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MEASUREMENT AND PREDICTION OF THE MEAN AND FLUCTUATING TEMPERATURE FIELD DOWNSTREAM OF A MULTI-BORE JET BLOCK IN WHICH ONE JET IS HEATED

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Abstract — Measurements were performed in water of mean and fluctuating velocity and temperature fields downstream of a multi-bore jet block which was designed to simulate flow obtained in nuclear reactor subassemblies. Power laws similar to those in grid turbulence were found to describe the decay of the fluctuating field and the growth of the length scales but significantly different exponents were obtained due to the nonisotropy produced in the jet block. A gradient diffusion model with a streamwise varying eddy diffusion coefficient was found to give excellent predictions of mean temperature profiles. Distributions of temperature fluctuation intensities were predicted with the transport equation for this scalar. Agreement between measurement and prediction was obtained by use of identical eddy diffusivities for the production and diffusion of the temperature fluctuations.

NOMENCLATURE

a, eddy diffusivity of δ [$mm^2 s^{-1}$];
A^*, proportionality factor, equation (6) [$mm^{3-n} s^{-1}$];
B, factor relating dissipation of δ and the mean square of δ [$m s^{-1}$];
d, diameter of bores in jet block [mm];
D, diameter of containment pipe [mm];
k_1, k_2, constants of proportionality;
L_f, Eulerian streamwise integral length scale [mm];
L_L, Lagrangian integral length scale [mm];
M, pitch between the bores [mm];
n, exponent in power law for turbulent diffusivity, equation (6);
Pr, Prandtl number;
q^2, twice the instantaneous turbulent energy $= u_i u_i$ [$m^2 s^{-2}$];
r, radial coordinate [mm];
R, time-scale ratio relating dissipation of velocity and scalar fluctuations;
S, volume flow of heated jet [$mm^3 s^{-1}$];
T, instantaneous temperature $= \bar{T} + \delta$;
$\bar{T}$, local mean temperature [K];
$\bar{T}_E$, bulk mean temperature of heated jet at exit of jet block [K];
$\bar{T}_k$, mean temperature of unheated water in test-section [K];
u, streamwise velocity fluctuation [$m s^{-1}$];
u_i, velocity fluctuation in ith coordinate direction [$m s^{-1}$];
$\bar{U}$, local streamwise mean velocity [$m s^{-1}$];
$\bar{U}_i$, local mean velocity in ith coordinate direction [$m s^{-1}$];
$\bar{U}_0$, bulk mean velocity in test section downstream of jet block [$m s^{-1}$];
$\bar{U}_T$, bulk mean velocity in bores of jet block [$m s^{-1}$];
v^1, Lagrangian velocity of a fluid particle [$m s^{-1}$];
x, x_1, streamwise coordinate;
x_i, coordinate in ith direction.

Superscript

$\bar{\ }$, denotes time averaging.

Greek symbols

α, molecular diffusivity of heat [$mm^2 s^{-1}$];
α_E, eddy diffusivity of heat [$mm^2 s^{-1}$];
δ, stream temperature fluctuation [K];
$\overline{\delta^2_{m0}}$, maximum mean square temperature fluctuation — measured near exit of block [K^2];
ε, dissipation of velocity fluctuations [$mm^2 s^3$];
ε_δ, dissipation or destruction of stream temperature fluctuations [$K^2 s^{-1}$];
λ_f, velocity microscale [mm];
λ_δ, microscale of stream temperature fluctuations [mm];
ν, kinematic viscosity [$mm^2 s^{-1}$].

INTRODUCTION

DIFFUSIVE properties of the flow in the exit plenum of fuel rod bundle assemblies of sodium-cooled nuclear power reactors are of considerable interest. Present

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research is centred on attempts to relate the mean and/or statistical properties of this flow to the performance of individual fuel rods or groups of adjacent ones. No instrumentation is so far available for the reliable measurement of the local instantaneous velocity field in liquid sodium. Emphasis is, therefore, being placed on obtaining the necessary information through the temperature field. Since velocity field information is required for a better understanding of the diffusive processes, a laboratory simulation using a more convenient fluid than liquid sodium, but with similar dynamic properties, was conducted as a first step.

To date, the basis of most predictive models has been the reformulation of an eddy diffusivity expressed in terms of Lagrangian parameters into one in terms of Eulerian quantities. This reformulated eddy diffusivity can then be expressed in terms of the velocity field through use of empirical relations [1] such as given by [2] or in terms of more fundamental parameters [3, 4] for subsequent use in the relevant differential equations. In order to be able to solve the latter for point values rather than averages over a cross-section as shown in [4], estimates of the turbulent diffusion of the scalar in addition to the dissipation of the scalar are required for closure of the equations. Different methods are available for this and are well summarized in [3].

In this work, the eddy diffusivity approach is used to solve the mean temperature field whereas the temperature fluctuation transport equation is used to yield the fluctuating temperature distribution. Model parameters were established from measurements at one point in a multi-bore jet block flow using water as the working fluid. Predictions for other points in the flow field based on data at one reference point agreed well with measured data.

Flows similar to the present one, have been reported and reviewed in Brodkey [5] and by Gal-el-Hak and Morton [6]. In the former, much larger blockage ratios were used than in the present work and partial tubes were not provided for continuity in the wall region. The combination of these two features is believed to be responsible for the peculiarities of the flow reported by Brodkey [5] but which were not observed in this work. Gal-el-Hak and Morton [6] on the other hand used a grid flow with a very small blockage ratio to generate the flow field but failed to present any form of predictive model.

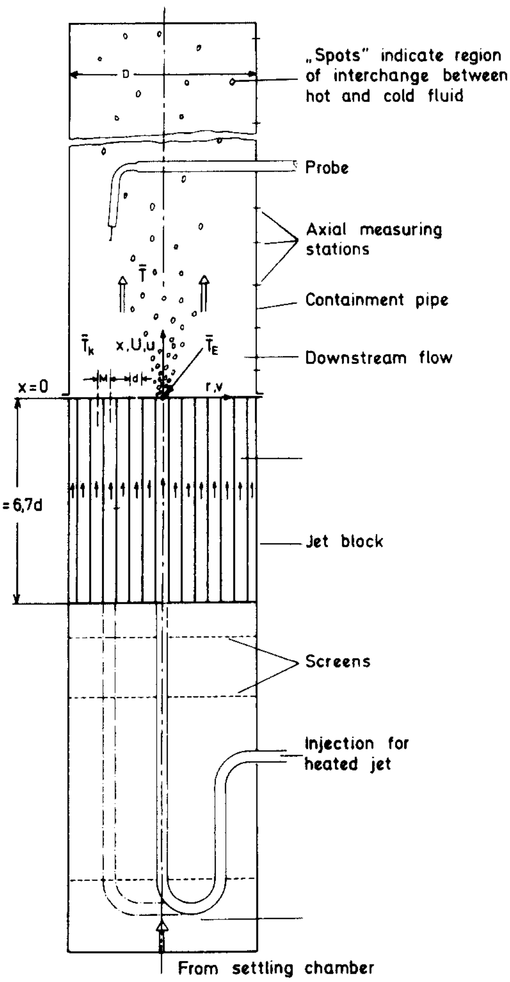

FIG. 1. Schematic of experimental apparatus.

DEVELOPMENT OF THE MATHEMATICAL MODEL

The basic flow together with the coordinate system is shown in Fig. 1. For steady flow of an incompressible fluid with negligible heating by dissipation and no internal heat sources, the energy equation is

$$\bar{U}_i \frac{\partial \bar{T}}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\alpha \frac{\partial}{\partial x_i}\bar{T} - \overline{u_i \delta}\right] \tag{1}$$

where the usual Einstein summation convention applies to repeated indices. In the present case, $\bar{U}_2 = \bar{U}_3 = 0$ except immediately behind the jet block and the Boussinesq assumption yields the necessary relationship between the turbulent and the mean field

$$\overline{u_i \delta} = -\alpha_E \frac{\partial}{\partial x_i}\bar{T}. \tag{2}$$

Since the flow field is uniform in the radial and azimuthal directions, α_E is taken to be a function only of the streamwise coordinate. Assuming further that $\partial \alpha_E(x_1)/\partial x_1 \ll \bar{U}_1$ leads to

$$\bar{U}_1 \frac{\partial \bar{T}}{\partial x_1} = [\alpha + \alpha_E(x_1)] \frac{\partial^2 \bar{T}}{\partial x_i \partial x_i}. \tag{3}$$

For water, $\alpha \ll \alpha_E(x_1)$ and as rapid changes are restricted to the radial direction, Equation (3) becomes in cylindrical coordinates

$$\bar{U}_1 \frac{\partial \bar{T}}{\partial x} = \alpha_E(x)\left[\frac{1}{r}\frac{\partial \bar{T}}{\partial r} + \frac{\partial^2 \bar{T}}{\partial r^2}\right]. \tag{4}$$

In order to relate the eddy diffusivity to the velocity field, the Lagrangian description of diffusion is used, equation (5)

$$\alpha_E(x) = v^1 L_L. \tag{5}$$

The particle velocity, v^1, is assumed to be proportional to the streamwise velocity fluctuation, u, and the Lagrangian length scale, L_L, is assumed to be proportional to the Eulerian one, L_f. Introducing the additional assumption that both $\sqrt{\overline{u^2}}$ and L_f follow a simple power law relationship as a function of x, similar to that found in grid turbulence, changes equation (5) to

$$\alpha_E(x) = A^* x^{n-1}. \tag{6}$$

For $x/d > 5$ (approximately) and the boundary condition that for large r, $\bar{T} = \bar{T}_k$, the solution to equation (4) in closed form is

$$\frac{\bar{T} - \bar{T}_k}{\bar{T}_E - \bar{T}_k} = \frac{Sn}{4\pi A^* x^n} \exp\left[-\frac{\bar{U}n}{4A^* x^n} r^2\right] \tag{7}$$

where $S = \bar{U}_T(\pi d^2/4)$ = volume flow of heated jet and $\bar{T}_E$ is the mean temperature of the heated jet at the jet block exit plane. A^* is an empirical constant. The steady-state energy balance for the temperature fluctuations is [3]

$$\bar{U}_i \frac{\partial \overline{\delta^2}}{\partial x_i} = -2\overline{u_i\delta}\frac{\partial \bar{T}}{\partial x_i} - \frac{\partial \overline{u_i\delta^2}}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\alpha \frac{\partial \overline{\delta^2}}{\partial x_i}\right) - 2\alpha \overline{\frac{\partial \delta}{\partial x_i}\frac{\partial \delta}{\partial x_i}}. \tag{8}$$

$\overline{u_i\delta}$ is given by equation (2). $\overline{u_i\delta^2}$ is modelled by the gradient approximation

$$\overline{u_i\delta^2} = -a\frac{\partial \overline{\delta^2}}{\partial x_i} \tag{9}$$

where it is further assumed that $a = \alpha_E(x)$ which means that a is also a function of x alone, say, $a(x)$.

The justification for this assumption is that equations (2) and (9) are identical except for the quantity transported by u_i. In the first case, the instantaneous temperature is the scalar being transported for which

$$\overline{u_i T} = -\alpha_E \partial \bar{T}/\partial x_i$$

that is,

$$\overline{u_i\delta} = -\alpha_E(\partial \bar{T}/\partial x_i)$$

(since $\overline{u_i \bar{T}} = 0$) applies. In the second, the scalar is $\overline{\delta^2}$, the behaviour of which is governed by the same molecular properties during the transport by u_i, hence leading to the assumption that $a = \alpha_E$. A comparison of this with other models for the diffusion term is given in a later section.

Finally, a model is required for the dissipation of the temperature fluctuations. Accepting that this dissipation occurs at high wavenumbers, where the flow is locally isotropic, and introducing the temperature microscale, leads to

$$\varepsilon_\delta = \alpha \overline{\frac{\partial \delta}{\partial x_i}\frac{\partial \delta}{\partial x_i}} \tag{10a}$$

$$= 12\alpha\frac{\overline{\delta^2}}{\lambda_\delta^2}. \tag{10b}$$

For isotropic turbulence λ_δ is related to the microscale of the velocity field by equation (11), if the turbulence Reynolds number and $\sqrt{\overline{u^2}}\,\lambda_\delta/\alpha$ are small [7]

$$\lambda_f^2 = \lambda_\delta^2 Pr. \tag{11}$$

This transforms equation (10b)

$$\varepsilon_\delta = \frac{12\nu}{\lambda_f^2}\overline{\delta^2} \tag{12a}$$

$$= \frac{B}{x}\overline{\delta^2} \tag{12b}$$

where the approximation has been introduced that $\lambda_f^2 \propto x^{-1}$ for this particular flow. The significance of this last result is that ε_δ is independent of Prandtl number.

Further simplification of the model is possible if it is accepted that

(a) $\bar{U}\dfrac{\partial \overline{\delta^2}}{\partial x} \gg \dfrac{\partial}{\partial x_i}\left[a(x)\dfrac{\partial \overline{\delta^2}}{\partial x_i}\right]$;

(b) $\partial^2 \overline{\delta^2}/\partial x^2$ is negligible compared with the second-order derivatives of $\overline{\delta^2}$ in the other two directions, and

(c) molecular diffusion is negligible compared with turbulent diffusion thus reducing equation (8) to (13) where cylindrical coordinates have been introduced

$$\bar{U}\frac{\partial \overline{\delta^2}}{\partial x} = A^* x^{n-1}\left[2\left(\frac{\partial \bar{T}}{\partial x}\right)^2 + 2\left(\frac{\partial \bar{T}}{\partial r}\right)^2 + \frac{\partial^2 \overline{\delta^2}}{\partial r^2} + \frac{1}{r}\frac{\partial \overline{\delta^2}}{\partial r}\right] - \frac{B}{x}\overline{\delta^2}. \tag{13}$$

The boundary conditions applying to equation (13) are $\overline{\delta^2}\ (x, D/2) = 0$ and

$$\frac{\partial}{\partial r}[\overline{\delta^2}(x, D/2)] = 0$$

for $D \gg$ width of temperature field. D is taken as the diameter of the containment pipe (Fig. 1).

APPARATUS AND INSTRUMENTATION

Experimental data for verification of the model were obtained in a water tunnel consisting of a settling chamber, swirl eliminator, screens to ensure a flat velocity profile at the inlet to the jet block and provision for the injection of heated water into the central bore of the jet block (Fig. 1). The jet block consisted of 158 bores of 7.2 mm dia., placed on a triangular pitch of 8.2 mm. The length-to-diameter

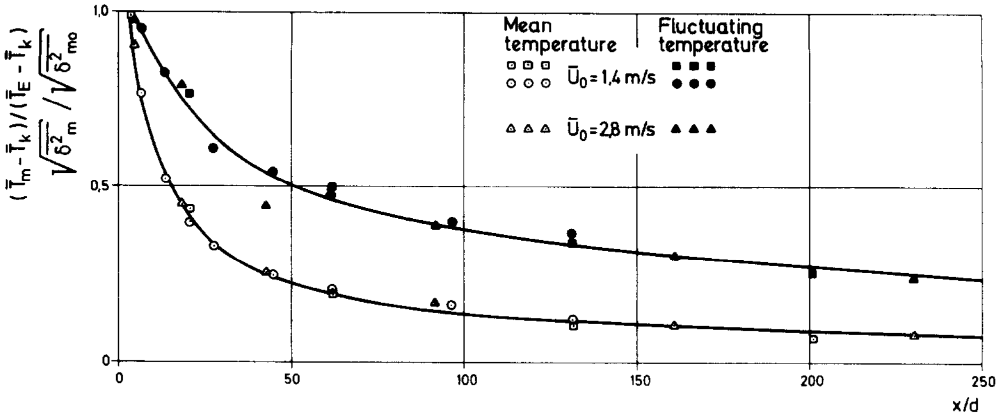

FIG. 2. Axial decay of mean and fluctuating temperatures.

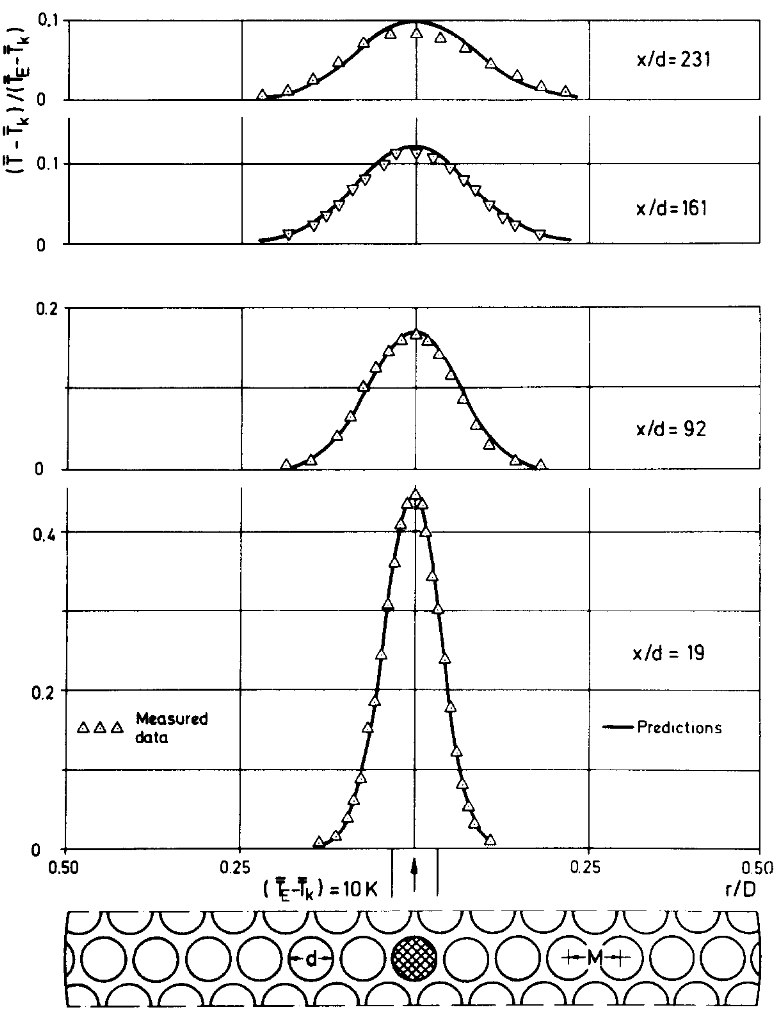

FIG. 3. Comparison of measured and predicted mean temperature profiles, $\bar{U}_0 = 2.8\,\mathrm{m\,s^{-1}}$.

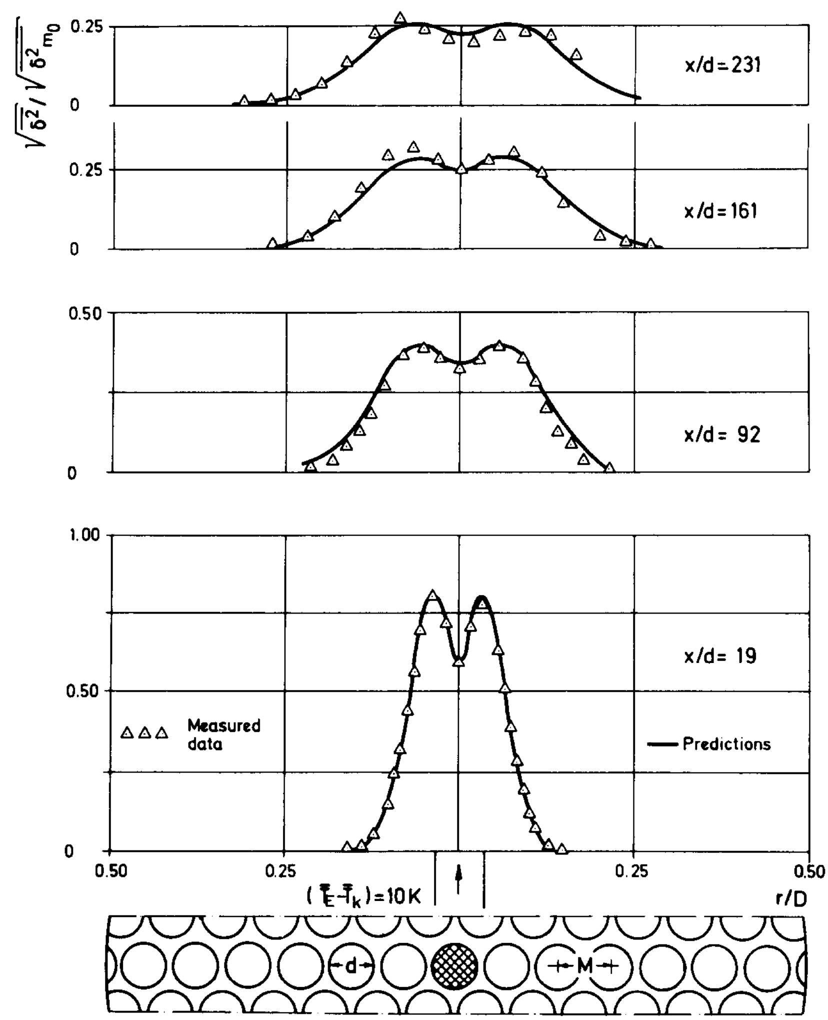

FIG. 4. Comparison of measured and predicted temperature fluctuation intensities, $\bar{U}_0 = 2.8\,\mathrm{m\,s^{-1}}$, $B/\bar{U} = 2.2$.

ratio of individual bores was 16.7 : 1. The downstream flow was contained by a 110 mm dia. pipe. Injection of heated water into the central bore was controlled to ensure the same mass flow existed as in the remaining bores.

Velocity measurements were performed with a DISA 55 M11 constant temperature anemometer using DISA 55 R11 cylindrical hot-film probes at a hot-to-cold resistance ratio of 1.18. Temperature measurements were performed with a DISA 55 M20 constant current anemometer with a $10\,\mu\mathrm{m} \times 1.2\,\mathrm{mm}$ long platinum–iridium wire operated at 3 mA in order to obtain only a temperature response. Compensation for the wire's roll-off due to thermal inertia was found to be unnecessary [8].

COMPARISON OF PREDICTIONS AND MEASUREMENT

Equation (7) can be used to predict the mean temperature field once the constants A^* and n have been determined. At $\bar{U}_0 = 2.8\,\mathrm{m\,s^{-1}}$ the power laws fitting the $\sqrt{u^2}$ and L_f data are given by [8]

$$\sqrt{\left(\frac{u^2}{U}\right)} = 0.73\left(\frac{x}{d}\right)^{-0.833} \tag{14a}$$

$$\frac{L_f}{d} = 0.14\left(\frac{x}{d}\right)^{0.44} \tag{14b}$$

from which $n = 0.61$. $\bar{U}$ is the local mean velocity which differs slightly from $\bar{U}_0$ because of boundary layer growth in the containment pipe. (The coefficients in equation (14) supersede those of [9].) $S = 168\,560\,\mathrm{mm^3\,s^{-1}}$, leaving A^* as the only constant to be determined from the temperature field (Fig. 2). At $x/d = 19$ and $r = 0$, $A^*d^n = 3020\,\mathrm{mm^3\,s^{-1}}$ for d in mm. Predictions of mean temperature at various x/d are compared with experimentally obtained temperature profiles in Fig. 3. Excellent agreement is observed.

The temperature fluctuation field can be predicted with equation (13) once the constant B has been established — the remaining constants being the same

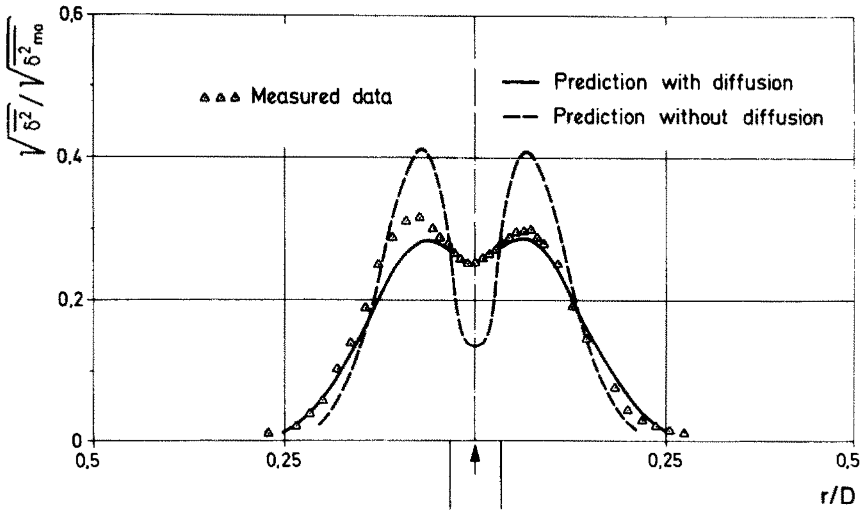

FIG. 5. Effect of turbulent diffusion, $\bar{U}_0 = 2.8\,\mathrm{m\,s^{-1}}$, $B/\bar{U} = 2.2$, $x/d = 161$.

as for the mean temperature equation. Equation (13) was solved numerically for various values of B. Predicted profiles of $\overline{\delta^2}$ were then compared with measured ones at $x/d = 19$. The value of B giving the best fit at this point was used for predictions at various other x/d. Again, excellent agreement between measured and predicted profiles was obtained for a significant distance downstream (Fig. 4) in which $\overline{\delta^2_{mo}}$ is the maximum mean square temperature fluctuation obtained near the exit of the jet block — the decay of the peak $\sqrt{\overline{\delta^2}}$ being shown in Fig. 2. Use of the same model also permits the significance of turbulent diffusion to be assessed by repeating the predictions but with the diffusion term deleted. A typical result is shown in Fig. 5 at $x/d = 161$.

DISCUSSION OF MODEL AND RESULTS

An important step in the development of equation (13) was use of the isotropic, low Reynolds number result of equation (11). If this can be shown to be a reasonably good approximation in the present flow, application of the model to other Prandtl number fluids is simplified. This is because a change to, say, liquid sodium for which the kinematic viscosity is almost the same as for water at ambient temperature and $\sqrt{\overline{u^2}}\,\lambda_\delta/\alpha$ is also small, the factor B/x in equation (13) will be unaffected and the addition of the molecular diffusion term to equation (13) for such a case, does not introduce any new unknowns.

Assuming isotropic conditions, allows λ_f^2 in equation (12a) to be evaluated by means of the isotropic dissipation result,

$$\varepsilon = -\frac{3}{2}\bar{U}\frac{d\overline{u^2}}{dx} \tag{15a}$$

$$= 30\nu\frac{\overline{u^2}}{\lambda_f^2} \tag{15b}$$

which together with equation (12a) yields

$$\varepsilon_\delta = \frac{\varepsilon\overline{\delta^2}}{0.833\,\overline{q^2}} \tag{16}$$

hence $B/\bar{U} = \varepsilon x/0.833\,\overline{q^2}\,\bar{U}$. Substitution using the decay law of equation (14a) gives $B/\bar{U} = 1.0$ compared with 2.2 of Fig. 4. As will be seen below, this result is consistent with those by others but does make the isotropic assumption for dissipation and the flow as a whole somewhat doubtful.

It is also of interest to compare the present model with one listed in [3] and summarized by

$$\overline{u_2\delta} = -k_1\frac{(\overline{q^2})^2}{\varepsilon}\frac{\partial\bar{T}}{\partial x_2} \tag{17a}$$

$$\overline{u_i\delta^2} = -k_2\frac{(\overline{q^2})^2}{\varepsilon}\frac{\partial\overline{\delta^2}}{\partial x_i} \tag{17b}$$

$$\varepsilon_\delta = \frac{1}{R}\frac{\varepsilon\overline{\delta^2}}{\overline{q^2}} \tag{17c}$$

where $k_1 = 0.037$ for free shear flows (not the case here), k_2 is unspecified and R, a time-scale ratio, is in the range of 0.5–0.71. The x dependence of the eddy diffusivities $k_1(\overline{q^2})^2/\varepsilon$ and $k_2(\overline{q^2})^2/\varepsilon$ in equations (17a) and (17b) is $x^{-0.66}$ which compares with $x^{-0.39}$ in this work. The difference is consistent with lack of isotropy in the present flow but it is noteworthy that the exponents for the two diffusivities are the same in each model. Comparison of equations (2) and (17a) gives

$$k_1 = \alpha_E(x)\varepsilon/(\overline{q^2})^2.$$

Substituting experimental values, shows that $k_1 = 0.0108(x/d)^{0.27}$ which for the larger values of x/d is in good agreement with the nominal value of 0.037 in [3]. For the present model it was assumed that the diffusion coefficient for $\overline{\delta^2}$, equation (9) is equal to α_E of equation (2). Except for a constant, this is consistent with equations (17a) and (17b). Equation (17c) reduces to $\varepsilon_\delta \propto \overline{\delta^2}/x$ which also has the same form as equation (12b). Furthermore, $B/\bar{U} = 1.66$ for $R = 0.5$ which compares well with that of 2.2 (Fig. 4). In fact if $\overline{u_2^2}$ and $\overline{u_3^2}$ are both about $0.66\overline{u^2}$, then the two estimates of $B/\bar{U}$ are identical — a result consistent with the observation that the flow is not isotropic, but one which cannot be easily verified experimentally. Furthermore, comparison of equations (16) and (17c) shows that under isotropic conditions, $R = 0.833$ instead of 0.5. The present results support the lower value of R.

CONCLUSIONS

A model has been presented which predicts the mean and fluctuating temperature fields with good accuracy provided that the velocity field is known and that two constants, one for each field, are available as empirical data. Under isotropic flow conditions, these constants can be obtained by calculation but present experimental data show significant variations from an isotropic model. Comparison of the present results with those of others, obtained generally in free shear flows, shows good agreement. In particular, the present results support a nonisotropic value for the time-scale ratio relating dissipation of velocity and scalar fluctuations. Of special interest is the application of the model approximations to fluids of much lower Prandtl number than used here but an evaluation of this time-scale ratio will have to await the availability of suitable experimental results.

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MESURE ET CALCUL DU CHAMP DE TEMPERATURE MOYENNE ET FLUCTUANTE EN AVAL D'UN BLOC D'OU SORTENT PLUSIEURS JETS DONT UN SEUL EST CHAUFFE

Résumé—Des mesures des champs de vitesse et de température moyennes et fluctuantes dans l'eau sont effectuées en aval d'un bloc multi-jets qui est réalisé pour simuler un écoulement obtenu dans des sous-assemblages de réacteur nucléaire. Des lois en puissance semblables à celle de la turbulence de grille ont été trouvées pour décrire la décroissance du champ fluctuant et la croissance des échelles mais des exposants très différents sont dûs à l'anisotropie produite dans le bloc de jets. On a trouvé un modèle de diffusion par gradient avec un coefficient de diffusion turbulente variable dans le sens de l'écoulement pour prédire de façon correcte les profils de température moyenne. Des distributions d'intensités de fluctuation de température sont prédites par l'equation de transport de ce scalaire. Un accord entre les mesures et le calcul est obtenu en utilisant des diffusivités turbulentes identiques pour la production en la diffusion des fluctuations de température.

MESSUNG UND BERECHNUNG DES MITTLEREN UND DES FLUKTUIERENDEN TEMPERATURFELDES STROMAB EINES VIELLOCH-DÜSENBLOCKES, IN DEM EINE DÜSE BEHEIZT WIRD

Zusammenfassung—Es wurden Messungen der mittleren und fluktuierenden Temperatur- und Geschwindigkeitsfelder in Wasser stromab eines Vielloch-Düsenblockes durchgeführt, der zur Simulation der Strömung in Kernreaktorbauteilen konstruiert wurde. Dabei wurden Gesetzmäßigkeiten zur Beschreibung des Abklingens des Feldes der Fluktuation und des Anwachsens des Längenmaßstabs ähnlich denen bei Gitterturbulenz gefunden, aber es ergaben sich infolge der Anisotropie, die im Strahlblock erzeugt wurde, signifikant abweichende Exponenten. Es wurde gefunden, daß sich ein Ausbreitungsmodell mit einem strömungsabhängigen veränderlichen Scheindiffusionskoeffizienten ausgezeichnet zu Berechnungen des mittleren Temperaturprofils eignet. Die Verteilungen der Temperaturfluktuationsintensitäten wurden mit der entsprechenden Transportfleichung bestimmt. Zwischen Messung und Rechnung wurde bei Verwendung gleicher Scheindiffusionskoeffizienten für das Entstehen und die Ausbreitung der Temperaturfluktuation gute Übereinstimmung erreicht.

ИЗМЕРЕНИЕ И РАСЧЕТ ОСРЕДНЕННЫХ И ПУЛЬСАЦИОННЫХ ПОЛЕЙ ТЕМПЕРАТУРЫ ДЛЯ СИСТЕМЫ СТРУЙ ЗА ПЕРФОРИРОВАННОЙ ПРЕГРАДОЙ (ОДНА ИЗ СТРУЙ НАГРЕТА)

Аннотация — Измерены осредненные и пульсационные поля скорости и температуры в потоке воды за перфорированной преградой, моделирующей течение в узлах ядерного реактора. С помощью степенных законов типа используемых для описания турбулентности за решеткой предлагается описывать затухание поля пульсаций и рост масштабов длины. Показатели степени в данном случае существенно отличаются из-за неизотропности, создаваемой преградой. Градиентная модель диффузии с переменным по направлению течения коэффициентом турбулентного перемешивания, как выяснилось, позволяет с высокой степенью точности определять профили осредненных температур. Распределения интенсивностей флуктуаций температур рассчитывались с помощью уравнения переноса для этого типа скаляра. Использование аналогичных коэффициентов турбулентного перемешивания для случая возникновения и диффузии флуктуаций температуры привело к согласованию между данными опытов и результатами расчетов.