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Burnout Conditions for Flow of Boiling Water in Vertical Rod Clusters

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This paper deals with a new concept for predicting burnout conditions for forced convection of boiling water in fuel elements of nuclear boiling reactors.

The concept states the importance of considering the ratio of heated channel perimeter to total channel perimeter.

The perimeter ratio concept was arrived at from an experimental study of burnout conditions in rod clusters consisting of three rods of 13 mm. outside diameter and 830 mm. heated length. Data were obtained for pressures between 2.5 and 10 kg./sq. cm., surface heat fluxes between 50 and 120 W./ sq. cm., mass flow rates between 0.03 and 0.33 kg./sec., and steam qualities between 0.01 and 0.52.

The rod clearance for the experiment were 2 and 6 mm. The diameter of the channel was 41.3 mm. Additional runs were also performed after unheated displacement rods were introduced in the channel. The rod clearance in this case was 6 mm.

In the ranges investigated the measured burnout steam qualities at the outlet of the channel decrease with increasing heat flux and decreasing pressure. Furthermore it has been found that the influence of rod clearance is, in the range investigated, of small significance for engineering purposes.

It has also been observed that the present burnout steam quality data for the rod clusters are much lower than those earlier obtained for round ducts. This may be explained physically by means of the perimeter ratio concept.

It has also been found that the surface shear stress distribution around the channel perimeter and especially the position of maximum shear stress is of great importance for predicting burnout conditions for flow in channels.

Finally the new method has helped in understanding and interpreting experimental results which earlier may have seemed inconsistent.

During recent years much attention has been devoted to the problem of predicting the maximum surface heat flux which can be employed on fuel elements in pressurized or boiling nuclear reactors without danger of melting the fuel material.

The maximum heat flux is generally called the *burnout heat flux*, and the flow conditions causing burnout are defined as burnout conditions.

The thermodynamics and fluid mechanics of the phenomena causing burnout are very complicated; indeed no physical model has been established which completely explains the process and which can be used for analytical prediction of burnout heat flux. However a large number of empirical correlations based on experimental results exist. The main features of these in-

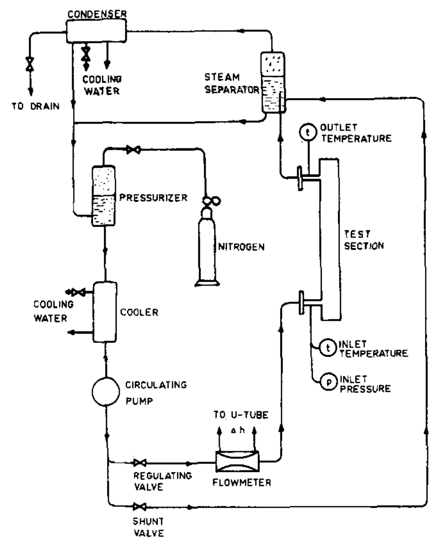

Fig. 1. Flow diagram.

vestigations are that they show a very large scatter in the experimental data, and that the correlations are in poor agreement with each other, in some cases even contradictory. Especially the effects of channel geometry have not been understood.

Surveys of available correlations and experimental data may be found in papers by Collier (*1*), De Bortoli et al. (*2*), Pexton (*3*), and Cicchitti et al. (*4*).

It is generally accepted that two distinctly different types of burnout exist. The first type occurs with steam qualities close to 0 and with high heat fluxes and is in the literature often defined as the point where departure from nucleate boiling occurs. The other type occurs with high qualities and relatively lower heat fluxes. In the intermediate ranges of heat fluxes and steam qualities the two types may blend into each other, showing characteristics from both types and resulting in rather complicated flow patterns and burnout models.

The latter burnout type may briefly be described as follows. With the high steam qualities in question fog flow occurs in the channel. The bulk of the fluid then consists of saturated vapor with a dispersion of small water droplets. The wall is covered by a thin layer of superheated water, and the cooling of the wall is achieved by evaporative cooling. Close to the water layer the steam is superheated. By diffusion the water droplets are continuously transferred to the water film, and simultaneously water evaporates from the liquid surface and into the vapor core. Furthermore water is also transferred from the film to the vapor core by re-entrainment. The net effects of these processes are that the water film thickness decreases in the direction of flow, that the average vapor velocity increases as one proceeds downstream in the duct, and finally that the shear stress between vapor and liquid phase also increases in the flow direction. This shear stress produces surface waves or ripples on the liquid surface. As the shear stress increases, the amplitude of these waves and ripples also increases. At the burnout point the amplitude of the surface waves has grown to such an extent that the film is destroyed, leaving the wall dry. This decreases the heat transfer coefficient significantly, causing a large increase of wall temperatures.

During 1961 slightly different modifications of this flow model were proposed by Collier (*1*), Goldman et al. (*5*), Isbin et al. (*6*), and Becker and Hernborg (*7*).

A research program concerning chiefly the second type of burnout has been in progress for about one year at the Heat Engineering Laboratory of AB Atomenergi in Sweden. The ultimate purpose of this program is to arrive at a method which safely predicts the burnout heat flux in fuel elements in nuclear pressurized and boiling reactors as a function of flow variables.

The method of attacking the problem has been to simulate the reactor fuel elements by test sections which are electrically heated. It is desirable to carry out full-scale experiments, but such experiments would be very time consuming and expensive. In addition it would be difficult to interpret or analyze, in terms of the basic flow variables, the results obtained in full-scale test sections consisting of a large number of rods.

Therefore the first phase of the research program dealt with test sections of simple geometry, and the influence of pressure, surface heat flux, steam quality, and mass flow rate was studied. The selected geometry was round ducts and until now thirteen different ducts have been tested. The lengths of these ducts varied from 0.6 to 3.0 m. and the diameters from 4 to 13 mm. Some of these results have been presented in reports by Becker et al. (*7, 8*). A final report covering this study is now in progress.

The prime objective of the present study has been to investigate the influence of geometry on burnout conditions and to examine the possibility of direct application of earlier burnout results for round ducts to the more complicated geometry of rod clusters. Considerable attention has been devoted especially to the effects of varying the rod clearance in the cluster.

A low-pressure loop for a maximum operating pressure of 10 kg./sq. cm. was available in the laboratory when it was decided to start the present experimental study. Although it would have been desirable to carry out experiments at higher pressures, it was decided in order to save the time of building a new loop to use the low-pressure apparatus for this study. This arrangement was satisfactory as the prime purpose of the investigation was to examine the effects of geometry and rod clearance.

DESCRIPTION OF APPARATUS

The loop

The flow diagram for the loop is shown in Figure 1. From the outlet of the pressure vessel containing the test section the water vapor mixture enters a steam separator. In the steam separator the saturated water is mixed with cold water supplied to the separator through a duct acting as a shunt in parallel with the test section. Leaving the separator the liquid flows to a pressurizer and then, after passing through a cooler, the water enters the suction side of the circulating pump. The steam leaving the separator is condensed in a condenser, from which the condensate passes out through a duct connected to the water pipe between the steam separator and the pressurizer.

The mass flow rate through the test section is controlled by means of one valve

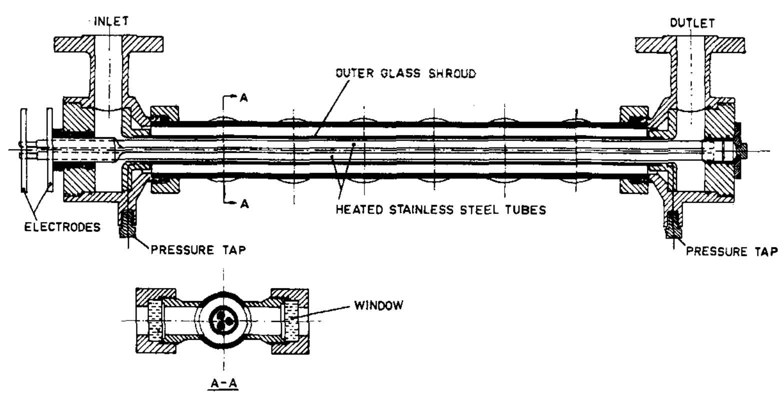

Fig. 2. Pressure vessel and test section.

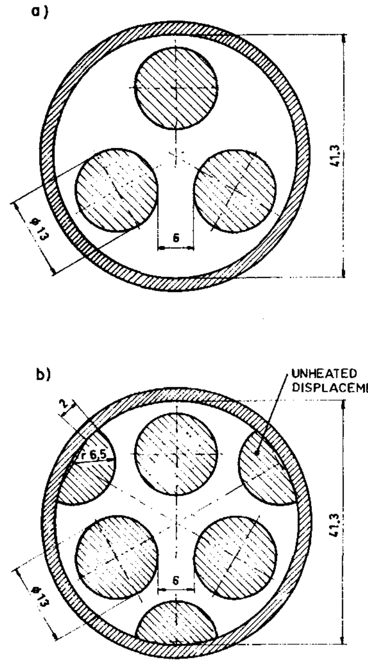

Fig. 3. Channel cross sections.

in the shunt line and one regulating valve in front of the test section.

The constant pressure in the loop is obtained by means of nitrogen which is supplied to the pressurizer from a high pressure nitrogen bottle through a constant pressure reduction valve.

The circulation in the loop was achieved by means of a one-stage centrifugal pump providing a head of approximately 45 m. water at flow rates between 0 and 12 liters a minute.

The loop was insulated with layers of glass wool 55 mm. thick. The glass wool was protected on the outside by 1-mm. aluminum plates.

Test Section

The test section was mounted in a pressure vessel as shown in Figure 2. The test section to be studied was a rod cluster consisting of three parallel vertical stainless steel tubes of 13 mm. outside diameter and wall thickness 0.5 mm. A cross section of the rod cluster with an outer glass shroud of 41.3 mm. inside diameter is shown in Figure 3. Copper rods of 11-mm. diameter and plated with zirconium oxide to a diameter of 12 mm. were placed inside the stainless steel tubes. At the downstream end of the elements the copper cylinders and the stainless steel tubes were silver soldered together. The three elements were elongated by 200 mm. long stainless steel tubes of 13 mm. outside diameter and supported by a compact stainless steel cylinder of 36.5-mm. diameter. At the upstream end the elements were silver soldered into a similar steel cylinder. This cylinder penetrated through a seal to the outside of the pressure vessel. The pressure vessel was supplied with windows so that the boiling processes could also be studied visually.

The rod cluster was heated electrically by direct current supplied through copper electrodes, soldered to the heavy stainless

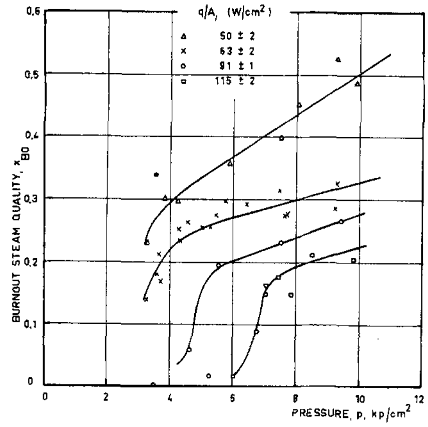

Fig. 4. Measured burnout conditions for 6-mm. rod distance cluster.

steel cylinder and to the copper rods coming out of the steel tubes. The length of the heated sections was 830 mm. This design of the heating elements was necessary in order to avoid bending due to magnetic forces between the elements. With this arrangement the magnetic fields created by the current in the copper rods and the stainless steel tubes cancel each other.

In order to maintain the rod spacing three 3-mm. diameter cylinders were welded to the rods in the middle of the heated length, and any bending effects due to magnetic forces and temperature gradients were negligible.

Instrumentation

The mass flow rate through the test section was obtained by means of a calibrated venturimeter and a U tube filled with oil. The accuracy of the flow rate measurement is estimated to about 1%.

The static pressure in the loop was measured with a precision manometer calibrated from 0 to 10 kg./sq. cm. and connected to the entrance of the rod cluster channel.

Test section inlet and outlet fluid temperatures were measured with copper constantan thermocouples mounted in wells 150 mm. deep and of 3 mm. inside diameter, attached to a recorder.

The pressure drop across the test section was measured with a U tube filled with oil. This pressure drop was negligible for all runs performed in this study.

The heat supplied to the rod cluster was obtained by measuring the current and the voltage across the cluster. The voltage was

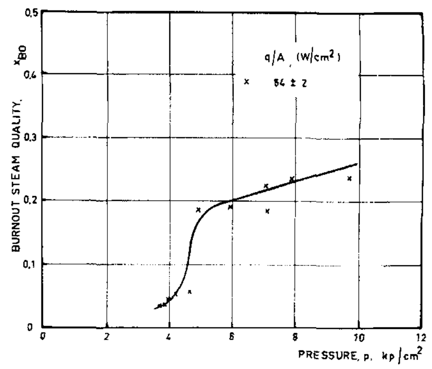

Fig. 5. Measured burnout conditions for 2-mm. rod distance cluster.

measured with a precision voltmeter of ¼% rated accuracy, and the current was obtained by measuring the voltage across a precision shunt calibrated to yield 60 mV. at 3.000 amp. For this measurement a millivoltmeter with a rated accuracy of ¼% was used.

Burnout Detector

In order to protect the rod cluster a burnout detector was used to switch off the heat supply when an imbalance in average temperature between the first and second half of the rod cluster appeared. This temperature imbalance appeared suddenly and indicated that burnout conditions had been reached in the test section.

RESEARCH PROGRAM AND RANGE OF VARIABLES

The research program established at the start of the investigation was as follows.

The effects of rod clearance should be studied in the range from 2 to 6 mm. In view of the possibility that rod clearance effects are small in this range, only two test sections were manufactured, one with 2-mm. rod clearance and one with 6 mm. Runs were performed with each geometry for three to four values of the surface heat flux. These values were selected in the range 50 to 120 W./sq.cm.

For each value of the surface heat flux one test series, consisting of eight to twenty-five runs, was performed in the pressure range between 2 and 11 kg/sq.cm. The inlet temperature was kept almost constant throughout the investigation and varied from 69° to 78°C.

During the investigation circumstances which will be explained in a later para-

TABLE 1

Geometry	Heat flux, W./sq. cm.	Pressure, kg./sq. cm.	Number of runs
Rod clearance 6 mm. No displacement rods	50 ± 2	2.6 — 10	8
	63 ± 2	2.6 — 10	17
	91 ± 1	4.3 — 10	5
	115 ± 2	6.0 — 10	8
Rod clearance 2 mm. No displacement rods	64 ± 2	3.8 — 10	10
Rod clearance 6 mm. and displacement rods	68 ± 2	2.5 — 10.4	22
	90 ± 3	2.8 — 10.1	10
	113 ± 1	4.4 — 10.4	8

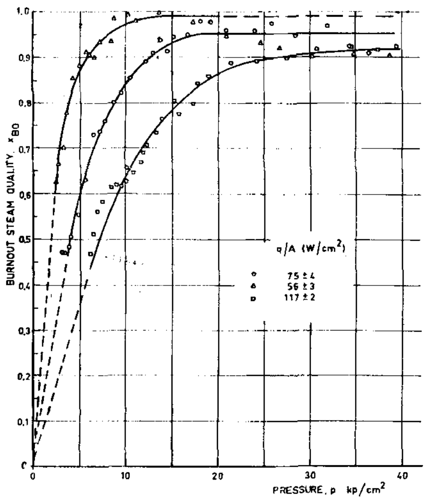

Fig. 6. Measured burnout conditions for 9.93-mm. diameter duct of 2,080 mm. length (reference 7).

graph made it desirable to introduce sections of unheated displacement rods in the channel. A cross section of the channel with displacement rods is shown in Figure 3*b*. With this geometry, and a rod distance of 6 mm., forty runs were performed in the same ranges of variables as for the original channel.

METHOD OF TESTING

Burnout conditions in the duct may be approached in two different ways. The most common method described in the literature has been during a certain run to keep the mass flow rate, pressure, and inlet temperature constant, while the surface heat flux is gradually increased until burnout occurs. In the other method the surface heat flux is kept constant, but instead the mass flow rate is gradually decreased until burnout conditions are reached, as indicated by the action of the burnout detector.

In the author's opinion the latter method gives the most accurate results. Moreover in his experience burnout runs may be performed two to three times as fast as with the common method. Furthermore it is believed that the constant heat flux method possesses many advantages also for purposes of correlating the data.

Throughout the present investigation the constant heat flux method was employed. All runs were started with a relatively large flow rate through the channel. With pressure, inlet temperature, and surface heat flux kept constant, burnout conditions were approached by decreasing the flow rate by small increments. Just before burnout these increments amounted to about 1% of the flow, and one set of data was taken after each step. The last set of data obtained before the burnout detector reacted was used to evaluate burnout conditions.

For a given geometry of the channel it is evident that burnout conditions can be defined by the relationship

$$f(p, t_{\text{in}}, q/A, x_{BO}) = O \qquad (1)$$

The mass flow rate $\dot{m}_{BO}$ is omitted, as this quantity is a dependent variable determined from a heat balance when the other quantities in Equation (1) are fixed. Equation (1) may of course also be written as

$$f(p, t_{\text{in}}, q/A, \dot{m}_{BO}) = 0 \qquad (1a)$$

For this case x_{BO} is a dependent variable and is omitted. In accordance with the results of Becker and Hernborg (7) and to other data for round ducts obtained by them which will be reported later, the effects of inlet water temperature are negligible for long channels. Equation (1) may then be written

$$x_{BO} = f(p, q/A) \qquad (2)$$

where x_{BO} is the exit quality at burnout.

The effects of mass velocity $\dot{m}$ may best be studied by altering the channel length, and a research program investigating mass velocity effects by this method is now in progress.

For a certain series of runs the surface heat flux was kept constant, and after each run the loop pressure was slightly changed.

Altogether eighty-eight runs were performed, divided into eight series according to Table 1.

In order to check the accuracy of the experimental techniques, heat balances relating the electric heat input to the enthalpy increase of water, were taken every day before starting ordinary runs. A selection of the heat balances obtained is shown in Table 2. On the basis of the heat balances, which included measurements of heat input, inlet temperature, and mass flow rate, it is concluded that the apparatus and instruments employed should yield satisfactory results for burnout conditions.

TABLE 2

Net heat input, kW.	Mass flow rate, kg./sec.	Δi_{water}, kW.	Error, %
24.65	0.262	24.04	—2.5
22.85	0.362	23.17	+1.4
37.6	0.414	37.26	—0.9
62.26	0.682	63.42	+1.9
87.38	0.682	86.61	—0.9
39.34	0.489	37.65	—4.3

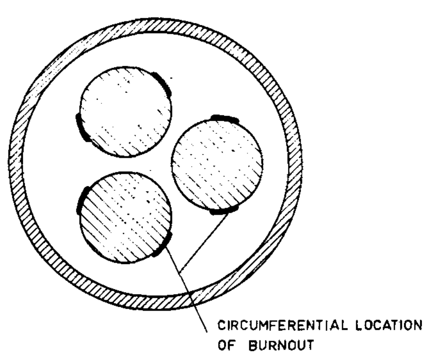

Fig. 7. Circumferential location of burnout.

COMPUTATIONS

The burnout position was taken as the end of the heated section, where the steam quality attains its highest value. Actually the burnout may occur a few millimeters from this position, owing to cooling of the heated sections by axial conduction through the unheated elongation tubes. However this cooling effect has been disregarded.

The fact that burnout occurs close to the exit where the steam quality reaches its maximum value has been verified previously for round ducts. In the present case this has also been noted after visual inspection of the test sections on the completion of the research program.

The surface heat flux q/A was obtained from the equation

$$q/A = \frac{EI}{3\pi d \cdot L}$$

where $3\pi dL$ is the total heated surface area of the three rods.

The mass flow rate $\dot{m}$ was obtained directly from the venturimeter calibration chart.

The pressure at the burnout position p was put equal to the measured absolute pressure at the inlet of the test section. The error introduced by this approximation was negligible, since the pressure drop through the test section for all runs was less than 20 mm. Hg.

The burnout quality was evaluated from the inlet water temperature and the heat input in accordance with

$$x_{BO} = \frac{\dfrac{3q/A \cdot \pi \cdot d \cdot L}{\dot{m}} - \displaystyle\int_{t_{\text{in}}}^{t_{\text{sat}}} di}{h_{fg}} \qquad (3)$$

Table 3* shows the data and computed values of steam quality and heat flux.

* Tabular material has been deposited as document 7418 with the American Documentation Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., and may be obtained for $1.25 for photoprints or for 35-mm. microfilm.

RESULTS AND DISCUSSION

The results are presented in Figures 4 and 5, where the steam quality at burnout x_{BO} is plotted against the static pressure p with the surface heat flux as parameter.

Figure 4 shows the results obtained with the cluster where the rods are 6 mm. apart. Qualitatively the picture is quite similar to the results of reference 7 obtained with round ducts. The burnout quality increases with decreasing surface heat flux and decreases monotonously as the pressure is decreased. One important difference should be noticed however. For the round ducts the curves approached the origin smoothly as shown in Figure 6, which is taken from reference 7. But in the present case the curves possess sharp breaks at pressures between 4 and 7 kg./sq. cm. This behavior probably indicates a change in the mode of flow, and it seems that for very low pressures, $p < 4$ kg./sq. cm., the curves may cross the horizontal axis of the diagram, indicating subcooled burnout.

The results for the 2-mm. rod distance cluster are presented in Figure 5. For this test section runs were only performed at 64 W./sq. cm. The results show the same characteristics as for the 6-mm. cluster. The reason for only applying one value of the surface heat flux was that the test section was damaged at the start of the 100 W./sq. cm. experiments, and it was decided for the time being not to proceed with the experimental program. However plans have been made to continue the experimental program in another loop where pressures up to 55 kg./sq. cm. may be applied.

Comparing the 64 W./sq. cm. data of Figures 4 and 5 for the two rod clusters one should note that for a rod clearance of 6 mm. somewhat higher values are obtained than for a rod clearance of 2 mm. The difference in burnout quality amounts to about 0.07 in the pressure range from 5 to 10 kg./sq. cm., and it is concluded that for engineering purposes the effect of changing the rod clearance from 2 to 6 mm. is not significant in the range investigated.

Visual inspection of the rods after the completion of the experimental program revealed that burnout occurred in the areas of the cross section indicated in Figure 7. This supports the conclusion that the rod clearance itself has negligible effects on the burnout conditions for the channel.

A comparison of the present results with burnout conditions for flow in round ducts reveals that burnout occurs at much lower values of the steam quality in the rod cluster. The comparison in question is given in Figure 8.

When one reverts to the fact that burnout does not occur in the narrow area between the rods of the cluster, it is difficult to conceive that the large reduction in burnout quality for the cluster compared with the round duct should have been caused by effects in the narrow flow area between the rods.

On the contrary at the time of this observation it seemed more logical to explain the low burnout values for the rod cluster by poor transverse diffusion of water droplets in the core of the relatively wide flow area between the rods and the outer shroud.

In order to decrease the average diffusion distance for the droplets to reach the water film on the surface of the heated tubes three displacement rods were placed in the channel as shown in Figure 3*b*. Only one geometry having a rod clearance of 6 mm. was studied for this case. Three series of runs were performed with surface heat fluxes of 68, 90, and 113 W./sq. cm. The results, which are shown in Figure 9, reveal the same characteristic features as for the corresponding rod cluster without displacement rods. Figure 10 shows a comparison between the two cases. It should be noted that almost identical results have been obtained for the two clusters, and it is concluded that if all other variables are kept constant, the change of cross section due to the displacement rods has negligible effect on burnout conditions.

It is therefore further concluded that the diffusion of droplets within the core of the flow is not the only controlling mechanism in the process of supplying water to the liquid film on the heated surface.

PRESENTATION OF NOVEL BURNOUT MODEL FOR FLOW IN CHANNELS

However the discrepancy between burnout values for round ducts and the present case of a heated rod cluster in a tube may be explained by recognizing that a basic physical difference exist between the two cases.

For the round duct the total perimeter of the cross section is heated, while for the rod cluster only a part of the perimeter is heated.

When one returns to the flow models discussed in the introduction which were based on climbing film flow theory, the difference between the two cases become evident.

In the round duct the film thickness is gradually decreased by evaporation at a constant rate around the perimeter. In the rod cluster evaporation takes place only on the rods, while the liquid film on the unheated outer tube is not subjected to evaporation but flows upwards through the channel at an almost constant mass flow rate.

A substantial part of the liquid phase of the fluid therefore does not participate in the cooling process of the heated rods. Basically this explains why the measured steam qualities for the rod clusters are so small compared with the values for a round duct. If it had been possible to exclude the liquid on the outer wall from the computation

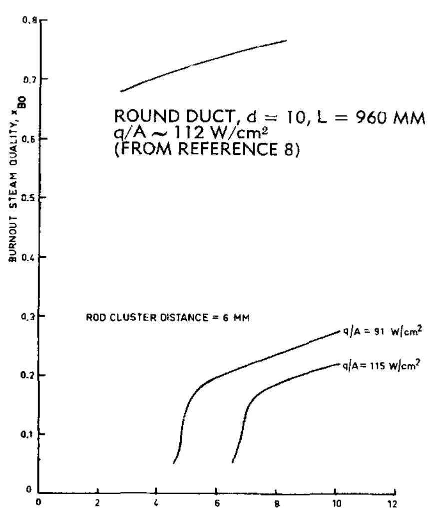

Fig. 8. Comparison of burnout in rod cluster with round duct results.

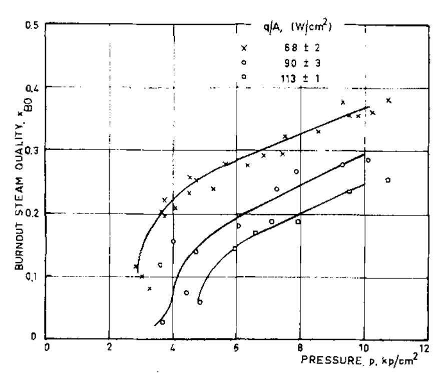

Fig. 9. Measured burnout conditions for 6-mm. rod cluster with displacement rods.

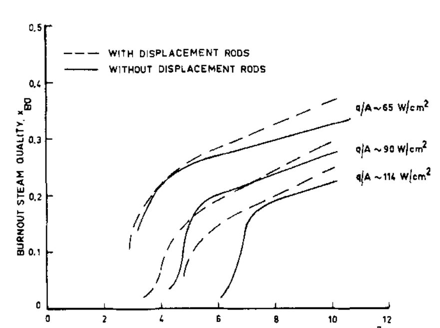

Fig. 10. Influence of displacement rods on measured burnout conditions.

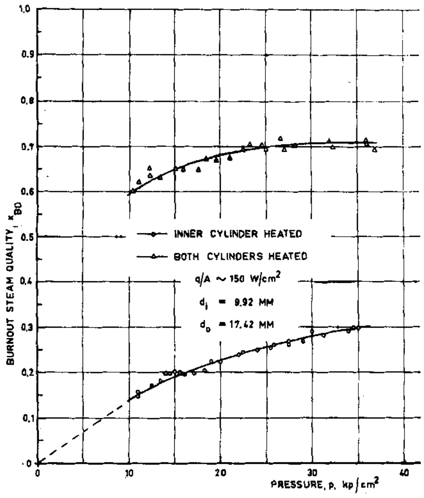

Fig. 11. Burnout data for annular channel (reference 9).

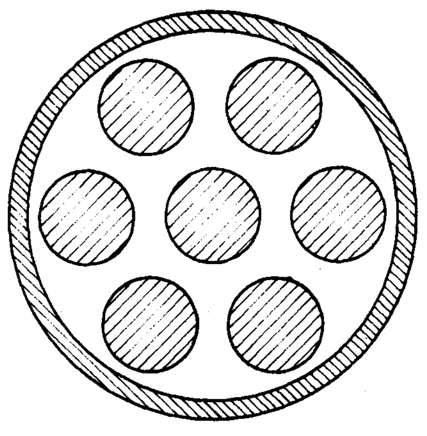

Fig. 12. Cross section of a boiling reactor fuel element.

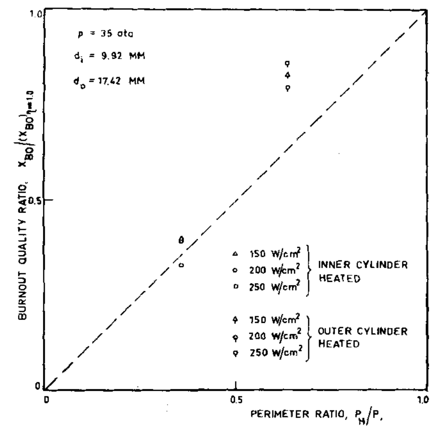

Fig. 13. Effect of perimeter ratio.

of measured burnout quality, it is likely that the burnout results for the rod cluster would come quite close to corresponding round duct data.

In order to understand burnout conditions for flow in channels it is therefore necessary, in addition to the conventional geometrical considerations, to consider whether the total or only a fraction of the channel perimeter is heated.

For this purpose the following nondimensional number is introduced:

$$\eta = \frac{P_H}{P} \qquad (4)$$

For a channel with a η value of unity the problem of predicting burnout conditions may be formulated by the function

$$f(x_{BO}, p, q/A, \dot{m}, L/D_E) = 0 \quad (5)$$

If one deals with the more general case of partly heated channels, Equation (5) should be modified to read

$$f\left[x_{BO}, p, q/A, \dot{m}, L/D_E, \frac{P_H}{P}\right] = 0 \quad (6)$$

Hitherto the importance of the perimeter ratio P_H/P has not been acknowledged. However by applying this concept it is possible to understand and interpret burnout results previously presented in the literature which may have seemed inconsistent. This will be done in detail in a later paper. At present only a few examples of using the concept will be given.

Returning to Figure 10, which shows the results for rod clusters with and without displacement rods, one may conclude that the main cause of the similar results for the two channels is that both channels have almost the same η value. In this connection it should be noted that the reduction of the average diffusion distance for the water droplets to reach the water film on the heated rods has little effect on the results, indicating that the main resistance to mass transport of water from the outer shroud is the re-entrainment resistance for the water in the film on the outer shroud.

Other evidence for the validity of the η value concept has been found by Becker and Hernberg (9). They studied burnout conditions for flow in annular channels and found that the burnout steam quality under certain conditions may be more than twice as high when both cylinders are heated as when only the inner cylinder is heated. An example of their results can be seen in Figure 11. For the case of both cylinders heated, when the η value for the channel is unity, their results compared very well with round duct results.

A similar observation has also been made by Collier (*10*), who found that the burnout surface heat flux for the inner cylinder increased when heat was applied to an outer heated surface, simulating neighboring rods in a fuel element.

On the basis of the η value concept the observations by Collier (*10*) and Becker and Hernborg (9) may be easily understood. The application of heat to the outer cylinder decreases the quantity of water flowing on the outer shroud, with the result that the concentration of water droplets in the channel core increases, the cooling properties of the medium being improved.

For further information about data pertinent to the subject see a report by Levy et al. (*11*), which summarizes results collected from the literature and shows that internally heated annuli data generally are much lower than data obtained with round ducts.

A common design of fuel elements for boiling nuclear reactors is shown in Figure 12. Here a relatively large number of heated fuel rods are placed in an outer unheated shroud. For accurate and safe design of such elements quantitative knowledge about the influence of the η value on burnout conditions is necessary.

However it seems likely that burnout conditions in rod clusters will improve with increasing number of rods, as then the η value for the cluster approaches unity. This improvement may be of great significance in the optimisation of fuel elements.

An experimental program investigating channels with different η values is now in progress, and the results so far have been promising. The channels for this program consist of annular sections, and also the rod cluster discussed in this paper will be further studied in a loop designed for pressures up to 55 kg./sq. cm.

Preliminary results from the annular study (9) are shown in Figure 13. The ratio of burnout quality obtained when only one cylinder was heated to the burnout quality obtained when both cylinders were heated is here plotted against the η value. Data for heat fluxes of ~ 150, 200, and 250 W./sq. cm. and a pressure of 35 kg./sq. cm. are shown. The inner and outer diameters of the annulus were 9.92 and 17.42 mm. respectively.

When η approaches zero, one may deduce from physical considerations that the burnout quality for the channel also approaches zero.

The data for the case of heating only the inner cylinder fall close to a straight line connecting the origin with the point representing the case of a totally heated annulus. The data for only heating the outer cylinder fall above this line.

The relatively high burnout qualities obtained for the latter case may be explained by considering that owing to the higher shear stress acting on the inner cylinder (see the next paragraph), the climbing water film on this cylinder will be destroyed before the film on the outer wall, with the result that the water concentration in the vapor core increases, improving the cooling properties of the water vapor mixture.

It is hoped that when the present experimental program is completed the location of the curve in Figure 13 will be established, giving the dependence of burnout conditions on the channel η value.

CROSS-SECTIONAL LOCATION OF BURNOUT POINT

As mentioned in an earlier section burnout occurred on those parts of the tubes which were confronting the wide flow areas of the channel rather than the narrow space between the tubes. This observation may be explained by a study of the magnitude of the vapor shear stress, acting on the climbing water films. The shear stress, which causes the surface waves or ripples to appear, attains its maximum value just in the areas of the channel surface where burnout occurred.

Pressure	$2.5 < p < 11$ kg./sq. cm.
Steam quality	$0.03 < x < 0.53$
Heat flux	$50 < q/A < 120$ W./sq. cm.
Mass flow rate	$0.03 < \dot{m} < 0.33$ kg./sec.
Rod cluster heated length	$L = 830$ mm.
Rod diameter	$d = 13$ mm.
Rod clearance	$s = 2$ and 6 mm.

At the AERE laboratories in Winfrith, England (*12*), burnout conditions were studied in a dumbbell shaped cross section as shown in Figure 14. Here burnout occurred at the areas marked in the figure, and it can be noted that these areas are subjected to the highest surface shear stresses.

In the earlier mentioned investigation of burnout conditions in annular sections by Becker and Hernborg (*9*), it was observed that when equal heat fluxes were applied on both walls, burnout always occurred on the inner wall. This phenomenon may be explained by recognizing that the velocity distribution for one-phase turbulent flow is asymmetric such that the maximum velocity occurs closer to the inner than the outer wall. When one assumes that this is also the case for two-phase flow, the ratio of the surface shear stresses may from a simple force balance be written

$$\frac{\tau_i}{\tau_o} = \frac{r_o}{r_i}\,\frac{r_m^2 - r_i^2}{r_o^2 - r_m^2}$$

where r_m is the radii of maximum velocity. Knudsen and Katz (*13*) suggested that r_m is equal for turbulent and viscous flow, and r_m is then given by

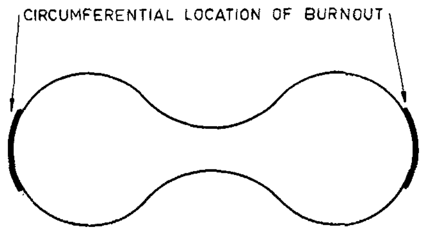

Fig. 14. Dumbbell cross section.

$$r_m^2 = \frac{r_o^2 - r_i^2}{2 \ln\left(\frac{r_o}{r_i}\right)}$$

From the above discussion it can be concluded that burnout may be expected in those areas of a heated channel where the surface shear stress attains its highest value.

CONCLUSIONS

Burnout conditions for flow of water in a rod cluster consisting of three rods have been measured in the following ranges of variables:

In the ranges investigated the measured steam quality at burnout x_{Bo} generally decreases with increasing heat flux and decreasing pressure.

The influence of rod clearance is in the range investigated of small significance for engineering purposes.

The introduction of unheated displacement rods has no effect on the results, as long as no change takes place in the ratio heated channel perimeter to total channel perimeter.

The present burnout steam quality data are much lower than earlier obtained results for round ducts.

On the basis of experimental results and the interpretation of these results a new concept has been introduced. This concept states the importance of considering the ratio of heated perimeter to total channel perimeter, for the understanding of burnout conditions in channels.

It can also be concluded that the surface shear stress distribution around the channel perimeter, and especially the position of maximum shear stress, is of great importance for predicting burnout conditions in a channel.

The new concept has already proved its success in explaining experimental results which earlier seemed to be inconsistent, and it is hoped that the concept may provide the designers of fuel elements for nuclear boiling reactors with the necessary tools for applying data obtained in simple geometries to the design of the complicated geometries encountered in fuel elements.

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NOTATION

d	= diameter, m.
E	= voltage, v.
h_{fg}	= latent heat of evaporation, KJ/kg.
I	= current, amp.
i	= enthalpy, KJ/kg.
L	= heated length, m.
$\dot{m}$	= mass flow rate, kg./sec.
P	= perimeter, m.
P_H	= heated perimeter, m.
p	= pressure, kg./sq. cm.
Δp	= pressure drop across test section, mm. Hg
q/A	= surface heat flux, W./sq. cm.
r	= radii, m.
s	= rod clearance, m.
t_{in}	= inlet temperature, °C.
x_{Bo}	= burnout quality, dimensionless
η	= perimeter ratio, dimensionless

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