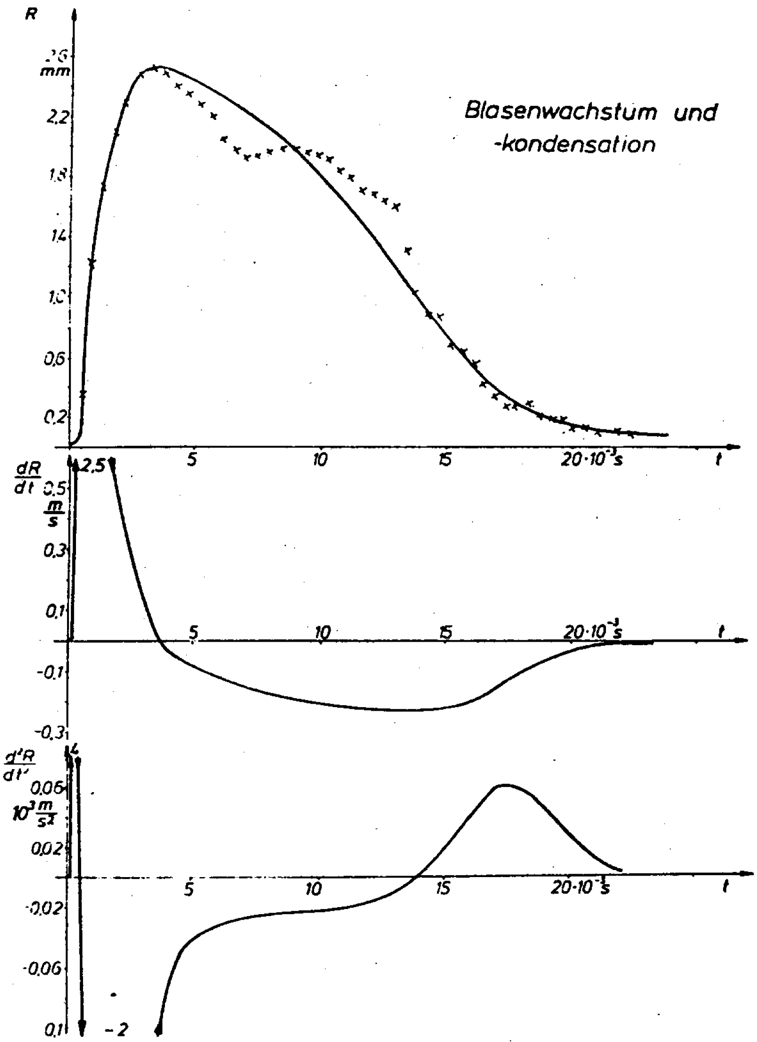

Fig. 1: Bubble-growth and recondensation velocity

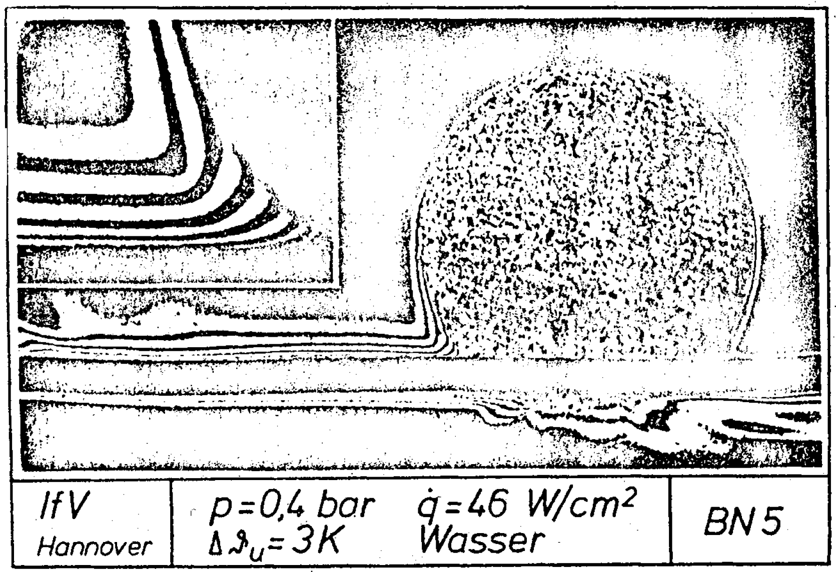

Fig. 2: Interferience fringes round a growing bubble

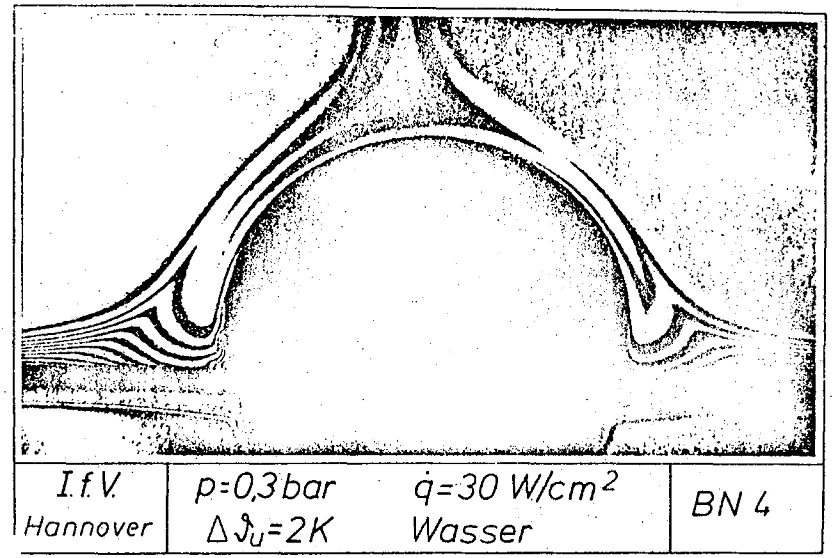

Fig. 3: Interferience fringes round a growing bubble

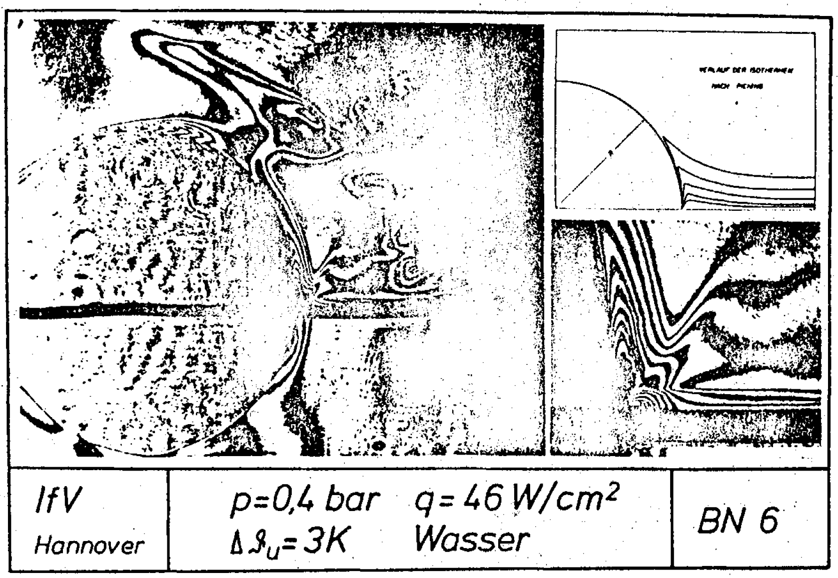

Fig. 4: Interference fringes round a recondensing bubble

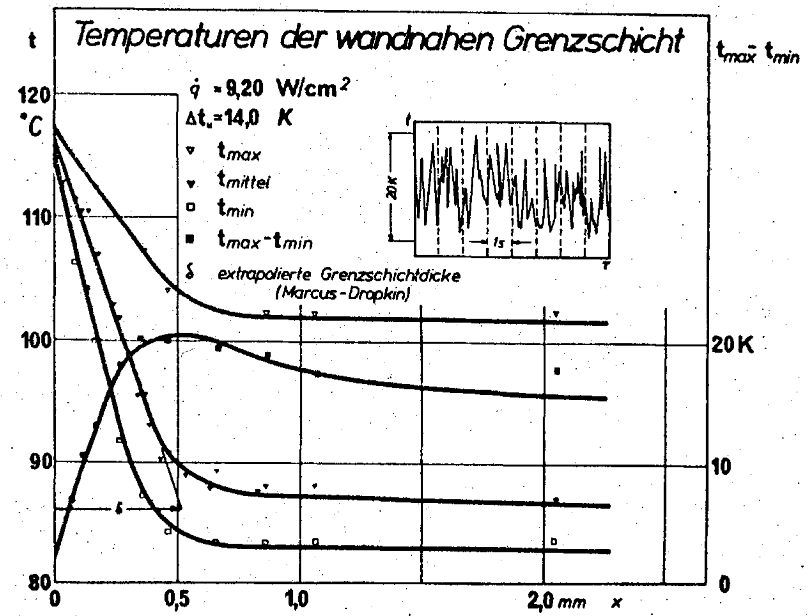

Fig. 5: Temperature distribution near the heated wall

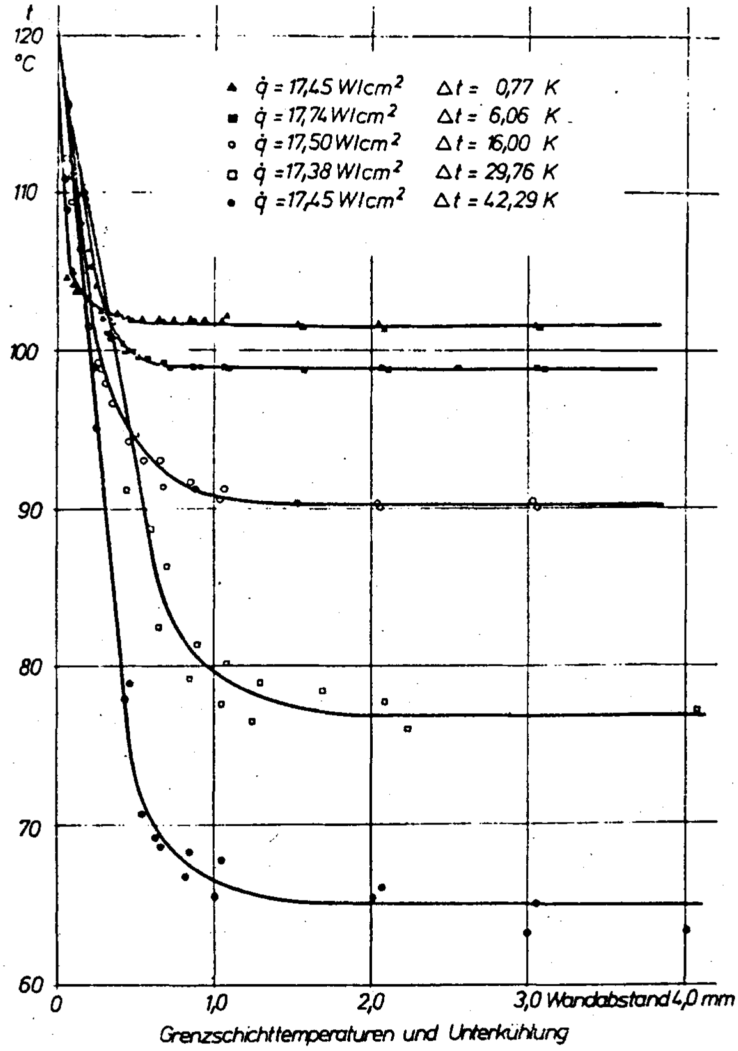

Fig. 6: Temperature distribution near the heated wall with different sub-cooling

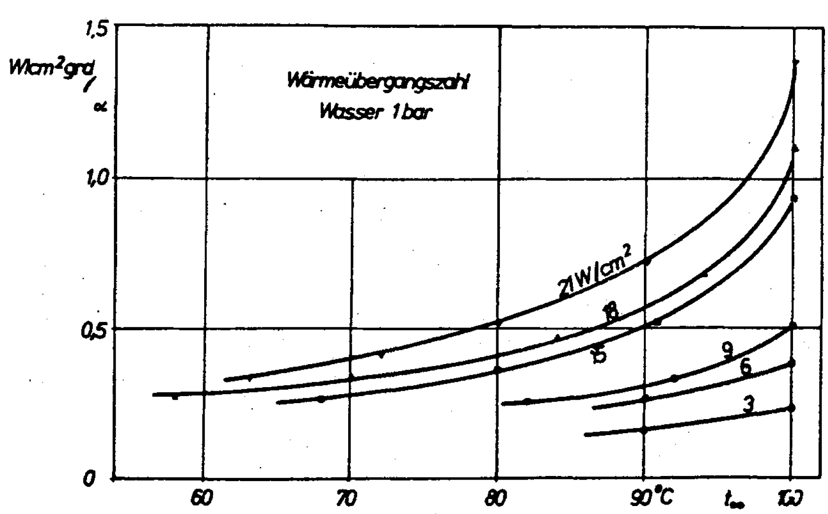

Fig. 7: Heat transfer coefficient with sub-cooled pool-boiling

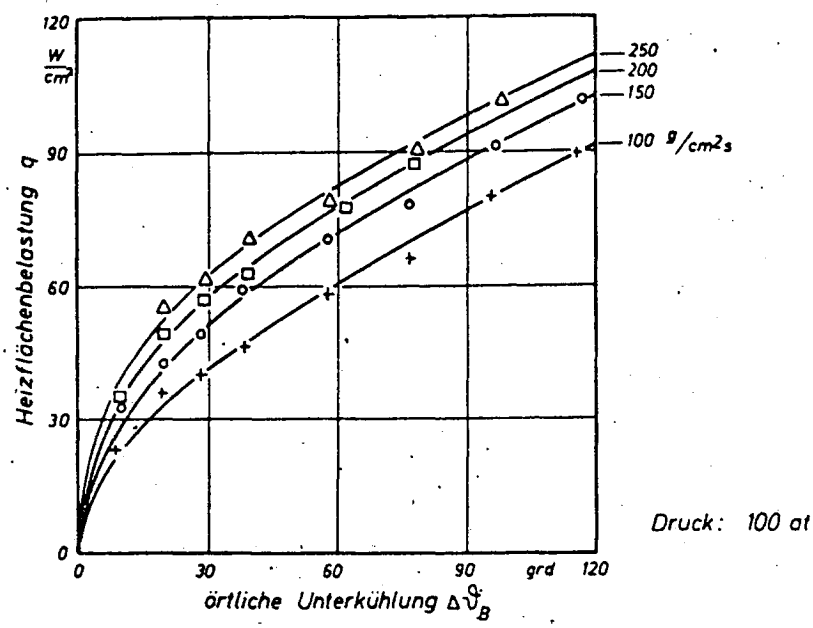

Fig. 8: Onset of sub-cooled boiling with water at 100 bar

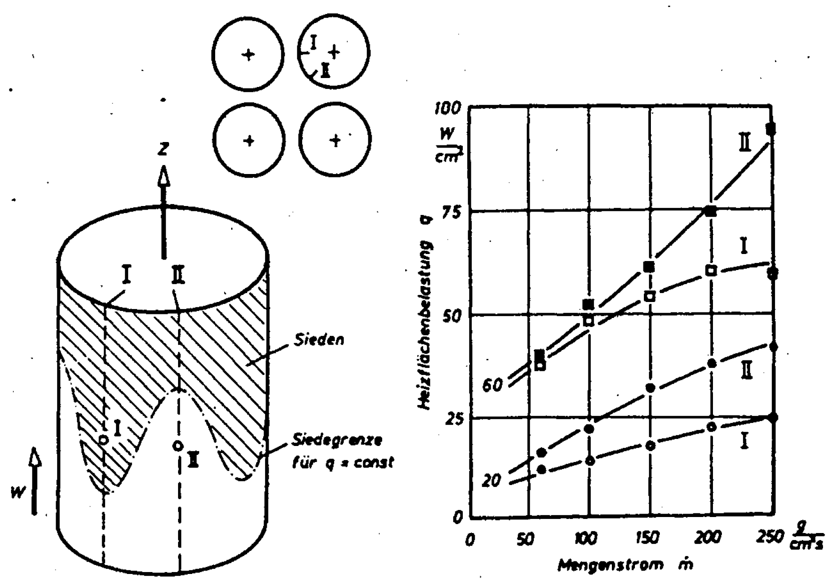

Fig. 9: Boiling boundary in a rod cluster