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INTERPRETATION OF MEASURED VARIATIONS OF THE EDDY CONDUCTIVITY

LARRY D. ECKELMAN* and THOMAS J. HANRATTY
Department of Chemical Engineering, University of Illinois, Urbana, Illinois, U.S.A.

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Abstract—An interpretation is given of the observed variation of eddy conductivities, ε_h, in a heated channel. A homogeneous model which assumes constant turbulence properties and a plug flow explains the gross features of the eddy conductivity profile. The large variation of ε_h close to the wall is explained as mainly due to the time dependency of the turbulent diffusion process. In order to get closer agreement with measurements, the homogeneous model has to be modified to account for the variation of average velocity and turbulence intensity. This is done and values of the von Kármán constant for heat transfer are calculated which are in good agreement with experiment.

NOMENCLATURE

a, channel half width or pipe radius;
C_p, heat capacity at constant pressure;
E, diffusion coefficient;
k, thermal conductivity of fluid;
q, heat flux per unit time per unit area;
Q, heat flux per unit time per unit length;
r, radial distance;
R, Lagrangian correlation coefficient;
Re, Reynolds number $= 4a\,U_b/\nu$ for a channel or $2a\,U_b/\nu$ for a pipe;
t, time;
T, temperature of the fluid;
T_c, temperature of the fluid at center;
T^+, dimensionless temperature $= (T_c - T)\,\rho C_p U^*/q$;
u, velocity fluctuation in the axial direction;
U, local average axial velocity;
U_0, centerline velocity;
U_b, bulk averaged velocity;
U^*, friction velocity $= \sqrt{(\tau_w/\rho)}$;
v, velocity fluctuation normal to the wall;
x, distance in axial direction;
x_0, characteristic scale in axial direction;
y, distance in normal direction;
y^+, dimensionless normal distance $= y\,U^*/\nu$;
$\overline{Y^2}$, mean squared displacement;
α, thermal diffusivity $= k/\rho C_p$;
ε_h, eddy diffusivity for heat transfer;
ε_m, eddy viscosity;
ρ, fluid density;
τ, Lagrangian time scale;
τ_w, shear stress at wall;
μ, fluid viscosity;
ν, kinematic viscosity $= \mu/\rho$.

1. INTRODUCTION

MEASUREMENTS of fully developed temperature and concentration profiles in turbulent flows are often correlated through the use of eddy diffusivities and eddy conductivities. This paper presents an interpretation of the observed variation of eddy conductivities.

For this purpose, we consider the measurements of Sage and his coworkers [1], who conducted heat transfer experiments in a rectangular channel with a half width a of 0·338 in. and an aspect ratio of 17·75. One of the walls was heated and the opposite wall was cooled at the same rate. The measurements were influenced by both viscous dissipation and compression work.

* Presently with the Environmental Protection Agency. Evansville, Indiana.

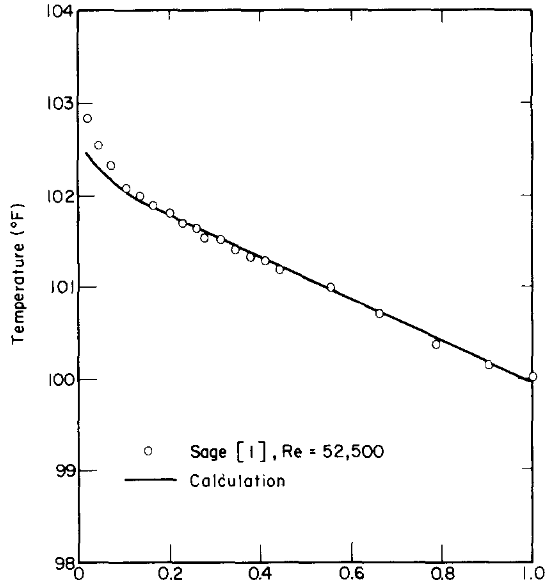

FIG. 1. Temperature profile.

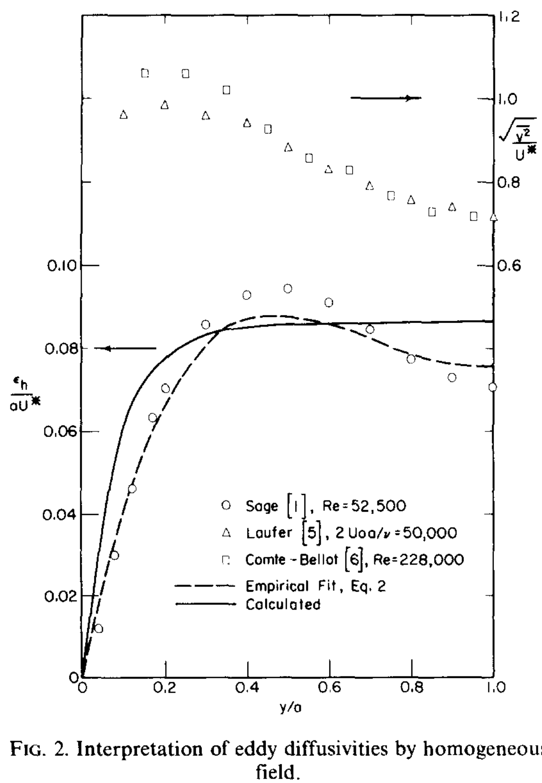

FIG. 2. Interpretation of eddy diffusivities by homogeneous field.

However, these effects are ignored, since as shown by Blanco and Gill [2], they cause a maximum correction of 12 per cent in the run considered in this paper.

Far downstream the fully developed temperature profile shown in Fig. 1 was obtained. If the flow were laminar, this temperature profile would be a straight line. The larger slopes observed near the wall for turbulent flow indicates a larger resistance to heat transfer. This can be interpreted as due to the variation of the flow field and turbulence properties across the channel and, as previously pointed out by Hanratty [3], to the time dependency of the turbulent diffusion process defined by Taylor [4].

From the temperature profile in Fig. 1, the eddy conductivities ε_h shown in Fig. 2 are calculated from the heat flux q using

$$\frac{q}{\rho C_p} = -(\alpha + \varepsilon_h)\frac{\mathrm{d}T}{\mathrm{d}y} \tag{1}$$

where α is the molecular thermal diffusivity. For comparison, the component of the turbulent intensity perpendicular to the wall $(\overline{v^2})^{\frac{1}{2}}/U^*$, measured by Laufer [5] and by Comte-Bellot [6], is also shown. It is noted that the moderate variation in the intensity is comparable in magnitude to the variation in ε_h observed for $y/a > 0{\cdot}4$. Close to the wall, where ε_h is showing a very rapid variation, the intensity is almost constant. The region in the immediate vicinity of the wall, where viscous effects are important ($y^+ < 30$) is not shown in Fig. 2. Here the intensity varies very rapidly.

Johnk [7] has made extensive measurements of temperature profiles for air flowing in a heated 3 in. pipe. Eddy conductivities calculated from his measurements at Reynolds numbers of 17000 and greater [8] are shown in Fig. 3. The dashed line is an empirical fit [9] to these eddy diffusivities using an equation of the form proposed by Reichardt [10].

$$\frac{\varepsilon_h}{aU^*} = 0{\cdot}0752 \left[1 + 2{\cdot}245\left(\frac{r}{a}\right)^2\right]\left[1 - \left(\frac{r}{a}\right)^2\right]. \tag{2}$$

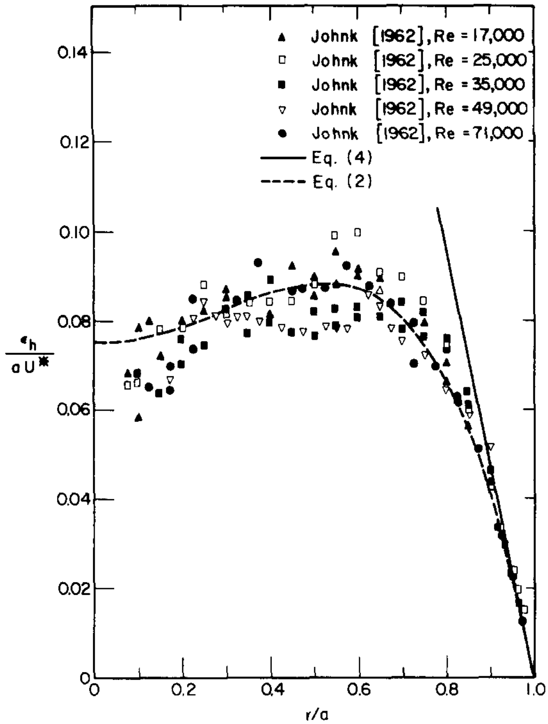

FIG. 3. Eddy diffusivities in a pipe.

The eddy diffusivities obtained from pipe heat transfer data show the same trend as the measurements of Sage [1]. In fact, close to the wall the numerical agreement between the two sets of measurements is within experimental error. Johnk and Hanratty [8] have interpreted the measurements of Johnk [7] and have shown that in the region $y^+ > 30$ to $y/a < 0{\cdot}15$ the temperature profile can be described by

$$T^* = 3{\cdot}3 + 5{\cdot}1 \log_{10} y^+. \quad (3)$$

This suggests that in the wall region the eddy diffusivity is given by

$$\frac{\varepsilon_h}{aU^*} = 0{\cdot}45\left(\frac{y}{a}\right). \quad (4)$$

As seen in Fig. 3, this is a good representation of the limiting behavior of the eddy diffusivity profile outside the viscous region for $r/a \to 1$.

The viewpoint taken in this paper is that the gross features of the variation in ε_h outside the viscous region can be interpreted by using a model for a homogeneous velocity field. The variation of ε_h in the viscous region, which will not be considered in this paper, is intimately connected with the variation of the properties of the flow field and should probably be explained by using a model for the turbulence structure of the type used by Sirkar and Hanratty [11]. We interpret the large variation in ε_h from $y^+ > 30$ to $y/a < 0{\cdot}15$ as being mainly due to the time dependency of the turbulent diffusion process. The effects of the nonhomogeneities in the turbulence properties and of the variation of the average velocity are introduced as semi-empirical corrections to the homogeneous model.

In the second section of this paper, we assume a homogeneous turbulent plug flow and predict the variation of the eddy diffusion coefficient. In the calculations, we use the bulk averaged velocity and the turbulence intensity measured at $y/a = 0{\cdot}7$. In the third section, we develop a model for diffusion in the wall region for which U is varying but for which the turbulence properties normalized with respect to U are constant. Calculations based on this model use the value of $(\overline{v^2})^{\frac{1}{2}}/U$ measured in the region close to the wall. This model agrees with equation (4) and disagrees with measurements of ε_h far from the wall where $(\overline{v^2})^{\frac{1}{2}}/U$ is varying. In section

of turbulence intensity by introducing a semi-empirical correction.

2. MODEL FOR HOMOGENEOUS TURBULENCE AND PLUG FLOW

Taylor [4] described turbulent diffusion from a source or sink located in an infinite homogeneous field and Batchelor [12] and Hanratty [3] have shown how this description may be applied to more general transport problems.

It has been observed experimentally that diffusion from sources in a homogeneous flow field may be described by a gaussian distribution both for small and for large diffusion times. Consider a continuous line source of heat of strength Q per unit time per unit length in a uniform flow with velocity U_b large enough that diffusion in the flow direction x can be neglected. If the field is of infinite extent, the temperature distribution in the y-direction is then given as

$$U_b \rho C_p T = \frac{Q}{\sqrt{(2\pi)}\sqrt{(\overline{Y^2})}} \exp(-y^2/2\overline{Y^2}). \quad (5)$$

According to Taylor [4], the mean squared displacement is given as

$$\overline{Y^2} = 2\overline{v^2} \int_0^t (t-s) R(s)\, \mathrm{d}s \quad (6)$$

where $\overline{v^2}$ is the mean squared component of the velocity fluctuations in the y-direction and $R(s)$ is the Lagrangian correlation coefficient of the diffusing particles. For small time

$$\overline{Y^2} \cong \overline{v^2}\, t^2 \quad (7)$$

and for large time

$$\overline{Y^2} \cong \text{const} + 2\overline{v^2}\, \tau t, \quad (8)$$

where τ is the Lagrangian time scale defined as

$$\tau = \int_0^\infty R(s)\, \mathrm{d}s. \quad (9)$$

If we use Einstein's [13] definition of a diffusion coefficient,

$$E = \frac{1}{2} \frac{\mathrm{d}\,\overline{Y^2}}{\mathrm{d}\,t},$$

we see that turbulent diffusion from a line source is time dependent in that E is a function of time. As $t \to 0$ the diffusion coefficient E increases linearly with time and at large times it reaches a constant value equal to $\overline{v^2}\,\tau$.

We would now like to apply Taylor's interpretation of turbulent diffusion to the heat transfer section shown in Fig. 4 in which heat is being transferred from a hot surface to a cold surface separated by a distance $2a$. Fluid flows at a velocity U_b. The rate of heat transfer per unit area is q.

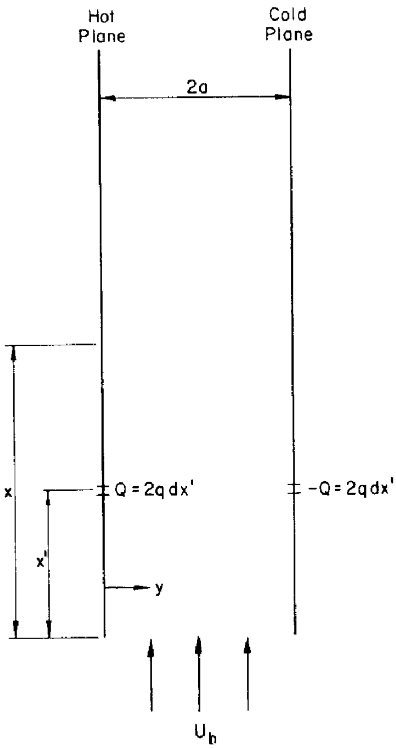

FIG. 4. Representation of problem.

Consider the differential source at $y = 0$, $x = x'$ for which $Q = 2\,q\,\mathrm{d}\,x'$ add the differential sink at $y = 2a$, $x = x'$ for which $Q = -2\,q\,\mathrm{d}\,x'$. We cannot use (5) directly to describe this source–sink pair since we are now considering a finite field. We consider the case where heat originating from this source–sink pair does not diffuse out of the field; and therefore, we can synthesize a solution from (5) by placing an infinite series of reflecting sources and sinks at $y = -2\,a$, $-4\,a$, $-6\,a$, $\ldots + 4\,a$, $+6\,a$, $+8\,a \ldots$ [3]. The temperature field for this source–sink pair can thus be given as

$$U_b \rho C_p T = \frac{2q\,\mathrm{d}\,x'}{\sqrt{(2\pi(\sqrt{[\overline{Y^2}\,(t)]}}} \left\{ \sum_{-\infty}^{+\infty} (-1)^n \exp\left(-\frac{(2na+y)^2}{2\overline{Y^2}(\lambda)}\right)\right\}. \quad (10)$$

Here $\overline{Y^2}$ is a function of the amount of time t the diffusing material has been in the field and t can be related to the location in the channel in the following way

$$t = (x - x')/U_b. \tag{11}$$

Now if we want to calculate the temperature profile at some location in the field x due to source–sink pairs located at values of x' from 0 to x, we obtain

$$U_b \rho C_p T = \int_0^x \frac{2q\, \mathrm{d}\, x'}{\sqrt{(2\pi)}\sqrt{[\overline{Y^2}(t)]}}$$

$$\left\{\sum_{-\infty}^{+\infty} (-1)^n \exp\left(-\frac{(2na + y)^2}{2\overline{Y^2}(t)}\right)\right\} \tag{12}$$

where t is given by (11). At large values of x (12) predicts a fully developed profile. If we assume that the Lagrangian correlation coefficient is given as

$$R(t) = \exp\left(-\frac{t}{\tau}\right) \tag{13}$$

and if we take

$$\frac{(\overline{v^2})^{\frac{1}{2}}}{U^*} = 0{\cdot}79$$

$$\frac{U_b \tau}{a} = 2{\cdot}75$$

we compute the curve shown as a solid line in Fig. 1. From this temperature profile and the definition of an eddy diffusivity, equation (1), we calculate the ε_h-profile shown as a full line in Fig. 2. The value of τ used in the calculations was chosen so that the computed and measured eddy diffusivity profiles agree at $y/a = 0{\cdot}7$.

It is seen that the computed ε_h-profile has the same gross features as the measured ε_h-profile. At large distances from the wall the diffusing material has been in the field a long period of time and therefore, we compute $\varepsilon_h = \overline{v^2}\,\tau$, corresponding to the limiting value of the line source eddy diffusion coefficient. The diffusing material close to the wall which is influencing the temperature gradients has been in the field for relatively short time periods and therefore, has smaller values of ε_h corresponding to the smaller values of the line source eddy diffusion coefficient found for small times.

As mentioned in the introduction, the differences between the ε_h-profile for the homogeneous model and the measurements are interpreted as due to the variation of the average velocity and the turbulence properties across the channel. We conclude that the variation of U is playing a major role in determing these differences in the wall region since the use of a value of $\overline{v^2}$ corresponding to the measurements close to the wall in the homogeneous model would make the discrepancy between the calculated and measured values of ε_h even greater.

3. INFLUENCE OF VARIATION IN THE LOCAL AVERAGE VELOCITY

In order to examine the effects of the variation of local average velocity, we use an approach similar to that employed by Sutton [14] to describe diffusion in the lower atmosphere. The turbulence properties will be assumed to be homogeneous if normalized with respect to the local average velocity. Particular attention will be given to obtaining an improved representation of the eddy diffusivity in the regions close to the wall.

Studies of diffusion from wall sources have been made by Poreh and Cermak [15] and by Wieghardt [16]. These measurements indicate that wall diffusion in an infinite medium can be represented reasonably well with an equation of the form

$$U \rho C_p T = d \exp\left(-\frac{y^n}{b}\right). \tag{14}$$

As shown by Pasquill [17], the constants d and b can be defined from a heat balance

$$2q\Delta x' = \int_{-\infty}^{\infty} \rho U C T\, \mathrm{d}\, y \tag{15}$$

and from the definition

$$\overline{Y^2} = \int_{\infty}^{\infty} y^2 \rho UCT \, \mathrm{d}y \Big/ \int_{\infty}^{\infty} \rho UCT \, \mathrm{d}y. \quad (16)$$

From (15) and (16) the following relations are obtained for d and b:

$$d = \frac{nq\Delta x' \, [\Gamma(3/n)]^{\frac{1}{2}}}{[\Gamma(1/n)]^{\frac{3}{2}} \, (\overline{Y^2})^{\frac{1}{2}}} \quad (17)$$

$$b = \left(\frac{\Gamma(1/n)}{\Gamma(3/n)}\right)^{(n/2)} (\overline{Y^2})^{(n/2)}. \quad (18)$$

For the case of $n = 2$ we obtain equation (5).

The definition $\overline{Y^2}$ at a given distance $(x - x')$ from a source was easily obtained in the previous section from Taylor's representation of $\overline{Y^2}(t)$ by using the relation $t = (x - x')/U$ for a plug flow. Since we now want to consider the case of variable velocity a somewhat different approach will be used.

The trajectory of a diffusing particle is given as

$$\frac{\mathrm{d}Y}{\mathrm{d}x} = \frac{v}{U + u} \quad (19)$$

where u is the fluctuating velocity in the x-direction and v is the fluctuating velocity in the y-direction. It follows from (19) that

$$\overline{Y^2} = 2 \int_0^{x-x'} ((x - x') - \xi) \, R(\xi) \, \mathrm{d}\xi \quad (20)$$

where

$$R(\xi) = \overline{\left(\frac{v}{U + u}\right)_x \left(\frac{v}{U + u}\right)_{x+\xi}}. \quad (21)$$

We see that the evaluation of $\overline{Y^2}$ depends on our ability to evaluate $R(\xi)$. Since measurements of $R(\xi)$ are not available, it is necessary to make assumptions regarding its form. If $U \gg u$,

$$R(\xi) \cong \overline{\left(\frac{v}{U}\right)_x \left(\frac{v}{U}\right)_{x+\xi}}. \quad (22)$$

It will be assumed that

$$\frac{(\overline{v^2})^{\frac{1}{2}}}{U}$$

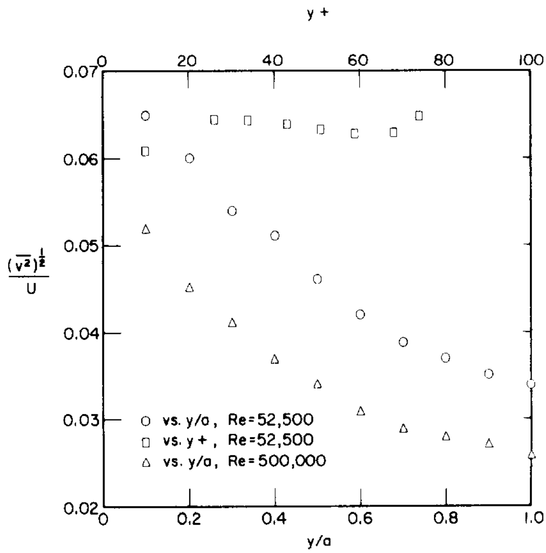

FIG. 5. Variation of intensity.

and the x-length scale of the turbulent velocity fluctuations are independent of y. It, therefore, seems reasonable to use the following form for $R(\xi)$:

$$R(\xi) = \frac{\overline{v^2}}{U^2} f\,(\xi/x_0) \quad (23)$$

where x_0 is a characteristic length scale. If the turbulence is homogeneous and the velocity profile is uniform, $U = U_b$, we see that $\xi = U_b t$ and therefore that

$$x_0 = U_b \tau. \quad (24)$$

Values of $(\overline{v^2})^{\frac{1}{2}}/U$ calculated from Laufer's measurements [5] are shown in Fig. 5. It is seen that $(\overline{v^2})^{\frac{1}{2}}/U$ is relatively constant from $y^+ = 10$ to $y/a = 0{\cdot}2$ and, therefore, that (23) might give reasonable results over this region.

Calculations have been carried out for the heat transfer problem outlined in Fig. 4 using (14), (20), (23), and the procedures outlined in the previous section for handling multiple wall sources and sinks of heat in a finite field. The experiments of Poreh and Cermak [15] and of Wieghardt [16] suggest values of n in the range

1·6–1·8. We have used a value of $n = 2$ in our calculations. From Fig. 5 we obtain values of $(\overline{v^2})^{\frac{1}{2}}/U$ of 0·063 at $Re = 52\,500$ and of 0·048 at $Re = 5000\,000$. The variation of U with y was determined by using the Cess [18] equation for the eddy viscosity.

$$\frac{\varepsilon_m}{\nu} = \frac{1}{2}\left\{\frac{0{\cdot}4\,a^2}{9}\left[1 - \left(\frac{y}{a}\right)^2\right]\left[1 + 2\left(\frac{y}{a}\right)^2\right]^2 \left[1 - \exp\left(-\frac{y^+}{21{\cdot}0}\right)^2\right]\right\}^{\frac{1}{2}} - \frac{1}{2}. \quad (25)$$

We assume that $f(\xi/x_0)$ is given by the equation

$$f\left(\frac{\xi}{x_0}\right) = e^{-\xi/x_0}. \quad (26)$$

From the matching of the measured and calculated eddy diffusivities at $y/a = 0{\cdot}7$ discussed in the previous section for a homogeneous field, we obtain an estimate of $x_0/a \cong 2{\cdot}75$. From the matching at $y/a = 1{\cdot}0$ for a non-homogeneous field discussed in the next section, we also obtain the same estimate. Calculated eddy conductivities in the region $y^+ = 30$ to $y/a = 0{\cdot}15$ are shown in Fig. 6 for $Re = 52\,500$ and for $x_0/a = 2{\cdot}75$. It is seen that good agreement is obtained with measurements as represented by equation (4). A value of the von Kármán constant for heat transfer of 0·43 is predicted for $Re = 52\,500$. This is to be compared with the value of 0·45 indicated by the experiments of Johnk [8]. In order to illustrate the effect of the variation of U on ε_h as suggested by (14), we have carried out the same calculation using a plug flow assumption, $U = U_b$; and the value of

$$\frac{(\overline{v^2})^{\frac{1}{2}}}{U^*} = 0{\cdot}97$$

suggested by the measurements of Laufer [5] close to a wall shown in Fig. 2. It is seen that much poorer agreement between the calculated and measured values of eddy conductivity is obtained.

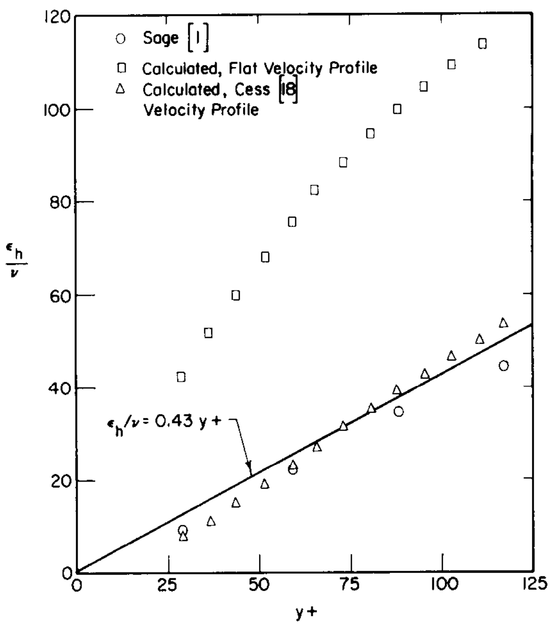

FIG. 6. Eddy diffusivity close to wall. $Re = 52\,500$.

It is seen in Fig. 6 that the logarithmic region where equation (4) is valid covers only a small range of y^+ at $Re = 52\,500$. Therefore, calculations were carried out at $Re = 500\,000$ using a value of $x_0/a = 2{\cdot}75$. As seen in Fig. 7 good

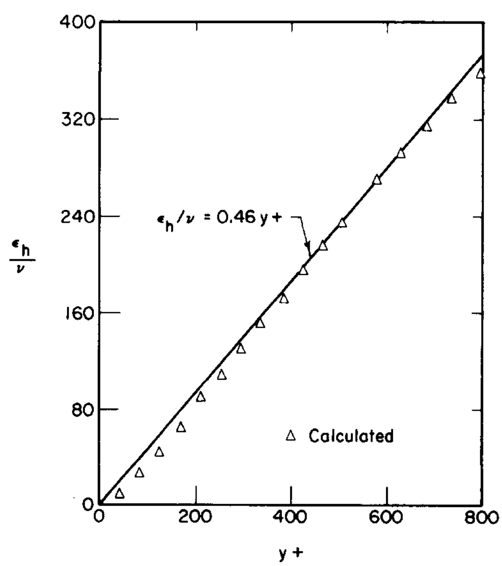

FIG. 7. Eddy diffusivity close to wall, $Re = 500\,000$.

agreement is obtained with (4) and a von Kàrmàn constant for heat transfer of 0·46 is calculated.

4. EMPIRICAL CORRECTION FOR THE VARIATION OF TURBULENCE PROPERTIES

The values of ε_h computed by the methods outlined in the previous section deviate considerably from measured ε_h for $y/a > 0{\cdot}15$ (see Fig. 8). We interpret this as being due primarily to the variation in the turbulence properties. For example, if we had used a value of $(\overline{v^2})^{\frac{1}{2}}/U = 0{\cdot}039$ corresponding to $y/a = 0{\cdot}7$, much better agreement would be obtained in the central region of the channel.

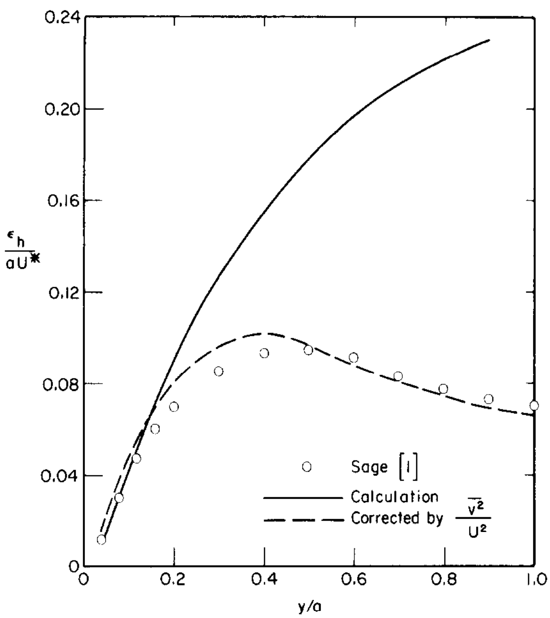

FIG. 8. Empirical correction of calculated eddy diffusivities.

In order to illustrate the influence of the variation of turbulence properties, we assume that the x-scale of the turbulence is approximately constant over the channel cross section. From a consideration of some of the ideas advanced in section 2, we would expect the eddy conductivity in the region where

$$\frac{(\overline{v^2})^{\frac{1}{2}}}{U}$$

is varying to correspond to diffusional behavior at large times and therefore, that ε_h is varying approximately as $\overline{v^2}/U^2$. We have, therefore, corrected the values of ε_h calculated in the previous section by the ratio of the local value of $\overline{v^2}/U^2$ to the value of $\overline{v^2}/U^2 = 0{\cdot}00397$ valid for the region close to the wall. The value of $x_0/a = 2{\cdot}75$ used in these calculations was selected so that the calculated ε_h agrees with the measured ε_h at $y/a = 1{\cdot}0$. It is seen that the trend of the calculated values of ε_h is the same as that for the measured ε_h. It would appear that the deviation of the measured eddy conductivities from those calculated for large y/a by methods outlined in the previous section can be interpreted as mainly due to the decrease in $\overline{v^2}/U^2$ with increasing y.

ACKNOWLEDGEMENT

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INTERPRETATION DES VARIATIONS MESUREES DE CONDUCTIVITE PAR TURBULENCE

Résumé—On donne une interprétation de la variation observée des conductivités par turbulence ε_h dans un canal chauffé. Un modèle homogène qui suppose des propriétés de turbulence constantes et un écoulement par tranche explique l'allure du profil de conductivité par turbulence. La grande variation de ε_h près de la paroi est expliquée comme étant principalement due à la dépendance vis à vis du temps du processus de diffusion par turbulence. Afin d'obtenir un meilleur accord avec les mesures, le modèle homogène doit être modifié pour tenir compte de la variation de la vitesse moyenne et de l'intensité de turbulence. Les valeurs de la constante de Von Kármán relatives au transfert thermique sont calculées et trouvées en bon accord avec l'expérience.

INTERPRETATION VON GEMESSENEN ÄNDERUNGEN DER WIRBELAUSBREITUNG

Zusammenfassung—Es wird eine Interpretation der beobachteten Änderungen der Wirbelausbreitung ε_h in einem geheizten Kanal gegeben. Ein homogenes Modell, welches konstante Turbulenzeigenschaften annimmt und eine Pfropfenströmung erklären die grobe Charakteristik des Wirbelausbreitungsprofils. Die grosse Änderung von ε_h nahe der Wand wird mit der Zeitabhängigkeit des Turbulenzvermischungsprozesses erklärt. Um bessere Übereinstimmung mit den Messungen zu bekommen, muss das homogene Modell verändert werden, um den Änderungen der Durchschnittsgeschwindigkeit und Turbulenzintensität Rechnung zu tragen. Dies wird gemacht und Werte der von Kármán-Konstanten für Wärmeübertragung berechnet. Sie stehen in guter Übereinstimmung mit dem Experiment.

ИНТЕРПРЕТАЦИЯ РЕЗУЛЬТАТОВ ИЗМЕРЕНИЙ ВИХРЕВОЙ ПРОВОДИМОСТИ

Аннотация—Дается объяснение наблюдаемых изменений вихревой проводимости ε_h в нагреваемом канале. Однородная модель, в которой характеристики турбулентности считаются постоянными, а течение стержневым, объясняет основные особенности профиля вихревой проводимости. Значительное изменение ε_h вблизи стенки объясняется, в основном, зависимостью процесса турбулентной диффузии от времени. Для получения лучшего соответствия с измерениями требуется модификация однородной модели для учета изменений средней скорости и интенсивности турбулентности. При этой модификации рассчитаны значения постоянной Кармана для теплообмена, которые хорошо согласуются с экспериментом.