ATKE 15-8 (47–52) 1970

Two-phase problems in nuclear reactors[1]

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Abstract

The primary circuit fluid in water-cooled reactors serves two purposes, one being to provide cooling and the second to serve as neutron moderator. It is in performing these functions satisfactorily and reliably that the problems in two-phase flow in nuclear reactors reside.

In assessing the moderator properties of the fluid flowing through the core it is important to have accurate information on its steam quality. The determination of the steam quality presents difficulties due to sub-cooled boiling which occurs in all modern power reactors. Efficient cooling depends on an adequate heat transfer from the fuel elements surface to the fluid and on stable flow conditions in the core. Problems of critical heat flux in boiling and instabilities and pulsations in two-phase flow are discussed. The authors presentations are explained on the strength of his own test data.

Zusammenfassung

Zweiphasenprobleme im Kernreaktor

Bei wassergekühlten Reaktoren hat das Primärkreis-Medium zwei Aufgaben, nämlich die der Kühlung und die der Neutronenmoderierung. Aus der einwandfreien und zuverlässigen Erfüllung dieser Aufgaben erwachsen die Probleme der Zweiphasenströmung im Kernreaktor.

Für die Moderatoreigenschaften des das Core durchströmenden Fluids muß dessen Dampfgehalt genau bekannt sein. Seine Bestimmung bereitet insbesondere bei dem in jedem modernen Leistungsreaktor auftretenden unterkühlten Sieden Schwierigkeiten. Für die Kühlung müssen hinreichend guter Wärmeübergang von der Brennelementoberfläche an das Fluid sowie stabile Strömungsverhältnisse im Core gewährleistet sein. Es werden die Probleme der kritischen Heizflächenbelastung beim Sieden sowie der Instabilitäten und Pulsationen in Zweiphasenströmungen diskutiert. Die Ausführungen werden anhand eigener Messungen erläutert.

EURATOM KEYWORDS

TWO-PHASE FLOW
WATER COOLED REACTORS
IN PILE LOOPS
MODERATORS
REACTOR CORE
STEAM QUALITY
SUBCOOLED BOILING
POWER REACTORS
COOLING
HEAT TRANSFER
FUEL ELEMENTS
SURFACES
FLUIDS
STABILITY
CRITICAL HEAT FLUX
BOILING
MEASUREMENT
HOT CHANNELS

1. Introduction

The fluid flowing in the primary loop of a nuclear reactor serves two purposes: Firstly, it serves for heat transport, and secondly, in the case of water-cooled reactors, it also acts as neutron moderator. A full understanding of its thermodynamic and hydrodynamic behaviour under the conditions prevailing in reactors is therefore of great importance, especially as heat transport in the cooling channels of the reactor core represents a system of impressed heat flux and because under conditions of insufficient cooling, the temperature may rise to a level where destruction of the reactor core is liable to result.

While for the prediction of the moderator effect the factors of interest are primarily the coolant density and in boiling and two-phase flow, the steam quality in the reactor core, the other function, i. e. cooling, depends on two requirements being met:

> Efficient heat transfer from the surface of the fuel elements to the coolant
> and
> stable flow conditions at adequately high velocities to ensure safe removal of the heat absorbed by the coolant due to heat transfer from the core to a heat sink.

Thus we have as the most important problems of two-phase flow to obtain information on, and achieve control of, fluid density or steam quality, respectively, and of the heat transfer in the core, and to ensure stable flow conditions.

2. Hydrodynamic and thermodynamic conditions in two-phase flow

As a rule, modern water-cooled power reactors are designed with sufficiently high power densities for local boiling to take place in the zones of maximum heat flux, i. e. in the so-called "hot channels" even during operation in the sub-cooled range. Steam bubbles are liable to form on a heat-emitting liquid-cooled wall when the surface temperature of the wall exceeds the saturation temperature of the liquid. Steam bubbles tend to originate from active boiling nuclei, i. e. cavities resulting from the natural roughness of the wall and grow very rapidly due to the supply of energy and fluid from the superheated liquid boundary layer directly adjoining the heating surface, this layer being in a thermodynamically meta-stable state. Evaporation takes place instantaneously where the heating surface offers active nuclei. As it forms and develops, the steam bubble derives more than 90% of the energy stored in it indirectly from the superheated boundary layer and only, a minor portion is supplied directly by the heated wall. In other words, the greater part of the heat transport between the wall and the coolant takes place via the liquid phase.

Experience has shown that in a cooling channel having liquid admitted in the sub-cooled state and a water/steam mixture leaving at the other end, the point where steam bubbles tend to form first is not the point where saturation temperature is reached but, on high heat flux heating surfaces rather at a point where the bulk of the liquid is still considerably sub-cooled. This phenomenon is referred to as "sub-cooled boiling".

The processes in a high heat flux channel with coolant entering considerably sub-cooled are shown schematically in Fig. 1.

There are four distinct zones. In zone I the high degree of sub-cooling of the fluid causes straight single-phase flow to prevail without any boiling.

Due to the heat supplied, the temperature of the coolant on its way through the channel rises steadily and, consequently, the heating surface temperature will eventually reach a value sufficient to provide initial nuclei for steam bubbles. Sub-cooling of the flow is, however, still high enough to prevent the steam bubbles from growing beyond the very thin bound-

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[1] Paper presented at the Reaktortagung of the Deutsches Atomforum e.V., Frankfurt (Main), 15.–18. April, 1969.

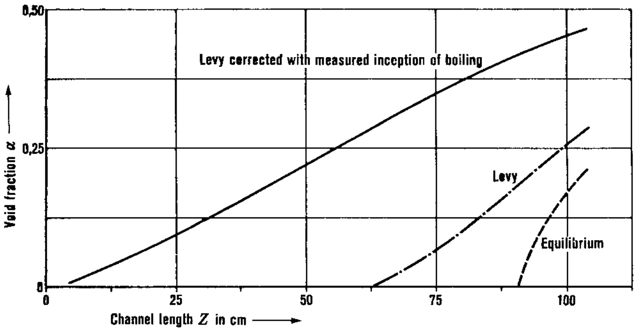

Fig. 3: Influence of boiling onset on steam quality. $P = 100$ kgf/cm², $m = 100$ g/cm² s, $\Delta\vartheta_{in} = 40$ deg C, $q = 80$ W/cm²

Fig. 3: Einfluß des Siedebeginns auf den Dampfgehalt. Druck 100 at, Mengenstromdichte 100 g/cm² s, Eintrittsunterkühlung 40 grd, Heizflächenbelastung 80 W/cm²

qualities, individual steam bubbles are likely to be uniformly distributed in the fluid flow and this is referred to as "bubble flow".

As boiling increases, large individual bubbles tend to form in a transition range, especially with relatively small mass flow densities which are liable to disturb considerably the steady process of fluid transport through the cooling channel. This is referred to as "slug flow". As steam quality increases further, a point will be reached where so much liquid has evaporated that the liquid column which has been more or less coherent up to that point is broken up by the steam, leaving liquid only deposited and flowing up on the heating surface as a film while in the free flow area steam with entrained water droplets prevails. This flow regime is termed "annular flow".

Before discussing the equilibrium of forces and problems arising in this type of two-phase flow it appears desirable first of all to consider the process of straight heat transfer from the heating surface to the boundary layer of cooling fluid on it.

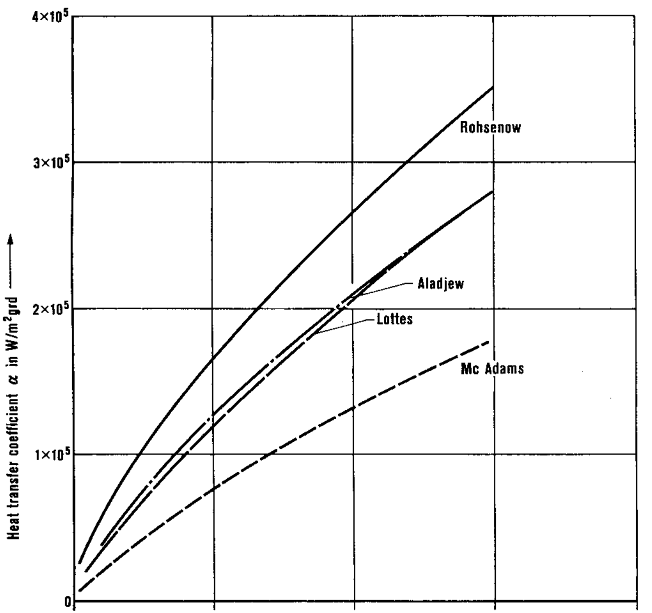

Fig. 4: Heat transfer coefficients during nucleate boiling $p = 70$ bar, $m = 200$ g/cm² s

Fig. 4: Wärmeübergangszahlen beim Blasensieden

3. Heat transport from wall to cooling fluid

Heat transfer in boiling generally permits very high heat flux levels because, firstly, the agitating effect of the steam bubbles causes intense turbulence on the heat emitting wall and, secondly, the steam bubbles are capable of carrying away large amounts of energy in the form of latent heat, i.e., heat of evaporation. As a typical example, Fig. 4 is for a mass flow of 200 g/cm²s and a pressure of 70 kgf/cm² and provides an idea of the heat transfer coefficients to be expected in boiling under conditions of forced convection. The values calculated according to the methods of 4 different authors [4 to 7] have been potted. It is known from numerous tests that during boiling the heat transfer coefficients depend to a large extent on the impressed heat flux and rise considerably as the rate of heat transfer is increased. Therefore, the heat flux has been selected as abscissa in Fig. 4. The proportion of the heat transfer due to forced convection is independent of the heat flux and, in the case of the example illustrated in Fig. 4, amounts to approximately 20 000 W/m² deg C. The graph shows that the heat transfer coefficients tend to improve considerably as the rate of heat transfer is increased and with heat flux levels of 300 W/cm² attain values as high as some 200 000 to 300 000 W/m² deg C. This trend of heat transport is most conducive to the safety of a water-cooled reactor because, as a result, when the heat flux is increased, the surface temperatures of the fuel elements rise but little.

The reason for the improvement in heat transport is to be found in the high rate of increase in the number of boiling nuclei and steam bubbles as the heat flux is increased. However, if the heat flux is increased beyond a preset value, the steam bubbles suddenly form a solid blanket which isolates the heating surface from the cooling fluid. The result is a sudden breakdown of heat transport leading to a marked temperature rise and eventually what is termed "burnout", destruction of the heating surface. The heat flux level at which heat transport from the initially high values of nucleate boiling suddenly decreases to low insufficient values of film boiling is termed the "critical heat flux".

Physically, two different processes can be distinguished in the formation of film boiling. They are associated with the previously mentioned flow regimes viz. bubble flow and annular flow.

During bubble flow, the bubbles accumulate mainly near the heated wall whereas water-phase fluid prevails in the core of the flow. Thus the maximum steam quality is to be observed close to the heating surface. During nucleate boiling, there is a steady and intense fluid exchange between the boundary layer adjacent to the heat surface and the core of the flow because the amount evaporated has to be replaced by liquid. As evaporation increases, a sudden breakdown of this mechanism of fluid exchange is observed. The bubble layer detaches from the wall, the liquid stagnates for a short period on the heating surface and, on account of the high heat flux, this leads to violent evaporation and, consequently, to a steam film forming on the heated surface. Thus, nucleate boiling has changed into film boiling, a process described in American literature as "Departure from Nucleate Boiling".

Conditions are different in the case of annular flow. Here a liquid film forms on the wall whereas the core of the flow is made up of steam. In contrast to bubble flow, the distribution of the steam quality has a maximum at the centre of the flow area. As heat flux is increased, the proportion evaporating from the water film rises, resulting in a reduction of the

applied to some ten different points. The actual burnout values, i. e. those measured, are shown by the dotted line in the graph. In order to bring out even better the percentage difference existing between the individual predictions, a range of scatter of ± 10% about the measured burnout curve as the mean value has been shown by crosshatching. From this, the conclusion can be drawn that *Tongs* estimation of the uncertainty in his method is too conservative rather than too optimistic.

Special studies in connection with the burnout problem have been directed towards exploring the possibilities of raising the critical heat flux and determining the burnout levels to be expected under transient conditions of coolant flow and reactor power. An effective means of improving the critical heat flux is provided by simple swirl or turbulence-producing fittings in the fuel element bundle. If these are made in the form of spiral fins extending over the full length of the fuel element it is possible–as measurements have shown–to increase the critical heat flux by more than 100%. But even short spiral vanes with a length of 30 to 50 mm which can be fitted to existing spacers are apt–as other measurements have proven–to ensure an improvement in the critical heat flux of up to 40% without attracting a penalty in the form of, say, fretting corrosion or manufacturing difficulties as in the case of full length fins.

The critical heat flux during power and mass flow transients is an area that has seen little research up to now. Measurements of the burnout during rapid power increase have recently been made on 4-rod and 9-rod clusters [11]. These have shown that, depending on the geometry in the core as well as the duration and gradient of the power excursion, appreciably higher critical heat flux levels may in some cases be expected than in steady state operation. However, because of the small number of measuring points investigated, this improvement should not, for the time being, be taken advantage of in general design practice.

Power reactors are invariably designed with a high safety factor against burnout. Nevertheless, the question as to what heat transfer coefficients are to be expected under conditions of film boiling would be of interest in the case of reactor accidents, such as pump failure and coolant loss. As an example, the heat transfer coefficients during film boiling have been plotted in Fig. 7 for a mass flow of 70 g/cm²s against the system pressure for various heat flux levels. It can be seen that in film boiling–similar to what was found during nucleate boiling–the heat transfer coefficients tend to vary considerably with the heat flux applied. On the average, however, the heat transfer coefficients are well within a range where appreciable heat flux values are obtainable at heating surface temperatures near the safe limit, i.e. where no destruction of the fuel element does occur.

4. Heat transport from reactor core to heat sink

As mentioned initially, it is important that in addition to adequate heat transfer from the fuel element wall to the coolant satisfactory heat transport is ensured from the reactor core to the heat sink, be it a steam raising unit or a turbine connected into the primary loop. Stable flow conditions through the reactor core as are necessary to this end depend on equilibrium existing between the driving forces and the resisting forces. In a heated channel where evaporation occurs the thermodynamic and hydrodynamic conditions can be represented by the mass balance, energy balance and force balance. As each phase flows at a different velocity, it is necessary to consider the balances separately for each of the two phases.

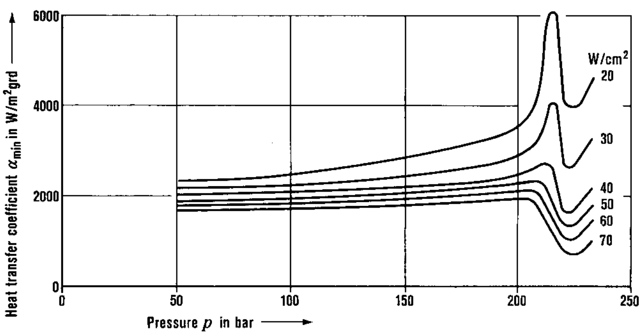

Fig. 7: Heat transfer coefficients during film boiling $m = 70$ g/cm² s

Fig. 7: Wärmeübergangszahlen beim Filmsieden, $m = 70$ g/cm² s

Regarding the volume element $F \cdot dz$ of a heated channel, the mass balance is given by the continuity equation reproduced in equation (1) with the simple statement that the mass storage in time within the volume element is equal to the difference between the quantity entering and the quantity leaving.

$$\frac{\partial}{\partial t}\left[\varrho_W(1-\alpha)+\varrho_D\,\alpha\right]+\frac{\partial}{\partial z}\left[\varrho_W\,w_W(1-\alpha)+\varrho_D\,w_D\,\alpha\right]=0 \qquad (1)$$

where

α the volume fraction of steam in the volume element under consideration

ϱ_W, ϱ_D the density of the water or steam respectively

w_W, w_D the flow velocity of the two phases

The coordinate of the channel length extending in the flow direction is designated z and the time t.

Similar as in the case of the mass balance, the change in time of the energy available in the volume element in the energy balance of equation (2), too, is obtained as the difference between the inflowing and outflowing energies increased, however, by the heat introduced into the volume element by the heating of the channel.

$$\frac{\partial}{\partial t}\left[\varrho_W\,h_W(1-\alpha)+\varrho_D\,h_D\,\alpha\right]+ + \frac{\partial}{\partial z}\left[\varrho_W\,h_W\,w_W(1-\alpha)+\varrho_D\,h_D\,w_D\,\alpha\right]=q\,\frac{U_b}{F} \qquad (2)$$

In this equation, the specific enthalpy is designated h whereas U_b represents the heated circumference of the volume element and q the heat flux passing from the channel wall into the cooling fluid.

With regard to the force balance represented by equation (3), the condition to be satisfied is that the momentum change in time in the volume element has to be equal to the difference between the inflowing and outflowing kinetic energies plus the end forces acting on the element.

$$\frac{\partial}{\partial t}\left[\varrho_W\,w_W(1-\alpha)+\varrho_D\,w_D\,\alpha\right]+\frac{\partial}{\partial z}\left[\varrho_W\,w_W^2(1-\alpha)+\varrho_D\,w_D^2\,\alpha\right]= = -\frac{\partial p}{\partial z}-\tau_W\,\frac{U_W}{F}-g\left[\varrho_W(1-\alpha)+\varrho_D\,\alpha\right] \qquad (3)$$

In view of the friction-affected flow and the buoyancy in the vertical channel this equation has the last two terms indicated added to it. In equation (3), U_W is the wetted circumference