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FORCED CONVECTION HEAT TRANSFER FOR PARALLEL FLOW THROUGH A ROUGHENED ROD CLUSTER

V. WALKER
University of Bradford, Bradford, Yorkshire, England
L. WHITE and P. BURNETT
Reactor Development Laboratory, U.K.A.E.A., Windscale Works, Seascale. Cumberland, England

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Abstract—For Advanced Gas-Cooled Reactors, methods are required for estimating the temperature distribution over the cladding of the cluster fuel elements, in considerable detail and with maximum accuracy. The first part of the paper describes the formulation of a temperature calculation procedure embodied in a computer programme, HOTSPOT. The fuel channel power distribution and coolant flow rate are specified, then, step by step along the channel, determinations are made of the flow distribution among the cluster sub-channels. the mean coolant temperature in each sub-channel, with an allowance for heat exchange between adjacent sub-channels, and the local cladding-coolant temperature differences. The main part of the paper then contains a description of the design, execution and analysis of a major experiment to test the calculation procedure. The experiment involved a 15 ft long cluster of 36 roughened rods, with electrical resistance heating of 900 kW, the distribution of which could be controlled, and with more than 600 thermocouples installed to determine the temperature distribution.

The paper is based on work done at the Reactor Development Laboratory, U.K. Atomic Energy Authority, Windscale, Cumberland, England.

NOMENCLATURE

f, friction factor;
St, Stanton number;
Re, Reynolds number (also R in statistical treatment of results);
N, Biot number;
C, dimensionless brace loss factor;
K, correction factor;
P, proportion;
X, Y, functions in Rapier's [8] transformation equation;
p, radial power distribution;
z, axial distance;
S, region of heated surface;
d, equivalent diameter;
d_r, rod diameter to root of roughness;
e, roughness height;
b, can wall thickness;
r, radius;
s, interface length between adjacent coolant zones;
l, length of roughened rod over which pressure drop is determined;
c_p, coolant specific heat at constant pressure;
u, coolant velocity;
ρ, coolant density;
t, coolant temperature;
T, can temperature;
q, heat flux per unit area;
k, thermal conductivity;
h, heat transfer coefficient.

Suffixes
1, transformed; fuel material;
2, can material;
g, gap between rods of a rod ring;

r, rod;
w, wall;
b, bulk.

Mean values designated by "barred" symbols.

Note that the overall equivalent diameter $\bar{d}$ embodied in the cluster Reynolds number, $\overline{Re}$, relates to an equivalent fully-roughened cluster having the same pressure loss characteristics as the actual cluster which contains a proportion of smooth surface. For the definition and method of calculation of $\bar{d}$ see [8] or [9].

INTRODUCTION

THIS investigation constituted an advanced stage of the heat transfer studies for the development of nuclear fuel elements for Advanced Gas-Cooled Reactors (AGR's). A typical fuel element arrangement, the one used for this investigation, is shown in Fig. 1. It consists of 36 fuel rods with a centre tube of about the same diameter which is associated with fuel charging and discharging operations. The surfaces of the stainless steel fuel cans are "roughened" by regularly spaced ribs, the rib height being very small compared with the size of the flow passages. Over a period of years a large quantity of heat transfer and friction data has been accumulated for many roughened surface configurations of the transverse rib type. Walker and Wilkie [1] have given a summary of the data with a discussion of the choice of an optimum roughened surface. It will be noted from Fig. 1 that this is a rather open cluster arrangement, only 26 per cent of the cross-sectional area of the circular channel being occupied by the fuel rods. This feature has a bearing on the treatment of flow and heat transfer.

Optimisation of cluster layout

For the preliminary design of a fuel element, leading to the choice of the number of rods in the cluster, the total flow area, the roughness dimensions, etc., simplified heat transfer and pressure loss calculations are made in which all the rod surfaces are lumped together and differences in can surface temperature and heat flux across the cluster are ignored. Subsequently it is necessary to carry out more detailed performance analyses on a chosen design to estimate the temperature distributions along and across the cluster for different power distributions, and eventually to determine the precise positions of the rods in the cluster to achieve the most favourable temperature distributions. This optimisation process may be governed by a specified maximum can temperature or the need to minimise bowing, or a combination of both. The optimisation criteria become more sophisticated as understanding increases of the factors that govern fuel element endurance. In any case the requirements from the heat transfer studies are data and calculation methods to enable fuel element temperature distributions to be determined in considerable

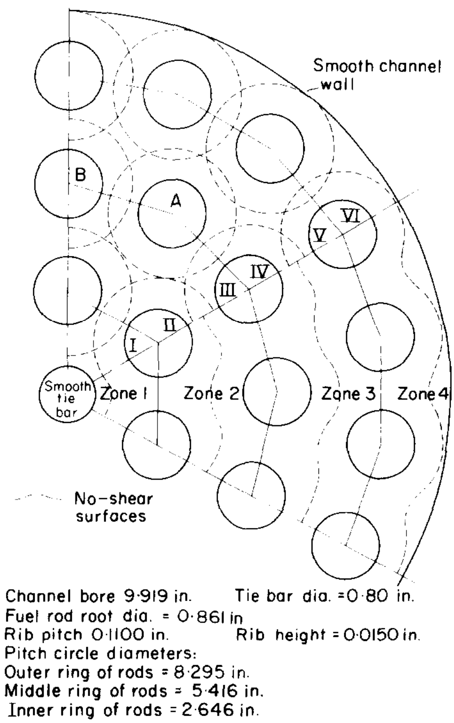


FIG. 2. Layout of cluster.

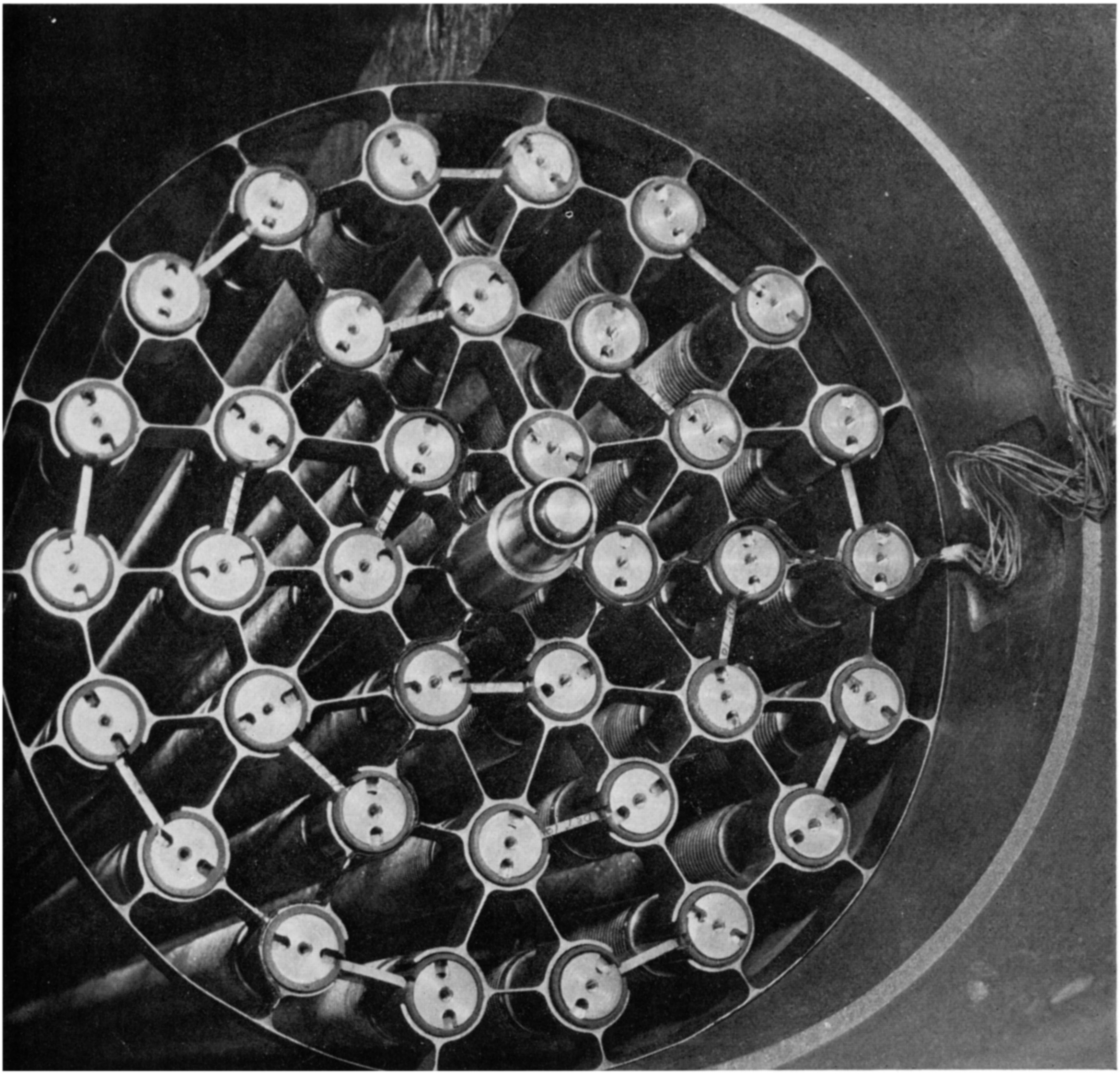


FIG. 1.

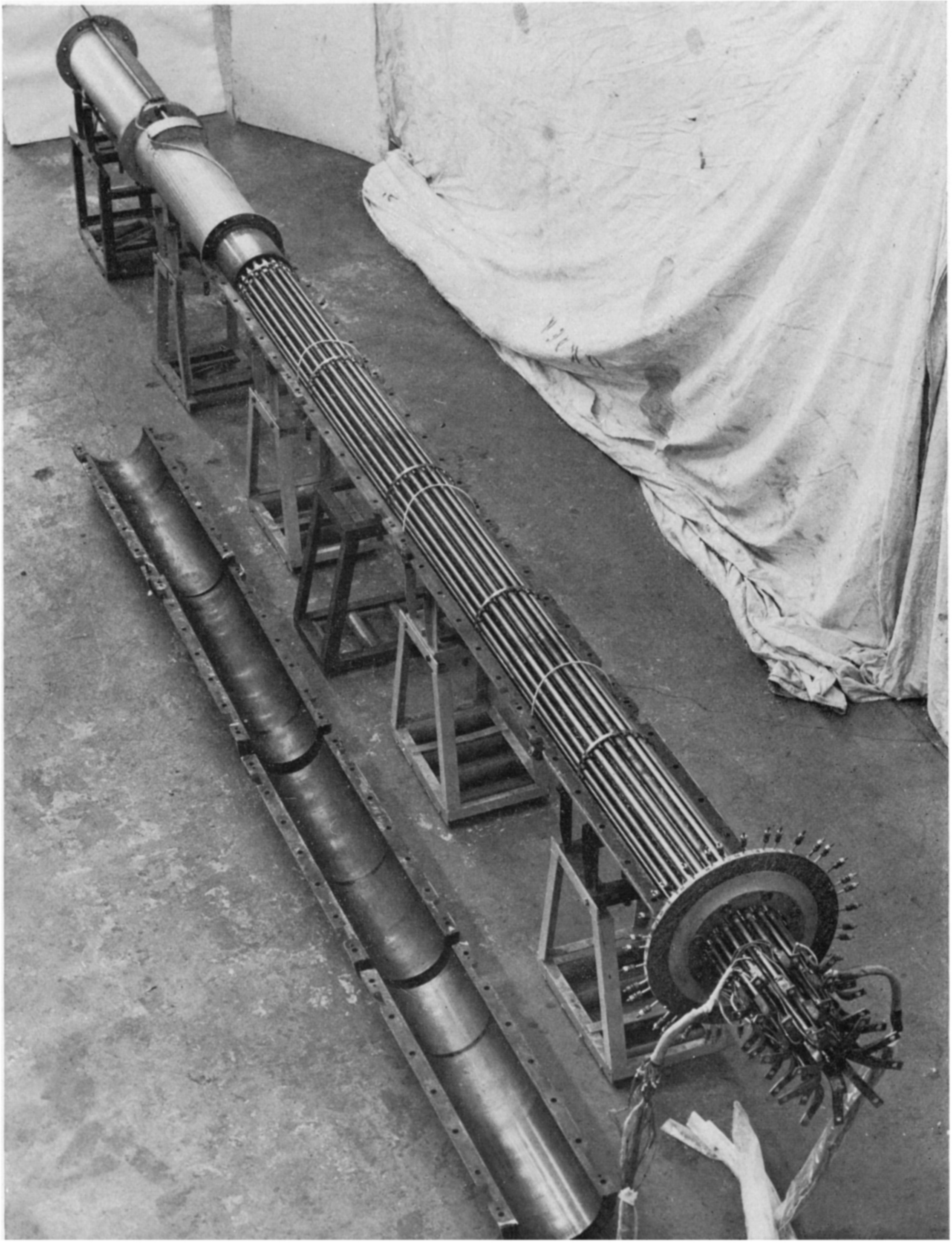


FIG. 3.

detail with the highest possible accuracy. This paper is concerned with such detailed heat transfer analyses of fuel cluster designs.

A segment of the cluster arrangement studied is shown in Fig. 2; (although the layout is characteristic the dimensions are not, the model being scaled up from a typical fuel cluster). The procedure for detailed heat transfer calculations is embodied in an IBM 7090 computer programme (HOTSPOT) [2]. The starting point is a given channel coolant flow and inlet temperature, and a detailed power distribution across the cluster and along the channel. In a step-by-step progression along the channel, estimates are made of the distribution of the coolant into a number of parallel flow zones on the basis of equality of pressure gradients, the heat flows into those zones and therefore the rates of increase of coolant temperature. Account is also taken of net displacements of coolant between zones and of heat interchange between them. Finally, zonal heat transfer coefficients are introduced and a distribution of can-coolant temperature difference is superimposed on the calculated coolant temperature distribution.

It will be noted from Fig. 2 that the fuel rods have been arranged in three rings containing 6, 12 and 18 rods, and the flow area has been rather coarsely divided into four "annular" zones. Because the main power generation gradients in the cluster are in a radial direction, subdivision into annular zones was the minimum requirement. Greater subdivision was thought to be not required with these open cluster arrangements but would become necessary if the spacing of the rods was reduced to the extent that adjacent rods interacted and caused temperature peaking, for example a sixth harmonic variation in the case of the rod labelled A in Fig. 2. Not very much is known about temperature peaking around rods in roughened clusters arising from the shapes of the flow passages, but for a smooth cluster the rod pitch/diameter ratio has to be somewhat less than 1·25 before temperature peaking becomes appreciable; see Redman, McKee and Rule [3]. HOTSPOT has therefore been compiled for rather open clusters in which the rods are arranged on any number of pitch circles, with the cluster concentric in the channel and with a circumferentially symmetric power distribution. It is noted in passing that various devices have been used to apply the programme to wider situations lacking circumferential symmetry.

AN OUTLINE OF THE HOTSPOT COMPUTER PROGRAMME

HOTSPOT was formulated from data taken from a variety of experimental sources, most of which involved simple configurations rather than clusters, the data being fitted together on the basis of theoretical considerations. An outline of the basis of HOTSPOT is given at this point, but a fuller examination of its validity will be made when the results of the present investigation are discussed.

The cluster heat transfer calculation procedure must embrace:

(a) the division of the total channel coolant flow between the various zones,
(b) zonal Stanton numbers,
(c) a net heat interchange when there is a temperature difference between adjacent coolant zones.

HOTSPOT was written so that a variety of formulae for friction factors, Stanton numbers, etc., could be accepted. In the following paragraphs a brief account is given of the origins of the data that would have been fed into HOTSPOT at the outset of the investigations on this particular 36-rod cluster.

Friction factor data

The problem was to apply to the various cluster zones the extensive data for roughened surfaces obtained from experiments with a single roughened rod mounted concentrically in a smooth circular pipe. A method was required for transforming such experimental data to enable them to be applied to situations with different proportions of rough and smooth perimeter, including the case of a fully-roughened passage. Such transformation methods have been discussed in the literature; the original paper by Hall [4] contains the key ideas, while Wilkie [5] has compared the various transformations. The basic idea is that, in the experiments with a roughened rod mounted within a smooth pipe, the annular flow passage is considered as two regions, adjacent to the rough and smooth surfaces respectively, separated by the cylindrical surface of zero shear stress. In order to apply to a cluster the friction factor data for the annular region around the single roughened rod it is further necessary to allow for the shape of the passages around the rods in a cluster. It has been assumed that the "equivalent–diameter" concept allows for changes in passage shape. It was perhaps fortunate that the passages around the rather widely spaced rods in AGR clusters could be represented by annuli without much distortion as illustrated in Fig. 2. The outermost cluster flow region, zone 4 of Fig. 2, is bounded by a combination of smooth and roughened surfaces and may be treated by the general transformation method, the precise shapes of the passage and the zero shear surface again being ignored to reduce the treatment to that of an equivalent annulus.

The transformation method outlined, involving the division of a flow area into two regions by a surface of zero shear stress, involves the assumption that there exists a substantial degree of independence between the two regions, making it possible to treat them separately. Experience shows that the methods built upon this assumption are a fair approximation rather than strictly true, and it has been found necessary to introduce empirical correction factors. For example it is found that the transformed f–Re relation for a smooth surface is not independent of the degree and quantity of roughened surface present. It was therefore proposed to allow for the effect of the roughened rods on the smooth outer boundary by multiplying a common friction factor for a smooth surface, $f = 0{\cdot}046\ Re^{-0{\cdot}2}$, by a correction factor K. At the outset of this investigation it was expected that K would need to be set at about 1·4 and also that the friction factors of the fully roughened passages in the cluster should be higher, by roughly 10 per cent, than the transformed values from single roughened rod experiments. These correction factors were derived from examinations of experimental data, in the transformation of which the zero shear surface had been supposed to coincide with the position of zero velocity gradient, which remained the usual assumption until quite recently. However, work of Kjellström [6], Lyall [7] and others has now indicated that the surface of zero shear stress is significantly displaced from the radius of maximum velocity in a mixed rough-smooth annulus. The implication is that, if the transformation of all the single rod data was now repeated with the correct zero shear surface, the correction factors would be brought much closer to unity.

Stanton number data

The intention was to use the transformed single rod Stanton numbers directly, changes of passage shape again being allowed for by the equivalent diameter concept. The situation was simpler than for friction factors since Stanton numbers are much less sensitive to errors in the transformation technique, for example in the location of the zero shear surface.

In any flow zone the heat supplied from each surface is not usually proportional to the associated coolant mass flow rate and consequently there is a net transfer of heat across the zonal no-shear surface. It is necessary to adjust the single rod transformed Stanton number (St_1) to allow for this effect and Rapier [8] has produced the following general correction which is embodied in HOTSPOT:

$$\frac{St_1}{\text{Effective Stanton number } (St)} = 1 + Y.X.St_1\sqrt{\left(\frac{2}{f_1}\right)}$$

where Y is a function of the ratio: distance between rod and associated no-shear surface to radius of fuel rod,

X is a function of the overall zonal coolant temperature rise per unit axial length of channel and the coolant temperature rise within the no-shear surface and zone boundary, if all the heat released to that sub-zone were retained within it,

f_1 is the transformed friction factor for the zone.

The largest transformation ratio (St_1/St) exists in the outer flow zone where the smooth channel boundary is approximately an adiabatic surface. A typical value for this zone would be 1·04.

Mixing data

The mixing of heat between adjacent zones results from temperature differences across the rods and from differences in the temperatures of the adjacent coolant flows. A temperature difference across the rods leads to a re-distribution of heat flux around the rod by conduction in the can and fuel. The net effect is a flow of heat across the rod. Also if a bulk coolant temperature difference exists between the adjacent flows there will be a net transfer of heat through the gaps between rods. This problem has been studied by Rapier [10] whose equation forms the basis of HOTSPOT mixing assessments.

Considering one rod ring, an effective Stanton number St' is defined for heat transfer between adjacent annular passages (a and b say).

$$St' = (St'_g \times P) + St'_r(1 - P) = \frac{q}{\bar{\rho}\,\bar{u}\,\bar{c}_p\,(\bar{t}_a - \bar{t}_b)}$$

where q = heat flux per unit area of total interface between a and b

p = proportion of interface occupied by circumferential rod gaps

$\bar{\rho}$ = mean coolant density for the two zones

$\bar{u}$ = mean coolant velocity for the two zones

$\bar{c}_p$ = mean coolant specific heat for the two zones

$\bar{t}$ = bulk coolant temperature

suffix g = gap, suffix r = rod.

The zonal subdivision of the channel flow area into annular passages results in a distribution of heat transfer coefficient around any one rod and it is assumed that only the first harmonic of the resultant rod surface temperature distribution survives conduction damping. The mathematical analysis of damping will not be reproduced here but the result is that:-

$$St'_r = \left[\frac{N_1 + N_2}{1 + N_1 + N_2}\right] \times \frac{St_1}{2}.$$

where $N_1 = \dfrac{k_1}{\bar{h}\,.\,r^2}$ (for fuel if present)

$N_2 = \dfrac{k_2 b}{\bar{h}\,.\,r^2}$ for cladding

St_1 = average Stanton number for rod

k_1 = thermal conductivity of fuel

k_2 = thermal conductivity of cladding

b = wall thickness of can

r = radius of fuel pellet (assumed solid)

$\bar{h}$ = average heat transfer coefficient from can to coolant.

Heat exchange between zones via the coolant in the circumferential gaps between the rods is complex and not at all well understood. Although Rapier [10] offers some physical basis for his correlation it should perhaps be regarded as largely empirical and subject to considerable uncertainty. The correlation is

$$P\,St'_g = \tfrac{1}{20}\sqrt{\left(\frac{f_1}{2}\right)}\left[\frac{\bar{d}}{\bar{d} + 2d_r}\right]$$

from which the rate of heat transfer, through the gaps, per unit axial length of cluster is

$$\frac{\bar{\rho}\,\bar{u}\,\bar{c}_p\,s\,(\bar{t}_a - \bar{t}_b)}{20}\sqrt{\left(\frac{f_1}{2}\right)}\left[\frac{d}{\bar{d} + 2d_r}\right]$$

where $\bar{d}$ = average transformed equivalent diameter of adjacent zones

d_r = rod diameter

$\bar{f}_1$ = average transformed friction factor for adjacent passages

s = total length of interface (gaps + rods) between passages.

Heat balance equations are developed for each coolant zone within the cluster and include mixing terms calculated from the above equation. These, along with force balance equations for the parallel paths, are solved simultaneously in HOTSPOT to determine the coolant conditions in each flow zone.

Following this outline of the HOTSPOT programme, it will be appreciated that, despite the apparent power and flexibility of the computer calculations, they could not be regarded as reliable, proven assessments of cluster fuel element temperature distributions. It was necessary to check calculations against measured cluster temperatures. An account of an experiment designed for that specific purpose occupies the remainder of this paper.

CONCEPT OF THE CLUSTER EXPERIMENT

It was a requirement that the test should be an adequate one in the sense that the outcome should be a version of HOTSPOT unique within limits such that in subsequent applications of HOTSPOT to the calculation of fuel element temperatures in reactors, the uncertainties would be acceptably small. The experiment was required to yield a comparison between measured and calculated temperatures such that any discrepancies could subsequently be minimized by a unique combination of (empirical) changes to the following factors in the calculation procedure:

(a) The relative friction factors of the coolant zones, and therefore the flow distribution.
(b) The Stanton numbers for the various zones.
(c) Heat interchange between adjacent coolant zones.

With the exception of a short development length at cluster entry, the Stanton number distribution has its full effect on rod temperatures over the whole length. On the other hand consider the factors (a) and (c). The distribution of coolant flow directly affects the coolant temperature rise in the various zones, therefore is best investigated by an arrangement in which there is a large temperature rise, i.e. a long heated cluster. Similarly heat mixing between coolant zones can be tested only when there is sufficient length for significant temperature differences to develop and for the development to be affected by mixing. It was proposed that the influence of mixing on the development of the temperature distribution with axial distance could be distinguished from the influence of flow distribution if tests were made with several radial power distributions. Suppose the power distribution could be set such that all coolant zones had very nearly the same temperature rise; then mixing could have little effect. If the power were now varied in different ways from the "zero-mixing" case, temperature distributions could be observed which showed up the effects of reversing the direction of the mixing heat fluxes. It was therefore essential to design the experiment with means for changing the radial power distribution in the cluster.

The test cluster design had the dimensions given in Fig. 2 and a continuous heated length of 14·5 ft. The d.c. power supplies available for heating the cluster amounted to 900 kW which, at the maximum Reynolds number, would give an accurately measurable can-coolant temperature difference, exceeding 50°C, with the chosen cluster dimensions. Preliminary HOTSPOT runs were made with different assumptions about the distributions of Stanton number and friction factor and the intensity of heat mixing to verify that, with an estimated experimental scatter on the thermocouple readings, the proposed experiment would adequately distinguish between the alternatives.

It is mentioned that the experiment was designed to meet several further requirements. The detailed temperature distribution immediately downstream of the coolant entry to the heated cluster was of interest, therefore a short, unheated cluster, which could be rotated by remote control to vary the relative orientation, was placed upstream to create the appropriate flow disturbance. In fact there were two unheated clusters so that, with the flow direction through the test section reversed, the decay of the coolant temperature distribution produced by the heated cluster could be studied as it passed through the two unheated ones, enabling the degree of mixing at a break between two fuel elements, and the effect of orientation there, to be determined. The two unheated clusters are in position in the photograph of the test section, Fig. 3. The results of these and other subsidiary measurements are only relevant to the particular spacers and end fittings used and are not discussed in the paper.

The cluster experiment was carried out in nitrogen at 340 lbf/in^2 abs., gas temperatures not exceeding 160°C, and surface temperatures not in excess of 220°C. In AGR's the coolant is carbon dioxide at much higher temperatures. The tests embraced reactor Reynolds numbers, and the more detailed problems involved in relating the results to reactor conditions have been studied in some detail [11], but that is a separate problem and need not be considered here.

DESIGN OF EXPERIMENT

The test section and other circuit components are shown in Fig. 4. Two unheated clusters each 4·2 ft long and one heated cluster 14·5 ft long were installed vertically within a longitudinally split channel which was carried upon a support plate mounted between the flanges of the surrounding pressure vessel. The external surfaces of both the flow channel and the pressure vessel were lagged to minimise heat losses.

The rods were made by wrapping square-section wire on to the outer surface of smooth stainless steel tubes (on a single start helix) and vacuum brazing. The rods of the outer ring were made from 0·035 in. wall tube and the remaining rods from 0·040 in. wall tube. This difference allowed larger powers to be generated in the outer ring rods. The variation in wall thickness around any one tube was not greater than ± 2 per cent about the mean wall thickness and the majority were considerably better.

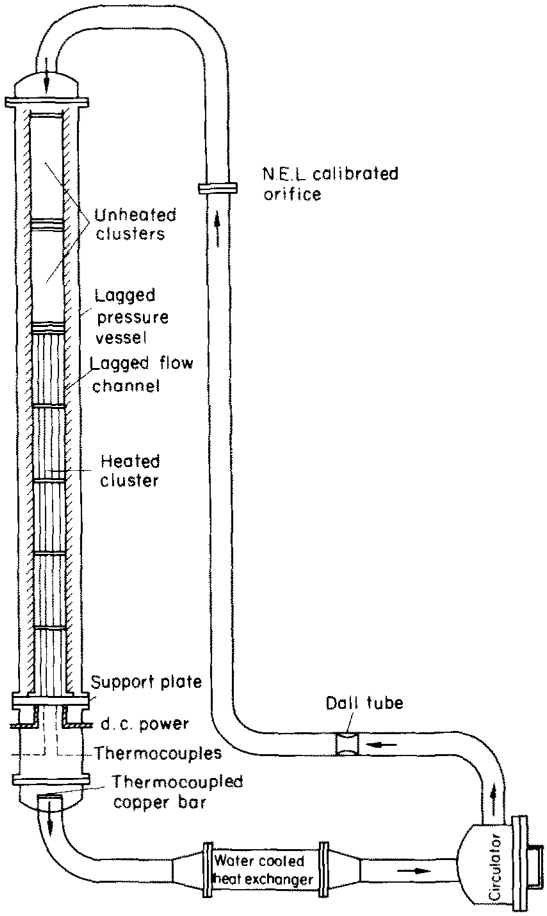


FIG. 4. Flow diagram.

The tubes were resistance heated by direct current and were arranged as 18 parallel electrical circuits, two adjacent rods of any one rod ring being connected in series by means of a cross-connection, located in the upper grid (Fig. 1). The maximum variation of electrical resistance (measured over a 4 in. gauge length) along any one rod and between any pair of rods forming one circuit did not exceed 0·7 per cent.

Six separately variable motor generator sets supplied current at potentials up to 80 V d.c. Each of the generators fed two, three or four parallel circuits, and each circuit contained one 0–10 V d.c. variable booster unit and one pair of cluster rods, known as an electrical zone. Zones common to any one generator could be varied independently of other zones, and each booster unit gave fine control of its individual zone. Since each generator supplied zones in only one rod ring, any circumferentially symmetric power distribution could be achieved, including any one of the three rod rings heated in isolation. Within the limits of the 12·5 per cent power supplied by a booster, zones common to one generator could be varied independently, thus allowing limited circumferential variation and simulation of a cross-channel power gradient.

All power supply connections to the rods were made at the lower end of the cluster as shown in Fig. 4. The electrical bus bars, which were brazed into the lower ends of the rods, were positioned within the bottom support plate and electrically insulated from it by sleeves manufactured from sintered and glass filled PTFE, and the same material was used to insulate the rod ends from the top grid. Both grids were machined from solid stainless steel plate. In addition to the end grids, the rods were supported along their length by four anti-bowing braces. These were designed to allow an adequate coolant flow over the heated rods where they passed through a brace and at the same time to produce only localized variations in the axial static pressure gradient and rod temperature.

INSTRUMENTATION AND CALIBRATION

Temperature measurements

Temperatures at 650 points were measured by Chromel-P/Alumel (Hoskins) thermocouples, and were recorded on the punched tape output of a data logging system at a rate of about 2 readings per s. Thermocouples in the rods were brazed into 0·040 in. square holes spark machined mid-way between ribs. The two wires were inserted into the square hole and constrained to lie on the straight edge perpendicular to the axis of the rod, thus minimizing the increment of e.m.f. picked up from the heating current in the rod. The hole was filled with braze and the surplus cleaned off the outside to leave the rod profile undisturbed. The thermocouple wires were fed through the inside of the roughened tubes and hollow bus bar connections to seals in the pressure vessel.

Each thermocouple was calibrated for d.c. "pick-up" by means of a current reversal technique. A further potential source of error, discussed by Walker and Rapier [12], is that a thermocouple reading might differ slightly from the undisturbed rod surface temperature. Although the upper bound on this error was put at 3 per cent of the surface-coolant temperature difference, it was decided to make further experimental checks. One roughened rod of each wall thickness, 0·035 in. and 0·040 in., was individually tested in a smooth circular pipe over the cluster range of heat transfer coefficient, and in each case the readings of 14 brazed thermocouples were compared with 14 thermocouples spot welded to the inside tube surface. It was established that the brazed thermocouples in the 0·040 in. wall tubes measured inside surface temperature, and in the 0·035 in. tubes a slightly lower temperature to the extent of one third of the temperature difference across the tube wall. These findings supersede the earlier conclusion [12] that this type of brazed thermocouple indicates the undisturbed outer surface temperature. Appropriate corrections were made in the analyses of the cluster temperature measurements.

Thermocouples were arranged within the the heated cluster as shown in Fig. 5. There were similar planes of thermocouples on the unheated clusters, positioned four inches from each end of each cluster. In the present experiment the most downstream plane was used as a measure of the coolant temperature at inlet to the heated cluster. 12 thermocouples mounted on a 1 in. dia. copper rod suspended across the coolant gas outlet gave a measure of outlet temperature.

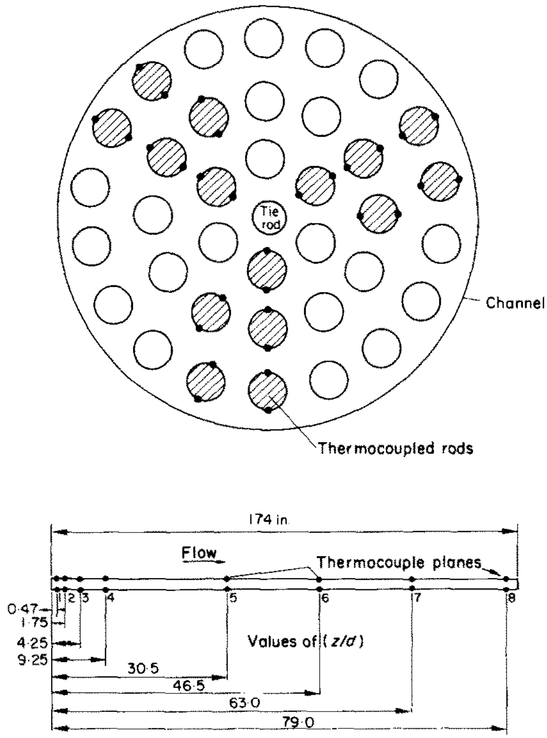


FIG. 5. Thermocouple positions.

Electrical power measurements

The potential drop across a standard resistance in each of the 18 circuits, together with the electrical resistance of the rods at the appropriate temperature, enabled the power per rod to be calculated as I^2R. By summing these powers and adding the known contribution of the various bus-bars and electrical connectors, the total power could be calculated and compared with the product of measured zone voltages and currents. This comparison showed agreement to $\pm$ 0·5 per cent.

Flow measurements

The coolant mass flow rate was measured initially with a Dall tube, a proprietary form of truncated venturi meter, employed because of its low pressure loss. After serious mass flow rate discrepancies had been traced to an unstable flow condition apparently generated by this particular Dall tube installation, and accompanied by acoustic effects, a precisely made corner-tap orifice meter was used. This was calibrated in the National Engineering Laboratory water loop and the discharge coefficient found to differ by a maximum of 0·27 per cent from that calculated from B.S. 1042: Part 1: 1964. It is estimated that the measurement of coolant mass flow rate was correct to $\pm$ 0·25 per cent.

SINGLE ROD TESTS

It was accepted that, to achieve a best fit to the measured cluster temperatures, the HOTSPOT programme might have to be adjusted empirically in ways that would not be fully understood at the time. However, it would be necessary to seek an understanding of these programme adjustments in terms of more basic experimental data, particularly those obtained from tests on single rods, to give confidence in the use and extrapolation of HOTSPOT. Although extensive single rod roughened surface heat transfer and friction data has been accumulated it was considered necessary to make accurate tests with some of the actual cluster rods to take account of significant second-order effects including:

(a) The degree of effectiveness of conduction in the tube wall and ribs in redistributing the heat flux to regions of locally high heat transfer coefficient, notably the rib tips, see [13].
(b) Small variations in rib shape [14]. The present ribs had radii of approximately one quarter the rib height on the outer corners and fillets of braze metal of about the same radius at the root.

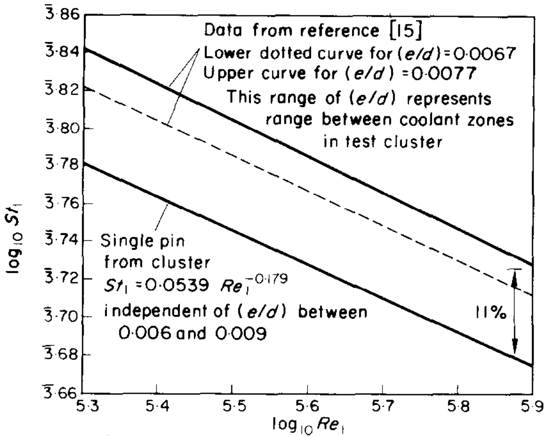
Single rod tests were therefore made on two rods as used in the cluster in two different sizes of smooth pipe. These tests, which were combined with the thermocouple calibrations described earlier, were made in nitrogen at the same value of Prandtl number, mean coolant temperature and surface-coolant absolute temperature ratio, as the cluster tests. The method of transformation of the friction [9] and heat transfer [5] data did not require measured coolant temperatures and velocity profiles across the annulus. These transformations implicitly retain the assumption that the zero-shear surface coincides with the radius of maximum velocity. The Reynolds number range was from 2×10^5 to 10^6 while roughness height/diameter (e/d) ratios varied (by the use of two channels) between 0·006 and 0·009. Thus the cluster range of e/d, 0·0067 and 0·0077, was covered.

The results are presented in Fig. 6 from which the following conclusions were drawn.

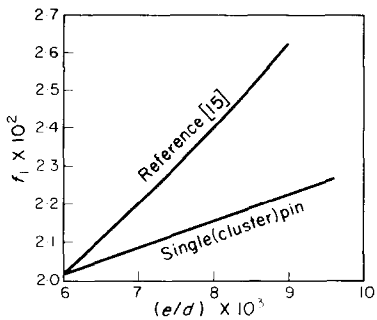
(a) There was no variation of Stanton number with (e/d) for the test range of this parameter of 0·006–0·009. This is a not unexpected result for the form of rib profile tested.

(b) The single stainless steel rod Stanton numbers were on average about 11 per cent lower than the published data [15] which can be ascribed to the different degrees of conduction damping in the two cases and also (to a lesser extent) to differences in rib profile.

(c) The cluster single rod friction factor which, as expected, did not vary with Reynolds number, agreed with the published data at a value of (e/d) of 0·006 but although increasing with increasing values of (e/d) did so at a much slower rate than originally expected. Other data [14] for roughened cans of similar rib profile are in fair agreement with the present results and would point directly to the combined effect of rib tip rounding and root fillets as being a major cause of the shallow slope recorded.



Stanton number against Reynolds number



Friction factor against roughness height to diameter ratio (independent of Reynolds number)

FIG. 6. Single rod data.

As a result of these single rod tests the following equations (taken from Fig. 6) were used in the cluster analysis.

$$St_1 = 0{\cdot}0539\, Re_1^{-0{\cdot}179}$$

$$f_1 = 0{\cdot}7\,(e/d) + 0{\cdot}016.$$

CLUSTER TEST PROGRAMME

The main series of test runs for comparison with HOTSPOT comprised six radial power distributions at each of two (mean cluster) Reynolds numbers, $3{\cdot}3 \times 10^5$ and $6{\cdot}8 \times 10^5$. The distributions were:

Type of power distribution	Outer ring power per rod / Average power/rod in heated rods	Middle ring power per rod / Average power/rod in heated rods	Inner ring power per rod / Average power/rod in heated rods
Flat	1·00	1·00	1·00
Nominal reactor	1·09	0·94	0·84
Steep	1·20*	0·85	0·70
Outer ring only heated	1·00	0	0
Middle ring only heated	0	1·00	0
Inner ring only heated	0	0	1·00

* This power distribution was unattainable at the higher Reynolds number, the appropriate figures being 1·18, 0·88, 0·71.

The runs with power in only one ring of rods were used to test the HOTSPOT treatment of the mixing of heat between cluster passages. The power levels were increased with Reynolds number to keep the rod-coolant temperature differences in the range 50–60°C. In addition, the coolant inlet temperature was adjusted to give a constant bulk outlet temperature and thus standardise T_w/T_b at the cluster outlet end.

PRESENTATION AND DISCUSSION OF CLUSTER RESULTS

Circumferentially averaged temperatures

The HOTSPOT programme provides, for each test condition and chosen axial station, a radial distribution of rod surface temperatures consisting of six values, one for each of the six regions of surface I–VI as defined by the boundaries between flow zones and depicted in Fig. 2.

We note however that rods in the same ring are not necessarily identically situated with regard to flow area. There is only one type of rod in the innermost ring but two in each of the other rings and in the intermediate ring, rod B was found to run hotter than rod A. Denote by ΔT one of these second-order temperature differences between two temperature measurement stations which HOTSPOT assumed to be identical, for example the radially outward sides of rods A and B. Then, if the short heat transfer coefficient entry length is excluded, ΔT would be expected to vary with axial distance z in the following manner:-

$$\Delta T = \alpha + \beta [1 - \exp(-\gamma z)]$$

for an axially uniform heat input, where the first term is the difference between the surface-to-local coolant temperature differences for the two types of rod and the composite second term represents the build-up of a temperature difference between the two coolant regions, asymptotically to a value which is limited by diffusion of heat in the coolant. The principal concern was that the temperature differences in the coolant might build up to a substantial value. It turned out that, although the smallness of ΔT, and the consequent large relative scatter in the measurements did not permit the precise development to be determined, there was no evidence of a build-up beyond quite a short entry length and in the worst case, i.e. the inside sectors of rods A and B, ΔT did not exceed 8 per cent or $\pm$ 4 per cent, of the circumferential mean can-coolant temperature difference for the ring.

Modifications to HOTSPOT to fit cluster results

The measured temperatures for the main programme of 12 test runs are set out in Tables 1 and 2. Also given are the final discrepancies between measured and calculated temperatures after the data fed into HOTSPOT had been adjusted by trial and error to achieve the best fit. In Table 3 are listed two sets of Stanton number and friction factor equations, firstly a consensus of data previous to the present

Table 1. Experimental surface temperatures for tests with all rods heated (°C)

$Re \times 10^{-5}$	Power distribution / Axial station / Surface	Flat 65 in.	Flat 100 in.	Flat 135 in.	Flat 170 in.	Nominal Reactor 65 in.	Nominal Reactor 100 in.	Nominal Reactor 135 in.	Nominal Reactor 170 in.	65 in.	100 in.	135 in.	170 in.
	VI	131·9 −0·9	148·4 −0·9	163·4 +0·5	179·2 +2·1	139·7 0	157·4 −0·6	173·4 +1·0	192·6 +0·3	151·5 −0·3	170·6 −0·6	188·3 +1·0	208·2 +1·3
	V	135·4 −0·2	154·8 −0·6	172·2 +1·3		142·1 0	161·9 −0·4	182·4 −1·3		152·1 −0·2	172·9 −0·8	192·9 −0·5	
3·3	IV	135·3 +1·3	158·4 −2·0	175·9 +0·4	195·1 +1·8	130·3 +1·4	152·6 −1·3	170·9 +0·2	189·9 +1·6	124·9 +0·9	146·7 −1·1	166·1 −0·6	185·6 +0·4
	III	139·3 +1·8	161·9 +1·3	183·5 +2·0	207·2 +1·2	131·5 +1·5	152·4 +0·6	172·4 +0·8	193·8 +0·4	123·2 +0·7	142·2 −0·4	161·0 −0·8	180·6 −1·3
	II	142·7 −0·9	164·8 −0·6	187·7 −0·8	210·1 +0·1	127·1 −1·0	146·1 −0·2	166·8 −0·8	186·7 +0·1	113·9 −1·3	130·8 −0·9	149·3 −1·5	167·3 −1·0
	I	143·9 −0·5	165·5 +1·1	190·2 −1·0	211·6 +1·5	126·2 +0·1	143·8 +1·5	166·2 −1·3	184·3 +1·1	110·6 +0·9	126·8 +0·6	145·5 −1·5	162·0 −0·5
	VI	137·4 −0·5	150·8 −0·6	163·1 +1·0	176·1 +2·3	144·6 −0·9	159·4 −1·3	172·6 +0·4	186·5 +1·7	146·9 −1·2	161·8 −1·4	175·2 −0·3	190·8 0
	IV	140·4 −0·1	157·0 −0·3	169·3 +4·0		146·4 −0·3	163·3 −0·6	176·7 +2·8		147·8 −0·6	164·6 −1·2	180·6 −0·9	
	V	140·2 +1·1	160·7 −2·7	174·0 +0·9	189·8 +2·2	135·5 +0·5	155·0 −2·3	169·6 0	185·3 +1·2	128·6 +0·1	146·8 −2·0	161·6 −0·7	176·6 −0·6
	III	143·5 +1·7	162·8 +1·4	180·8 +2·4	201·0 +1·4	136·5 +0·7	153·7 +0·5	170·5 +0·9	189·0 −0·2	127·5 −0·3	143·3 −0·5	158·5 −0·5	174·7 1·1
	II	146·0 −0·1	165·0 +0·1	184·0 +0·4	202·2 +1·0	131·4 −0·7	148·3 −0·7	165·6 −0·9	181·4 +0·6	119·0 −1·6	132·8 −0·8	148·0 −1·0	163·1 −0·9
	I	146·0 +0·5	164·5 +1·3	186·8 −1·4	202·7 +2·5	129·6 +0·4	145·1 +1·0	164·5 −1·8	178·6 +1·1	116·3 −0·3	128·8 +0·6	144·5 −1·2	157·7 −0·1

+ ve Discrepancy indicates HOTSPOT prediction greater than experimental measurement.

− ve Discrepancy indicates HOTSPOT prediction less than experimental measurement.

Table 2. Experimental surface temperatures for tests with single rings of rods heated (°C)

Power distribution		Outermost ring only heated				Intermediate ring only heated							
$\overline{Re} \times 10^{-5}$	Axial station / Surface	65 in.	100 in.	135 in.	170 in.	65 in.	100 in.	135 in.	170 in.	65 in.	100 in.	135 in.	170 in.
3·3	VI	132·3 −0·3	146·7 −0·6	160·7 −0·6	174·2 −0·3	48·4 +2·3	50·4 +3·0	52·7 +3·8	55·9 +4·0	47·6 +0·2	47·6 +0·5	47·8 +0·7	48·0 +1·1
	V	128·5 −2·2	140·6 −3·3	156·7 −8·5		61·1 +0·1	62·7 +5·7	67·9 +7·5		48·0 +0·4	48·5 +1·1	49·3 +1·8	
	IV	59·0 +3·6	68·0 +3·4	78·3 +2·1	89·6 −0·1	126·5 −0	139·9 −4·5	144·1 +0·1	152·7 −0·3	48·8 +2·0	50·6 +2·5	52·9 +2·8	55·6 +2·9
	III	49·3 +2·0	52·2 +2·7	56·8 +2·3	62·9 +0·9	130·2 +0·9	143·7 −1·3	154·3 −1·0	166·0 −2·2	58·1 +4·8	64·8 +6·3	72·2 +6·9	82·7 +4·2
	II	47·5 +0·7	49·5 +0·9	52·3 +1·0	57·1 −0·4	61·7 +3·2	72·9 +1·5	84·7 −0·9	93·3 −0·1	130·5 +2·6	142·2 +2·8	152·2 +4·2	165·9 +1·5
	I	47·0 +0·3	47·5 +0·7	48·5 +1·1	51·0 +0·5	51·0 +3·5	56·8 +3·6	64·1 +3·0	81·6 −7·2	144·6 +1·1	163·3 +1·0	180·8 +1·0	192·6 +5·6
6·8	VI	137·2 −1·1	149·4 −1·5	160·5 −1·0	177·2 −6·1	59·0 +1·4	60·6 +1·7	62·3 +2·4	64·7 +2·7	58·4 +0·2	58·5 +0·3	58·5 +0·6	58·6 +0·9
	V	133·1 −1·9	143·4 −3·1	155·8 −6·5		66·0 +4·5	71·1 +5·6	76·0 +6·8		58·7 +0·5	59·2 +0·9	60·0 +1·3	
	IV	68·7 +4·1	76·6 +3·9	85·5 +2·8	95·8 +0·4	129·7 −0·5	138·0 −1·7	144·2 −0·9	152·5 −2·4	59·0 +1·5	60·5 +1·6	62·0 +1·9	64·3 +1·6
	III	60·2 +1·4	62·6 +1·7	66·1 +1·4	70·8 +0·3	132·6 +0·5	143·0 −0·6	153·6 −2·2	164·5 −4·4	67·5 +4·4	73·5 +5·4	80·0 +5·7	84·5 +7·8
	II	59·2 +0·6	60·7 +0·8	63·1 +0·8	67·2 −0·4	70·4 +3·4	79·8 +2·1	89·7 +0·2	94·3 +3·4	132·0 +2·2	140·7 +2·7	148·1 +4·4	158·9 +1·9
	I	58·6 +0·2	58·9 +0·6	59·9 +0·6	61·6 +0·4	60·8 +2·6	65·5 +2·5	71·0 +2·3	86·2 −7·1	143·5 +0·7	158·2 +1·0	173·2 +0·2	177·3 +9·1

+ ve Discrepancy indicates HOTSPOT prediction greater than experimental measurement.
− ve Discrepancy indicates HOTSPOT prediction less than experimental measurement.

Table 3. Stanton number and friction factor equations

Position in cluster	Consensus of previous data (1)	Data to fit cluster measurements (2)	Column (2) / Column (1) $\overline{Re} = 3.3 \times 10^5$	$\overline{Re} = 6.8 \times 10^5$
Zone 1	$St_1 = 0.0539\, Re_1^{-0.179}$	$St_1 = 0.0275\, Re_1^{-0.1242}$	1.023	1.064
2		$St_1 = 0.0380\, Re_1^{-0.1491}$	1.031	1.054
3		$St_1 = 0.0401\, Re_1^{-0.1549}$	1.010	1.028
4		$St_1 = 0.0419\, Re_1^{-0.1672}$	0.903	0.911
Rod surfaces in Zone 4	$f = 1.4 \times 0.046\, Re^{-0.2}$ $f = f_1 = 0.7(e/d) + 0.016$	$f = 1.264 \times 0.046\, Re^{-0.2}$ $f = 0.903 \times f_1$	0.903 (Zone 4)	
Rod surfaces in Zones 2 and 3	$f = 1.10 \times f_1$	$f = 1.163 \times f_1$ (Zone 3) $f = 1.164 \times f_1$ (Zone 2)	1.057 (Zone 3) 1.059 (Zone 2)	
Rod surfaces in Zone 1	$f = 1.10 \times f_1$	$f = 1.119 \times f_1$	1.017 (Zone 1)	
Smooth tie tube	$f = 1.4 \times 0.046\, Re^{-0.2}$	$f = 1.424 \times 0.046\, Re^{-0.2}$		

Note that when used in HOTSPOT all the Stanton number equations were modified as described earlier, the modification being important only for the rough surface in Zone 4 where the heat flux from the opposite boundary was zero, and that Re denotes the appropriate value for each zone or sub-zone.

cluster results, and secondly, the equations that were judged to give a best fit to the cluster temperature measurements; the final column of the table shows the magnitude of the differences between the two sets of equations. In column (1) the Stanton number equation is the one derived from the single rod tests and no distinction is drawn between the four zones. The rough surface friction factor, f, in zone 4 is again just the single rod equation, but in zones 1, 2 and 3 a factor 1·10 has been included. The need for a factor greater than unity in wholly roughened passages was suggested by friction measurements in a rectangular channel [16] and the particular value of 1·10 was found to give good agreement between calculated and measured pressure loss for a series of clusters [17]. Finally the factor of 1·40 on the smooth surface friction factor, as representing the influence of an adjacent rough surface, was derived from the large amount of data for a rough/smooth annulus. The St and f relations in column (2) were chosen retrospectively to achieve a good fit between the calculated and measured surface temperatures. The cluster temperature distribution is influenced by the distribution of the specified total coolant flow into the various zones and therefore by the relative values of the zonal friction factors. The absolute levels of the friction factors in column (2) have then been adjusted to yield the same overall cluster pressure loss as column (1). Moreover, where a change in zonal flow resistance from columns (1) to (2) was indicated, there was no basis, in the cases of zones 1 and 4 containing both types of surface, for ascribing different proportions of the change to the rough and smooth surfaces. The same correction factor was therefore applied to both the rough and smooth surfaces in a zone, and the common factor is quoted in the final column of the table.

It had been anticipated that the existing formula for the diffusion of heat between adjacent sub-channels might have to be multiplied by a correction factor to obtain a fit to the cluster results. It became apparent that no constant correction factor could produce a reasonable fit. The intensity of mixing appeared to vary markedly with axial distance, starting at a very low level in the entry region of the cluster and then increasing. The HOTSPOT mixing expression was therefore multiplied by the following empirical correction factor which included the axial distance z:

$$0{\cdot}7\left[1 - \exp\left(-\left\{\frac{z}{19\bar{d}}\right\}^2\right)\right]$$

where $\bar{d}$ is the average equivalent diameter for the cluster. The results of all the runs with single rings heated and the comparison with HOTSPOT using the modified mixing expression are given in Table 2. The dependence of the correction factor on z is perhaps not difficult to understand. The HOTSPOT mixing formula had been based on the assumption that the heat flow between zones is directly proportional to the difference between their bulk mean temperatures. In reality the heat flow between zones will lag behind the bulk temperature difference in the entry region as the fine structure of the temperature distribution is being developed. A development length would emerge as a consequence of a more detailed treatment of the mixing process based on finer subdivision of the flow area.

Margins of uncertainty in revised version of HOTSPOT

It was the objective of this experimental programme to establish a version of HOTSPOT with acceptably small margins of uncertainty and the approach to this objective has been discussed in connection with the concept of the experiment. The degree of success must obviously depend upon the experimental scatter, particularly of the rod thermocouples. The question now is: "What departures from the revised St, f and mixing equations would start to show a significant deterioration in fit?" It was always realised that the flow distribution, i.e. the relative friction factors of the various zones, would be particularly difficult to establish with precision, therefore the success in doing so will be examined. In Table 3 the most surprising feature of the revised equations is that the friction factor of zone 4 has turned out smaller than expected and so has the Stanton number. Could the measured temperatures not be fitted equally well by other, possible more reasonable, zonal friction factors and Stanton numbers, particularly in zone 4? Calculations have therefore been made with the friction factors in zone 4 deliberately maladjusted by factors, 1·2, 1·1, 0·9 and 0·8 on the values quoted in column 2 of Table 3. For each of these four cases the zonal St–Re equations were re-optimized to give minimum discrepancies between calculated and measured temperatures at the mid-axial station. The modified mixing expression was used for all cases. The adequacy of the equations thus derived to correlate the measured cluster temperatures has been examined statistically and compared against the "best fit" data of column 2, Table 3.

The differences, which are given in Table 1, between the measured temperatures and the HOTSPOT calculations using the equations in column 2 of Table 3, were analysed as a mixed level factorial experiment by a method due to Wilkie [18]. The four independent variables are:

- axial distance z (4 levels)
- region of heated surface S (6 levels)
- radial power distribution p (3 levels)
- Reynolds number R (2 levels)

The 24 combinations of z and S occur in any one of the six experimental runs from which Table 1 is formed. The error associated with these two variables, which was determined from high-order interactions of z and S, was shown by the analysis to be larger than the error associated with variables p and R which represent different runs. The standard deviation quantifying the error associated with the z and S variables was found to be 0·94°C. The sources of this error include variations in thermocouple installation and calibration, cluster geometry, electrical zone power settings, and inexact corrections for wall thickness variations. The error associated with the p and R variables (i.e. between runs) would normally be obtained from the high order interactions involving p and R. The only interactions which can really be considered, p^2

and p^2R, can yield only an inaccurate estimate of error. An alternative, and possibly inflated, measure of error can be obtained by including also the main effect R and the first-order interaction pR. The conclusion from either approach is that the main effect of p (radial power distribution) is significant at the 99 per cent probability level.

This implies that the St–Re equations in Table 3 should each include a further term involving p to achieve the best possible fit. The existing equations provide a very good fit to the experimental data at the intermediate radial power distribution but result in a systematic difference from the measured temperatures at the extreme power distributions. Thus, the calculated temperatures are 1·0°C less than measured for the steep radial power distribution, and 1·0°C more than measured for the flat distribution. Even so the equations of column 2, Table 3 must be considered a very good fit to the experimental data. No other effect was significant even at the 90 per cent confidence level.

Referring now to the statistical analyses of the four cases for which the zone 4 friction factors were adjusted by multiplying factors of 1·2, 1·1, 0·9 and 0·8, it was again found that the effect of radial power distribution (p) was significant but was independent of the zonal multiplying factors used. However, it was now found that two other effects, those of z and the interaction zS, were also variously significant at the 95 per cent confidence level. In the whole of this statistical treatment significance is implied when the ratio of the "mean square" (for the effect being examined) to the relevant error variance is greater than that number defined by Fisher's [19] F test. The mean square itself is a measure of the magnitude of the differences between experimental and calculated temperatures. The magnitudes of the mean squares of z and zS for the cases considered have been plotted in Fig. 7. An effect of z alone significant implies that all the slopes of can temperature versus axial distance (z) as predicted by HOTSPOT are different from the experimental data to an equal extent for all surfaces (S). The interaction zS alone significant means that all slopes of can temperature with axial distance are different from HOTSPOT and are steeper or shallower depending upon the surface being examined but that the mean discrepancy in slopes is zero. The mean discrepancy in slopes is not zero when z and zS are together significant. These effects

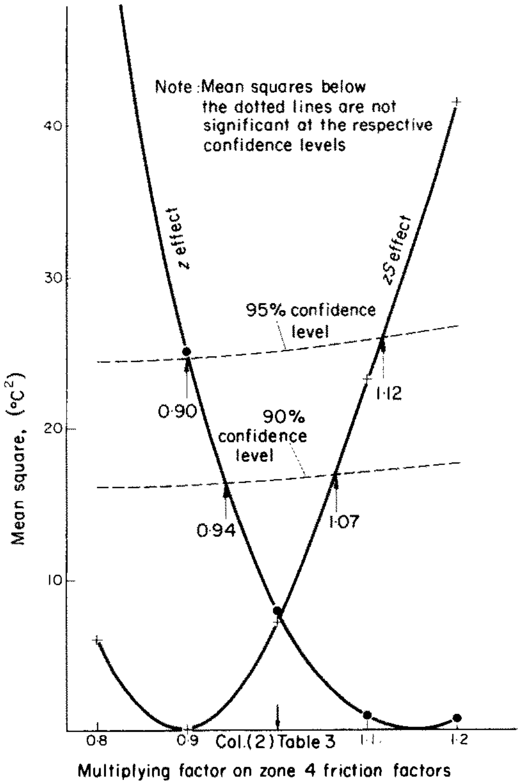


FIG. 7. Statistical analysis of influence of zone 4 friction factors.

are illustrated in Fig. 8. In Fig. 7 it is shown at the 95 per cent confidence level that neither z nor zS is significant for zone 4 friction factor multipliers between 0·90 and 1·12. Thus HOTSPOT maladjusted by any factor between these limits would provide a fit not significantly different from the data of column (2) Table 3 at the 95 per cent level. However, since the intersection of the z and zS curves in Fig. 7 is essentially coincident with the column (2) data it is clear that this represents the best of all fits to the experimental data. The necessity for the very large number of thermocouples and the attention to detail in all experimental measurements is illustrated by Fig. 7; an even

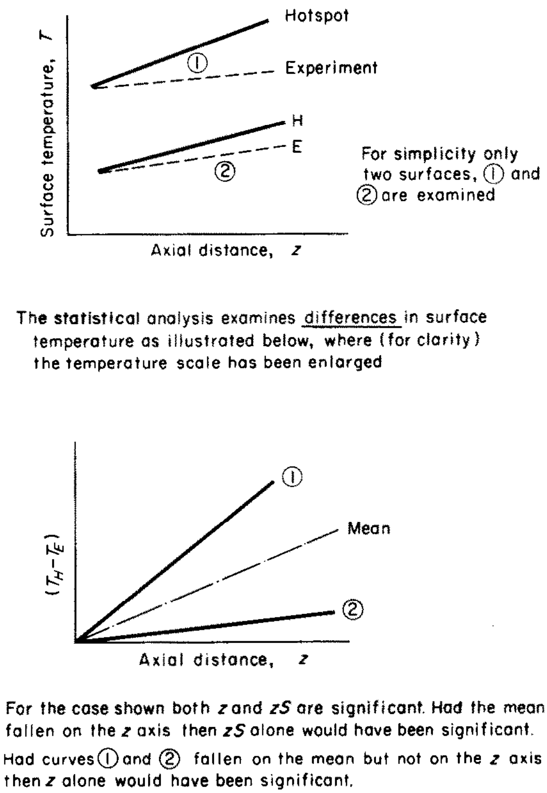


FIG. 8. Illustration of z and zS effects.

smaller experimental scatter would have brought the limits of significance closer together than the 0·90 and 1·12 found in the present analysis. With the results as they stand the acceptance band around the best fit is appreciably reduced as shown in Fig. 7 if the 90 per cent rather than 95 per cent confidence level is adopted.

DISCUSSION OF EMPIRICAL MODIFICATIONS TO HOTSPOT PROGRAMME

The statistical analysis has confirmed that the initial equations (column 1 of Table 3) would give axial trends in zonal temperatures clearly at odds with the observed slopes. It may nevertheless be suggested that as the initial equations contained empirical factors, a change from one set of factors to another calls for little comment. However, the initial equations were the culmination of an extensive series of investigations into the behaviour of rough and smooth surfaces and their interactions in annular and other simple channel shapes, and the extent to which they had to be modified raises the question of the feasibility of predicting cluster performance from more basic data. Moreover, if the transformation of all the single rod data was to be repeated with the correct radius of zero shear, the main effect would be to increase the rough surface friction factor and reduce the value for the smooth surface. An examination of these changes indicates that the empirical factors in column (1) of Table 3 would substantially be accounted for; therefore present knowledge of the location of the zero shear surface offers no explanation for the failure of the original equations to correlate the cluster measurements.

Other possible causes for the shortcomings of the original equations include momentum transfer between adjacent coolant zones, effects of passage shape, the adjustment to St in zone 4 to allow for the adiabatic boundary, and the fact that support features must to some extent distort the flow through the cluster. These possibilities will now be examined in turn.

Momentum transfer between zones turns out to be negligible according to either the theoretical estimate embodied in HOTSPOT or an alternative assessment derived by analogy from the empirical equation for the heat transfer between zones. Both estimates are tentative. However, for the purpose of this discussion of the cluster measurements, the fact which overrides the uncertainties is that zone 4 has the highest mean coolant velocity, some 9 per cent above zone 3, therefore momentum transfer would appear to be in the wrong direction to contribute to an explanation of the unexpectedly large flow rate in zone 4.

(Fig. 2). These distances, the corresponding local equivalent diameters, and, for comparison, the mean equivalent diameters for each zone, have been calculated for the high $\overline{Re}$ and are as follows:

Zone	Minimum distance to zero shear surface (in.)	Corresponding local equivalent diameter (in.)	Mean equivalent diameter for zone (in.)
2	0·262*	1·364	1·99
3	0·289*	1·548	2·15
4	0·273	1·440	2·21

* Taken as mid-way between rods.

With the rather broad sub-division of the cluster into only four flow zones and six heated surface regions the actual variations of passage width around the rod surfaces are ignored. Each segment of rod surface is taken to be surrounded by a uniform width annular flow region, and the circular zero shear boundaries of these annuli have been indicated on Fig. 2 to give an impression of the distortion involved. Ultimately HOTSPOT determines the first harmonics of the variations of surface and coolant temperature around each rod, thereby removing the step changes at zone boundaries, and discards the higher harmonics because they are sufficiently damped by circumferential diffusion to be ignored to a first approximation. A further consideration is that only the first harmonic produces thermal bow. A more complete treatment of the actual passage shapes would start with greater subdivision of the flow area and proceed to the determination of the locations of zero shear surfaces, local relative roughness (i.e. ratio of rib height to local equivalent diameter), friction factor, shear stress, Stanton number, heat transfer coefficient and so on, with allowance for circumferential diffusion in the coolant and rods.

Comments on the possible outcome of such an extended treatment are necessarily tentative. Minima in the distance from a rod to a surface of zero shear are found on the six radial lines which pass through the centre of three rods

There is apparently nothing in the above figures to mark out zone 4 as very different from the others. However, it is recollected only half of the rods in the intermediate ring were associated with the minimum distance to a zero shear surface (type B in Fig. 2) and they were found to operate significantly hotter than the type A rods in the same ring by an amount equivalent to 6 per cent lower. If the lower St for type B rods was taken as an indication of the effect of very unequal equivalent diameters around a rod surface, and it is observed that all the rod surface in zone 4 were subject to comparably large equivalent diameter variations, there would be a partial explanation of the low St in zone 4. A reduction in effective f in zone 4 would be expected for the same reason.

Another factor, significant only in zone 4, is the reduction in effective St to take account of the fact that heat flows beyond the surface of zero shear. The correction applied by HOTSPOT, based on the analysis of single rod tests, is a reduction in mean St for the zone of rather less than 4 per cent. However, a calculation of the distance of the zero shear surface from the radially outward point of an outer ring rod, leads to the conclusion that St for that point should be reduced by about 9 per cent. As that is the point of temperature measurement we have a further contribution, of up to 5 per cent, to the explanation of the low St in zone 4.

This brief discussion of passage shape effects has suggested the sources of a substantial part of the observed St (and to a smaller extent f) reduction in zone 4, but much more work would be required to substantiate and quantify the effects.

There remains the possibility that the blockage caused by the rod supports, unequally distributed across the flow area, might be a further factor in the unexpected behaviour of zone 4. The discussion will be confined to the four braces spaced at intervals of 35 in., along the test cluster. The pressure loss over a typical 35 in. length depends upon $(4fl/d + C)$ where C is the dimensionless brace pressure loss factor. For these braces, somewhat thickened by electrical insulation, C would be about 0·25 and $4fl/d$ is close to 1·59. With a low loss coefficient in zone 4, the zone flow rate would not be constant but would vary axially, being a maximum in the brace region and tending to decay to the normal cluster value at a distance from the brace. A simple calculation model divides a brace pitch length into two regions, a fraction δ of the length, including the brace, over which the zone 4 flow rate is enhanced by a constant factor, and the remainder $(1 - \delta)$ which has the fully-developed flow uninfluenced by the brace. The following table shows, for values of δ from zero to 1·0 and for C (zone 4) of 0·15 and 0·05, the enhanced mean velocity (u/u_∞) in the brace region and the reduced coolant temperature rise $(\Delta t/\Delta t_\infty)$ in zone 4.

Zone 4 C	0·15		0·05	
δ	$\frac{u}{u_\infty}$	$\frac{\Delta t}{\Delta t_\infty}$	$\frac{u}{u_\infty}$	$\frac{\Delta t}{\Delta t_\infty}$
1·0	1·03	0·97	1·06	0·94
0·50	1·05	0·975	1·11	0·95
0·25	1·09	0·98	1·205	0·96
0	1·29	1·0	2·25	1·00

The case $\delta = 0$ implies that the flow displacements into and out of zone 4 occur immediately before and after a brace; although the mass flow increase through the brace itself is very substantial, the extra flow does not remain in zone 4 over a finite distance and therefore does not affect the zone temperature rise (on the assumption, a considerable one, that the displaced flow enters and leaves zone 4 at the mean coolant temperature for that zone). Consider the case $\delta = 0{\cdot}5$ and C (zone 4) $= 0{\cdot}15$. If, as in the cluster experiment analysis, the coolant temperature rise is interpreted in terms of friction factor, the zone 4 f would be underestimated by 5 per cent. Moreover, if the rod temperature measurements are made outside the region of enhanced zone flow rate, a distinct possibility as the relevant thermocouples were 4·0 in. upstream of a brace whereas the disturbance is likely to be more prolonged downstream, the zone 4 St would be underestimated by 2·5 per cent. It cannot immediately be concluded that the brace disturbance is a substantial cause of the low f and St in zone 4, nor would further numerical speculation be profitable at this stage. The form and magnitude of support disturbances merit further investigation.

CONCLUDING REMARKS

Although a series of adjustments had to be made to fit HOTSPOT to the cluster results, the correction factors were relatively small, and can be at least partially understood. It is of interest to reflect on the value of the considerable effort expended on more basic experiments with simple configurations and on semi-theoretical developments in an attempt to establish a method for predicting cluster performance, in preference to a series of ad hoc cluster experiments.

Cluster experiments on the scale of the one described are very time consuming. It would have been unthinkable to try and explore a wide range of roughened surface configurations by means of a series of cluster experiments.

Moreover, as roughened surface heat transfer and friction data, obtained from single rod experiments, accumulated, there was a natural desire for a procedure which would enable them to be applied to exploratory cluster calculations. Indeed it was only as a result of such studies that ideas were clarified on the cluster configurations which would be of interest. Moreover cluster experiments as part of an ad hoc programme may be ill-defined. As discussed in relation to the concept of the present experiment, it is vital that the adequacy of an experiment to resolve the outstanding uncertainties be considered in advance, and it is doubtful whether this can be done unless the various factors that govern cluster performance have been identified and separately studied. Yet again, a laboratory cluster experiment cannot reproduce every detail of the conditions in a reactor channel; the situation must be analysed in sufficient detail to create an awareness of these differences, and to enable the relevant factors to be separately studied and allowances made for them. Finally, although the introduction of empirical factors means that HOTSPOT cannot be used with confidence for appreciably different cluster designs, some freedom of application can reasonably be assumed, immediately, for instance, to optimise the fuel rod pitch-circle diameters of this particular cluster for reactor conditions.

If a purely ad hoc approach is untenable, the danger of over-reliance on calculations based on theory and simple experiments also exists, and in particular the apparent power and comprehensiveness of computer calculations may lead to an unwarranted degree of confidence in the accuracy of the answers. The balance between definitive cluster experiments and more basic approaches is a matter for judgement, but there is a somewhat surprising lack of evidence of other comprehensive cluster experiments.

There is scope for a number of further investigations including:

(a) A fundamental re-examination of the treatment of heat transfer and friction data for mixed rough-smooth passages. It is likely that, even with a more accurate location of the surface of zero shear stress, the present transformation method has now reached the limit of its usefulness and will be superseded.

(b) The treatment of heat transfer and friction in the complex passage shapes occurring within clusters.

(c) Heat and momentum transfer between adjacent flow zones, covering a range of rod spacing, degree of roughness and helical as well as strictly transverse ribs.

(d) Detailed velocity distribution measurements as a direct check on the zonal flow distribution part of the HOTSPOT calculations, with an extension to determine the flow redistribution produced by typical fuel element supports.

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TRANSFERT THERMIQUE À CONVECTION FORCÉE POUR UN ÉCOULEMENT PARALLÈLE À TRAVERS UNE GRAPPE DE TIGES RUGUEUSES

Résumé—Pour des réacteurs performants refroidis par gaz, on souhaite disposer de méthodes pour estimer la distribution de température sur l'enveloppe de l'ensemble des éléments combustibles de façon très détaillée avec une précision maximum. La première partie de l'article décrit la formulation d'un procédé de calcul de température incorporé dans un programme de calculateur HOTSPOT. On se donne la distribution de puissance du canal combustible et le débit de flux refroidissant, puis par pas le long du canal on détermine la distribution de l'écoulement parmi les sous-canaux de l'ensemble, la température moyenne du réfrigérant dans chaque sous-canal, en tolérant des échanges thermiques entre les sous-canaux adjacents, et les différences de température locale l'enveloppe réfrigérant. La partie principale de l'article contient ensuite une description du montage, l'exécution et l'analyse d'une expérience qui teste le procédé de calcul. L'expérience est relative à une grappe de 36 tiges de 4,56 m de long avec une puissance de chauffage de 900 kW donnée par une résistance électrique, à distribution contrôlée et avec plus de 600 thermocouples installés de façon à déterminer la distribution de température.

Cet article est basé sur le travail mené au Reactor Development Laboratory U.K. Atomic Energy Authority, Windscale, Cumberland, Angleterre.

WÄRMEÜBERGANG BEI ERZWUNGENER KONVEKTION AN EINEM PARALLEL ANGESTRÖMTEN, RAUHEN STABBÜNDEL

Zusammenfassung—Für fortgeschrittene, gasgekühlte Reaktoren benötigt man Methoden, um die Temperaturverteilung über die Hülle der Bündelbrennelemente in allen Einzelheiten und mit grösster Genauigkeit berechnen zu können. Der erste Teil der Arbeit beschreibt die Formulierung eines Verfahrens für die Temperaturberechnung, das in ein Rechenprogramm HOTSPOT eingebaut ist. Die Verteilung der

Wärmestromdichte im Kanal und die Massenstromdichte des Kühlmittels werden vorgegeben, um dann stufenweise entlang des Kanals die Geschwindigkeitsverteilung in den Unterkanälen des Bündels, die mittlere Kühlmitteltemperatur in jedem Unterkanal mit Berücksichtigung des Wärmeaustausches zwischen den benachbarten Unterkanälen und die örtliche Temperaturdifferenz zwischen Hülle und Kühlmittel zu bestimmen. Der Hauptteil der Arbeit beschäftigt sich mit einer Beschreibung des Entwurfs, der Prüfung und Analyse eines umfangreicheren Versuchs zur Erprobung des Berechnungsverfahrens. Der Versuch wurde an einem 4·57 m langen Bündel mit 36 rauhen Stäben mit elektrischer Widerstandheizung von 900 KW, deren Verteilung geregelt werden konnte, durchgeführt. Zur Bestimmung der Temperaturverteilung waren über 600 Thermoelement eingebaut. Der Arbeit liegen Untersuchungen zugrunde, die am Reactor Development Laboratory, U.K. Atomic Energy Authority, Windscale, Cumberland, England durchgeführt wurden.

ПЕРЕНОС ТЕПЛА ПРИ ВЫНУЖДЕННОЙ КОНВЕКЦИИ В ПАРАЛЛЕЛЬНОМ ПОТОКЕ ЧЕРЕЗ ПУЧКИ ШЕРОХОВАТЫХ СТЕРЖНЕЙ

Аннотация—Для современных охлаждаемых газом реакторов требуются весьма подробные и максимально точные методы расчета распределения температуры по обшивке пучков топливных элементов. В первой части статьи описывается методика расчета температуры, включаемой в программу счетно—решающего устройства. Определялись распределение энергии по топливному каналу и скорость потока охладителя, а затем шаг за шагом вдоль канала проводились определения распределения потока вдоль пучков дополнительных каналов, средней температуры охладителя в каждом дополнительном канале с учетом теплообмена между смежными дополнительными каналами и разностей локальных температур обшивки и охладителя. Основная часть статьи содержит описание конструкций, исполнения и анализа основного эксперимента для опробования методики расчета. Для эксперимента использовался пучок из 36-ти шероховатых стержней длиной 15 фут. с электрическим сопротивлением нагрева 900 кбт, распределение которого можно было контролировать.

Более чем 600 термопар были установлены для определения распределения температуры.

Статья подготовлена по работе, выполненной в лаборатории реакторов общества по атомной энергии, Кумберленд, Англия.