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 Fuel Elements Using a Scalloped Coolant Channel
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Abstract

An analysis of the temperature structure in the GCR-2 fuel elements and coolant stream at the position where the maximum fuel element surface temperature exists was presented in a previous paper (ORNL CF 58-5-97). It was felt that the peripheral temperature variation existing on the fuel rods as brought out in that analysis was due mainly to the poor flow distribution of the coolant with respect to the heat flux. The most expedient way to alleviate this situation without changing the fuel element assembly itself is to scallop the channel so that it becomes, in effect, seven channels merged together to form a single passage. This geometry was studied by use of the IBM 704 digital computer in much the same way the earlier problems were investigated. Since the heat transfer coefficient depends much more strongly on free flow area than on equivalent diameter, the free flow area of the model reported on herein was made equal to that of the 3.25 in. circular channel so that a comparison of the results of the two configurations would be meaningful.

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NOMENCLATURE

c_p	specific heat of coolant
f	friction factor (as defined in McAdams' "Heat Transmission")
k	thermal conductivity of coolant
K	"total thermal conductivity" including the effects of eddy diffusivity
T	temperature
V	average coolant velocity
u	local axial velocity of coolant
w	rate of volume heat generation in fuel
y	distance from nearest solid boundary (except where used to denote coordinate system)
y_g	one half distance between two solid boundaries
μ	dynamic viscosity of coolant
ρ	density of coolant

I. INTRODUCTION

A previous paper (ORNL 58-5-97) indicated a large peripheral temperature variation in the GCR-2 fuel elements. The instability of the design due to the deflection of the rods resulting from this temperature variation was also established and it together with other shortcomings resulting from the non-uniformity in surface temperature leave much to be desired. The advantages of a septafoil configuration, such as high surface to volume ratio, short internal thermal path and ease of fabrication may be retained, however, if the channel is fluted and better guidance thereby imparted to the coolant. (See Fig. II)

To find the effect of scalloping the channel wall a study of a channel having a flow area equal to that of the 3.25 in. diameter channel studied before was initiated. The radius of the scallop was found by considering seven independent channels, each with one centrally located fuel rod, so that the annulus between the rod and channel wall represented $1/7$ of the flow area in Fig. I.

Figure I

Figure II

The seven channels were centered on the vertices and center of a regular hexagon and brought together until they merged. Then they were brought closer to each other until the flow area was once again equal to that of Fig. I.

II. METHOD OF ANALYSIS

The problem was solved as before by numerical methods utilizing a code written for the IBM 704 digital computer. In order to be consistent with former assumptions variables were given the same numerical values as in the previous analysis of the 3.25 in. dia. channel wherever possible. The equations solved were

$$\frac{\partial}{\partial x} \left[K(x,y) \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial y} \left[K(x,y) \frac{\partial T}{\partial y} \right] - \rho C_p u(x,y) \frac{\partial T}{\partial z} (x,y,z) = 0 \quad (1)$$

in the coolant and

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{w}{k_{UO_2}} = 0 \quad \text{in the fuel} \quad (2)$$

together with the boundary conditions that demanded continuity of heat flux across the fuel surface and no heat flux at the channel wall. Here x and y denote two orthogonal axes in the plane of Fig. II while z denotes the dimension normal to this plane.

Assuming that the eddy diffusivity for heat flow is equal to the eddy diffusivity of momentum and that the fluid velocity and its space derivative

depends on the distance a fluid particle is from the nearest wall according to the "universal velocity distribution" one finds that¹

$$K = k - c_p \mu + 0.4 c_p \sqrt{f/2} \rho V y (1 - \frac{y}{y_\delta}) \quad (3)$$

A space averaged value of K was used after K(x,y) was calculated for the fluid region, the numerical value used being the same as the one used in the circular channel study.

The velocity of the fluid was considered to behave as though the flow between solid boundaries was the same as in a long straight tube with the boundaries acting as the walls of the tube.² The expression used for determining the velocity of the fluid at any point was

$$u = 5.5V \sqrt{f/2} + 2.5V \sqrt{f/2} \ln \frac{\sqrt{f/2} \rho V y}{\mu} \quad (4)$$

The axial temperature gradient, $\partial T / \partial z$, in the coolant was assumed constant in x and y since it has been shown previously that a condition of thermal equilibrium exists at the axial position in question.³ Since Eq. 1 was solved at a particular axial location, $\partial T / \partial z (x,y,z)$ simply became a constant.

Equation 1 with the simplifications noted above was then

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} - \rho \frac{c_p}{K} \frac{\partial T}{\partial z} u(x,y) = 0 \quad (1')$$

III. DISCUSSION

Because of the large expenditure of time and money necessary to consummate calculations such as the one done, only one channel size was investigated. As mentioned before, the free flow area of the channel studied is the same as that of the 3.25 in. circular channel used in previous computations and so a comparison of the results obtained is made with that case.

From Fig. III the improvement in surface temperature structure wrought by scalloping the channel becomes evident. The variation of temperature on the surface of the outer rods in the circular channel is about 350°F whereas the variation for the case of the scalloped channel is only 250°F. Note that the "degrees" used in the abscissa of Fig. III is measured from axis A-B or A'-B' in Fig. I and II.

Two other advantages of a fluted channel over a circular channel can be surmised from the figure. One is that the average temperature of the fuel rod surface is appreciably lower in the "clover leaf" configuration. The other advantage (and perhaps most important of all) is that the maximum surface temperature on the rods in a scalloped channel is approximately 250°F less than in a circular channel of equal flow area for the same heat flux from the fuel.

Turning to a comparison of Fig. IV with Fig. V it should be pointed out that the values shown are not to be considered absolutely accurate. The many approximations necessitated by the available computer codes together with the simplifications required to solve the problem in finite time makes an exact analysis impossible. However, the trends that become manifest by a comparison of the two cases is believed valid. The tendency for the isotherms in the fluid to be more circular and follow the fuel rod surface in the fluted channel case is apparent and is consistent with expectation. Thus it is seen that the increased guidance afforded by the flutes around the outer rods increases the geometric symmetry of the configuration with the anticipated improvement in performance. The increased symmetry of the fuel element configuration is the property that should be

FIGURE III

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FIGURE IV TEMPERATURE DISTRIBUTION IN GCR-2 FUEL ELEMENTS AND COOLANT STREAM
HEAT FLUX.....18.0 BTU/FT SEC.
AVERAGE COOLANT TEMP.....858° F.
FUEL ELEMENT DIAMETER.....0.75"

FIGURE V. TEMPERATURE DISTRIBUTION IN GCR-2 FUEL ELEMENTS AND COOLANT STREAM
HEAT FLUX.....18.0 BTU/FT² SEC.
AVERAGE COOLANT TEMP.....858° F
CHANNEL DIAMETER..... 3.25"
FUEL ELEMENT DIAMETER.....0.75"

sought after. It may be accomplished by actually fluting the channel or inserting fluted graphite sleeves into circular channels.

Some mention has been made of using CO_2 as a coolant. Preliminary calculations show that a sleeve around the fuel element assembly will be essential for such a system to avoid reactions between the gas and the graphite moderator by having a by-pass flow on the outside of the sleeve (in this case the sleeve would be made of a ceramic material) to keep the moderator below about 850°F . Since a sleeve will be necessary in such a case, the additional advantage of fluting the flow passage can easily be attained.

IV. CONCLUSIONS

On the basis of the single calculation done, for a perhaps arbitrary choice of channel size, one may surmise the following for at least a limited range of channel sizes:

(1) Scalloping the channel leads to smaller temperature variation around the clad surface. (In this case the variation was about 250°F compared to approximately 350°F for the circular channel).

(2) Scalloping the channel lowers the maximum surface temperature realized. (Here the maximum surface temperature was decreased from almost 1500°F for the circular channel to about 1225°F for the fluted channel).

(3) Scalloping the channel results in lower average temperatures for the fuel elements with no change in heat flux. (In this case the average surface temperature was decreased by approximately 100°F by fluting the channel).

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3. L. G. Epel, Supplementary Comments to ORNL CF 58-5-97, ORNL CF 58-8-37, August 12, 1958.

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