10. S. Ergun, Fluid flow through packed columns, *Chem. Engng Prog.* **48**, 89–94 (1952).
11. G. Schneebeli, Experiences sur la limite de validite de la loi de Darcy et l'apparition de la turbulence dan un ecoulement de filtration, *Huille Blanche No. 2*, **10**, 141–149 (1955).
12. J. C. Ward, Turbulent flow in porous media, *Proc. Am. Soc. Civ. Engng No. HY5* **90**, 1–12 (1969).
13. S. Irmay, Theoretical models of flow through porous media, *R.I.LE.M. Symp. Transfer of Water in Porous Media*, Paris (1964).

Int. J. Heat Mass Transfer. Vol. 24, No. 4, pp. 768–770, 1981
Printed in Great Britain

0017-9310/81/040768-03 $02.00/0
Pergamon Press Ltd

THE EFFECT OF SUBCHANNEL SHAPE ON HEAT TRANSFER IN ROD BUNDLES WITH AXIAL FLOW

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(*Received* 12 *February* 1980 *and in revised form* 11 *July* 1980)

NOMENCLATURE

A, anisotropy factor, K_ψ/K_r, equation (1);
b, gap width between adjacent rods;
Cp, specific heat at constant pressure;
d, rod diameter;
de, subchannel equivalent diameter $= 4F/S$;
F, flow area of subchannel;
h, duct height, Fig. 1;
k, turbulence kinetic energy;
K_ψ, effective conductivity parallel to surface;
K_r, effective conductivity normal to surface;
p, rod pitch;
Q, heat transfer/unit length between adjacent subchannels;
Re, subchannel Reynolds number, $\rho Ude/\mu$;
S, wetted perimeter;
Stg, gap Stanton number, $Q/b(T_i - T_j)\rho UCp$;
T_i, T_j, bulk mean temperatures in adjacent subchannels, Fig. 1;
U, mean axial velocity;
y, normal distance from wall;
$\hat{y}$, normal distance from wall to surface of no-shear,
Y, mixing factor, equation (3).

Greek symbols

ε, dissipation of turbulence kinetic energy;
μ, dynamic viscosity, evaluated at bulk mean temperature;
ρ, density, evaluated at bulk mean temperature.

INTRODUCTION

IN THE rod bundle of a nuclear reactor the heat transfer across the narrow gaps between the fuel rods is considerably higher than predicted by isotropic turbulent diffusion theory, and is relatively independent of gap width [1]. Work repoorted earlier [1, 2] showed that these phenomena were caused by a substantial anisotropy of the effective conductivity: the value in the direction through the gap, parallel to the rod surface, was much higher than the value normal to the surface. Turbulence driven secondary flows were found to be unimportant.

Much of the experimental data on inter-subchannel heat transfer has been reduced to simple correlations by Rogers and Rosehart [3], and Ingesson and Hedberg [4], and these show that the heat transfer rate through the gaps is strongly influenced by the shape of the adjacent subchannels as characterized by the ratios p/d and p/de. To investigate the effect of subchannel shape on the inter-subchannel heat flow the earlier theoretical analysis [2] has been extended to predict gap Stanton numbers in ten different subchannel geometries for three of which experimental data is available [1].

The basic shape of the adjacent subchannels is shown in Fig. 1 together with the boundary conditions; details of the ten geometries are given in Table 1. For each geometry the adjacent subchannels remain symmetrical to one another. It should be noted that the geometries 1b, 2a and 3a simulate an infinite square array, and the experimental results were obtained for geometries 1b, 2b and 3b. All surfaces were smooth, the flow was fully developed both thermally and hydraulically, and the fluid was atmospheric air.

In the earlier work it was found that the measured velocity

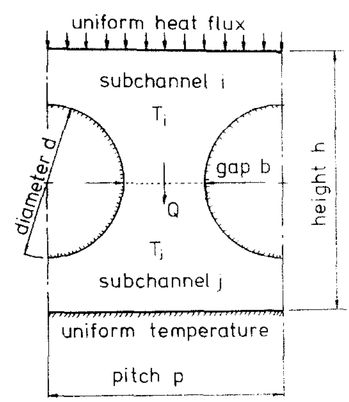

FIG. 1. Geometry investigated including thermal boundary conditions (all surfaces adiabatic except upper and lower flat walls).

Table 1. Shape parameters for the geometries investigated

Geometry	p/d	p/de	h/d
1a	1.1	1.40	1.66
1b*	1.1	2.03	1.37
1c	1.1	2.74	1.20
2a*	1.375	0.98	2.08
2b	1.375	1.2	1.8
2c	1.375	1.8	1.4
3a*	1.83	0.56	3.47
3b	1.83	0.74	2.75
3c	1.83	1.6	1.5
3d	1.83	2.17	1.2

*The equivalent diameter of this geometry is equal to that for the subchannels formed by rods in an infinite square array at the same pitch/diameter ratio.

and temperature distributions could only be reproduced if the effective diffusivity in the direction parallel to the rod surface was greater than the diffusivity in the direction normal to the surface by an anisotropy factor A; the normal diffusivity was computed using the '$k-\varepsilon$' turbulence model. The distribution of anisotropy which gave the best overall agreement with the experimental results was given by the expression:

$$A = 50\exp\{-(3y/\hat{y})^2\} + 2. \quad (1)$$

Although exact agreement was not achieved with this anisotropy distribution (see results in Tables 2 and 3) the comparisons were sufficiently close to show broad trends and it is believed that the extension of the analysis to a number of geometries which cover a wide range of shape parameters helps to clarify the effect of shape in the empirical correlations. The results have been expressed in the form of a gap Stanton number and are compared with the predictions of the correlations proposed by Rogers and Rosehart, and Ingesson and Hedberg.

COMPARISON WITH ROGERS AND ROSEHART

For adjacent subchannels having the same shape, and in the absence of flow disruption due to structural elements, the Rogers and Rosehart correlation for rods in a square array and geometries of the present form becomes:

$$Stg = 0.004\left(\frac{de}{b}\right)Re^{-0.1}. \quad (2)$$

The gap Stanton numbers given by this expression are compared in Table 2 with those computed. A striking feature of the comparison is the way the Stanton numbers given by equation (2) vary in the opposite direction from those computed as de/b is altered.

The parameter de/b in equation (2) reflected the influence of the experimental results of Rowe and Angle [5] who found the heat flow through the gap to remain virtually unchanged as the gap width was reduced by a factor of four: hence the form of the correlation $Stg \propto 1/b$.

The present results suggest that the Rogers and Rosehart correlation, equation (2), does not adequately represent the effect of subchannel shape.

COMPARISON WITH INGESSON AND HEDBERG

An alternative method for the prediction of inter-subchannel heat flow was proposed by Ingesson and Hedberg. An effective conductivity is calculated, using a turbulent Prandtl number, by assuming the diffusivity in the gap to be equal to the diffusivity in the central region of a circular tube having a diameter equal to the equivalent diameter of the subchannel. The temperature gradient through the gap is derived by assuming the bulk mean temperatures in the adjacent subchannels to act at the respective centroids of the subchannels. The heat transfer calculated in this way must then be multiplied by an empirical 'mixing factor' Y to give agreement with experiment. It was found that the following expression provided a fair correlation for a wide range of experimental data and could be used for any rod configuration:

$$Y = 0.95\left(\frac{p/d}{(p/d-1)}\right)^{1/2}\left(\frac{p}{d}\cdot\frac{p}{de}\right)^{3/2}. \quad (3)$$

This procedure has been applied to the ten geometries of the present work and the 'theoretical' gap Stanton numbers determined (i.e. before multiplication by the mixing factor). These were compared with the computed gap Stanton numbers and hence the mixing factor calculated. Computations were done both with isotropic diffusivities ($A = 1$) and with anisotropic diffusivities. The 'computed' mixing factors are compared in Table 3 with those given by equation (3).

Two conclusions can be drawn: the mixing factors predicted by equation (3) are high by a factor of two (a suggestion that the correlation was based upon results from rod bundles including the enhanced mixing due to the structural elements and imprecise location of the rods); secondly, the mixing factors computed with the anisotropic diffusivities are strongly dependent on the shape of the subchannel as characte-

Table 2. Comparison of gap Stanton numbers predicted by equation (2) with those computed and measured ($Re = 90000$)

		$Stg \times 10^4$		
Geometry	de/b	Equation (2)	Computed (anisotropic diffusivity)	Measured
1a	7.857	100.44	65.41	
1b	5.419	69.27	72.21	94.9
1c	4.015	51.32	84.19	
2a	3.741	47.82	49.70	
2b	3.056	39.07	57.32	53.8
2c	2.037	26.04	71.42	
3a	3.929	50.22	33.83	
3b	2.974	38.02	43.22	29.5
3c	1.375	17.58	85.20	
3d	1.014	12.96	114.63	

Table 3. Comparison of mixing factors Y: calculated from equation (3), computed and measured

Geometry	p/de	Computed: Isotropic diffusivities	Computed: Anisotropic diffusivities	Predicted equation (3)	Measured
1a	1.4	0.51	3.98	6.02	
1b	2.03	0.59	5.40	10.51	7.00
1c	2.74	0.71	7.55	16.49	
2a	0.98	0.51	1.80	2.85	
2b	1.2	0.55	2.34	3.83	2.17
2c	1.8	0.64	3.42	7.08	
3a	0.56	0.41	0.83	1.47	
3b	0.74	0.45	1.12	2.20	0.76
3c	1.6	0.90	2.72	7.08	
3d	2.17	1.29	4.04	11.18	

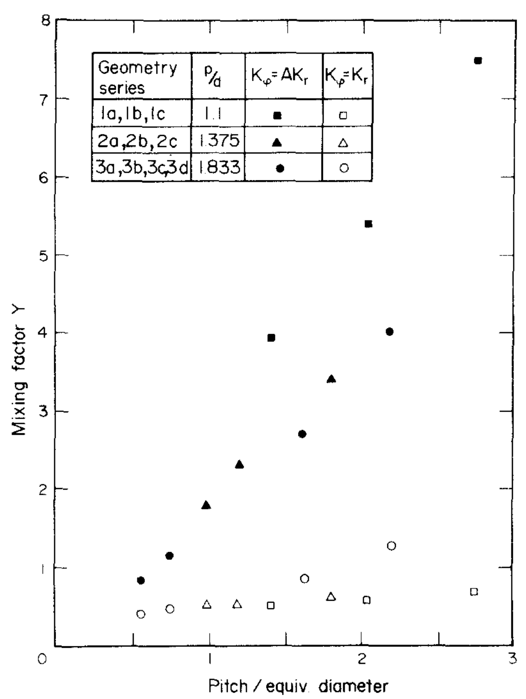

FIG. 2. Computed mixing factors (Y) with anisotropic effective diffusivity ($K_\psi = AK_r$) and isotropic diffusivity ($K_\psi = K_r$).

rized by p/de. This can be seen in Fig. 2.

Note that the mixing factors derived from the computations with isotropic diffusivity show only a weak dependence on p/de: the strong influence of subchannel shape on the mixing factor is a direct consequence of the anisotropy of the effective diffusivity.

For the computed results reported here secondary flows were suppressed. Computations were performed which included secondary flows (calculated using the model of Launder and Ying [6]) for both isotropic and anisotropic diffusivities, and although these increased gap Stanton numbers by 10–15% they did not significantly alter the results shown. In particular, the inclusion of secondary flows did not allow the effects of shape on heat flow to be reproduced.

CONCLUSIONS

The anisotropy distribution used for the computations presented here is tentative and the results are only indicative of trends. Nevertheless firm conclusions may be drawn about the effect of subchannel shape on inter-subchannel heat flow:

(i) The correlation, equation (2), proposed by Rogers and Rosehart is unlikely to predict correctly the effect of subchannel shape.

(ii) The prediction procedure of Ingesson and Hedberg and the results presented here show that the effect of subchannel shape appears to be characterized by the ratios p/de and p/d.

(iii) The strong influence of subchannel shape is a direct consequence of anisotropic effective diffusivities.

REFERENCES

1. W. J. Seale, Turbulent diffusion of heat between connected flow passages, Part 1. Outline of problem and experimental investigation, *Nucl. Engng Design* **54**, 183–195 (1979).
2. W. J. Seale, Turbulent diffusion of heat between connected flow passages, Part 2. Predictions using the '$k - \varepsilon$' turbulence model, *Nucl. Engng Design* **54**, 197–209 (1979).
3. J. T. Rogers and R. G. Rosehart, Mixing by turbulent interchange in fuel bundles — correlations and influences, ASME Paper 72-HT, 1–13 (1972).
4. L. Ingesson and S. Hedberg, Heat transfer between subchannels in a rod bundle, in *Fourth International Heat Transfer Conference*, Vol. 3, pp. 114–126, Paper FC7.11.
5. D. S. Rowe and C. W. Angle, Cross flow mixing between parallel flow channels during boiling, Part 2. Measurements of flow and enthalpy in two parallel channels, Report BNWL-371, Pt. 2 Battelle Northwest, Washington D.C. (1967).
6. B. E. Launder and W. M. Ying, Prediction of flow and heat transfer in ducts of square cross-section, *Proc. Inst. Mech. Engrs* **187**(37/73), 455–461 (1973).