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INLET TURBULENCE INTENSITY LEVEL AND CROSS-STREAM DISTRIBUTION EFFECTS ON THE HEAT TRANSFER IN PLANE WALL JETS

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CONTRACTOR REPORT

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INTRODUCTION

Numerical simulation has become established, along with experimental and analytical investigation, as a useful tool for the analysis and design of engineering equipment that encounters fluid flow and heat transfer. An important requirement for employing the numerical simulation tool is the specification of the appropriate initial and boundary conditions to complement the conservation equations that govern the momentum and energy transfers of the flow within the domain of interest.

One requirement that is crucial to obtaining meaningful results is the proper specification of the values of the dependent variables at the inlet of the flow domain. Earlier contributions by Sturgess et al. [1], Nallasamy and Chen [2], and Crawford [3] have focused on some aspects of the problem.

Ideally, the values of the dependent variables at the domain inlet should be obtained from measurements. A full complement of measured values of the dependent variables at the inlet is, however, almost always unavailable. The numerical analyst is thus required to make estimates of at least some of these variables at the inlet in order to initiate his numerical code.

The specific flow problem addressed in the present investigation is the effect of the turbulence intensity level and its cross-stream distribution at the inlet on the heat transfer prediction in a two-dimensional turbulent wall jet. The results obtained from numerical simulation are compared with the experimental data of Hishida et al. [4].

FORMULATION

Governing Equations

In the present work, the essentially parabolic flow situation of a plane jet is described using the fully elliptic two-dimensional form of the Navier Stokes equations. Thus, the governing conservation equations for the mean turbulent motion and heat transfer obtained by applying the Reynolds decomposition and time averaging of the instantaneous continuity, momentum, and energy equations are written as follows:

$$\frac{\partial}{\partial x_j} (\rho U_j) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j} (\rho U_i U_j) = - \frac{\partial}{\partial x_i} P + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial}{\partial x_j} U_i \right) - \frac{\partial}{\partial x_j} (\rho \, \overline{u_i' u_j'}) \tag{2}$$

$$\frac{\partial}{\partial x_j} (\rho \, C_p \, U_j \, T) = \frac{\partial}{\partial x_j} \left(\lambda \frac{\partial}{\partial x_j} T \right) - \frac{\partial}{\partial x_j} (\rho \, C_p \, \overline{u_j' T'}) \quad . \tag{3}$$

The closure of the Reynolds stresses is achieved using the k-ε turbulence model. Transport equations for k, the turbulence kinetic energy, and ε, its dissipation rate, are written as follows:

$$\frac{\partial}{\partial x_j} (\rho U_j k) = \frac{\partial}{\partial x_j} \left(\frac{\mu_t}{\sigma_k} \frac{\partial k}{\partial x_j} \right) + \rho G_k - \rho \varepsilon \tag{4}$$

and

$$\frac{\partial}{\partial x_j} (\rho U_j \varepsilon) = \frac{\partial}{\partial x_j} \left(\frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right) + \rho \frac{\varepsilon}{k} (C_1 G_k - C_2 \varepsilon) \tag{5}$$

where ρG_k, the turbulence kinetic energy production, is given by

$$\rho G_k = \mu_t \left[2 \left\{ \left(\frac{\partial u_i}{\partial x_i} \right)^2 + \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)^2 \right\} \right] . \tag{6}$$

Boundary Conditions

Solid Boundary

In the present investigation, the near-wall region of the flow domain is not resolved numerically. Instead, the standard wall-function approach is used to impose wall boundary conditions on the velocity and temperature as well as the turbulence kinetic energy and its dissipation rate. The formulation used for the temperature wall function is that presented by Hammond [5].

Open Boundary

The need to specify boundary conditions for an open boundary parallel to the direction of mean jet motion, as well as for an exit boundary at some downstream location, is a direct consequence of the treatment of the flow as elliptic rather than parabolic. The open boundary is located sufficiently far away from the slot from which the jet issues. This makes it possible to impose zero normal gradient conditions for all the variables at the open boundary. An open boundary located ten slot widths from the origin was found to be adequate for achieving the desired boundary condition for the present investigation. A similar approach was adopted by Amano and Brandt [6] and Leschziner and Rodi [7].

Inlet Boundary

One serious limitation associated with most experimental data of fluid flow and heat transfer available in the open literature is the lack of a complete set of data for all the variables of interest at the inlet plane of the flow domain. The fluid flow and heat transfer numerical analyst is thus almost always constrained to specify as best he can the values of the flow variables required at the domain inlet in order to initiate his code.

In the present study, the effect of the intensity level and cross-stream distribution profile of the turbulence kinetic energy (TKE) at the inlet plane on the heat transfer in plane wall jets is demonstrated. Four different values of the TKE level, varying through one order of magnitude, were investigated. Also, its cross-stream distribution was varied from a uniform profile to various plausible profiles assumed below and similar to the one-seventh power law used to specify turbulent velocity profiles.

<u>The Cross-Stream Turbulence Intensity Profile</u>

It is generally known from experimental data that for wall-bounded flows the TKE is maximum at the wall, being the region of the highest shear production and minimum at the center where there is no production. A possible profile of the TKE distribution in a fully-developed wall-bounded flow is shown schematically in Figure 1b.

The mean value of the TKE is usually specified as a percentage of the kinetic energy of the mean flow at inlet. Thus

$$\bar{k} = C_k \, U_{in}^{\ 2} \tag{7}$$

where

$$u = U + u' \quad . \tag{8}$$

However, the maximum and minimum values of the TKE for the k(y) profile in Figure 1b are not known and these can be varied to investigate their effect on the heat transfer.

The one-seventh power law profile for the turbulent velocity in a two-dimensional planar channel, as depicted in Figure 1a, is

$$u = u_{max} \left[\frac{4y}{W^2} (W - y) \right]^{1/7} \tag{9}$$

where

$$u_{max} = U(8/7) \quad . \tag{10}$$

A plausible profile for the TKE, as shown in Figure 1b, and complementary to that above for the streamwise velocity, is

$$k = k_{min} \left[1 + (\beta - 1) \left\{ 1 - \left[\frac{4y}{W^2} (W - y) \right]^{1/7} \right\} \right] \tag{11}$$

where

$$\beta = k_{max}/k_{min} \quad . \tag{12}$$

The minimum TKE, k_{min}, which appears in equation (11) is related to the mean TKE, $\bar{k}$ which is known from equation (7), in conjunction with the total TKE per unit depth convected into the flow domain of interest at the inlet plane obtained from

$$w \, U \, \bar{k} = 2 \int_{o}^{w/2} dy \, u \, k \quad . \tag{13}$$

Note that for convenience, the origin for the integration above is taken at the channel centerline. Substituting the u(y) and k(y) profiles into the RHS of equation (13) and integrating yields

$$k_{min} = \bar{k} \; [9/(\beta+8)] \quad . \tag{14}$$

The effects of various k(y) profiles at the inlet plane can now be investigated by varying the parameter β. A value of unity for β yields a uniform k(y) profile. The corresponding $\varepsilon(y)$ profile is specified as

$$\varepsilon = C_{\mu}^{3/4} \, k^{3/2} \, L \tag{15}$$

where L is an appropriately specified turbulence length scale.

In fully-developed axisymmetric flows, the corresponding equations for the u(y) and k(y) profiles appropriate to the coordinate systems, shown in Figure 2, are as follows:

$$u = u_{max} = \left[\frac{1}{D}(D - 2y)\right]^{1/7} , \tag{16}$$

where

$$u_{max} = U\ (120/98) \quad . \tag{17}$$

Also,

$$k = k_{min}\left[1 + (\beta - 1)\left\{1 - \left[\frac{1}{D}(D - 2y)\right]^{1/7}\right\}\right] , \tag{18}$$

where

$$\beta = k_{max}/k_{min} , \tag{19}$$

and

$$k_{min} = \bar{k}\ [6/(\beta + 5)] \quad . \tag{20}$$

<u>Exit Boundary</u>

The exit boundary is located sufficiently far downstream that the zero normal gradient condition can be specified for all the dependent variables.

NUMERICAL SCHEME

The governing partial differential equations subject to the appropriate boundary conditions, as presented in the previous section, are solved using the finite-volume SIMPLE algorithm of Patankar and Spalding [8] and Patankar [9]. A staggered grid scheme in which the momentum vector cells are displaced from the scalar cells, as outlined in the above references, was adopted.

The computation was carried out on a 40 W by 10 W flow domain where W is the slot width. A 52 x 32 non-uniform grid distribution was used.

RESULTS AND DISCUSSION

The experimental data of Hishida et al. [4] have been used to provide the necessary physical basis for evaluating the numerical predictions. The results obtained from the numerical simulations indicate a significant effect of the magnitude and cross-stream distribution of the turbulent kinetic energy on the predicted heat transfer in the immediate vicinity of the slot. A comparison of the predicted and measured Nusselt numbers for an inlet flow Reynolds number of 1700 and TKE values at the inlet of between 0.5 and 5 percent of the mean flow kinetic energy is presented in Figure 3. The difference in predicted Nusselt number, due to different TKE intensity levels at inlet, is restricted to an x/w value of about 15 from the inlet. All the predictions collapse onto a single curve for x/w values greater than 15. The predicted Nusselt number exhibited a maximum over-prediction of about 30 percent in this region of the flow.

Curves A, B, C, and D in Figure 3 show clearly the significant influence of the intensity level of the TKE at the inlet on the predicted heat transfer in the development region of the jet. A similar but less intense effect is observed in Figure 4 which shows the effect of the cross-stream distribution of the TKE at a single TKE intensity level of 1 percent of the inlet mean flow kinetic energy. These predictions demonstrate the importance of the proper specification of the TKE intensity level as well as cross-stream distribution in order to obtain correct heat transfer predictions especially in the first 15 slot widths from the inlet slot.

Figures 5 and 6 are similar to Figures 3 and 4 but at almost double the flow Reynolds number. The predicted Nusselt numbers in the latter two figures are generally higher than those obtained at the lower Reynolds number flows. However, the trends observed at the higher Reynolds numbers are the same as were observed for the lower Reynolds number flows.

CONCLUSION

A numerical study has been undertaken in which the influence of the turbulent kinetic energy intensity level and cross-stream distribution at the inlet on the heat transfer in a two-dimensional turbulent wall jet was investigated. Both parameters were shown to influence significantly the predicted Nusselt number in the developing region of the jet, with the zone of influence restricted to about 15 slot widths from the point of issue. However, this influence did not extend beyond the x/w = 15 location and all the predictions were observed to collapse onto a single curve in the fully-developed jet region. The predicted Nusselt number in the fully-developed region showed a maximum over-prediction of about 30 percent when compared with the experimental data.

A proper specification of the turbulence kinetic energy at the inlet, preferably obtained from the experiment, is very important for the correct prediction of the heat transfer in the development region of a wall jet.

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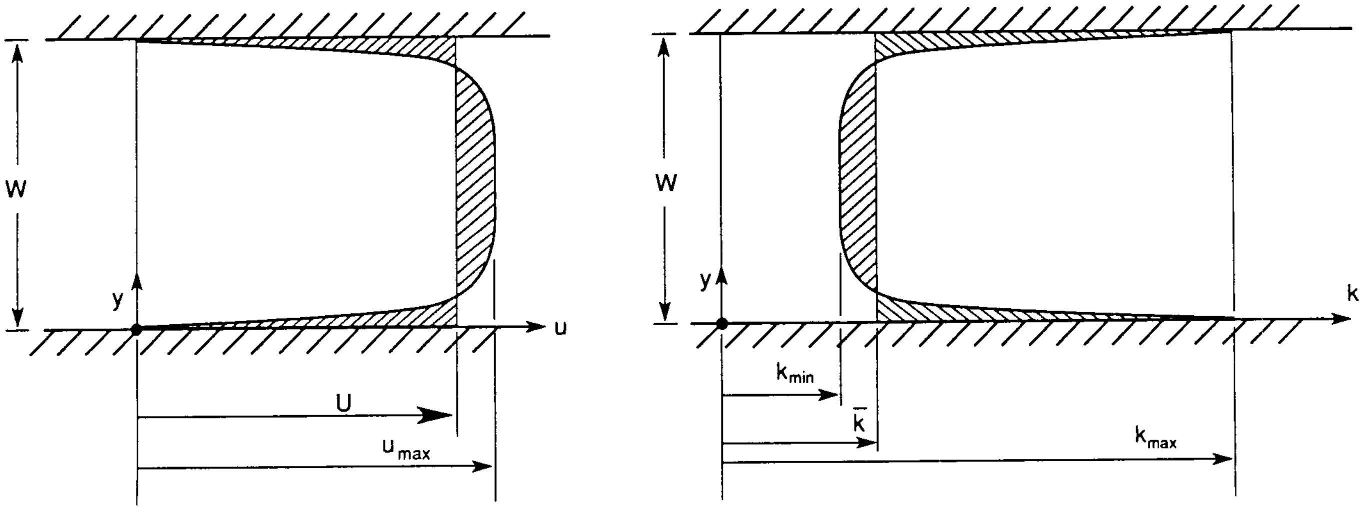
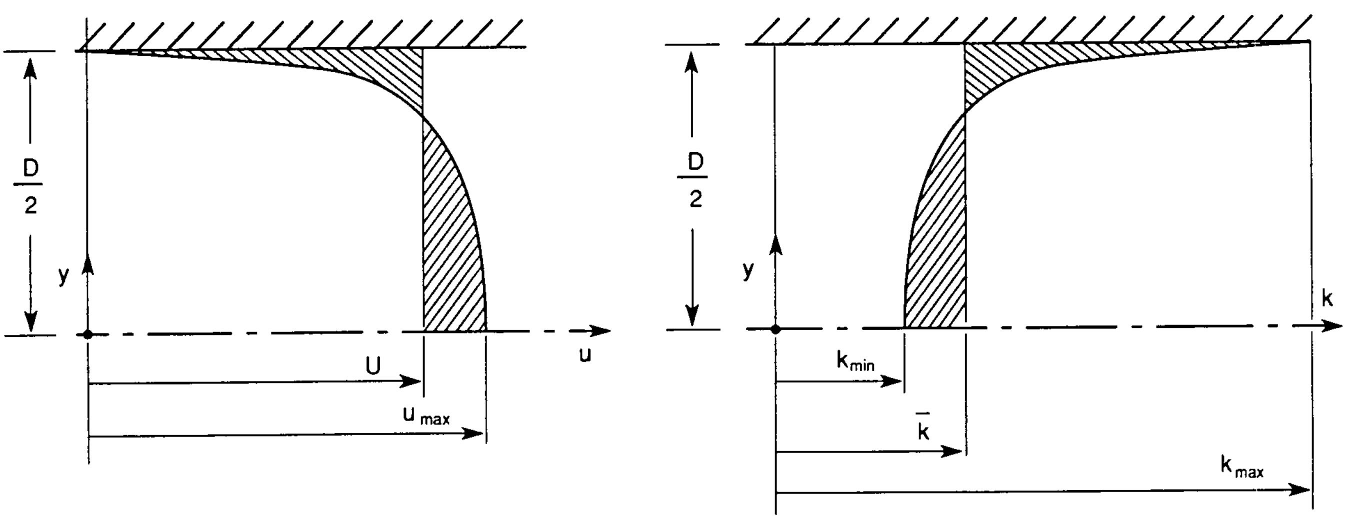


(a) u (y) – PROFILE

(b) k (y) – PROFILE

Figure 1. Streamwise velocity and TKE profiles for fully-developed flow in two-dimensional planar channels.



(a) u (y) – PROFILE

(b) k (y) – PROFILE

Figure 2. Streamwise velocity and TKE profiles for fully-developed flow in axisymmetric channels.

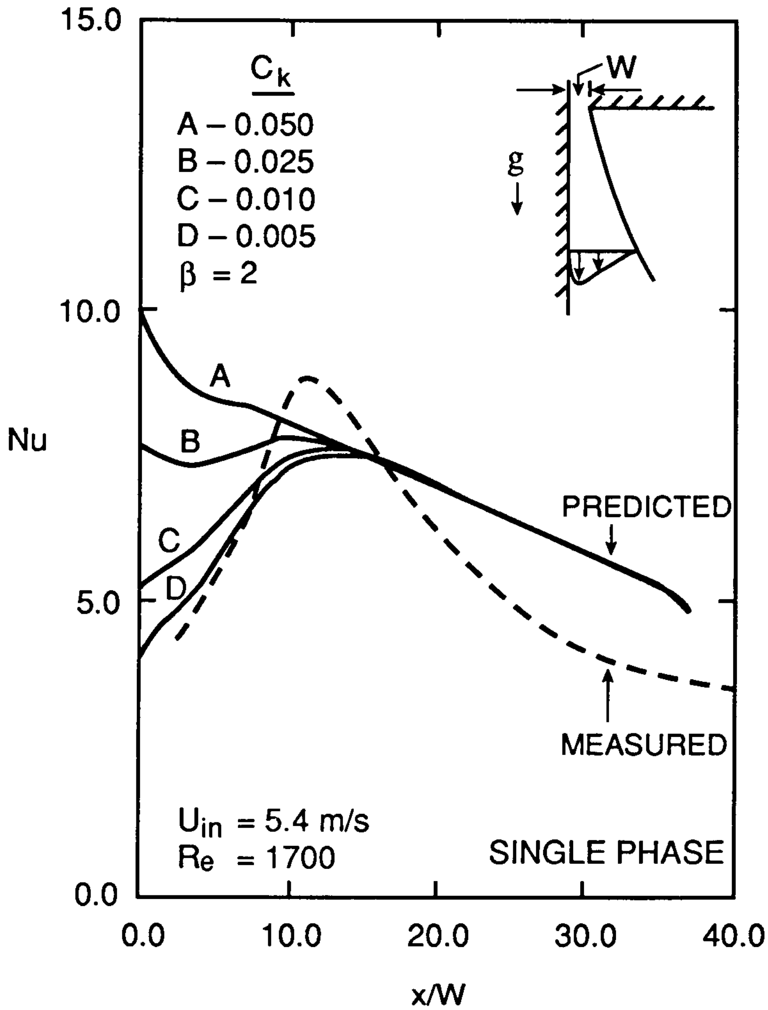


Figure 3. Effect of turbulence intensity at inlet for Re = 1700.

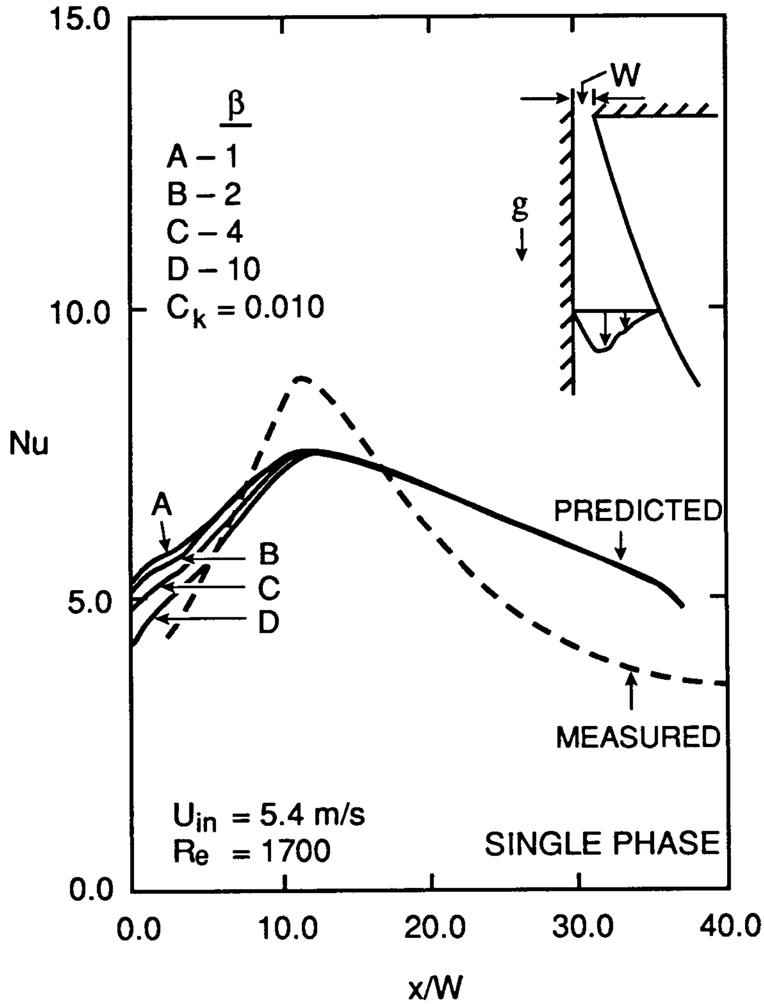


Figure 4. Effect of turbulence intensity cross-stream distribution at inlet for Re = 1700.

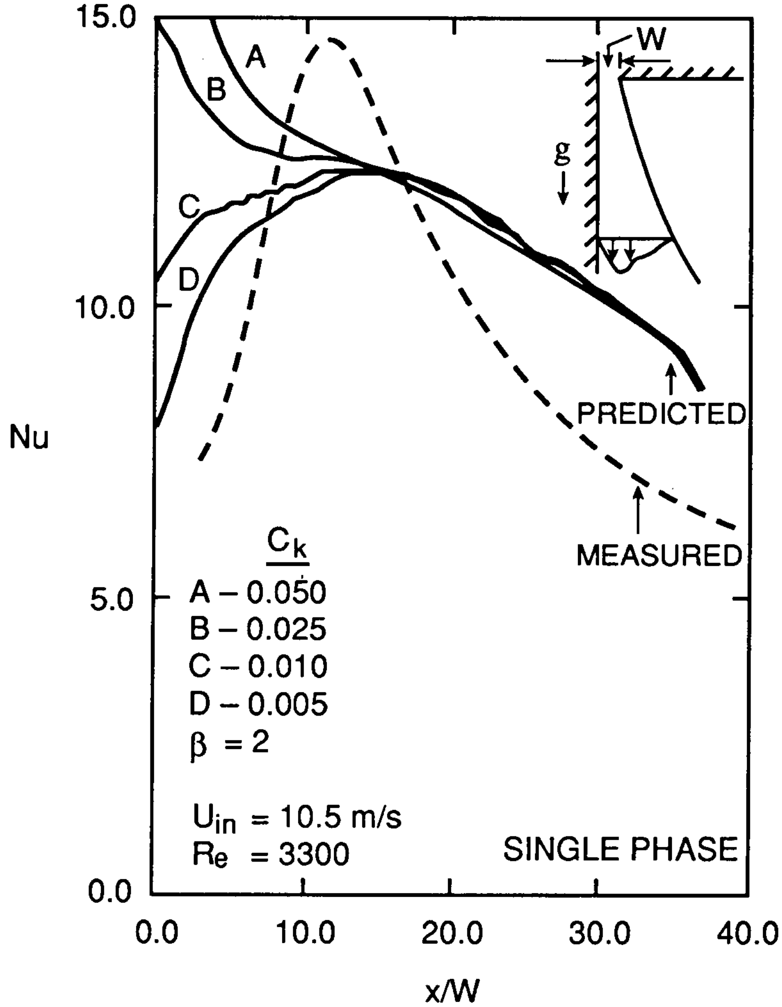


Figure 5. Effect of turbulence intensity at inlet for Re = 3300.

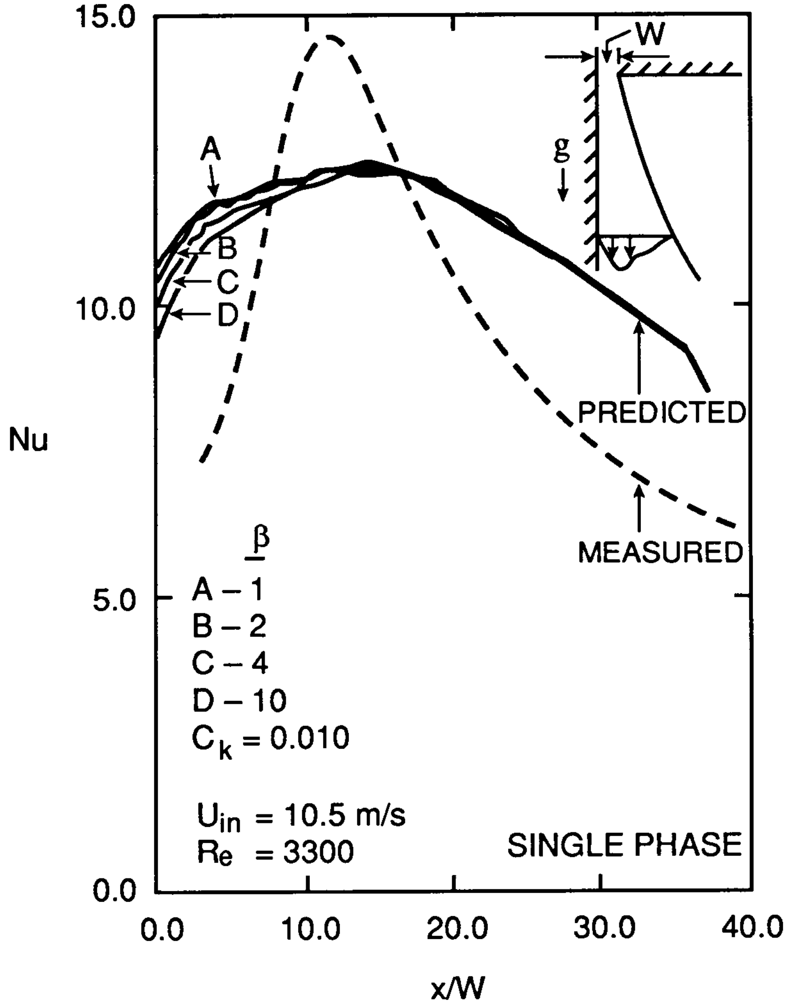


Figure 6. Effect of turbulence intensity cross-stream distribution at inlet for Re = 3300.

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16. ABSTRACT

The effect of the turbulence intensity level and its cross-stream distribution at the inlet on the numerical prediction of the heat transfer in a two-dimensional turbulent-wall jet has been investigated. The investigation was carried out within the framework of the standard k-ε turbulence model. The predicted Nusselt number showed the influence of the turbulence intensity level and its cross-stream distribution at the inlet to be significant but restricted to the first 15 slot widths from the inlet slot. Beyond this location, all the predictions were observed to collapse onto a single curve which exhibited a maximum over-prediction of about 30 percent when compared with the available experimental data.

17. KEY WORDS

Turbulence Intensity Level
Two-Dimensional Turbulent Wall Jet
k-ε Turbulence Model

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