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TECHNICAL NOTE

Spectral measurements and mixing correlation in simulated rod bundle subchannels

X. Wu and A. C. Trupp

Department of Mechanical and Industrial Engineering, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2

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1. INTRODUCTION

Nuclear reactor fuel channels generally consist of a cluster of fuel rods arranged in a flow tube with the coolant moving axially through the subchannels formed between neighbouring fuel rods and between the peripheral fuel rods and the flow tube. The necessity to predict the bulk coolant temperature distribution among the various subchannels of the fuel bundle in reactor core design requires information on coolant mixing rates between the various homogeneous and heterogeneous subchannels. Under normal operating conditions consisting of fully developed turbulent flow, three different mechanisms contribute to the overall mixing process; namely, turbulent diffusion, turbulent convection and convection by mean motion. Turbulent diffusion is of conventional gradient-type and is caused by small-scale turbulence of the order of magnitude of the dissipation scale. Turbulence convection originates from the large-scale motions of eddies comparable in size to the geometric characteristic length and is of non-gradient-type. Convection by mean motion denotes the transport by secondary flow of the second kind which in turn is caused by non-uniformities in wall turbulence and appear in channels which do not possess axial symmetry. The combined effect of these individual transport phenomena markedly modifies the temperature and velocity fields on the fuel channel transversal plane and hence influences the subchannel mixing process. In recent years, more and more evidence has been accumulated to partially identify the turbulent convection mechanism† for subchannel mixing. This mechanism seems to entail an energetic and almost periodic flow pulsation (eddy crossings) through the gaps between rods and the gaps between rods and walls. This mechanism is described next.

Rowe *et al.* [1] were the first to systematically study the influence of macroscopic turbulence structure on the mixing processes in rod bundle subchannels. One of their conclusions drawn from the LDA measurements was that macroscopic flow processes exist adjacent to the rod gap region, including secondary flow and flow pulsation characterized by increased scale and dominant frequency with decreasing rod gap spacing. Hooper and Rehme [2] stressed the presence of an energetic large-scale and almost periodic momentum exchange process through rod-to-rod and rod-to-wall gaps through hot-wire cross-correlation measurements. Both the axial and azimuthal turbulent velocity components were found to be significantly correlated for a considerable distance from the gap between rods. The cyclic momentum exchange process generated by a pulsating flow between adjacent subchannels was claimed to be responsible for the increased levels of axial and azimuthal turbulence intensities in the open gap areas of rod bundle flow. Möller [3, 4] investigated the macroscopic flow pulsations using the same wall-bounded rod array as Hooper and Rehme [2]. Data via hot-wire measurements were evaluated to obtain energy spectra as well as autocorrelations and cross correlations. The dominant frequency of the flow pulsation was found to be a function of gap spacing and Reynolds number. Strong flow pulsations were found to persist for a rod gap with g/d as low as 0.007. This work was recently further analyzed by Rehme [5] and a simple correlation between mixing factor and g/d was developed and claimed to be applicable for any subchannel geometry.

Extensive turbulence structure studies via hot-wire measurements for fully developed turbulent flow through simulated rod bundle subchannels formed by a rod enclosed by a trapezoidal duct were reported by Wu and Trupp [6]. The reported experimental evidence defined an atypical character of turbulent flow structure in the simulated rod bundle. The abnormality of this flow was represented by a gap-size dependent, large-scale cross-gap eddy motion whose existence was first suggested by Rowe *et al.* [1] and later identified by Hooper and Rehme [2]. The experimental findings confirmed the universality of this phenomenon in the sense of its weak subchannel shape dependence, as claimed by Rowe *et al.* [1]. More importantly, the occurrence, augmentation and disappearance of the high k patch with the variation of gap size reported in ref. [6] settled an outstanding issue for one special case (rod–trapezoidal duct), as quoted by Rehme [5], that no information is available on the critical gap to diameter ratio below which the mixing rate decreases.

As a continuation of the turbulence structure studies described in ref. [6], this paper reports the further experimental work on power spectral measurements for fully developed turbulent flow through the simulated rod bundle. Following the approaches of Möller [4] and Rehme [5], this study was aimed at revealing the dependence of the dominant frequency of cross-gap eddy motion on flow and geometrical conditions and the implications of this cyclic motion on subchannel mixing. As stated, the simulated rod bundle subchannels were formed by a rod–trapezoidal duct. Six rod settings were chosen in the spectrum studies, with two different Reynolds number for each rod orientation. The geometric characters of the twelve test cases, together with Reynolds numbers and friction velocities, are tabulated in Table 1, where they are categorized into two groups according to the presence or absence of symmetry of the rod with respect to the duct vertical axis. Power spectral data were obtained

†From a Reynolds (momentum) equation viewpoint, this mechanism can also be considered as enhancement of turbulent diffusion via anisotropy.

NOMENCLATURE

B	bandwidth of digitalization
d	rod diameter
$E_{v'^2_{az}}$	energy-density spectrum of azimuthal component
f	frequency in energy spectrum
f_p	peak frequency in energy spectrum
f^*	friction coefficient, $2\mathrm{d}p/\mathrm{d}xD_h/(\rho\bar{V}^2)$
g	gap spacing
k	mean turbulence kinetic energy, $(v_z'^2+v_x'^2+v_y'^2)/2$
m'_{ij}	mass flow rate between subchannels i and j
q_{ij}	heat transport between subchannels i and j
Re	Reynolds number (based on average axial velocity)
Str	Strouhal number, $f_p d/v^*$
T_i, T_j	bulk temperatures of two adjacent subchannels
v^*	average friction velocity derived from pressure drop
w_{eff}	effective mean mixing velocity
Y	mixing factor.

for axial and azimuthal fluctuating velocities via a Krohn-Hite Model 3700 band-pass filter (cutoff frequency accuracy of 5%). Experimental errors associated with the power spectral densities were about $\pm 16\%$. For measurements conducted in the left-side gaps, the X-wire probe was oriented perpendicular to the gap centre line between the duct wall and rod surface; this orientation facilitated the collection of azimuthal turbulent velocity power spectral information. Further details on the equipment and measurement techniques can be found in refs. [6, 7].

2. RESULTS OF POWER SPECTRAL DENSITY

Typical power spectral density results for the azimuthal component of turbulent fluctuating velocity are presented in Fig. 1 in log–linear form for cases a2 and d2. In Fig. 1(a) (symmetric gap), the strong peak of $fE_{v'^2_{az}}(f)$ in the bottom gap is centered around 65 Hz (a relatively low frequency), whereas the weak peak at the higher frequency of about 1000 Hz which appears in the spectrum for the top gap is typical of the behaviour of wall turbulence (Bremhorst and Walker [8]). It is known that a peak in a spectrum (frequency domain) reflects the presence of a strong periodic component. Therefore, for the bottom gap, it seems reasonable to speculate that the physical picture behind this is a strong energy-containing large eddy motion along the azimuthal direction through the small rod-to-wall gap which interchanges its energy with the axial component as it moves to the subchannel central area, maintaining the same characteristic frequency. Figure 1(b) gives the azimuthal spectra data for the asymmetric setting case d2 (same bottom gap size 4.0 mm as in case a2). In the bottom gap area, the high peak of $fE_{v'^2_{az}}(f)$ centres around 69 Hz which is close to the 65 Hz found in symmetric setting case a2. However, for the left-side gap which also has the same gap size as case a2 (4.0 mm), the peak frequency is only 33 Hz. The difference in peak frequency suggests that while the phenomenon of large-scale cross-gap eddy motion is universal in the sense of subchannel shape as suggested by Rowe *et al.* [1] and Rehme [5], the periodicity of the cyclic eddy motion is subchannel geometry dependent. An important observation can also be made by comparing the two cases in Fig. 1. In the symmetric setting case (Fig. 1(a)), the $fE_{v'^2_x}/v^{*2}-f$ plot does not bear a visible peak in the lower frequency range for the top gap, implying the absence of large-scale cyclic eddy motion. On the other hand, in the asymmetric setting case such eddy

Table 1: Experimental conditions for spectrum analysis

Case	g_{bottom} (mm)	g_{bottom}/d	v^* (m s^{-1})	Re
		Symmetric setting		
a1	4.0	0.079	1.24	52 700
a2	4.0	0.079	0.55	21 300
b1	3.0	0.059	1.21	52 000
b2	3.0	0.059	0.64	26 000
c1	2.0	0.039	1.20	52 000
c2	2.0	0.039	0.63	26 000
		Asymmetric setting†		
d1	4.0	0.079	1.18	52 000
d2	4.0	0.079	0.64	26 300
e1	3.0	0.059	1.16	52 000
e2	3.0	0.059	0.61	26 000
f1	2.0	0.039	1.12	52 000
f2	2.0	0.039	0.59	26 000

† Set such that $g_{bottom} = g_{left\text{-}side}$.

motion through the top gap is clearly shown in Fig. 1(b) (peak frequency at 34 Hz). In the top gap region, experimental data consistently showed the existence of eddy motion in the asymmetric rod setting cases with little indication of such motion in symmetric rod setting cases.

So far, it is fairly certain that the coherent cross-gap eddy motion contributes significantly to the enhancement of transport by turbulence convection and it probably also influences the local turbulence production. What remains unclear is the precise description of the periodicity of such eddy motion in terms of the known quantities and the proportion of contribution to the total kinetic energy by the eddy motion characterized by the peak frequency. Hooper and Rehme [2] first suggested that the dominant frequency varies linearly with Reynolds number based on the mean subchannel velocity and the hydraulic diameter of the subchannel. Möller [3] found that peak frequencies could be correlated in terms of Strouhal number ($Str = f_p d/v^*$) and nondimensional gap size, as follows:

$$Str^{-1} = \left(\frac{f_p d}{v^*}\right)^{-1} = 0.808 g/d + 0.056. \quad (1)$$

Deviations as high as 15% occurred when equation (1) was used to correlate the data of Möller [3]. Figure 2 offers graphical comparison of the present data with Möller's correlation equation (1), excluding results from left-side gaps. The present data offer a correlation which has the approximate same slope as equation (1) but a higher intercept,

$$Str^{-1} = \left(\frac{f_p d}{v^*}\right)^{-1} = 0.822 g/d + 0.144. \quad (2)$$

This difference emphasizes the fact that, although the existence of large-scale cross-gap eddy motion has weak subchannel shape dependence, the quantitative description of such motion is still subchannel geometry dependent.

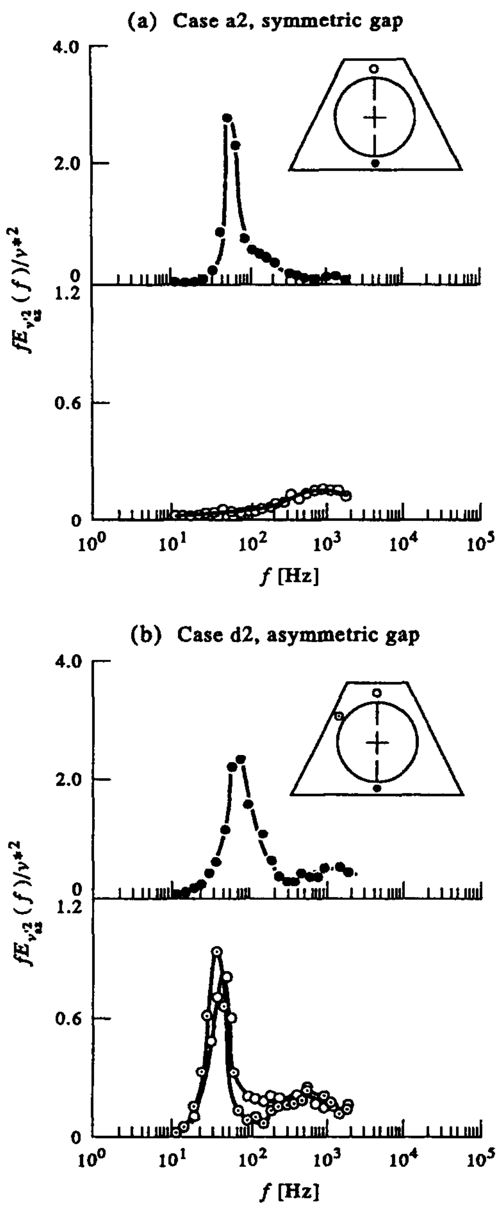

FIG. 1. Linear–log energy density spectra of azimuthal velocity component. (a) Case a2, symmetric gap. (b) Case d2, asymmetric gap.

3. MIXING CORRELATIONS

Admitting that the large-scale cross-gap eddy motion is one of the main mechanisms in the rod bundle subchannel mixing process, and perhaps the dominant one for a range of medium-small gaps, it becomes important to derive a semi-empirical quantative description about the mixing process based on the previous experimental information on power spectral densities. In doing so, the approach of Möller [4] and Rehme [5] was followed.

Assuming T_i and T_j are the bulk temperatures of two adjacent subchannels i and j, the heat transported through the gap per unit length by the effective subchannel mixing mechanism is

$$q_{ij} = m'_{ij} c_p (T_i - T_j) \quad (3)$$

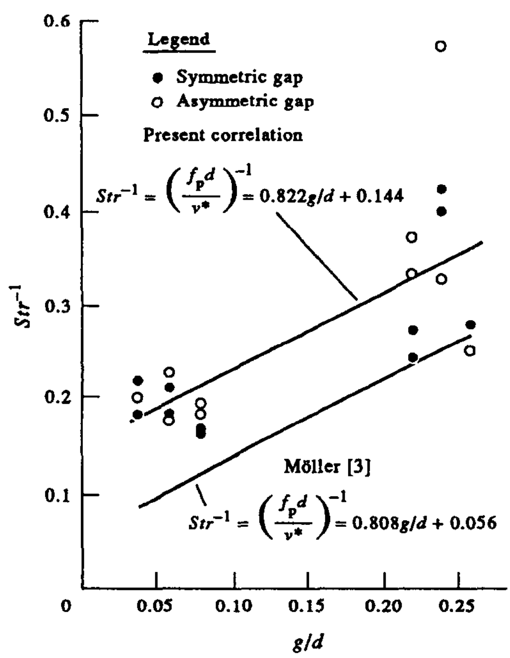

FIG. 2. Correlation of Strouhal number and nondimensional gap size.

where m'_{ij} is the instantaneous mass flow rate per unit length between subchannels i and j and can be expressed as

$$m'_{ij} = \rho w_{\mathrm{eff}} g \tag{4}$$

where w_{eff} is the effective mean mixing velocity. (It should be noted for homogeneous subchannels that $\overline{m'_{ij}} = 0$.) Based on the occurrence and disappearance of the high turbulence kinetic energy patch with the variation of g/d as reported by Wu and Trupp [6], it is judged that turbulence convection, manifested as periodic cross-gap eddy motion, is the dominant mixing mechanism in the following gap range (at least applicable for rod–trapezoidal duct)

$$0.020 \leqslant g/d \leqslant 0.100. \tag{5}$$

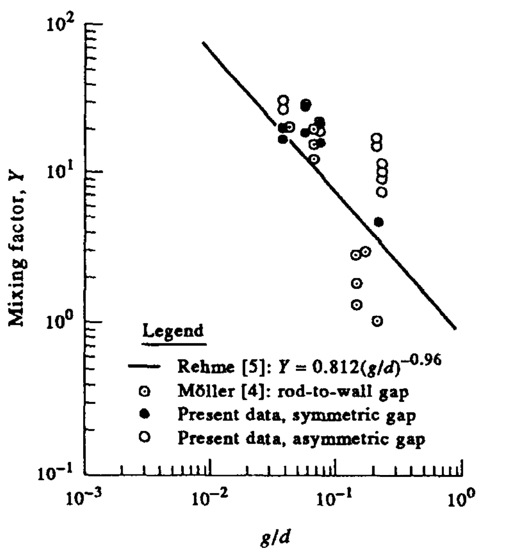

FIG. 3. Correlation of mixing factor and nondimensional gap size.

Since such cross-gap eddy motion is characterized by a peak in the spectral density function of azimuthal turbulence velocity, it is possible to express the effective mixing velocity in terms of the spectral data. Möller [4] calculated the mixing velocity w_{eff} to be

$$w_{\mathrm{eff}} = \sqrt{(E_{v'^2_{\mathrm{az}}}(f)B)} \tag{6}$$

where $E_{v'^2}(f)$ is the power spectral density of the azimuthal fluctuating velocity in the gap centre and B is the bandwidth of the digitalization. Equation (6) implies that only the bandwidth of the peak frequency contributes to the mixing velocity. As pointed out by Rehme [5], such handling is doubtful since the cross-gap eddy motions are not caused by large-scale eddies of one size at a certain frequency but by a spectrum of eddies of different sizes. In this research, following Rehme's suggestion [5], the mixing velocity is defined as

$$w_{\mathrm{eff}} = \sqrt{\left(\int_{f_p - f_p/4}^{f_p + f_p/4} E_{v'^2_{\mathrm{az}}}(f)\,\mathrm{d}f\right)}. \tag{7}$$

In order to facilitate comparison among different mixing results, Möller [4] followed the definition of intersubchannel heat mixing proposed by Ingesson and Hedberg [9],

$$q_{ij} = \rho c_p g(\bar{\varepsilon} Y)\frac{T_i - T_j}{\delta_{ij}} \tag{8}$$

where δ_{ij} is the mixing distance which is assumed to be the centroid distance between the subchannels i and j, and the mixing factor Y accounts for the increase of the effective viscosity compared to the reference eddy viscosity $\bar{\varepsilon}$ which is often taken as the mean value of pipe flow

$$\bar{\varepsilon} = \nu \frac{Re}{20}\sqrt{\left(\frac{f^*}{8}\right)}. \tag{9}$$

Table 2. Summary of mixing velocity and mixing factor (Re = 52 000)

Case	Gap	g/d	δ_{ij}	w_{eff} (m s^{-1})	$Y = w_{\mathrm{eff}}\delta_{ij}/\bar{\varepsilon}$	Equation (11)
			Symmetric gaps			
a1	bottom	0.078	0.090	0.34	15.4	9.40
a1	top	0.220	0.042	0.22	4.6	3.47
a2	bottom	0.078	0.090	0.46	20.7	9.40
b1	bottom	0.059	0.096	0.38	18.2	12.29
b2	bottom	0.059	0.096	0.56	27.6	12.29
c1	bottom	0.039	0.098	0.33	16.4	18.29
c2	bottom	0.039	0.098	0.40	19.4	18.29
			Asymmetric gaps			
d1	bottom	0.078	0.087	0.49	21.2	9.40
d1	top	0.220	0.038	0.77	14.6	3.47
d2	bottom	0.078	0.087	0.42	18.3	9.40
d2	top	0.220	0.038	0.87	16.5	3.47
e1	bottom	0.059	0.085	0.65	27.6	12.29
e1	top	0.240	0.037	0.53	9.9	3.20
e2	bottom	0.059	0.085	0.67	28.5	12.29
e2	top	0.240	0.037	0.61	7.6	3.20
f1	bottom	0.039	0.083	0.73	30.3	18.29
f1	top	0.240	0.036	0.50	9.0	2.96
f2	bottom	0.039	0.083	0.64	26.4	18.29
f2	top	0.240	0.036	0.41	7.3	2.96

A comparison between equations (3) and (8) gives the expression of mixing factor in terms of mixing velocity

$$Y = \frac{w_{eff}\delta_{ij}}{\bar{\varepsilon}}. \tag{10}$$

Rehme [5] recently proposed a correlation between mixing factor Y and nondimensional gap size g/d,

$$Y = 0.812(g/d)^{-0.96}, \tag{11}$$

universal in subchannel shape.

It is noted that the mixing factor Y in equation (11) was multiplied by a factor 0.85 to account for a profile of the mixing velocity. Figure 3 compares the present symmetric and asymmetric gap mixing factors (see Table 2) with those predicted by equation (11). All data were converted to a single Reynolds number ($Re = 52\,000$) assuming that w_{eff} is proportional to $Re^{0.9}$ as employed by Rehme [5]. For all the rod settings, the four subchannel centroids were defined as the intersections between the MVL (maximum mean axial velocity line) and the lines connecting the rod centre and the duct corners. The distance between adjacent subchannel centres was then taken as the MVL length connecting the two centroids. It is apparent that the present mixing velocity data for symmetric gaps offer an excellent comparison with Rehme's correlation, while those for asymmetric gaps are constantly higher than predicted by equation (11). From a mass conservation point of view, secondary flow in the flow passage cross-section formed by heterogeneous subchannels need not necessarily be confined within individual subchannels. In fact, preliminary numerical results [7] have indicated cross-gap secondary flows for the present asymmetric cases. Certainly additional numerical study is needed, and attempts should also be made to experimentally confirm the existence of cross-gap secondary flow. Nonetheless, such possible cross-gap secondary flow would inevitably enhance the exchange between adjacent asymmetric subchannels, thereby causing higher mixing factors.

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