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SHORTER COMMUNICATIONS

ON GAS MIXING IN ROD BUNDLES

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NOMENCLATURE

C_p, heat capacity;
D_h, hydraulic diameter;
p, pitch;
$\dot{q}'$ heat transfer per unit length;
St, Stanton number;
U, perimeter;
u, velocity;
u^*, friction velocity;
v', turbulence velocity;
Y, mixing factor;
α, heat transfer coefficient;
δ_{ij}, distance between centroids of subchannels i and j;
ε, eddy diffusivity;
ρ, density;
θ, temperature.

Subscripts
i, referring to subchannel i;
j, referring to subchannel j.

Superscript
$\bar{}$, mean value.

IN A RECENT paper in this journal Skinner, Freeman and Lyall [1] discussed the problem of heat mixing in a direction transverse to the flow direction for turbulent flow along rod bundles. They concluded that the mixing rate is much greater than can be explained by turbulent diffusion theory and attributed the large mixing to secondary flows within the subchannels of the bundle.

The problem has been studied for some time at the Studsvik laboratories and since our results partly support the conclusions of Skinner *et al.* [1], we would like to communicate them to the readers of the journal although our analysis is not completely finished.

The thermal calculation of gas- or steamcooled fuel elements for nuclear reactors is made in AB Atomenergi using the HECTIC-program devised by Kattchee and Reynolds [2].

In this program the heat transfer per unit length $\dot{q}'_{ij}$ between two subchannels i and j is calculated according to

$$\dot{q}'_{ij} = \rho c_p \varepsilon_{ij} \frac{\bar{\theta}_i - \bar{\theta}_j}{\delta_{ij}} \cdot U_{ij} \cdot Y \tag{1}$$

where ε_{ij} is the effective diffusivity, $\bar{\theta}_i$ and $\bar{\theta}_j$ the mean temperatures of the subchannels, δ_{ij} the distance between the centroids of the subchannels measured perpendicular to the common interface, which has the perimeter U_{ij}. Y is a "mixing factor" which will be discussed later.

The effective diffusivity is calculated by the expression

$$\varepsilon_{ij} = \tfrac{1}{2} \; \overline{(D_h \cdot u^*)}_{ij} \tag{2}$$

This relation for the diffusivity is, like that of Rapier [3] based on data for simple channels. For circular channels in fact the expressions yield the same result.

The mixing factor, Y, in equation (1) was included to allow greater flexibility in the use of the program, and to make it possible to use the program also if the assumptions made in the mixing theory should turn out to be incorrect, so that either the diffusivity cannot be calculated from equation (2) or the effective temperature gradient cannot be calculated from $(\bar{\theta}_i - \bar{\theta}_j)/\delta_{ij}$.

The present work comprised a compilation of the available literature data and an experimental study.

The experiments were made in two channels, the cross-sections of which are shown in Fig. 1. The inner surface was heated with an approximately constant heat flux. The outer surface was kept approximately at constant temperature by means of a water jacket with a large mass flow. The working medium was air at slightly above atmospheric pressure.

By measuring the air temperature at the inlet to the channel and the detailed velocity and temperature distributions at the outlet from the channel (after a length of 8 m) it was possible to calculate the gap heat-transfer coefficient, α_{ij}, assuming this to be constant along the channel.

Comparison with the theoretical value of Kattchee and

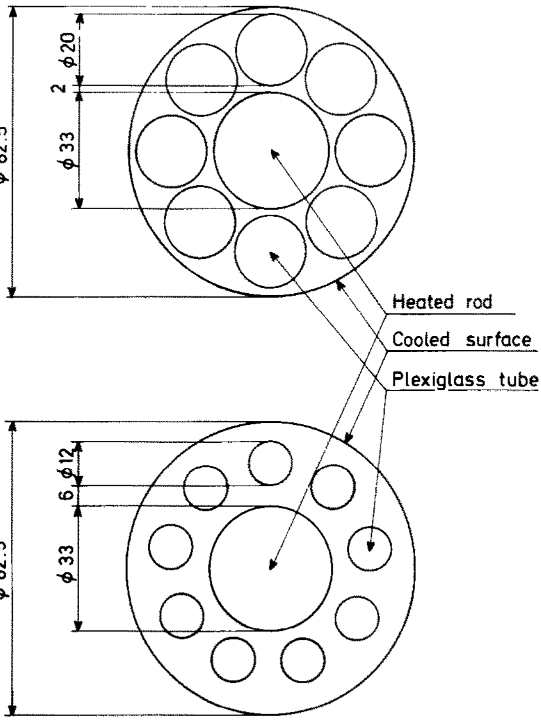

FIG. 1.

Reynolds [2] namely

$$\alpha_{ij} = \rho c_p \varepsilon_{ij}/\delta_{ij} \cdot Y \tag{3}$$

allowed calculation of the mixing-factor, Y.

Mixing-factors were also calculated from different sources in the literature. The results plotted against a geometrical parameter namely the pitch to hydraulic diameter ratio, p/D_h, are shown in Fig. 2. The regression line is given by

$$Y = 7{\cdot}75\, p/D_h - 5{\cdot}77\,. \tag{4}$$

Apparently, as p/D_h increases, a condition corresponding to narrower rod clusters, the mixing factor increases considerably above unity.

This is in agreement with the results of Skinner *et al* [1], but it does not necessarily mean that the high mixing rates cannot be explained by turbulent diffusion theory.

The large values observed for Y can be explained either by an underestimation of the turbulent diffusivity in equation (2), by an underestimation of the effective temperature gradient, by net cross-flows between the subchannels or by the secondary flows suggested by Skinner *et al.* [1].

It has not been proved that the last explanation is correct. The fact that the measurements of Skinner *et al.* [1] indicated the presence of crossflows in a direction opposite to that found by Nikuradse [4] justifies a discussion of the existence of these secondary flows. Finally, it is easy to show that the results obtained by the secondary flow model of Skinner *et al.* [1] can also be obtained by a turbulent diffusion model.

Consider two subchannels i and j with mean temperatures $\bar{\theta}_i$ and $\bar{\theta}_j$. The mean transverse turbulence velocity in the gap is v' and the average temperatures of the fluid bodies carried from the two subchannels are θ_i' and θ_j' respectively.

The gap Stanton number will then be

$$St_g = \frac{v'}{u} \cdot \frac{\theta_i' - \theta_j'}{\bar{\theta}_i - \bar{\theta}_j}\,. \tag{5}$$

Skinner *et al.* [1] apparently assume that the secondary flow velocity is about one third of the transverse fluctuation velocity. Their equation for the gap Stanton number may therefore be written

$$St_g = \frac{v'}{12\bar{u}}\,. \tag{6}$$

Equation (5) will give exactly the same result if it is assumed that $(\theta'_i - \theta'_j) = \frac{1}{12}(\bar{\theta}_i - \bar{\theta}_j)$, which means that the effective mixing length is much smaller than the distance between the centers of the subchannels. Without experimental evidence to check the assumptions this particular assumption is as valid as any other since in the end it leads to reasonable results.

Accordingly, although the mixing is much larger than was first expected, we conclude that this does not rule out

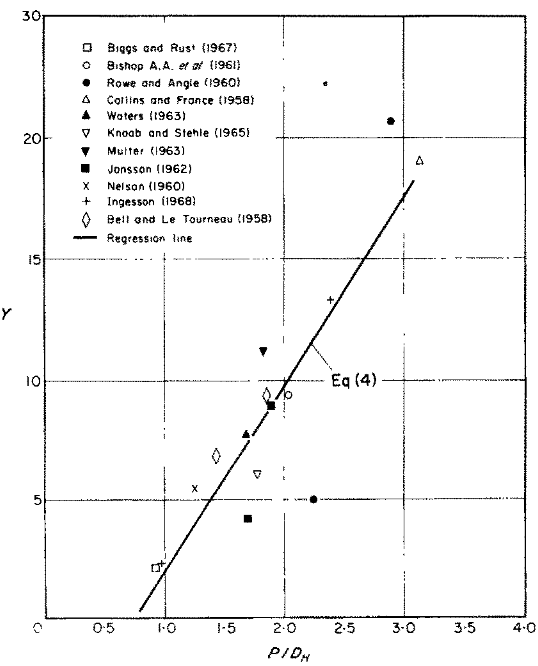

FIG. 2.

turbulent diffusion as being responsible for the main part of the transport.

Finally it should be pointed out that the decrease of v'/u^* at high Reynolds numbers found by Kjellström and Hedberg [5] is probably due to errors in the evaluation of the turbulent data. Later experience (see Kjellström and Hedberg [6]) indicates that the variations both of the exponent c in Collis' law and the direction sensitivity coefficient k^2 as functions of velocity must be considered in the evaluation. This was not done in the earlier measurements of these authors referred to by Skinner *et al.* [1].

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RELAMINARIZATION IN TUBES

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NOMENCLATURE

a, d, temperature dependence exponents for viscosity and specific heat, respectively; e.g. $\mu/\mu_i = (T/T_i)^a$;
G, mass flow velocity, $4\dot{m}/\pi D^2$;
H, enthalpy.

Nondimensional parameters and variables

$\bar{c}_p$, specific heat, $c_{p,b}/c_{p,i}$;
Q^+, local heat flux parameter, $q''_w D/(2k_b T_b)$;
q^+, heat flux parameter, $q''_w/(Gc_{p,i}T_i)$;
Re, Reynolds number, $4\dot{m}/(\pi D\mu)$;
$\bar{T}_b$, bulk static temperature, T_b/T_i;
$\bar{\mu}$, viscosity, μ_b/μ_i.

Subscripts

b, evaluated at bulk static temperature;
i, initial, inlet;
0, stagnation conditions;
trans, transition;
w, wall, heat transfer surface;
∞, free stream.

The absence of a subscript on gas properties indicates properties evaluated at gas bulk static temperature.

In recent years the transition from turbulent to laminar behavior has become a topic of interest in consideration of accelerated flows, as found in rocket nozzles, and of duct flows such as the heating channels of proposed nuclear rocket engines. For gaseous circular tube flow evidence of this effect appears in the early work of Humble *et al.* [1] and of Barnes [2]. An effect of such transition is shown in Fig. 1 which presents typical wall temperature data of Coon [3]. Predictions based on accepted constant and variable properties, turbulent flow correlations are shown for comparison. The transition causes a dangerous increase in wall temperature. In this note, recent work is discussed briefly, and the relationship between the transition for internal heat flows and for "external" accelerated flows is presented.

Independently, around 1963, Moretti and Kays [4], Launder [5] and McEligot [6] began to detail this transition process in a variable geometry duct, in a nozzle and in heated tubes, respectively. While it is likely that the process is a continuous one rather than a "critical" one, i.e. instantaneous change from one flow to the other, it is useful to

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