Seminar on Two-Phase Flow Thermohydraulics

Burnout power in transient conditions

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Reactor incidents or accidents are always accompanied by more or less fast transient conditions of the thermodynamic and hydraulic behaviour of the reactor coolant. A loss of flow due to a pump failure for example will lead to moderately fast changing values of mass flow rate and steam quality whereas a loss of coolant due to a leakage in the primary system of the reactor will produce a very rapid pressure change followed by severe transients in mass flow rates, steam quality and thermodynamic properties. From the safety point of view this loss of coolant accident is without any question the most important case but it also involves the most complicated thermodynamic and hydrodynamic conditions.

Before we are able to understand in detail the combined mechanism of the burnout behaviour during a loss of coolant accident with all its complicated thermodynamic and hydrodynamic details it seems useful and necessary to study first the different aspects combined with these phenomena in more simple transients like power excursions and mass flow diminuation. It was expected to get from these investigations an idea which theoretical model can be applied and which parameters have the most serious influence. The first simple question for example would be under which condition it is possible to treat a transient like a loss of flow or a loss of coolant likeaseries of quasi-stable conditions. In such a case steady-state burnout equations could be used, provided that at any time the local conditions at the burnout point are known.

In this short review dealing with burnout under transient conditions will be discussed mainly

power excursions and
mass flow decreasing.

Further a few results on "pump goes down" tests will be presented and finally a few words have to be said on loss of coolant tests just starting.

Power excursions

Looking in the literature for measurements on burnout tests with power excursions one can find some series of tests carried out in pool boiling with simple geometries like tapes or flat plates but only a few experiments with rods or rod bundles under forced convection.

Tests with pool boiling for example were made by Rosenthal and Miller /1,2/, Schrock and Johnson /3,4,5,6/, Harrison and Hall /7,8/, Kawamura, Akijama and Tachibana /9,10,11,12/, Sakurai /13/, Spiegler /14/, Hayashi /15/ and Cole /16/. In all of these cases the test geometries were small thin walled tapes. With similar test configurations but under forced convection power transient tests were made by Green and Quandt /17/, Susskind /18/, Martenson /19/, Grace /20/ and Schrock /3,4/. The power excursions used in these tests were very short and rapid, so that the critical heat flux was reached within a few milli-seconds. Only in a few tests the excursion time was in the maximum of one to two seconds. Usually the excursions started from zero power level.

These tests were mainly carried out in water with pressures between one and 140 bar and show as a common result that the critical heat flux under transient conditions was usually higher than in steady-state with the same geometrical, hydrodynamic and thermodynamic parameters. The difference between transient- and steady-state critical heat flux was mainly influenced by the power-time gradient of the excursion. Morgan /21/ and Gambill /22/ give a critical survey of these tests and Redfield /23/ used these papers to work out the burnout equation:

$$q_{cr,T} = q_{cr,S} \cdot e^{\frac{4{,}25 \cdot 10^{-3}}{t}} ;$$

for these power excursions. In this equation q_{cr}, T refers to the critical heat flux under transient condition and q_{cr}, S under steady-state conditions.

Tests with more reactor-like geometries had been made by Singer /24/, Elberg and Nyer /25/, Moxon and Edwards /26/ Kawamura /9/, Tong /27,28,29/ and at the Columbia University /30/.
Moxon and Edwards made their measurements in inside cooled tubes with uniform and cosine heat flux distribution. They found an improvement in the critical heat flux of 45% in the maximum due to the excursion behaviour. Outside cooled tubes were handled by Kawamura /9/ with an annular cross section. The tests of Singer /24/ and Elberg /25/ performed with inside cooled round tubes and rectangular channels give details on pressure pulsations, steam quality and outlet mass flow rate during the transient, but no values of the critical heat flux. Bundles of 19 and 21 rods were tested by Tong /27,28,29/ with power ramps of 15% per second, which means that the whole excursion time was between 3 and 13 seconds. Probably due to this slow excursion Tong found no difference between steady-state and transient conditions.

Recently a series of tests in rod clusters as well as in simple geometries like tubes and annulli were made by M.A.N. /31,32/. Due to the fact that the results of these tests have been published in the last few years they will be discussed here a little more in detail.

Before talking about the results of these measurements a few events occuring during a power transient should be briefly illustrated. In fig. 1 the temperature behaviour during a power transient is characterized in a temperature-time oszillogram. Time is plotted as abszissa from left to right, the heat produced in the rod is indicated by the current I. Initially the temperature of the heating surface which was measured at two opposite points of the rod during the test increased exponentially as the heat flux was increased.

This corresponds to the heat transfer conditions present during single phase forced convection. On inception of nucleate boiling the temperature gradient was substantially reduced. Within this range there was very violent steam generation liable to result in ejection of coolant. The inception of film boiling was marked by a sudden very steep temperature rise. By simultaneous recording of the heating surface temperature and the heating current, the heat produced in the rod at this moment is known. In order to prevent destruction of the rods, the energy supply was interrupted.

In the temperature pattern obtained after shutting off the heating current, three completely different phases can be recognized. For a certain period the heating surface temperature remains almost constant. The burnout spot is separated by a steam film from the coolant. Then the temperature drops off almost linearly with time as the burnout spot is wetted again by continued coolant flow. Eventually the temperature decreases exponentially to the cooling water temperature at the test section inlet. At this point cooling by forced convection has been fully restored.

The variations of the mass flow rate during the power transient clearly show the hydrodynamic processes in the test channel. As heating input and steam generation increase mass flow measured at the test section inlet decreases. On inception of film boiling the flow regime and consequentely the two-phase pressure loss change spontaneously and mass flow increases again to the original value.

Whereas under steady-state conditions the heat produced at every instant is transfered to the coolant, in the transient case part of the energy supplied is invariably stored in the heating element. Only the proportion transfered to the coolant is however relevant to the determination of the critical heat flux and therefore the heat stored in the rod wall during the transient up to the time film boiling starts was calculated and subtracted from the heat produced in the rod.

Looking for the results and keeping in mind the experience to be gained from literature one is tempted to assume that only the time of the transient or in other words the speediness of the power excursion has an influence on the critical heat flux. It is therefore obvious first to compare the results with the above-mentioned equation (1) given by Redfield. According to this equation the improvement in the critical heat flux should be restrained to very fast transients and very short excursion times. Fig. 2 shows that an evident improvement already can be found with excursion-times in the order of a few seconds and at not too steep excursion ramps. Therefrom we can gather that there should be an additional influence acting on the burnout behaviour under power transients for forced convection and complexe geometries.

During the M.A.N. test on four rod and nine rod clusters the observation was made that in addition to the speediness of the power transient an essential influence on the magnitude of transient burnout values is exerted by the acceleration and inlet effects in the flow. This acceleration influence tends to be different depending on the cluster geometry and the location of the burnout-endangered rod in the cluster.

Fig. 3 illustrates the improvements in burnout behaviour during power transients compared to the behaviour in steady-state operation. As abszissa the ratio of critical heat flux under transient condition and under steady-state conditions is plotted. The index A and the cross hatched areas refer to the outlet conditions of the test section, the hatched areas to the inlet condition. It can be seen clearly that in the nine rod cluster, simulating conditions in an open core, the improvement in burnout behaviour during power transients compared to steady-state operating conditions is much lower than in the more slender configuration of a four rod bundle of about twice the length or in an annulus.

A further contribution for discussing this geometrical effect gives fig. 4. Here as seen in the two upper curves results gained in an annulus and in a four rod cluster both with uniform heat flux are compared. It can be seen clearly that the improvement decreases with growing mass flow rate. For reasons of completeness it ought to be mentioned that these tests were performed with freon as modelling fluid. Very detailed comparising measurements where had been carried out by M.A.N. to show that the scaling laws given for example by Bourée or Stevens are also valid for these not too fast transients.

In fig. 4 in addition there are plotted test results taken from a four rod cluster with axial cosine heat flux distribution. Comparing these results the whose mean values of which are given as dotted line with the solid line of the axial uniform heat flux we can see that the transient improvement is reduced due to the non uniform heat flux. This influence of the axial power distribution can also be seen clearly in fig. 5. Here critical heat flux measurements in transient and in steady-state conditions taken in a four rod cluster with freon are plotted against the mass flow rate. Whereas at steady-state conditions the axial heat flux distribution has no influence; the transient behaviour is quite different. Uniform heat flux shows there a much better improvement than the cosine one.

The question is now which are the phenomena influencing and improving the critical heat flux under power transients. In the first empirical step of our discussion we have found that the transient time, the geometrical configuration, that is the slenderness of the cooling channel, and the heat flux distribution are effecting the measured burnout values. The influence is reduced with growing mass flow rates. Certainly there is a large accelerating process in the cooling channel during the power transient. This process is caused by the evaporating of the fluid and is the much higher the more slender and long the channel is. It can also be easily understood that the relativ benefit coming out from this acceleration for the critical heat flux is higher at low mass flow rates.

During this acceleration both, the flow profile and the temperature or density profile vary so that conditions are present such as normally obtained in an inlet zone of a channel. Burnout tests on very short test channels without a fully developed velocity and density profile produced similar high values for the critical heat flux. This may be an additional explanation for the improvement in burnout performance observed with power transients. Looking at these flow phenomena the transient time or better the power ramp of the transient certainly has an immediate influence on the acceleration and the density profile in the channel. This time dependency is shown in fig. 6 where some measurements with an uniform heated four rod bundle are reported.

Certainly mixing processes also effect the critical heat flux under power transients. It might also be possible that instabilities of a very short period have an additional effect, but the onset of instabilities is also a function of the flow regime, and there another question rises that is: whether there is bubble flow or annular flow in the cooling channel.

With annular flow in the cooling channel there may be a much simpler explanation for the burnout improvement with power transients. The liquid film at the heated wall is slowly becoming thinner due to the evaporation and the entrainment of the droplets and dryout occurs if this liquid film locally disappears. Under steady state conditions we can evaluate this liquid film thickness by a mass balance taking in account the mass flow in the film the entrainment and reentrainment of the droplets in the vapor core and the evaporation due to heat addition. Under the power transients now the first question would be whether the transient is fast compared with the mass and heat exchange process in the liquid film and at the phase boundary. As long as the liquid supply in the film, the evaporation, the entrainment and reentrainment process are approximately as fast as the power excursion the system has the possibility to keep equilibrium conditions at any time. In this case the transient can be treated as a series of quasi stable states.

With fast transients then the onset of film boiling is primarly a question of the time in which the existing liquid film evaporates from the wall. If this is true the critical heat flux should be expansively independend from the flow conditions outside of the liquid film. In this case certainly also thermodynamic non-equilibrium conditions have to be recognized. But for a clearer insight and better understanding of this problem much more fundamental test have certainly to be performed.

Mass flow transients

During a "pump goes down" accident in a reactor the flow of the cooling fluid in the core is reduced within 10 t0 15 seconds down to a few percent of the nominal velocity. Then the reactor is scrammed as fast as possible but due to the instrumentation there is a delay time between pump failure and scram. So we have in the case of loss of coolant a combined mass flow and power transient.

Up to now only a few papers can be found in the literature dealing with this problem. De Bortoli /33/ reports some results of measurements concerning the maximum allowable delay time until the reactor is shut down by scramming. The problem of "pump goes down" is treated more detailed by Tong /34/. He made two different test series with a nineteen rod cluster. In his first test series the mass flow rate was reduced under constant heat flux, while in the other test series mass flow rate and heat flux were lowered similar to the reactor behaviour. Not all of these tests were leading to burnout but if burnout occured, it was on the same level as under steady state conditions. Moxon and Edwards /35/ made measurements in inside cooled tubes and with clusters of 37 rods. In a similar way as Tong they reduced the mass flow rate by switching off the circulating pump and kept the heat flux constant. Their results show 10 to 20% higher burnout values as under steady state conditions.

Here again I want to present some measurements in detail wirked out by M.A.N. /31,32/. For a systematic planning of these tests and with the aim to get clear and reliable results it seemed adequate to separate in the first step within these "pump goes down" experiments the two variables, that is the mass flow and the power transients. Therefore in the first test series the heat flux was kept constant during the flow reduction. The power level was thereby varied between the operating conditions of watercooled reactors and a few percent below the critical heat flux under these steady state operating conditions. In a second test series then the mass flow rate and the heat flux simultaneously were reduced according to the realities during the loss of coolant in the reactor. Inlet sub-cooling and system pressure were kept constant during this procedure. Test were made with water in four rod clusters and with freon in four and nine rod clusters.

As an example fig. 7 shows an oszillogram recorded during these tests. Time is plotted from right to left as the abszissa. The variation of the mass flow density $\dot{m}$ at the test channel inlet and the pressure loss Δp measured across the heated cluster length is shown in the upper part of the diagram. The heat produced in the rod is indicated by the heating current I recorded during the test and was roughly equal in all four rods. Two rods had the heating surface temperature measured close to the test section outlet one thermocouple being provided on one rod and two on the other rod arranged in one plane at opposite locations. The variations of the three measured temperatures ϑ_1, ϑ_2 and ϑ_3 together with the current I are shown in the lower part of the diagram. As mass flow decreased the surface temperature rose though the heating input maintained constant until film boiling started in one tube at a definite rate of mass flow. Before an excessive temperature was attained which would have endangered the tube material the heating power was shut off.

The results of measurements of the critical heat flux during mass flow transients are reproduced in fig. 8, 9 and 10. Fig. 8 shows results taken with water in a four rod cluster whereas the results produced in the figures 9 and 10 are measured in freon as test fluid with four- and nine rod clusters. In all cases the radial and axial heat flux distribution was uniform. The black spots in these figures give the results of the transient measurements and in addition the results of burnout measurements under steady state condition are plotted as empty round marks.

For the transient tests at a relatively high mass flow density a constant heat flux was maintained and mass flow was decreased until film boiling occured. It can be clearly seen that there is almost a complete agreement between transient and steady-state measurements. Only at very low mass flow rates, the transient results tend to lie higher than the steady-state burnout curve would predict. This is certainly due to the fact that the liquid film at the heated wall needs a certain time until it is completely evaporated. In this range the mass flow rate has almost no influence on the critical heat flux and burnout is only a question of the drying out of the liquid film.

Generally spoken we can seenthat the burnout behaviour under these not too fast mass flow transients can be treated as a series of quasi stable conditions and there is no difference between steady state and transient burnout prediction if the local conditions are known at any time during the loss of flow.

For practical use an additional question is of great interest: whether axial non uniform heat flux distribution would change this result. Tests with a four rod cluster and axial cosine heat flux distribution as shown in fig. 11 proved that also in this case the transient values are within a narrow scattering area of a few percent in good agreement with steady-state measurements.

The results up to now seem to allow the conclusion that also in the combined transient with mass flow and power reduction the critical heat flux can be deducted from steady-state measurements. But for a concrete judge of the indicent it seemed to be adequate to imitate the real conditions during a loss of coolant in the reactor. Two results of such measurements are shown in fig. 12. In this figure the trial was made to show the course of the most important parameters as mass flow rate and heat flux during the measurement and so to demonstrate the burnout behaviour at this kind of transient. As abszissa the time is plotted and the ordinate scale is used for the mass flow rate and for the heat flux. The onset of film boiling is indicated with BO. The lower curves in this diagram show the course of the mass flow rate, the upper one the heat flux. In addition there are plotted curves of the critical heat flux like it would behave under steady-state constions. These curves are indicated by $q_{BO,stat.}$ The curves of the real heat flux at the rods are indicated by q. The roman numbers in brackets behind the indications refer to the two test cases I and II. From this picture one can see that the burnout during "pump goes down" is in the same magnitude as under steady-state conditions, perhaps there is a slight improvement to be expected. From these results we can deduce that the burnout behaviour of the loss of flow incident is conservatively predicted by steady-state burnout equations.

Burnout in pressure transients

Combined pressure, mass flow and power transients occure during the accident of loss of coolant. In this case we have a fast depressurisation combined with at first high fluid acceleration in the core and a power reduction due to the scram. Tests imitating these conditions are very complicated and difficult. Such tests are currently under way at AEG laboratories in Großwelzheim. First results as reported in the 1972 European Two-Phase Flow Meeting held a few days ago here in Rome were gained in inside cooled tubes and give an idea of the order of the heat transfer coefficient in the post dryout region. They also show that the onset of dryout is a little delayed compared to elaborations and estimations deduced from steady-state calculation. This delay time lies between a few tens of a second and a few seconds. Up to now, however, it is difficult to get from these preliminary tests an answer for the probable burnout improvement during these transients.

Certainly a steady-state consideration gives conservative results with respect to reactor safety. In the next month there will be a strong effort in this field and we hope that a lot of more test results will be available soon to put us into the position to give a clear answer to the question of the critical heat flux during the loss of coolant. In connection with this accident so many questions regarding the safe core behaviour as flow distribution, refilling process, balloning and steam binding are open that we think it needs a strong common effort of all institutions interested in the safety of light water reactors to overcome this problems as soon as possible.

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