Turbulence enhancement of stagnation point heat transfer on a circular cylinder

G. K. Hargrave*†, M. Fairweather*† and J. K. Kilham*

Heated turbulent air jets were used to study the turbulent enhancement of convective heat transfer to the stagnation region of a circular cylinder. Increases in heat transfer were found to be primarily dependent on the Reynolds number and turbulence intensity of the free stream, experimental data being successfully correlated on the basis of $NuRe^{-0.5}$ versus $TuRe$ or $TuRe^{0.5}$. The results are in good qualitative agreement with those obtained by previous workers in wind tunnel studies, but show that increases in stagnation point heat transfer are more susceptible to free stream turbulence than indicated in earlier investigations. Predictions of a phenomenological theory of the enhancement process are in reasonable agreement with experimental results. The effect of turbulence in increasing the stagnation point velocity gradient has also been evaluated.

Keywords: *heat transfer, convection, turbulence enhancement, cylinder, stagnation point, air flows*

Introduction

It is well established that free stream turbulence augments the rate of heat transfer in flows with large streamwise pressure gradients. This effect has been observed experimentally for turbulent air flowing around circular cylinders[1,2], spheres[3,4] and hemispherical-nosed cylinders[5]. Theoretical treatments capable of predicting the enhancement effect from actual turbulence properties of the free stream have also appeared in the literature[6-8]. The amplification of free stream turbulence by the selective stretching of vortex filaments in the diverging flow near a stagnation point, and the interaction of this intensified turbulence with the body boundary layer, is now accepted as being responsible for the augmentation process[9].

The main effect of free stream turbulence in enhancing heat transfer rates is found at the stagnation point of a body where an otherwise laminar boundary layer exists. The majority of experimental studies of stagnation point heat transfer have concerned two-dimensional flow normal to circular cylinders, most of this work having been conducted in wind tunnels. The present paper seeks to further these studies by examining the augmentation effect at the stagnation point of a circular cylinder placed in turbulent air jets. This work, together with that described in Ref 5, has been performed with a view to eventual application to heat transfer from impinging turbulent jet flames. Such flames are widely used in industry in order to provide high convective heat transfer rates.

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The present work also examines the effect of free stream turbulence on the stagnation point velocity gradient, an aerodynamic parameter required for the prediction of heat flux from known free stream properties.

Turbulent flow around a circular cylinder

Following the experimental findings of Kuethe *et al*[10], Sutera *et al*[9,11] proposed a vorticity-amplification theory to explain the evolution of turbulence in the flow approaching a cylinder and its effect on the stagnation point boundary layer. This theory suggests that turbulent fluctuations present in the free stream flow are susceptible to undergoing significant amplification as they are conveyed by a diverging mean flow towards the stagnation point of a body. Selective stretching of vortex filaments oriented laterally to the free stream direction was proposed as the mechanism responsible for the amplification of vorticity, and hence of free stream turbulence. For particular scales greater than a certain neutral scale, this process gives rise to high levels of turbulent energy near the stagnation zone since vorticity increases in amplitude more rapidly than it is dissipated by viscous action. This intensified turbulence is then considered to be the agent causing increases in shear stress and heat transfer at the surface of the body by inducing substantial three-dimensional effects in the stagnation point boundary layer. Scales smaller than the neutral are considered to be attenuated by viscous dissipation as they are convected towards the body, and therefore do not influence the boundary layer. Kestin and Wood[12] have also demonstrated that the flow field in the boundary layer formed at the stagnation zone of a cylinder is essentially three-dimensional in character.

Experimental verification of the vorticity-amplification theory for the two-dimensional flow around a cylinder has been obtained by Sadeh *et al*[13,14]. Flow visualization studies confirmed the presence of selective stretching and streamwise tilting of vortex filaments in the diverging flow approaching a cylinder. These processes were seen to lead to the development of an array of standing cross-vortex tubes distributed about the stagnation zone of the cylinder, with their axes parallel to the streamlines around the body and with their cores slightly outside the body boundary layer. Discrete vortices were also seen to be continuously drawn from this vortex array, being swept downstream by the main flow whilst penetrating the body boundary layer.

The idealized three-dimensional flow pattern which exists at the stagnation zone of a cylinder, deduced from the work described above, is illustrated in Fig 1.

Experimental work

Stagnation point velocity gradient

The stagnation point velocity gradient β describes the flow just outside the boundary layer of a body by defining the velocity gradient in the mean flow as it moves away

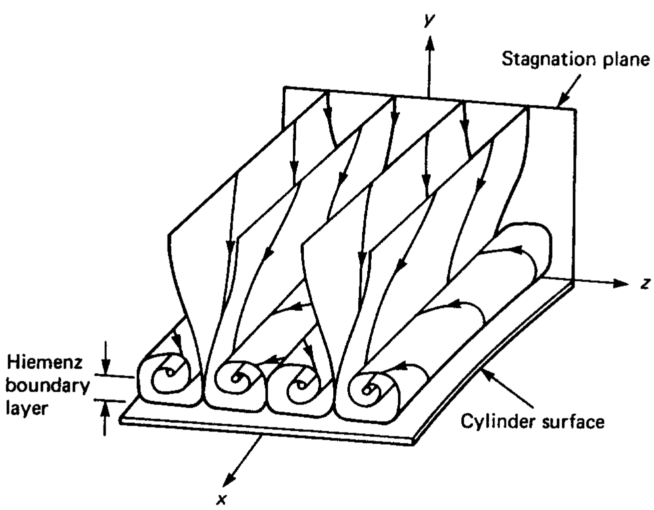

Fig 1 Idealized three-dimensional flow pattern at the stagnation zone of a cylinder

from the stagnation point around the body. As noted earlier, this aerodynamic parameter is required in the prediction of stagnation point heat transfer rates from known free stream properties. Such a prediction method is described in a later section.

Heat flux predictions for cylinders placed in laminar[15] and turbulent[6] free streams have previously been made on the basis of an analytical expression for β derived for cylinders in laminar flows. Assuming incompressible laminar flow at a two-dimensional stagnation point, therefore, potential flow analysis yields[16]

$$\beta = \frac{K u_\infty}{D} \tag{1}$$

with K equal to 4. For subcritical Reynolds numbers, experimental values of β are approximately 5% less than theoretical values[15], giving K equal to 3.8. However, heat transfer studies performed using both turbulent air jets[17,18] and premixed jet flames[19] have revealed that β is a function of free stream turbulence intensity as well as velocity. This finding was investigated by the present authors for the case of turbulent air jets impinging on a body of revolution (hemispherical-nosed cylinder) in the work reported in Ref 5, where it was found that the effects of free stream turbulence on β could be accommodated by assuming K to be a simple function of turbulence intensity.

In order to investigate this effect for the case of a cylinder, static pressure measurements were taken on the surface of such a body placed in turbulent air flows. Values of the velocity gradient parameter were then derived from static pressure distributions in the immediate vicinity of the stagnation point. The probe used in these experiments consisted of a 350 mm length of 22 mm outer diameter cylindrical copper tube, with a pressure tapping made from stainless steel hypodermic tubing of 0.8 mm inner diameter fixed flush with the outer surface of the cylinder. The hypodermic tube was connected to a micromanometer using narrow bore PTFE tubing.

Notation

a	Defined by Eq (10)
D	Diameter of cylinder
f'	Ratio of u at a point in boundary layer to value at boundary layer outer edge
k	Constant defined in Eq (5)
K	Defined in Eq (1)
Nu	Nusselt number
p	Pressure
Pr	Prandtl number
Re	Reynolds number
Re_T	Turbulent Reynolds number
T	Temperature
Tu	Turbulence intensity
u	Velocity component in x-direction
v	Velocity component in y-direction
x	Distance along surface of cylinder from stagnation point
y	Distance perpendicular to cylinder surface through boundary layer
z	Spanwise coordinate
α	Thermal diffusivity
β	Stagnation point velocity gradient
ε	Momentum and thermal eddy diffusivity
η	Transformed y coordinate
θ	Defined by Eq (9)
ν	Kinematic viscosity
ρ	Density
ψ	Stream function

Subscripts

e	Evaluated at outer edge of boundary layer
s	Stagnation point value
w	Evaluated at body surface
x	Local value
∞	Free stream value

Superscripts

Differentiation with respect to η

Isothermal air jets were generated using two 500 mm long cylindrical tubes with internal diameters of 16 and 32 mm. Both tubes included a facility for introducing fine wire meshes close to the input nozzle in order to smooth out turbulence generated by the input pipes. Various turbulence promoters, in the form of perforated metal plates, could also be mounted in the vicinity of the exit nozzle. In the present study five such promoters were used with the 32 mm diameter nozzle, and two with the smaller diameter tube. Exit turbulence intensities and mean flow velocities over the ranges 0.018–0.180 and 2.75–10.00 m s^{-1}, and 0.070–0.110 and 5.0–20.0 m s^{-1}, were obtained using the larger and smaller nozzle diameters, respectively.

In conducting these experiments the pressure probe was fixed so that it could be rotated about the axis of the cylindrical tube, thereby allowing the pressure tapping to be located at any position relative to the probe stagnation point. The tube used to generate turbulent air jets was mounted on a two-axis traverse, allowing the exit nozzle to be positioned axially and radially relative to the pressure probe. Axial and radial free stream velocities were measured using laser Doppler anemometry (LDA), the system employed being of a dual-beam, forward-scatter design utilizing a 2 W argon ion laser. The flow field was seeded with alumina particles of 1 μm mean diameter using a fluidized bed cyclone device.

Convective heat transfer from heated air jets

Convective heat transfer to cylinders was studied using heated air jets issuing from the 16 mm diameter cylindrical tube employed for stagnation point velocity gradient measurements. Four perforated metal plate turbulence promoters were used with this tube to generate exit turbulence intensities over the range 0.012–0.230, with mean exit flow velocities ranging from 12–16 m s^{-1}. Heated air was supplied to this tube using a series of electrical heating elements producing a mean temperature of approximately 600 K at the exit nozzle. A means of seeding this air was included to allow free stream velocity measurements using the LDA system.

A transient calorimeter, shown in Fig 2, was constructed for the measurement of heat flux at the stagnation point of a 22 mm diameter cylindrical body. In this device a 3.2 mm diameter by 1.0 mm thick copper slug, with a chromel–alumel thermocouple attached to the rear surface, was fixed using epoxy resin at the stagnation point of a 250 mm long solid brass cylinder. Operation of the calorimeter consisted of rapidly exposing the probe to the flow field using a pair of push–pull solenoids and monitoring the instantaneous temperature at the rear surface of the slug using a microcomputer-based data logging system. From the known thermal properties of the copper slug it was then possible to relate the rate of temperature rise at the rear surface to the heat flux at the exposed face[20]. The calorimeter was calibrated for heat losses by comparison with a steady state device[5].

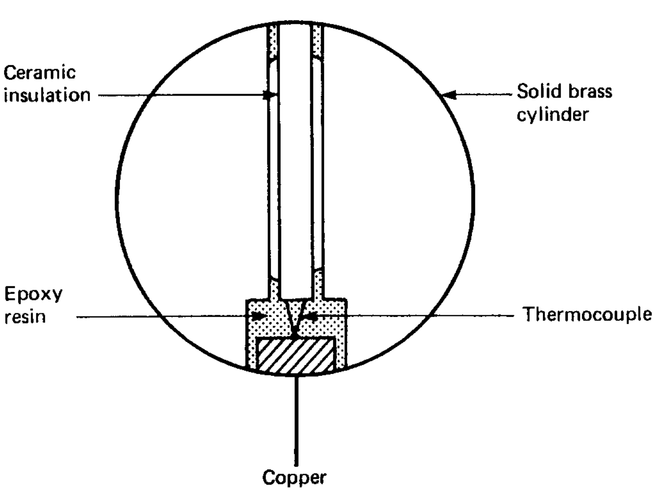

Fig 2 Schematic of the transient calorimeter

Temperatures along the axis of an air jet were measured using a precalibrated micro-suction pyrometer. Radial temperatures were determined by the use of fine wire chromel–alumel thermocouples.

Theoretical work

The phenomenological theory proposed by Smith and Kuethe[6], and used later by Galloway[7], may be employed to predict the influence of free stream turbulence on stagnation point heat transfer. Assuming a turbulent Prandtl number of 1, the boundary layer equations for constant property incompressible flow near a two-dimensional stagnation point may be written as

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{2}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\frac{\partial}{\partial y}\left((v+\varepsilon)\frac{\partial u}{\partial y}\right) \tag{3}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\partial}{\partial y}\left((\alpha+\varepsilon)\frac{\partial T}{\partial y}\right) \tag{4}$$

where the eddy diffusivity ε is used to accommodate the complexities of the enhancement process in a simple manner.

In line with the assumption that the enhancement process is caused by the penetration of free stream eddies into an otherwise laminar boundary layer[6,7], an eddy law may be formulated such that[5]

$$\varepsilon=kTu_\infty u_\infty y \tag{5}$$

Here, the fluctuating velocity within the boundary layer is expected to be proportional to the external free stream turbulence and flow conditions since these fluctuations are caused by penetration from the free stream. The term k is a constant which remains to be determined from comparisons with experimental data.

Using a stream function defined to satisfy the continuity equation in the normal way, the momentum and energy conservation equations may be transformed by defining

$$u_e=\beta x \tag{6}$$

$$\psi=(v\beta)^{0.5}xf(\eta) \tag{7}$$

$$\eta=(\beta/v)^{0.5}y \tag{8}$$

$$\theta=\frac{T_w-T(\eta)}{T_w-T_\infty} \tag{9}$$

$$a=\frac{k}{2}Tu_\infty Re_\infty^{0.5} \tag{10}$$

to give

$$f'''(1+a\eta)+f''(f+a)+(1-(f')^2)=0 \quad (11)$$

$$\theta''+\frac{\theta'(f+a)}{\left(a\eta+\frac{1}{Pr}\right)}=0 \quad (12)$$

where prime denotes differentiation with respect to η. The transformed boundary conditions are

$$f(0)=f'(0)=0 \quad \text{and} \quad f'(\infty)=1 \quad (13)$$

$$\theta(0)=0 \quad \text{and} \quad \theta(\infty)=1. \quad (14)$$

Eqs (11) and (12) were solved using Merson's method in conjunction with a Newton iteration in a shooting-and-matching technique[21]. The variation of $NuRe^{-0.5}$ with chosen values of k and $TuRe^{0.5}$ in Eq (10) was then obtained from

$$NuRe^{-0.5}=2\theta'(0) \quad (15)$$

where in deriving the above it has been necessary to assume $\beta=4u_\infty/D$.

Predictions of a model equivalent to that described, but which allows for density and property variations through the boundary layer as well as for the dependence of β on free stream turbulence, have also been used in the present study. This model was derived following the approach outlined above, but where the boundary layer equations for compressible flow were reduced to ordinary differential equations in the vicinity of the stagnation point using the Lees–Dorodnitsyn transformations[22]. The effect of free stream turbulence on heat transfer was incorporated in the boundary layer equations as described, with the same eddy law being used.

Results and discussion

Stagnation point velocity gradient

In measuring the static pressure distribution in the vicinity of the stagnation zone, the effects of varying radial velocity within the flow field were minimized by placing the pressure probe at axial locations which exhibited a substantially flat velocity profile over at least 80% of the cylinder diameter. Axial and radial profiles of mean velocity and turbulence intensity typical of the air jets used may be found in Ref 5.

Examples of the pressure distribution obtained in these experiments are given in Fig 3(a), where results for two free stream turbulence intensities at a constant mean velocity of $6.6\,\mathrm{m\,s^{-1}}$ are shown. Measured pressures around the probe were converted to local free stream velocities using Bernoulli's equation, the velocity distributions corresponding to the pressures shown in Fig 3(a) being given in Fig 3(b). In the vicinity of the stagnation zone the local flow velocity increases approximately linearly with distance around the body, and the effect of turbulence in increasing the velocity gradient at the stagnation point is readily apparent.

Values of the velocity gradient parameter K were obtained from plots such as those shown in Fig 3(b) by evaluating the gradient $d(u_x/u_\infty)/d(x/D)$ at the stagnation point. The dependence of this parameter on turbulence intensity determined in this way is shown in Fig 4, results being based on mean free stream velocities and turbulence

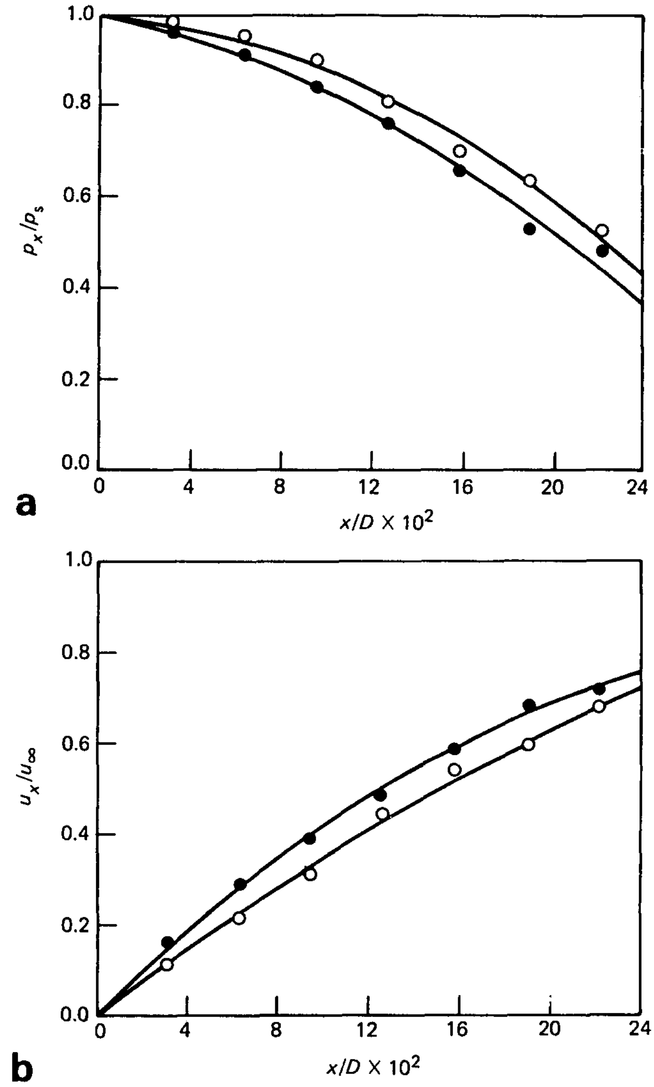

Fig 3 Distribution of (a) pressure and (b) velocity in the vicinity of the stagnation zone of a cylinder (○ $Tu_\infty=0.033$, ● $Tu_\infty=0.123$)

intensities over the ranges 3.0–$7.3\,\mathrm{m\,s^{-1}}$ and 0.018–0.178, respectively. A least-squares fit to this data yields

$$K=3.85+4.90Tu_\infty \quad (16)$$

where a first-order fit has been used owing to the scatter in the data. For such a fit a value of 3.85 is obtained for K for the case of a laminar free stream flow. This compares well with the experimental value[15] of 3.8 and the theoretical value[16] of 4 mentioned previously. In agreement with earlier findings[5], K was found to be invariant with mean free stream velocity over the limited velocity range examined.

Convective heat transfer from heated air jets

All heat flux measurements were again made in regions of the jets which exhibited substantially flat radial profiles of velocity and temperature over a significant proportion of the diameter of the cylindrical calorimeter. Profiles of mean velocity, turbulence intensity and temperature typical of the air jets used may be found in Ref 5.

Results for the axial variation of heat flux along the jet centreline at a number of turbulence intensities are

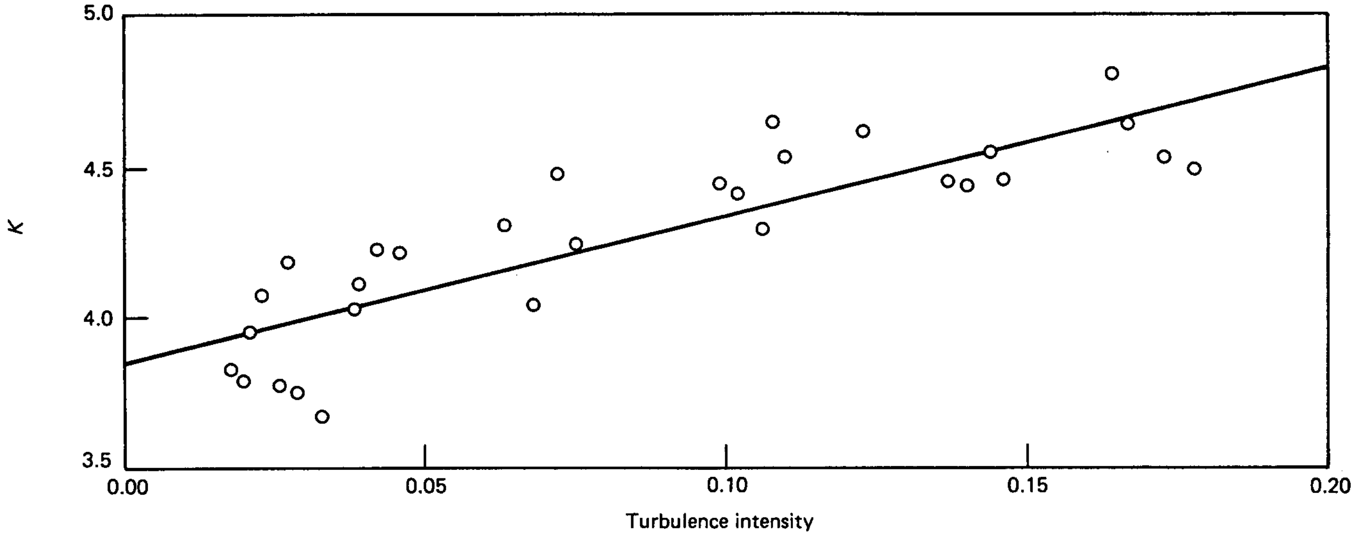

Fig 4 Variation of velocity gradient parameter K with turbulence intensity

given in Fig 5. These data were obtained in a jet issuing from the 16 mm diameter source, with a mean exit velocity of approximately $12\,m\,s^{-1}$, using all four turbulence promoters generating local turbulence intensities over the ranges indicated in the figure. Local values of mean velocity and temperature varied by less than 7% over the four turbulence intensity ranges considered. The effect of free stream turbulence in augmenting heat transfer rates at the stagnation point of the cylinder can be seen from this figure, and in agreement with earlier findings[2] the largest increases in heat flux occur for small increases in turbulence intensity at the lower values of turbulence intensity. Unlike the results of Lowery and Vachon[2], however, the data of Fig 5 indicate (even when plotted in terms of $NuRe^{-0.5}$) that the increase in heat flux reaches an asymptotic value for turbulence intensities of order 0.25 rather than 0.14.

All results from the present study are shown in terms of the variation of $NuRe^{-0.5}$ with turbulent Reynolds number in Fig 6, correlation in terms of the latter parameter having been suggested by the work of Van der Hegge Zijnen[23]. The dimensionless parameters in this, and subsequent, figures are based on mean free stream velocities and turbulence intensities, and on air properties evaluated at the mean boundary layer temperature. A least-squares fit to this data gives

$$NuRe^{-0.5} = 0.528(TuRe)^{0.151} \tag{17}$$

valid over the ranges $0.014 \leqslant Tu \leqslant 0.256$, $6837 \leqslant Re \leqslant 10742$, and $10.90\,m\,s^{-1} \leqslant u_\infty \leqslant 16.25\,m\,s^{-1}$.

The results given in this figure show that the relation between $NuRe^{-0.5}$ and Re_T is essentially linear over the turbulent Reynolds number range examined. This is in agreement with the experimental findings of other workers[1,2,6,24-26] although the latter works when taken as a whole show that a sharp increase in heat flux occurs for turbulent Reynolds numbers greater than approximately 2000 (see, for example, Miyazaki and Sparrow[27]). Insufficient data have been obtained in the present study to indicate any such transition. Also shown in Fig 6 is the empirical correlation derived by Dyban and Epick[28], which effectively represents an upper bound[27] to the data of Refs 1, 2, 6 and 24 to 26. As can be seen, the present results tend to over predict those of earlier studies over the majority of the Re_T range examined.

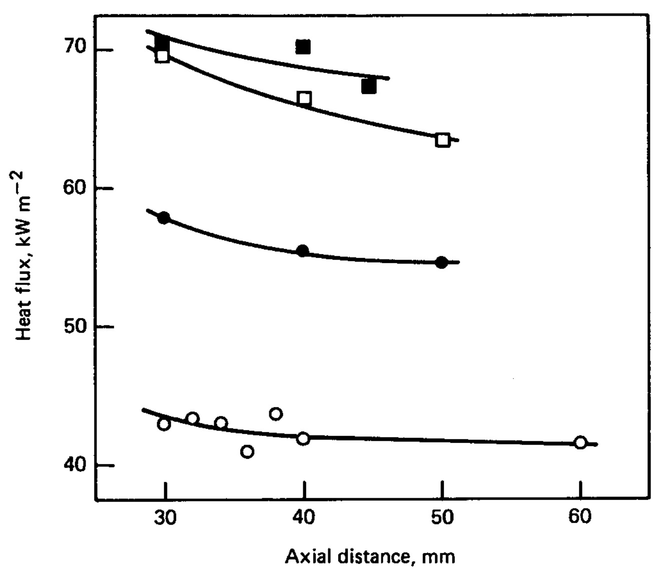

Fig 5 Effect of turbulence intensity on axial variation of heat flux (○ $Tu_\infty = 0.014$–0.022, ● $Tu_\infty = 0.047$–0.052, □ $Tu_\infty = 0.110$–0.123, ■ $Tu_\infty = 0.244$–0.256)

A number of workers have achieved a more successful correlation of experimental data on the basis of $NuRe^{-0.5}$ versus $TuRe^{0.5}$ values, correlation in terms of the latter parameter having been suggested by the phenomenological theory of Smith and Kuethe[6] described above. Miyazaki and Sparrow[27] have also demonstrated that Re_T cannot be regarded as a sufficient correlation parameter for flows with a wide range of Reynolds numbers. The present results are shown in this form in Fig 7, a least-squares fit to this data giving

$$NuRe^{-0.5} = 1.071 + 4.669\left(\frac{TuRe^{0.5}}{100}\right) - 7.388\left(\frac{TuRe^{0.5}}{100}\right)^2 \tag{18}$$

valid for the same ranges of Tu, Re and u_∞ as Eq (17). Also

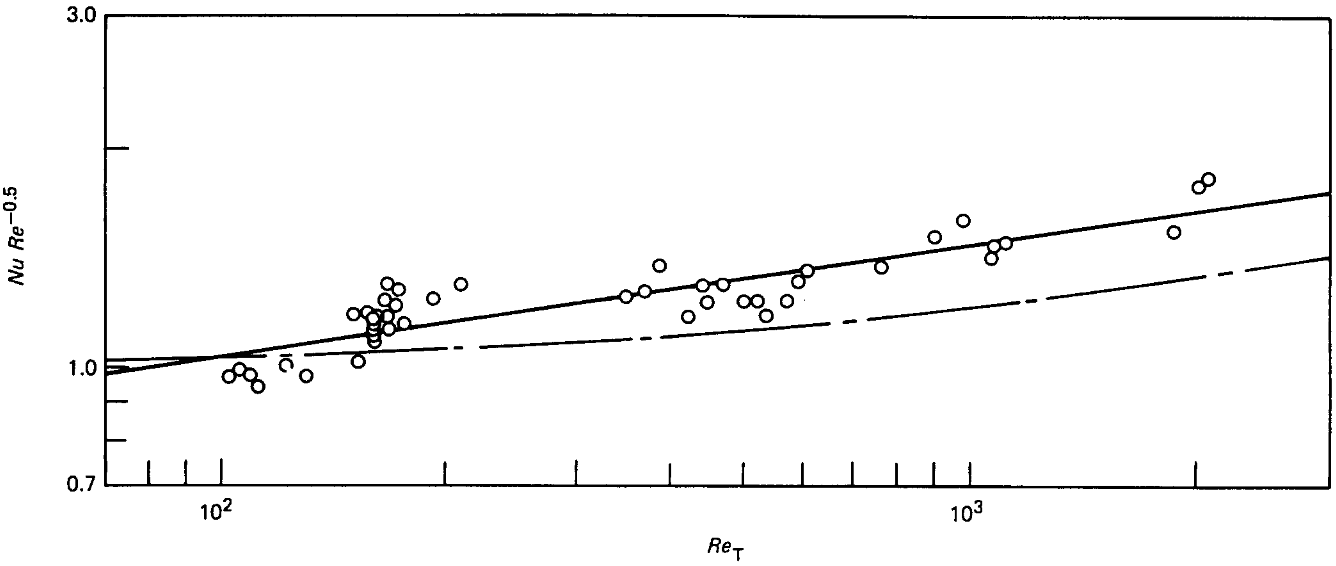

Fig 6 Heat flux data expressed as variation of $NuRe^{-0.5}$ with Re_T (= $TuRe$) (○ experimental, —— fitted, – – – – Ref 28)

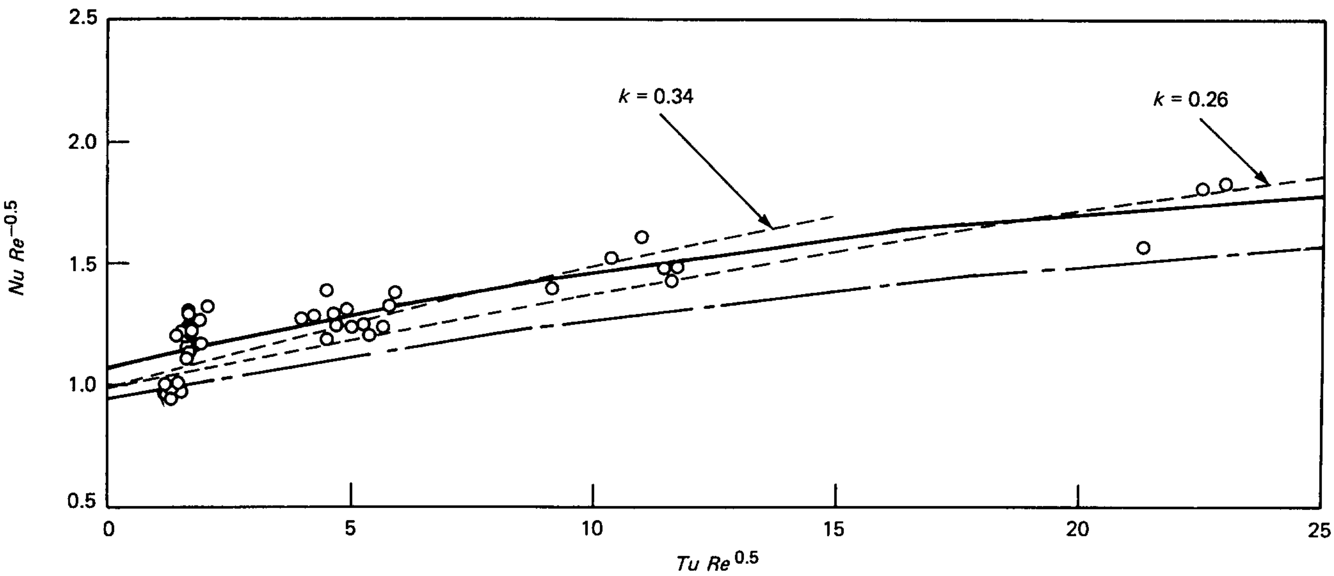

Fig 7 Heat flux data expressed as variation of $NuRe^{-0.5}$ with $TuRe^{0.5}$ (○ experimental, —— fitted, – – – – Ref 26, - - - numerical solution)

shown in this figure is the empirical correlation of Kestin and Wood[26] which was derived from a fit to their own experimental data and those of Refs 6, 24 and 28 among others. Again, the present data are seen to over predict those of previous workers over the majority of the $TuRe^{0.5}$ range examined.

A comparison between predictions of the phenomenological theory described earlier and the experimental data is also shown in Fig 7. These predictions were derived using a Prandtl number for air evaluated at a mean boundary layer temperature averaged over all experiments. Two fits to the experimental data are shown. The first, for $0 \leq TuRe^{0.5} \leq 25$, was obtained assuming $k = 0.26$ in the eddy law defined by Eq (5). For smaller values of $TuRe^{0.5}$, however, the experimental results are more closely approximated by $k = 0.34$. These values compare with 0.164 and 0.1 evaluated by Smith and Kuethe[6] and by Galloway[7], respectively. It may be noted that for the case of a laminar free stream, predictions of this theory agree well with the laminar theory of Squire[15] which gives $NuRe^{-0.5} = 0.978$ (using an averaged Prandtl number for air). This compares with a value of 1.071 obtained from Eq (18).

Because of the large temperature differences across the stagnation point boundary layer present in the flows examined, the constant k was also evaluated using the compressible model described earlier and expressing β as a function of free stream turbulence according to Eqs (1) and (16). Fitting of the experimental data was accomplished by calculating average mean free stream velocities, turbulence intensities and temperature differences across the boundary layer for each exit velocity and turbulence promoter used in the experiments. Comparison with experimental data was then made on a heat flux basis. In this manner values of 0.24 and 0.37 for k were obtained for the ranges $0 \leq TuRe^{0.5} \leq 25$ and $0 \leq TuRe^{0.5} \leq 15$, respectively.

Conclusions

Experimental measurements of convective heat transfer rates from heated air jets to a circular cylinder demonstrate that the local heat flux in the stagnation point region is sensitive to turbulence in the free stream flow. Increases in heat transfer were dependent on the Reynolds number and turbulence intensity of the free stream, the relationship between $NuRe^{-0.5}$ and Re_T, and between $NuRe^{-0.5}$ and $TuRe^{0.5}$, adequately correlating heat transfer measurements. The results are in good qualitative agreement with those obtained by previous workers in wind tunnel studies. However, for the range of Reynolds numbers and turbulence intensities examined, the present data show that increases in stagnation point heat transfer are more susceptible to free stream turbulence than indicated in earlier investigations. Predictions of a phenomenological theory of the enhancement process are in reasonable agreement with experimental results.

Measurements of the stagnation point velocity gradient on a cylinder have also been made. Results demonstrate that this parameter is increased by the presence of free stream turbulence, and that this effect can be accommodated by assuming the velocity gradient to be a simple function of turbulence intensity.

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