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FORCED CONVECTION BURNOUT FOR WATER IN ROD BUNDLES AT HIGH PRESSURES

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Abstract—Burnout data from several new 12-rod test sections are presented. The influence of power distribution, minimum wall-to-rod separation, and mass flux is investigated. The gross behavior of these test sections has been re-analysed by two computer programs which allow the determination of local coolant conditions in an internally connected, boiling bundle as was used in this study.

The rods were 0·440 in in diameter and wrapped with 0·022 in O.D. hypodermic needle tubing on a 6 in pitch. Burnout data were obtained at 1200 psia and at mass fluxes from 1–5 $\times$ 10^6 lb/h ft^2. Differences between the heat generation rates in the two interior rods and the remaining ten peripheral rods were 1:1, 1·55:1, and 2·64:1. The minimum wall-to-rod separation was 0·022 in in four test sections and approximately 0·032 in in a fifth test section.

The gross and local behavior of the test sections are compared to tubular data. Such a comparison indicates that a cold wall effect exists in the peripheral channels whereas the local behavior in the interior channels agrees closely with the tubular data.

NOMENCLATURE

A, cross-sectional area for flow;
C_p, heat capacity at constant pressure;
D_e, equivalent diameter;
f, friction factor;
G, mass flux;
g, gravitational acceleration;
h, heat-transfer coefficient;
K, Bankoff flow parameter;
l, length;
P, pressure;
Q, rate of energy flow;
T, temperature;
W, rate of mass flow;
X, quality;
Y, rectangular coordinate;
Z, rectangular coordinate;
α, void fraction;
λ, heat of vaporization;
ρ, fluid density.

Subscripts
G, gas;
i, height position;
j, channel number;
L, liquid.

INTRODUCTION

THE INTENSITY of thermal transport processes in small reactor cores requires accurate knowledge of heat transfer and hydrodynamic processes in open matrix (rod bundle) geometry, particularly when the entire core is cooled via nucleate boiling, both subcooled and saturated. High velocity (3 $\times$ 10^6 lb/h ft^2) coolant flow can stabilize both the mode of heat transfer from the elements and the bubble flow regime so that hydraulic instabilities cannot occur. Pressure drop through these cores may be one atmosphere per foot of axial flow path and appears to consist of approximately equal parts of frictional and momentum losses.

Data were not available in the range of parameters pertinent to these reactors when design studies were initiated. Although analytical and correlative studies provided confidence in the design, verification of both thermal and hydraulic performance was undertaken via an intensive research program funded by the AEC, directed by Atomics International, and conducted by the Engineering Research Laboratories of Columbia University under J. Casterline and Bruce Matzner.

BOILING HEAT TRANSFER IN ROD BUNDLES

Geometric effects in the rod matrix geometry could, it was felt, influence boiling heat transfer so that the experimental data from tubular or annular test sections might very well prove inapplicable. Fortunately, data had been accumulated at Columbia University from a study of 7- and 19-rod test sections under the D_2O Power Reactor Program [1]; these studies revealed that: (a) heat-transfer coefficients lie in a range from 15000 to 30000 Btu/h ft^2 degF at a pressure of 1000 psia, (b) coolant mass velocity does not influence the magnitude of the heat-transfer coefficient at a hydraulic diameter of 0·3 in and (c) the wire-wrapping of the elements appears to act as a fin, reducing the sheath temperature under the wire rather than causing a hot spot.

Data taken with the new 12-rod test section are summarized in Fig. 1. This test section has a hydraulic diameter of 0·095 in internal to the bundle and of 0·045 in at the periphery of the bundle. As can be seen from the figure, heat-transfer coefficients are slightly influenced by mass velocity at 1200 psi in this small hydraulic diameter apparatus. The trend, however, that is discerned indicates that mass velocity effects are very slight and that the heat-transfer coefficient is primarily dependent upon the heat flux. It should also be pointed out that, due to the steepness of the heat flux versus ΔT plot, very accurate measurements and calculations are required in order to obtain meaningful values of heat-transfer coefficients. Over the entire range investigated, boiling film ΔT's remained within the range of 15 to 30°F.

BURNOUT IN ROD BUNDLES

As was pointed out at the beginning of the previous section, geometric effects could be significant, making it questionable to rely entirely on tubular burnout data. In addition, cold wall effects (which are in reality flow distribution effects) reported by numerous workers in annular geometry clearly make it unreasonable to apply such data to the rod bundle geometry. Further, hydraulic diameter effects are significant within each type of test section investigated so that inversion of the mass velocity influence on burnout heat flux can be discerned more readily and can be more influential in one type of geometry relative to another. Accordingly, it was deemed prudent to fabricate an apparatus that would permit study of these effects in the range of interest to the reactor. The test section cross-section is presented in Fig. 2; in this case, each of the rods was wire-wrapped to assure accurate spacing in contradistinction to the reactor core, in which alternate rows of rods are

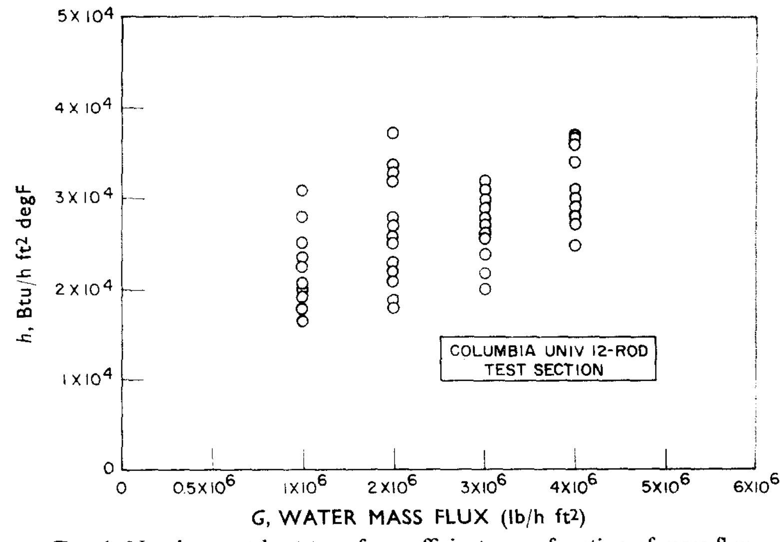

FIG. 1. Non-burnout heat-transfer coefficients as a function of mass flux.

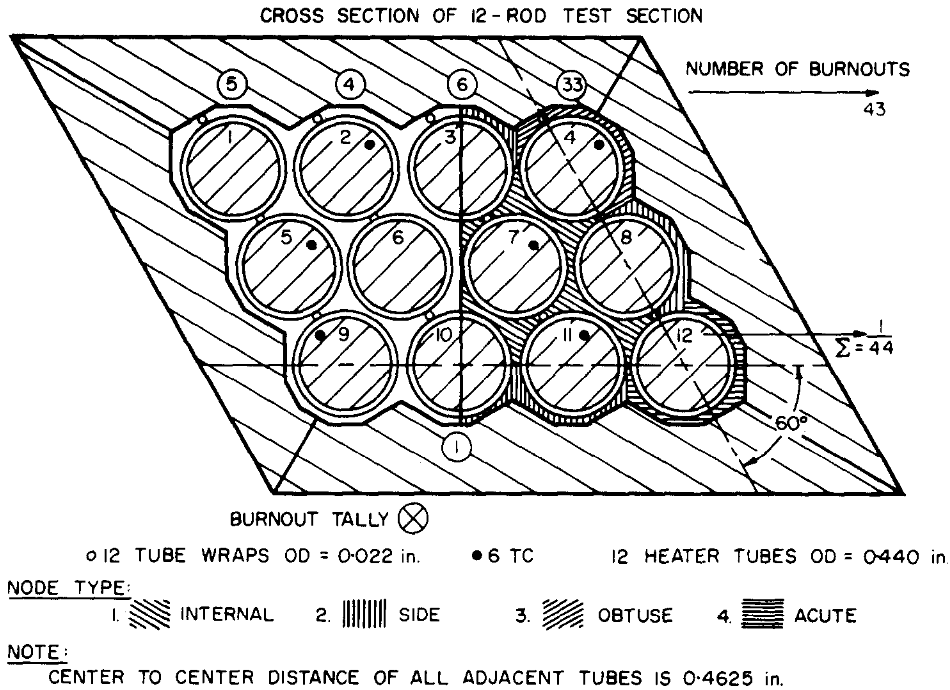

FIG. 2. Columbia test section with indicated burnout points during unheated wall tests of Test Section 2.

wrapped. The test section shown indicates the close clearance between the outer rods and the phenolic shroud material. The shroud in turn is backed up by a stainless steel parallelepiped. Eight pressure taps are disposed axially in order to follow the pressure profile in detail. Direct current electricity is passed through the 12 rods resulting in direct resistance heating of the 17-inch long heated section. In tests to date, up to $\frac{3}{4}$ MW of energy has been generated in the 12 rods.

Analysis of the tubular burnout data in the literature [2] resulted in the prediction that the smaller hydraulic diameter of the 12-rod test section would cause the burnout heat flux to be appreciably higher than the values obtained directly from the literature. In addition, the higher mass velocity coupled with the small hydraulic diameter gave indication that the bubble flow regime would persist to much higher values of exit quality than had been attained in more conventional experiments in this and other geometric arrangements.

Several series of burnout runs were made covering a range of mass velocities with burnout indication resulting from an electrical circuit burnout indicator. The data are summarized in Figs. 3 and 4 showing the effect on burnout heat flux of *average* exit steam quality for the various test sections operated. Figures 5 and 6 present the burnout heat flux data plotted versus *local* exit steam quality based on the calculated local conditions.

Detailed analyses of the burnout heat-transfer data are necessary in order to understand fully the trends and phenomena involved. Specifically, it was desired to know the local conditions involved for each burnout datum. Two computer programs were developed, and are discussed briefly in the appendix; these will allow the determination of local coolant conditions in an internally connected, boiling bundle as was used in this experiment. Also included in Figs. 3 through 6 are curves of performance prediction based on literature data and correlation [3, 4].

Unheated wall data (*Test Section 2*)

The first set of data obtained were the

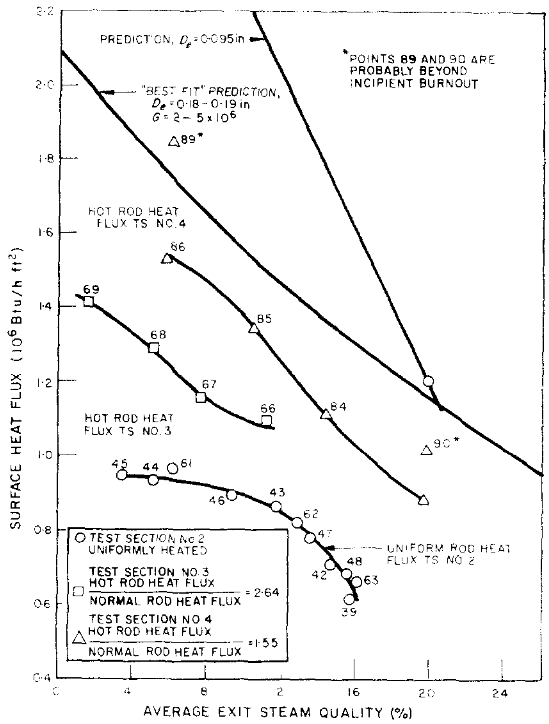

FIG. 3. Comparison of burnout data for uniformly heated and hot rod 12-rod test sections based on average exit steam quality and on mass flux of 3×10^6 lb/h ft^2.

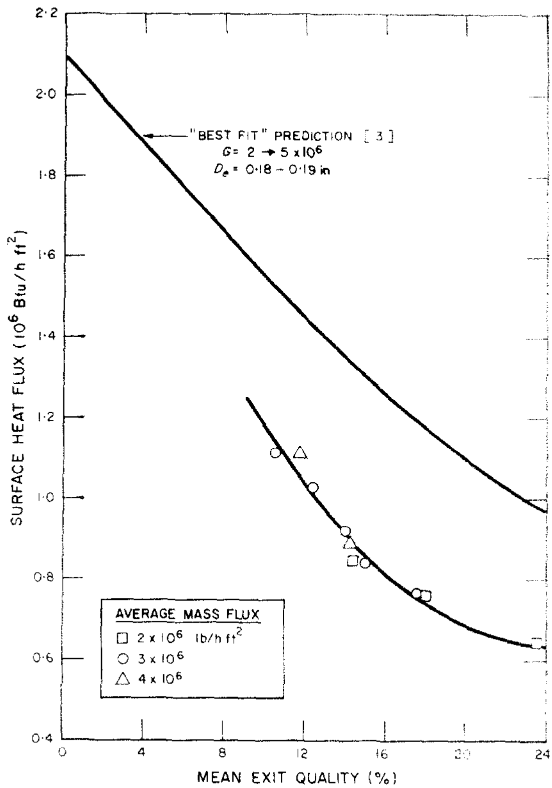

FIG. 4. Burnout data for uniformly heated 12-rod Test Section No. 5 based on average exit steam quality.

"unheated wall" data of Test Sections 1 and 2. The tests in which the unheated wall data were taken consisted of a series of runs where heat was uniformly generated throughout the bundle. As the number of burnout data from Test Section 1 is limited, only the results from Test Section 2 will be discussed. Characteristically, as presented in Fig. 3, the surface heat flux approached a limiting value at low exit qualities. This behavior is typical of that for relatively low mass velocity, high quality tubular data. Qualitative examination of these data indicated a definite trend in the physical location of the burnout points within the test section. Of the total 44 burnout points obtained in this series, no burnouts occurred at a point which was not adjacent to the phenolic-asbestos shroud (unheated wall). Examination of Fig. 2 will illustrate this point. It may be seen that of the 44 burnout points fully 43 occurred at the upper wall with 33 of these burnouts occurring on Rod 4, the obtuse corner. The biased location of the burnout points indicated immediately that previously unpredicted factors were present which probably perturbed the burnout positions in the test bundle.

Analysis for the unheated wall data required that detailed geometrical, two-phase flow hydrodynamic analysis be accomplished for the test bundle. Figure 2 also indicates the different channel designations. Considerable experimentation with the various calculational procedures was necessary to determine the importance of the final channel segregation. It was originally thought that since the bundles were of uniform heat flux, the mixed outlet qualities were nearly equivalent to the local qualities. This was quite untrue for the obtuse corner. Generally, it was found that channel type 1, the interior channel, tended to accumulate fluid due to its lower

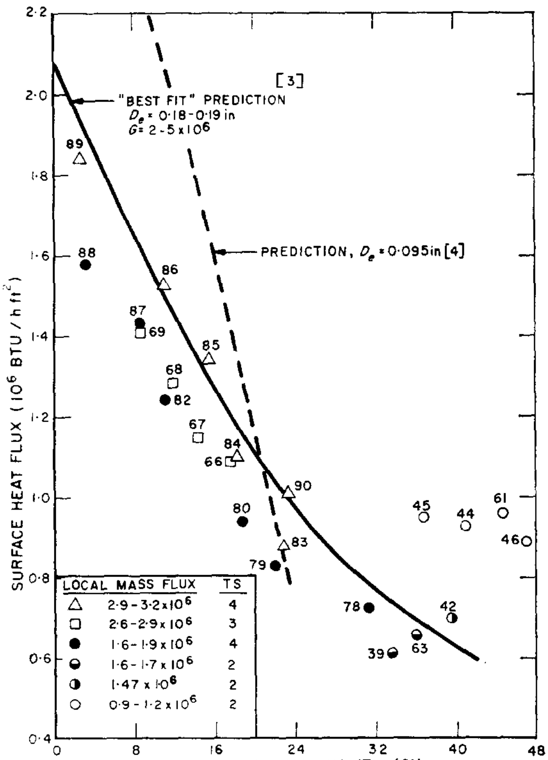

FIG. 5. Comparison of burnout data for uniformly heated and hot rod 12-rod test sections of Fig. 3 based on local exit steam quality.

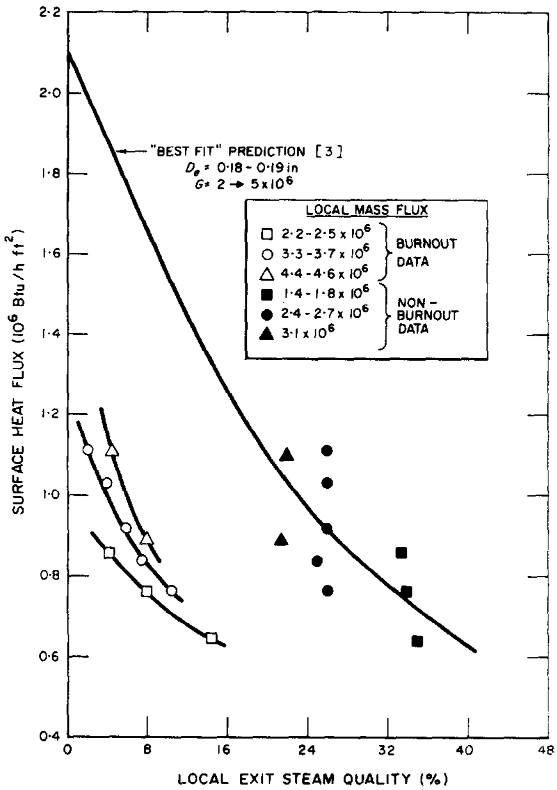

FIG. 6. Burnout data for uniformly heated 12-rod Test Section No. 5 of Fig. 4 based on local exit steam quality.

resistance to flow. Channels type 2, 3, and 4, all unheated wall channels, tended to dispel liquid due to their smaller hydraulic diameter and subsequent greater resistance to flow. In particular, channel type 4, the obtuse corner channel, has a high wetted perimeter resulting in a low hydraulic diameter, thus it expelled fluid more greatly than any of the others. This latter fact, coupled with indicated geometrical problems due to the test section construction caused numerous burnouts to occur on rod 4. It may be seen in Fig. 5 that re-analysis of the "unheated wall" burnout data to determine local quality and mass velocity at the burnout location cause the data to lie in a range similar to the "hot rod" and tubular data. At the high local qualities predicted for these burnout points, an inverse mass velocity influence is evident as would be expected for low mass velocity, high quality tubular data.

While the exact geometrical effect is not known it was generally concluded that the phenolic shroud which makes up the encasement for the test section was forced closer to the surface of rod 4 than the 22 mil specified for the test. This may be concluded as a distinct possibility since examination of the shroud material after the tests were conducted indicated that the wire wrap had indented the shroud wall by several mil. These separation problems were unavoidable and the test section design has been modified as indicated in the following section to eliminate these problems.

Test section modifications

Referring to Fig. 7, which demonstrates the effects of shroud separation on local qualities, the separation problem for the unheated wall is clearly shown. The separation which was estimated to be somewhat less than the 22 mil

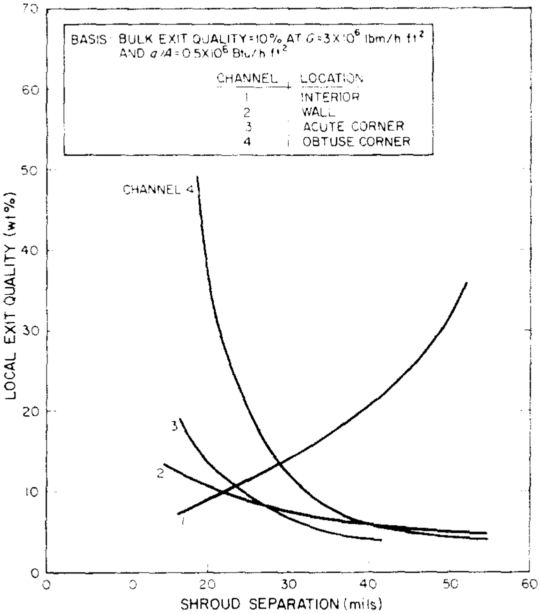

FIG. 7. Effect of shroud separation on local exit steam quality for various channels of the Columbia 12-rod experiment.

designed, cause disproportionately high qualities to be imposed in the obtuse corner. It is seen why so many of the burnouts took place in the obtuse corner. The geometrical analysis as presented in Fig. 7 depicts the favorable trend towards homogeneous quality in the peripheral channels with increased shroud separation. Further analysis indicated that if the side and acute channel separations were increased to 30 mil and the obtuse channel separation was increased to 40 mil the quality in the peripheral channels was as homogeneous as is reasonably possible within the limitations of the analytical procedure. The interior channels were allowed to remain at slightly higher qualities in order that burnout would occur in all the channels simultaneously, assuming an unheated wall effect. The actual modification, a uniform 32 mil separation except for 40 mil in the obtuse corner, has now been reflected in a new test section design, Test Section 5. Uniform heat flux burnout tests were conducted at Columbia University to investigate the exact nature of the "unheated wall" burnout without the severe geometrical perturbations.

Unheated wall data (Test Section 5)

Three salient features of the burnout data obtained from Test Section 5 may be noted. *Firstly*, all burnouts were located on peripheral rods. No burnouts occurred on the interior rods although the predicted local qualities in the interior channels were at least twice as great as those in the peripheral channels. *Secondly*, the burnout heat flux increases monotonically with decreasing mean exit quality (see Fig. 4). A limiting burnout heat flux is not reached within the range of the experimental data. *Thirdly*, no mass velocity effect is evident when the data are considered in terms of the mean exit quality. Significantly, due to an increase in shroud separation of approximately 10 mil, the gross behavior of Test Section 5 is entirely different from that of Test Section 2.

A mass velocity effect does exist when the data are analysed in terms of local quality at the burnout location (see Figure 6). The burnout heat flux increases with mass velocity at local qualities up to 16 w/o, the extent of the data. Due to the unheated wall effect, the burnout limits are somewhat lower than those for tubular data. The local qualities in the interior channels, however, reach and exceed the burnout limits of uniformly heated tubes without burnouts taking place on the interior rods. It is therefore possible to estimate conservatively the burnout limits for the interior channels of this compact reactor via tubular data in the literature.

Analysis of the "hot rod" burnout data

The "hot rod" burnout runs included tests where the difference between the heat generation rates in rods 6 and 7 and the remaining peripheral rods varied from 1·55:1 to 2·64:1. Using this power generation profile (at that time the effect of the unheated wall had not been completely analysed) the experimenters were able to run rods 6 and 7 to burnout without burning out the peripheral rods adjacent to the unheated walls. Obviously with this drastic power profile, extreme flow redistribution took place in the bundle. The 2-phase hydraulic codes were utilized to predict this redistribution. The "hot rod" burnout data, in Fig. 5, as affected by the local exit steam quality, show a direct mass velocity effect. As anticipated, the bubble flow regime persists to much higher values of exit steam quality than in previous test geometries. The burnout heat flux increases with local mass velocity at local qualities up to 25 per cent. Again, a comparison of these burnout data to those for tubular geometries suggests that the tubular data in the literature are applicable to the interior channels (no unheated walls) of a closely spaced rod bundle.

In conclusion, it is clear that boiling water reactors can be designed to yield high performance capability even with net steam generation so long as it is possible to separate the geometric effects required for high intensity cooling from the spatial requirements for a neutron moderator. It is our intention, at Atomics International, to pursue this line of research to other rod diameters and to higher mass velocities in order to increase further the power capability of this type of reactor. Application of the data gathered from this series of tests to reactor design has demonstrated adequate burnout safety factors for the hottest channels [5].

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APPENDIX

Code description

Two computer codes have been developed to predict hydrodynamic effects for compact reactors [6, 7]. The local qualities analysed have been checked against both of these codes and found to be totally consistent. The first code [6] is primarily a transient code to predict the overall behavior of a boiling water reactor under transient conditions. The second code, [7] which was the primary tool for the analysis presented here, is a steady state two-phase flow code ideally suited for local condition determinations. The codes use essentially the same basic equations and a brief description follows; the scope of this paper does not allow a detailed description into the exact calculational procedures and boundary condition applications.

Description of mixing model. Redistribution is predicted and accounted for in the reactor in the following manner. To illustrate, assume that the open matrix boiling-water reactor under study can be divided into three channels as illustrated in Fig. 8. The channels will distinguish themselves on the basis of geometry and heat addition rate.

Although each lateral flow channel is continuous and redistribution actually takes place continuously, it is assumed that the flow channels can be subdivided into separated nodes as shown in Fig. 8. The nodes are conceptually separated by a mixing region. Although the flow for any single node is constant, the flow rate can vary from node to node in the axial direction. This is accomplished in the flow model by interconnecting flow passages $b - b'$ and $a - a'$. Therefore, flow leaves the nodes located between stations Z_{i-1} and Z_i and enters a mixing region in which complete mixing of primary and cross-flow streams occurs. From the mixing region the flow may continue on in the Z direction only after redistribution has occurred along paths $a - a'$ and $b' - b$ in the Y direction and all mixing criteria have been satisfied. Thus, the basic assumption in the model is that the entire two-dimensional flow grid is composed of an array of separate one-dimensional flow problems. This assumption introduces negligible compromise of rigor so long as the change in thermal conditions that occur in a node is small when compared with the total change across the core.

The code performs a hydrodynamic balance radially throughout the particular node based

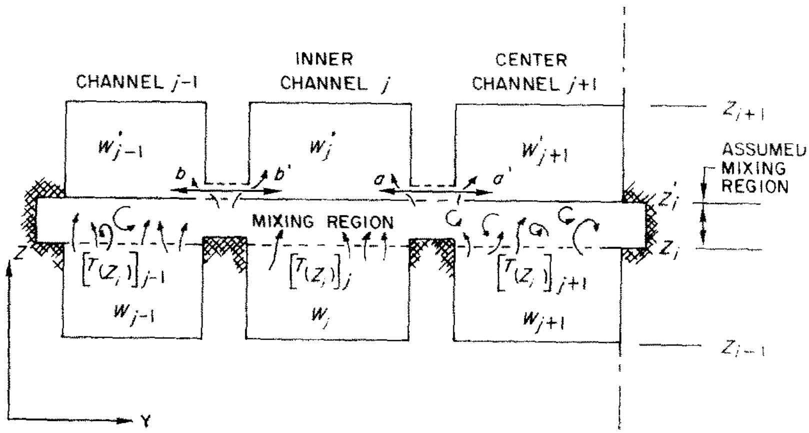

FIG. 8. Mixing model.

on the boundary conditions and the conditions from the previous node or node inlet. In a straightforward fashion mass (continuity), momentum, and energy are balanced by summation across each node and across each radial position. Briefly and generally, for a particular node (i) at a specific radial position (j), in the boiling region:*

Mass balance:

$$W_{(i-1)i} \pm W_{T_{ij}} - W_{ij} = 0 \tag{1}$$

where $\pm W_{T_{ij}}$ = the fluid transferred out of or into node ij; W_{ij} is made up of the sum of its two components: $W_{G_{ij}}$ (gas) and $W_{L_{ij}}$ (liquid).

Momentum balance:

$$\left.\begin{aligned}\Delta P_{ij} = {} & \frac{2(f_{ij})_{TP}(W_{ij})^2 \rho_{ij} \Delta l}{A_j^2 g_c D_j \rho_L^2} + \rho_{ij}\frac{g}{g_c}\Delta l + \\ & \frac{1}{A_j^2 g_c}\left[\frac{W_{G_{ij}}^2}{\alpha_{ij}\rho_G} + \frac{W_{L_{ij}}^2}{(1-\alpha_{ij})\rho_L} - \right. \\ & \left.\frac{W_{G_{(i-1)j}}^2}{\alpha_{(i-1)j}\rho_G} - \frac{W_{L_{(i-1)j}}^2}{(1-\alpha_{(i-1)j})\rho_F}\right]\end{aligned}\right\} \tag{2}$$

where Δl is the node length, ρ is the density, α is the void fraction, A is the node area, and D is the hydraulic diameter.

* For the single phase region the various gas terms are eliminated.

The local two-phase friction, $(f_{ij})_{TP}$, is determined by the standard relationship for the two phase multiplier [3];

$$f_{TP} = f_{SP}\left(\frac{1-x}{1-\alpha}\right)^2 \tag{3}$$

where f_{SP} is the single phase friction factor.

Energy balance:

For the non-boiling region;

$$Q_{ij} = C_p(-W_{(i-1)j}T_{(i-1)j} + W_{ij}T_{ij} \pm W_{T_{ij}}T_{ij}) \tag{4}$$

For the boiling region;

$$Q_{ij} = (W_{G_{ij}} - W_{G_{(i-1)j}} \mp W_{T_{ij}})\lambda_v \tag{5}$$

Variously;

$$Q_{ij} = (W_{ij}X_{ij} - W_{(i-1)j}X_{(i-1)j} \mp W_{T_{ij}})\lambda_v \tag{6}$$

where Q_{ij} is the heat generated in ij, C_p is the fluid heat capacity, λ_v is the heat of vaporization, and x is the local quality. The datum level for the inlet to boiling level enthalpy is based on the inlet temperature, the datum level for the boiling section enthalpy is based on the predetermined boiling temperature and system pressure as well as the calculated pressure drop. This is done since the boiling level may be at different axial positions throughout the bundle.

The slip ratio, as determined by Bankoff [8], is equal to

$$S = \frac{1 - \alpha}{K - \alpha} \quad (7)$$

This expression is used to determine the void fraction, α, as a function of the quality, x, and of the phase densities:

$$\alpha = \frac{K}{1 + \frac{\rho_G}{\rho_L}\left(\frac{1}{x} - 1\right)} \quad (8)$$

where [9]

$$K = 0{\cdot}71 + 0{\cdot}0001P \quad (9)$$

and P is the pressure in psia.

Résumé—Les données de caléfaction de quelques nouvelles sections d'essais à 12 barres sont présentées. L'influence de la distribution de puissance, de la séparation minimale entre la paroi et la barre, et du flux de masse est recherchée. Le comportement global de ces sections d'essais a été réanalysé par deux programmes de calculateur qui permettent la détermination des conditions de refroidissement local dans un faisceau d'ébullition, connecté intérieurement comme celui utilisé dans cette étude.

Les barres avaient 112 mm de diamètre et étaient entourées par du tube destiné à la fabrication d'aiguilles hypodermiques de 0,56 mm de diamètre extérieur, en hélice de 15,2 cm de pas. Les données de caléfaction furent obtenues à 82,7 bars et à des flux de masse de 4,9 à 24,5 kg/h.m². Les différences entre les vitesses de production de chaleur dans les deux barres intérieures et les dix barres périphériques restantes étaient 1/1, 1,55/1 et 2,64/1. La distance minimale entre la paroi et la barre était de 0,56 mm dans quatre sections d'essais et d'approximativement 0,81 mm dans une cinquième section d'essais.

Les comportements globaux et locaux des sections d'essais sont comparés avec les données sur les tubes. Une telle comparaison indique qu'un effet de paroi froide existe dans les canaux périphériques alors que le comportement local dans les canaux intérieurs était en accord étroit avec les données sur les tubes.

Аннотация—Приводятся данные по критическим тепловым нагрузкам при кипении для нескольких новых 12-ти стержневых рабочих участков. Изучается влияние распределения потоков тепла, минимального зазора между стенкой и стержнем и массового расхода. Общий режим этих рабочих участков рассчитывался по двум счетновычислительным программам, которые позволяют определять условия местного охлаждения при кипении в пучке, испытанном в этом исследовании.

Использовались стержни диаметром 0,440 дюйма с навитыми на них трубками из нержавеющей стали с внешним диаметром 0,022 дюйма с шагом в 6 дюймов. Данные по критическим тепловым нагрузкам были получены при абсолютном давлении 1200 фт/д² и при массовом расходе 1–5.10⁶ фунт/ч.фут². Разность между интенсивностью тепловыделения в двух внутренних стержнях и остальных десяти периферийных составляла 1:1, 1,55:1 и 2,64:1. Минимальный зазор между стенкой и стержнем был 0,022 дюйма в четырех рабочих участках и приблизительно 0,032 дюйма на пятом рабочем участке.

Общий и локальный режим рабочих участков сравнивается с данными для системы труб. Такое сравнение показывает, что в периферийных каналах существует охлаждающее влияние стенки, в то время как локальный режим внутренних каналов хорошо согласуется с данными для системы труб.