



## ENHANCED HEAT TRANSFER AND SHEAR STRESS DUE TO HIGH FREESTREAM TURBULENCE

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### ABSTRACT

Surface heat transfer and skin friction enhancements, as a result of freestream turbulence levels between  $10\% < Tu < 20\%$ , have been measured and compared in terms of correlations given throughout the literature. The results indicate that for this range of turbulence levels, the skin friction and heat transfer enhancements scale best using parameters which are a function of turbulence level and dissipation length scale. However, as turbulence levels approach  $Tu = 20\%$ , the  $St'$  parameter becomes more applicable and simpler to apply. As indicated by the measured rms velocity profiles, the maximum streamwise rms value in the near-wall region, which is needed for  $St'$ , is the same as that measured in the freestream at  $Tu = 20\%$ . Analogous to  $St'$ , a new parameter,  $Cf$ , was found to scale the skin friction data. Independent of all the correlations evaluated, the available data show that the heat transfer enhancement is greater than enhancements of skin friction with increasing turbulence levels. At turbulence levels above  $Tu = 10\%$ , the freestream turbulence starts to penetrate the boundary layer and inactive motions begin replacing shear-stress producing motions that are associated with the fluid/wall interaction. Although inactive motions do not contribute to the shear stress, these motions are still active in removing heat.

### INTRODUCTION

Quantifying high freestream turbulence effects on surface heat transfer and shear stress is important for improving predictions of the thermal loading and the aerodynamic losses on gas turbine blades, vanes, and endwalls. Although typical freestream turbulence levels which occur in gas turbines are greater than  $20\%$  (Kuotmos and McGuirk, 1989), most of the shear stress and heat transfer studies have focused on turbulence levels less than  $7\%$ . The emphasis of this paper is twofold. First, a comparison will be made between parameters that correlate the surface heat transfer and surface shear stress enhancements due to a turbulent freestream with levels between  $10\% < Tu < 20\%$ . Second, a comparison will be made between the enhancements of skin friction relative to heat transfer.

Although freestream turbulence studies date back to Kestin, Maeder, and Wang (1961) most of these studies have used freestream turbulence levels generated with grids which are limited to  $7\%$  or less. There are several correlations which have been developed as a result of

these lower (relative to the present study) freestream turbulence studies. The most widely used correlation was developed by Hancock and Bradshaw (1983) based on the enhancement of skin friction due to grid-generated turbulence. Hancock and Bradshaw's correlating parameter,  $\beta$ , is both a function of turbulence level and ratio of dissipation length scale to boundary layer thickness and is of the form:

$$\beta = \frac{Tu (\%) }{\left( \frac{Lu^{\epsilon}}{\delta} + 2 \right)} \quad (1)$$

Blair (1983) applied the  $\beta$  parameter not only to his measured skin friction enhancement but also his heat transfer enhancement data. Blair reported two significant findings with regards to the Hancock and Bradshaw  $\beta$  parameter. First, Blair identified a low Reynolds number effect which attenuated the enhancement. Later, however, Castro (1984) found that this effect became increasingly less significant at higher freestream turbulence levels. Second, Blair found that there were larger increases in the enhancement of heat transfer relative to skin friction as the freestream turbulence levels increased.

Just recently, there have been studies done at freestream turbulence levels above  $7\%$  which have extended the range of the  $\beta$  parameter and have suggested other correlating parameters. This work includes that done by MacMullin, Elrod and River (1989) and researchers from the heat transfer group at Stanford University including Maciejewski and Moffat (1989 and 1992a,b), Ames and Moffat (1990), and Sahm and Moffat (1992).

MacMullin, Elrod and River (1989) used a wall jet with turbulence levels ranging as high as  $20\%$ , but with a characteristically different velocity field than that of a boundary layer with a uniform mean field. When plotted in terms of the Hancock and Bradshaw  $\beta$  parameter, they found a large scatter in their data. For example at a  $\beta = 3.25$ ,  $St/St_{0,Re0}$  ranged from 1.48 to 1.8. Maciejewski and Moffat (1989) also did an unconventional boundary layer study in which they used a free jet and were able to generate turbulence levels up to  $60\%$ . They were able to achieve up to a  $\beta = 28$  and found that there was a continual increase in the surface heat transfer. In contrast to Maciejewski and Moffat's results of continued increases in heat

transfer, Johnson and Johnston's grid turbulence results showed that the shear stress enhancement peaked at  $\beta \approx 2.8$ .

Maciejewski and Moffat (1989) also proposed a new simpler parameter,  $St'$ , which uses the maximum rms velocity found in the near-wall region. Their results in combination with other investigations indicated that, independent of flow geometry,  $St'$  was a function of turbulence level alone.

Ames and Moffat (1990) studied both skin friction and heat transfer enhancement using a combustor simulator which generated turbulence levels as high as 20%. They proposed a TLR correlating parameter which is of the form:

$$TLR = Tu \left( \frac{\Delta}{L_u^\varepsilon} \right)^{0.33} \left( \frac{Re_\Delta}{1000} \right)^{0.25} \quad (2)$$

The TLR parameter uses integral quantities, where  $\Delta = \theta$  for shear stress enhancement and  $\Delta = \Delta_2$  for heat transfer enhancement, rather than boundary layer thicknesses. As pointed out by Ames and Moffat, defining the edge of a boundary layer with high freestream turbulence levels is quite difficult.

Later, Sahm and Moffat (1992) used combinations of jets and grids to study the effects of freestream turbulence levels as high as 30% on heat transfer and skin friction enhancements. Sahm found that both the  $\beta$  parameter and the TLR parameter were equal in correlating the skin friction and heat transfer enhancement. However, Sahm and Moffat point out that for their study there was a constant relation between the  $\beta$  parameter and the TLR parameter.

The following sections of this paper discuss the experimental facilities used for this study, the experimental flowfield investigated, and a comparison of the correlations given in the literature. There is also a comparison between the shear stress enhancement and heat transfer enhancement due to high freestream turbulence.

## FACILITY AND INSTRUMENTATION

Experiments were conducted in a boundary layer wind tunnel located in the Turbulence and Turbine Cooling Research Laboratory at the University of Texas at Austin. The closed-loop tunnel was driven by a 5-hp fan. Located downstream of the fan were heat exchangers, which maintained a constant mainstream temperature, and a series of fine mesh screens which conditioned the flow. Downstream of the screens and 9:1 tunnel contraction was the test section which was 244 cm long, 61 cm wide, and 15.2 cm high. The test section, schematically shown in Fig. 1, contained the turbulence generator, a

suction slot which removed any upstream boundary layer, an unheated leading edge plate, and the constant heat flux test plate.

The initial 60 cm of the test section was occupied by a turbulence generator specifically developed for this study (Whan-Tong, 1991 and Thole, 1992). High freestream turbulence levels were produced by high-velocity, normal jets injected into the mainstream crossflow. On both the floor and roof of the wind tunnel were a row of opposing jets. Flow for the normal jets was driven by a 7.5-hp fan in a secondary flow loop. The flow was provided by diverting 20% of the flow from upstream of the main wind tunnel fan.

Downstream of the turbulence generator was the constant heat flux test plate. The plate consisted of a serpentine, monel heating element sandwiched between two thin Kapton films. The length and width of the test plate were 136 cm and 61 cm. The heater plate was bonded to a 12.7 mm thick fiberglass composite (G-10). Below the plate were several layers of insulation which minimized the conduction losses to less than 1%. The heat transfer data were corrected for radiation losses which were between 15-20% of the total input power.

The measurements made for this study included surface temperatures, mean and rms velocity profiles, and turbulent integral length scales. Surface temperatures were measured using thermocouple strips previously used and reported by Sinha, Bogard, and Crawford (1990). The junction for these thin, Type E, thermocouples was 76  $\mu\text{m}$  thick, or less than  $y^+ = 2$ . The uncertainty in Stanton numbers for the highly turbulent flowfield was calculated to be  $\pm 5.5\%$  at the start of the heat flux plate and  $\pm 4.1\%$  at the end of the heat flux plate. A maximum deviation of 2.6% occurred between computed Stanton numbers using the boundary layer code TEXSTAN and measured Stanton numbers for the benchmark case.

The mean and rms velocities were measured using a Thermal Systems Inc., two-component laser Doppler velocimeter (LDV) system with counter processors. The measured velocities were corrected for velocity bias errors using residence time weighting. The total uncertainty, including both precision and bias, for the mean velocity measurements in the case of the highly turbulent flowfield was  $\pm 2.3\%$  in the freestream and  $\pm 3.5\%$  in the near-wall region. The total uncertainty for the fluctuating velocities in the case of the highly turbulent flowfield was found to be  $\pm 2.5\%$  in the freestream and  $\pm 3.7\%$  near the wall. The uncertainty for the skin friction coefficient, which was due to the uncertainty in calculating the friction velocity, was  $\pm 3.6\%$ . A maximum deviation of 3.6% occurred between calculated skin friction coefficients using correlations given by Kays and Crawford (1980) and coefficients obtained using a Clauser fit.

## NOMENCLATURE

$C_f$	Friction coefficient	$Tu$	Streamwise turbulence intensity, $u'/U_\infty$
$C_f'$	Friction coefficient based on $u'_{\text{max}}$	$u'$	RMS velocity in streamwise direction
$C_{f_0}$	Friction coefficient for a boundary layer with no freestream turbulence	$u_\tau$	Wall friction velocity
$D$	Turbulence generator jet hole diameter	$U$	Mean local velocity in streamwise direction
$L_u^\varepsilon$	Dissipation length scale,	$U_\infty$	Freestream velocity in streamwise direction
	$L_u^\varepsilon = - \frac{\left( \overline{u'^2} \right)^{3/2}}{U_\infty \frac{du'^2}{dx}}$	$x$	Streamwise distance measured from the turbulence generator jets
$Re_{\Delta_2}$	Enthalpy thickness Reynolds number	$y^+$	Nondimensional vertical distance, $y u_\tau / \nu$
$Re_\theta$	Momentum thickness Reynolds number	$\alpha$	Low $Re_\theta$ function
$St$	Stanton number	$\beta$	Turbulence scaling parameter (see eqn. 1)
$St_0$	Stanton number for a boundary layer with no freestream turbulence	$\Delta$	Boundary layer integral thickness
$St'$	Stanton number based on $u'_{\text{max}}$	$\Delta_2$	Enthalpy thickness
$TLR$	Turbulence scaling parameter (see eqn. 2)	$\delta$	Velocity boundary layer thickness
		$\delta_{th}$	Thermal boundary layer thickness
		$\Lambda_x$	Integral turbulent length scale
		$\theta$	Momentum thickness
		$\tau_{\text{total}}$	Total wall shear stress

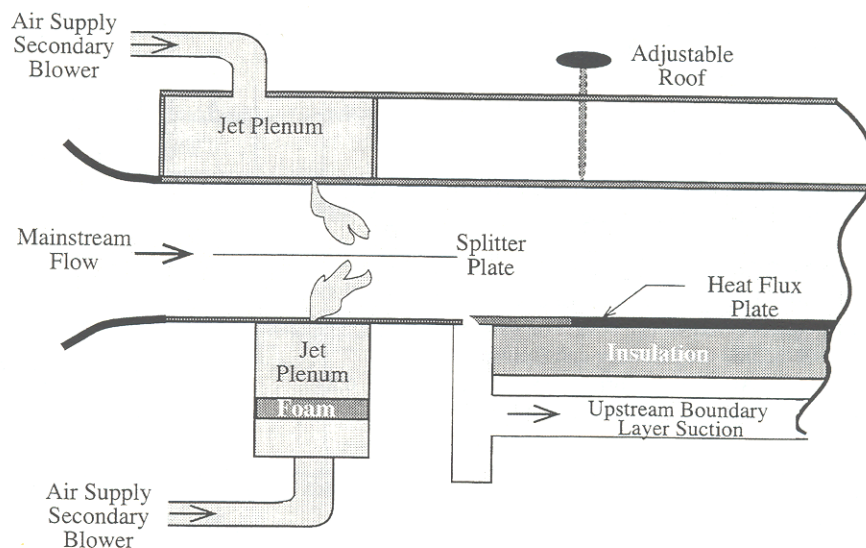


Fig. 1 Schematic of the wind tunnel test section including the turbulence generator.

A hot-wire anemometer system measured the velocity fluctuations used to obtain integral time scales. The integral length scales were calculated using the measured time scales deduced from the autocorrelation, the local mean velocity, and invoking Taylor's hypothesis.

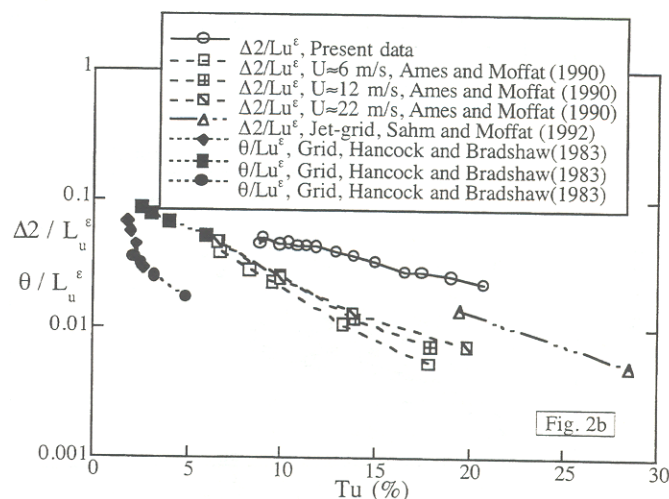
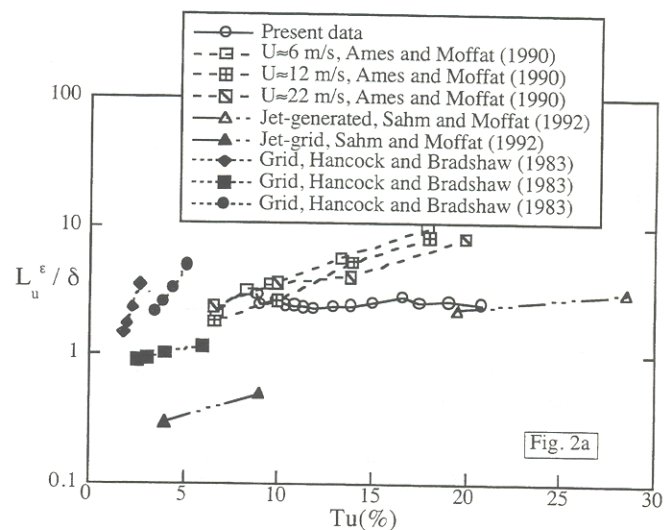
### TURBULENT FLOWFIELD

The operating condition for the normal jet turbulence generator required a jet-to-mainstream velocity ratio of 17 at a mainstream velocity of nominally 8 m/s. The region of interest for this study was located 130 jet diameters downstream from the jet holes. This streamwise location corresponds to 25 cm downstream of the start of the heat flux plate which was where the unheated starting length effects were negligible. At this location the turbulence level was  $Tu = 20\%$ , which then decayed to a level of  $Tu = 9\%$  at 300 jet diameters downstream from the jet holes. For the specific measurements of the streamwise turbulence decay, integral length scales ( $\Lambda_x$ ), and the dissipation length scales ( $L_u^\epsilon$ ) for this study refer to Thole and Bogard (1994). The mean and rms velocities were relatively uniform in the spanwise direction at  $\pm 4\%$  and  $\pm 9\%$ , respectively.

Figures 2a and 2b compare the flowfield in this study to that used by other studies in terms of the turbulence level and normalized dissipation length scale. In comparison to the Hancock and Bradshaw grid-generated studies, the other studies shown in Figs. 2a and 2b have much higher turbulence levels. Taking into account all of the data, the length scale ratios span two orders of magnitude.

In this study, the velocity and thermal boundary layer thicknesses were nominally the same thickness. The boundary layer growth with the decaying freestream turbulence was severely attenuated and the boundary layer had essentially a constant thickness of nominally  $\delta_{99} = 20$  mm along a streamwise distance of 60 cm. Attenuation of the boundary layer growth was also observed by Ames and Moffat (1990) and Sahm and Moffat (1992). Note that as the turbulence decays there is a loss of streamwise momentum flux which causes an increase in pressure in the freestream, which may cause the growth attenuation.

In two independent grid-generated freestream turbulence studies, both Blair (1983) and Simonich and Bradshaw (1978) indicated that there was a fixed value for the ratio of dissipation to integral length scales. However, they reported two different values with Blair having a ratio of  $L_u^\epsilon / \Lambda_x = 1.5$ , and Simonich and Bradshaw having a ratio



Figs. 2a,b Comparison of flowfield characteristics for several studies in terms of the dissipation length scale and (a) boundary layer thickness ratios and (b) integral thickness ratios.

of  $L_u^\epsilon / \Lambda_x = 1.1$ . For the study described here, the dissipation and integral length scales were also very similar having a dissipation to integral length scale ratio ranging between  $1.1 < L_u^\epsilon / \Lambda_x < 1.4$  over the region of interest. Data given by Ames and Moffat (1990), however, showed that this ratio varied from  $1.6 < L_u^\epsilon / \Lambda_x < 2.6$ , while data given by Sahm and Moffat (1992) varied from  $1.8 < L_u^\epsilon / \Lambda_x < 3.6$ . Assumptions that this ratio is a constant value can not be made, in particular when devices other than grids are used.

## HEAT TRANSFER ENHANCEMENT

As described in the introduction, there are three correlations which are available to quantify high freestream turbulence effects on surface heat transfer. These correlations include the Hancock and Bradshaw (1983)  $\beta$  parameter correlation, the Ames and Moffat (1990) TLR parameter correlation, and the Maciejewski and Moffat (1992)  $St'$  correlation.

Figure 3 shows  $\beta$  as a correlating parameter for the Stanton number enhancement due to high freestream turbulence levels. The Hancock and Bradshaw  $\beta$  parameter does an adequate job in scaling both the present data with that of Ames and Moffat (1990), but not the data of Sahm and Moffat (1992). Sahm and Moffat studied heat transfer in the presence of flat and convex walls, but only a limited set of data for the flat wall is discussed in this paper. Also shown in Fig. 3 is Blair's (1983) modification to the Hancock and Bradshaw correlation which accounted for his larger measured heat transfer enhancements relative to skin friction enhancements.

Figure 4 compares the data in terms of the Ames and Moffat (1990) TLR parameter. The TLR parameter does a better job in scaling all three data sets. As was pointed out earlier, the boundary layer thickness is difficult to quantify in high freestream turbulence studies and, hence, a better collapse using the TLR parameter may be due to using integral quantities.

The data plotted in terms of the Maciejewski and Moffat (1992b)  $St'$  parameter is shown in Fig. 5. Included in Fig. 5 are data from Sahm and Moffat (1992) analyzed using two different  $u'_{max}$  values. The Stanford University data given in Fig. 5 was obtained from the appendices of the corresponding reports. However, the  $u'_{max} / u_\tau$  values given in the Sahm and Moffat appendix were somewhat lower than those peak values typically found in the near-wall region. Hence, the Sahm and Moffat  $St'$  values for  $Tu < 20\%$  were scaled, using

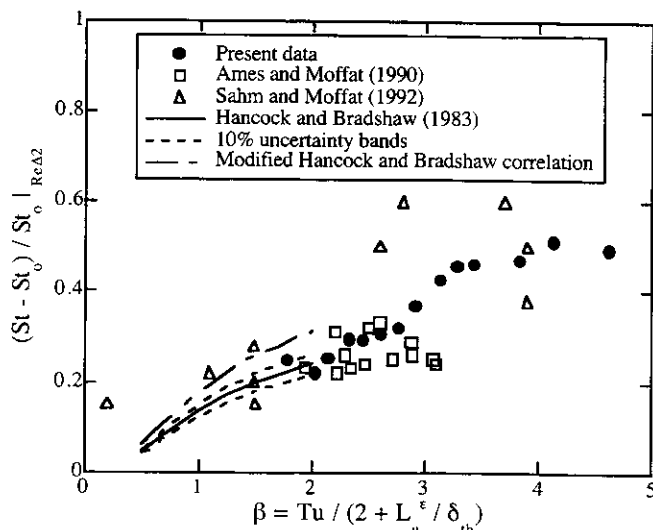


Fig. 3 Comparison of present data in terms of the Hancock and Bradshaw correlation (1983).

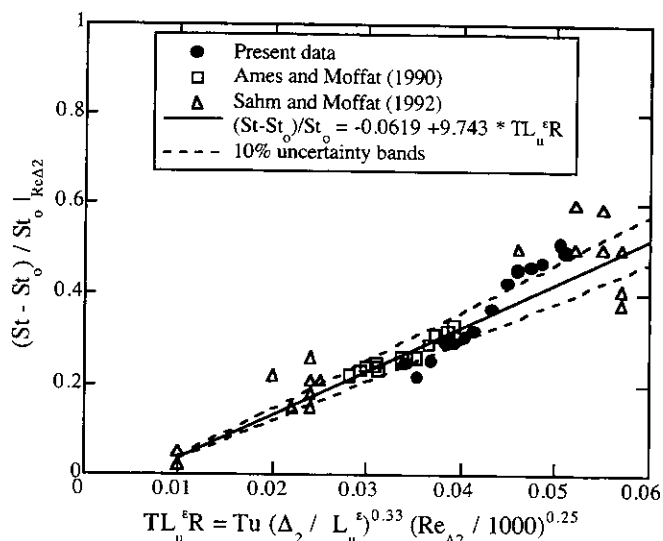


Fig. 4 Comparison of present data in terms of the Ames and Moffat (1990) correlation.

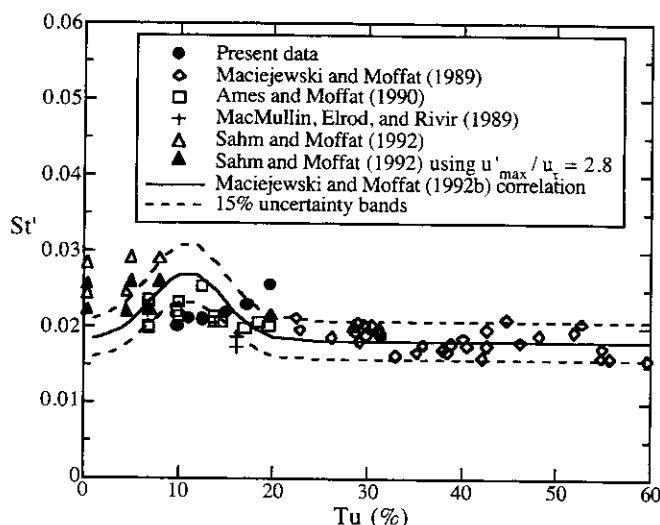


Fig. 5 Comparison of present data in terms of the Maciejewski and Moffat (1992b) correlation.

$u'_{max} / u_\tau = 2.8$ . Again, the data represented in Fig. 5 do not include all of the Sahm and Moffat data some of which show  $St'$  values below the correlation. The Sahm and Moffat data that are represented here may include some unheated starting length effects. Sahm and Moffat have extensive data in both the pre- and post-curved regions, but a full discussion of this data is beyond the scope of this paper. Although there is some scatter in Fig. 5, the collapse is relatively good. However, the data do not indicate the 46% increase in  $St'$  at a turbulence level of  $Tu = 11\%$  as given by the correlation.

Figure 6 shows the dependence of  $St'$  on the enthalpy thickness Reynolds number. The calculated  $St'$  distribution with  $Re_{\Delta 2}$  was based on turbulent boundary layer correlations given by Kays and Crawford (1980) and  $u'_{max} / u_\tau = 2.8$ . The calculated  $St'$  curve involved several steps with each step involving a turbulent boundary layer correlation. First, shear stresses were calculated based on  $Re_\theta$ . Second,  $Re_\theta$  was converted to  $Re_x$ . Third, Stanton numbers were calculated based on  $Re_x$ . Finally, using these Stanton numbers and an additional correlation,  $Re_{\Delta 2}$  was calculated.



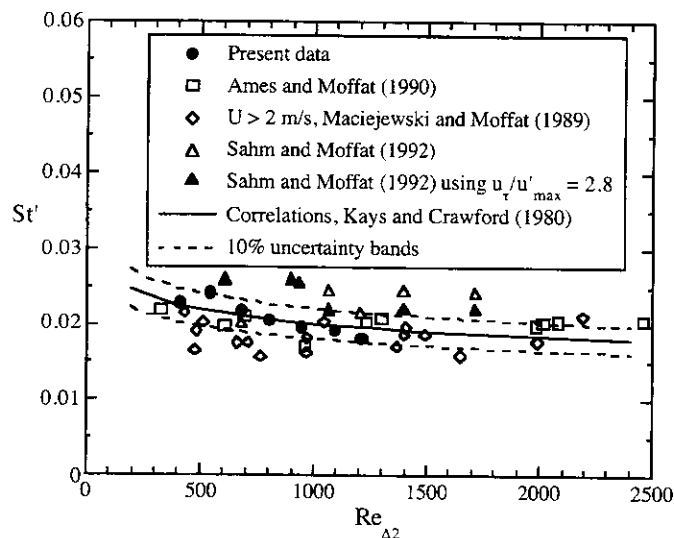


Fig. 6 Reynolds number effect on  $St'$  compared with correlations.

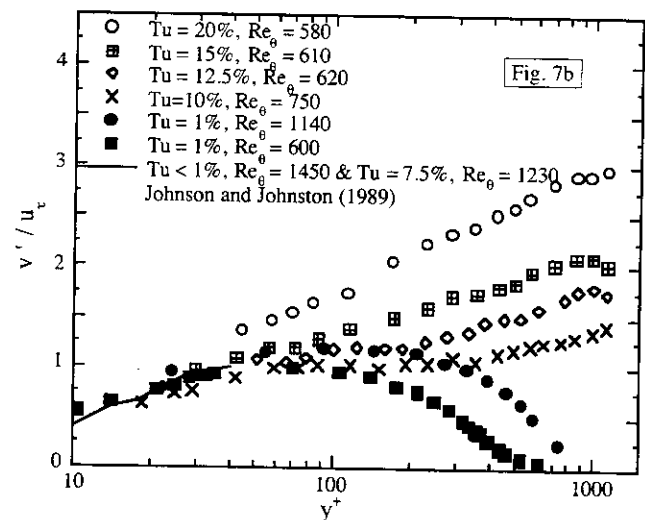
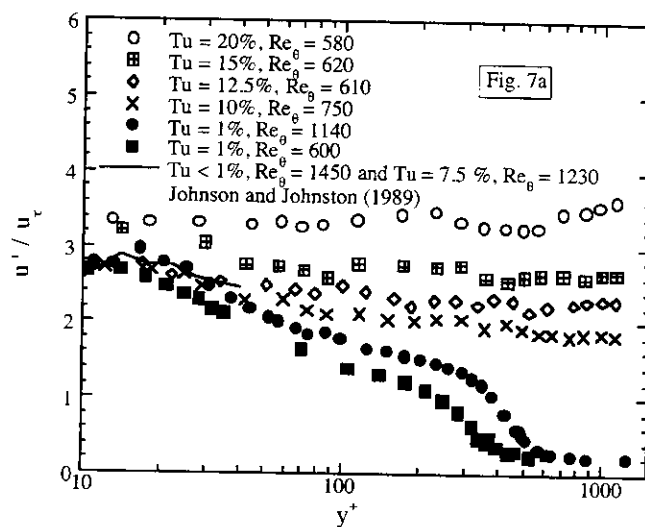
All of our data as well as most of Ames and Moffat's (1990) fall within the uncertainty of the values calculated from the correlations indicating a slight Reynolds number dependence. The Sahm and Moffat (1992) data is slightly higher while Maciejewski and Moffat's (1989) data is slightly lower than that predicted by the correlation. For the Maciejewski and Moffat data, the turbulence levels were quite high ( $Tu > 30\%$ ) and, hence, may have a stronger effect than the Reynolds number.

One of the difficulties in applying the  $St'$  correlation is that in order to determine the heat transfer coefficient; one must know beforehand what the  $u'_{max}$  value is. The  $u'_{max}$  used in this correlation is the value found in the near wall region ( $y^+ < 30$ ). However, if the turbulence levels are high enough,  $u'_{max}$  occurring in the near-wall region is the same rms velocity which occurs in the freestream. In this study, turbulence levels were measured throughout the boundary layer for freestream turbulence levels ranging between  $1\% < Tu < 20\%$ . Figures 7a and 7b show the streamwise and vertical rms distributions for this range of turbulence levels. The data of Johnson and Johnston's (1989) grid turbulence study is also shown in Figs. 7a and 7b. As seen in Fig. 7a, the streamwise rms velocity distributions for freestream turbulence levels below  $Tu = 15\%$  show that the freestream rms velocity is smaller than the  $u'_{max}$  which occurs inside the boundary layer. However, for the  $Tu = 20\%$  case, the freestream turbulence has penetrated very close to the wall such that the maximum streamwise rms value is the same as that of the freestream level.

The vertical rms velocity distribution shown in Fig. 7b is significantly different than the streamwise rms velocity distribution. The velocity distributions indicate that while the streamwise fluctuations have a relatively flat profile throughout the boundary layer, the vertical fluctuations become attenuated towards the wall. Large-scale eddies from the turbulent freestream have penetrated into the boundary layer, but only the vertical fluctuations of the large scale eddies are restricted by the wall which causes the attenuation through the boundary layer.

### SKIN FRICTION ENHANCEMENT

Similar to the heat transfer enhancement, the same correlations can be applied to scale the skin friction enhancement. The skin friction coefficient for the highly turbulent flowfield was obtained using a Clauser fit to the log-law, similar to previous studies. These previous



Figs. 7a,b Streamwise and vertical rms velocity profiles for several freestream turbulence levels plotted in terms of inner variables.

studies, including both grid-generated turbulence studies and the higher freestream turbulence studies, have shown that increased freestream turbulence levels cause fuller mean velocity profiles with sharply decreased wake strengths (Blair (1983), Ames and Moffat (1990), Thole (1992), and Sahm and Moffat (1992)).

In doing a Clauser fit, the data is forced to fall onto the log-law. To evaluate the accuracy of the wall shear stress using the Clauser fit, comparisons were made between the Clauser fit values for  $\tau_{w,loglaw}$  and measurements of the total stress, viscous plus Reynolds shear stress, near the wall. The total shear stress data were normalized using the shear velocity,  $\tau_{w,loglaw}$ , determined from a Clauser fit to the log-law and are shown in Fig. 8. The Clauser fit was done in the log-law region of the mean velocity profile between  $y^+ = 30$  and  $y/\delta_{99} = 0.2$ . The von Kármán's constant of  $\kappa = 0.41$  and  $C = 5.0$  were used in the log-law equation. Results from these measurements indicate a normalized total stress of nominally  $\tau_{total}/\tau_{w,loglaw} = 1$  for all freestream turbulence levels, confirming the accuracy of the log-law fit in determining the wall shear stress. The pressure gradient, expected due to the decaying freestream turbulence, was estimated to have less than a 1% effect on the total stress in the near wall region.

Figures 9a and 9b show the skin friction enhancement in terms of the Hancock and Bradshaw (1983)  $\beta$  parameter. Figure 9b shows the

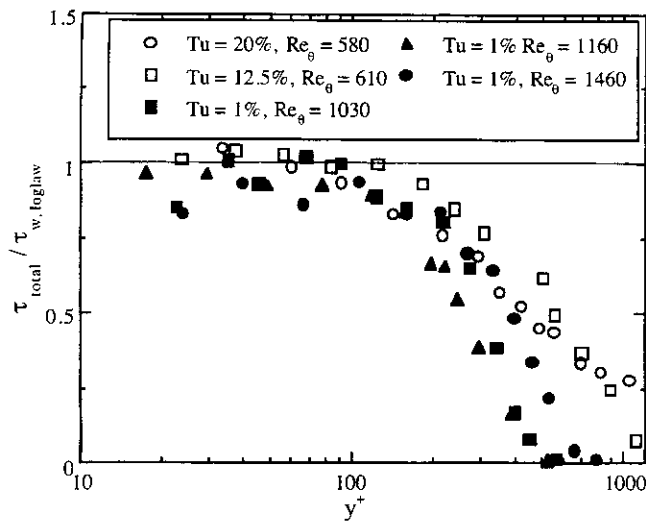
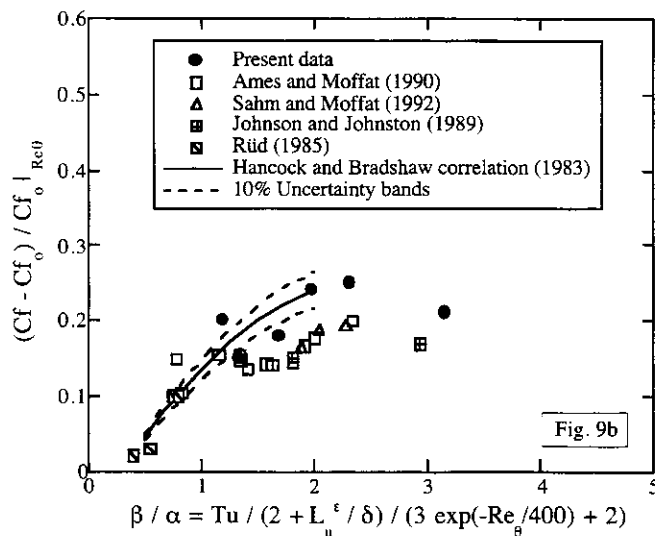
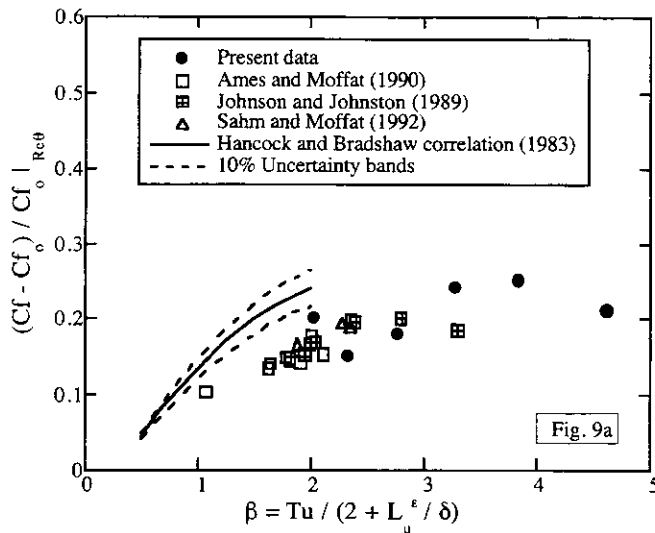


Fig. 8 Total shear stress normalized by log-law shear stress.



Figs. 9a,b Comparison of present data using the Hancock and Bradshaw correlation (a) without and (b) with low Reynolds number correlation.

data with the low Reynolds number correction given by Blair (1983). Although the data falls closer to the correlation with the low Reynolds number correction, there is more scatter in the data when the low Reynolds number correction is made.

The Hancock and Bradshaw correlation (1983) was obtained from their grid-generated study and has been found by other investigators, such as Blair (1983), to be in agreement with their own data. Except for the Johnson and Johnston (1983) and Rüd (1985) data, all of the other data shown in Figs. 9a and 9b were obtained from very high freestream turbulence tests (using devices other than grids). A large portion of this data falls below the Hancock and Bradshaw correlation even with the low Reynolds number correction (Fig. 9b). The data in Figs. 9a and 9b indicate that there is a leveling off of the skin friction enhancement. This is contrary to the heat transfer enhancement which was shown in Fig. 3.

Figure 10 shows the skin friction enhancement in terms of Ames and Moffat's TLR parameter. Again it is evident that the shear stress enhancement for the higher turbulent studies falls below that of Hancock and Bradshaw's grid-generated turbulence study. In using the TLR parameter for the skin friction enhancement, there is a larger scatter as compared with the \$\beta\$ parameter.

Analogous to \$St'\$ which was used to scale the heat transfer coefficient, a new parameter, \$Cf'\$, was found to scale the wall shear stress. Similarly, \$Cf'\$ uses the maximum rms streamwise velocity as the velocity scale and, hence, results in \$Cf' = 2 (u\_\tau / u'\_{max})^2\$. As was shown in Fig. 7a, the peak rms levels start to increase for freestream turbulence levels greater than 12.5% which accordingly results in a decrease of \$Cf'\$. Figure 11 shows \$Cf'\$ as a function of turbulence level for both the present data set as well as that of other investigators provided that the profiles were measured close enough to the wall to obtain the peak values. No length scale or Reynolds number effects on \$Cf'\$ were detected. Unlike \$St'\$, which remains constant at all turbulence levels, \$Cf'\$ starts to decrease above \$Tu = 12.5\%\$.

## COMPARISON OF HEAT TRANSFER AND SKIN FRICTION ENHANCEMENT

Enhancements of skin friction and surface heat transfer due to high freestream turbulence have been presented in the last two sections. Shown in Fig. 12 is a comparison of the skin friction and heat transfer enhancements in terms of the \$\beta\$ parameter. A consistent result for all

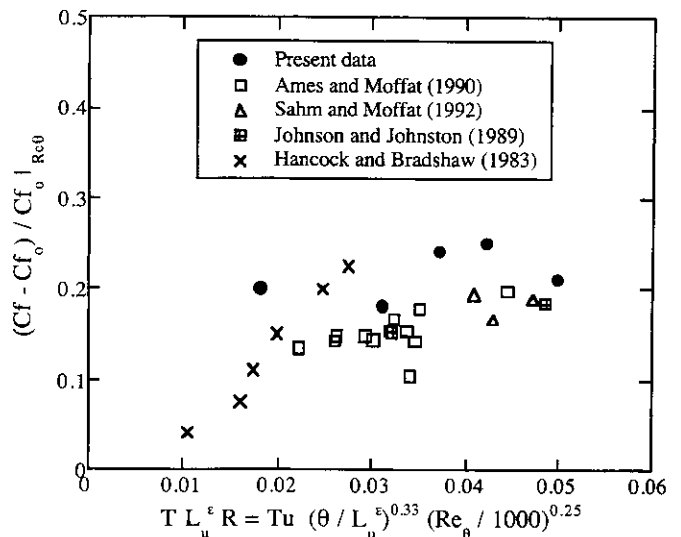


Fig. 10 Comparison of present data with the Ames and Moffat (1990) correlation.

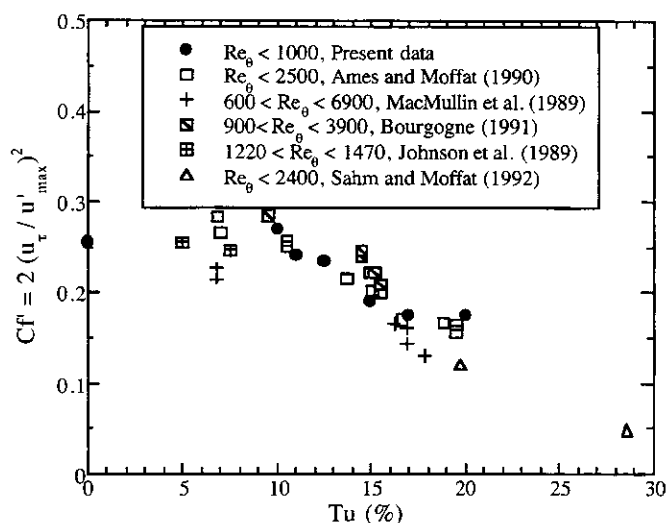


Fig. 11 Correlation of surface shear stress using  $C_f$ .

the data is a similar enhancement for skin friction and surface heat transfer at smaller  $\beta$  values, but a significantly larger heat transfer enhancement at larger  $\beta$  values. The disparity between enhancement of skin friction and heat transfer occurs because the enhancement of heat transfer steadily increases with increasing  $\beta$ , but the skin friction enhancement peaks at  $\beta \approx 3$  and decreases at larger  $\beta$  values.

At freestream turbulence levels below 10%, there is an enhancement of skin friction due to the increase in boundary layer entrainment. At freestream turbulence levels above 10%, the outer turbulence penetrates into the boundary layer replacing shear-producing motions associated with the fluid/wall interaction with turbulent freestream motions. These non shear-stress producing motions are called inactive motions.

The theory on inactive motions was first hypothesized by Townsend (1961) and later investigated by Bradshaw (1967). Inactive motions are large-scale eddies, typically in the outer part of the boundary layer. Active motions are responsible for the shear stress production and are smaller in scale.

The rms velocity profiles shown in Fig. 7a and 7b indicate the penetration of these large scale motions from the freestream into the boundary layer. These inactive motions from the freestream carry a large streamwise fluctuating component while the vertical fluctuating component is attenuated due to the wall. Velocity spectra and length scales, reported for this same study by Thole and Bogard (1994), have also indicated the presence of these large-scale motions throughout the boundary layer with high freestream turbulence levels.

In evaluating the correlations for heat transfer enhancement,  $St'$ , is particularly good at very high freestream turbulence levels. A question arises as to why, at the higher turbulence levels,  $St'$  shows no effect of length scale or Reynolds number. The reason that these effects are not apparent is because at these high turbulence levels ( $Tu > 20\%$ ), the large-scale motions from the freestream penetrate into the boundary layer with large streamwise fluctuating components. Although these motions are not active in producing shear stress (as shown by the decrease in  $C_f$  with increasing turbulence levels), these motions are still thermally active.

## CONCLUSIONS

The previous sections have compared the  $\beta$ , TLR,  $St'$ , and  $C_f$  correlations for a wide range of turbulent flowfield characteristics from several independent studies. Freestream turbulence levels ranged from

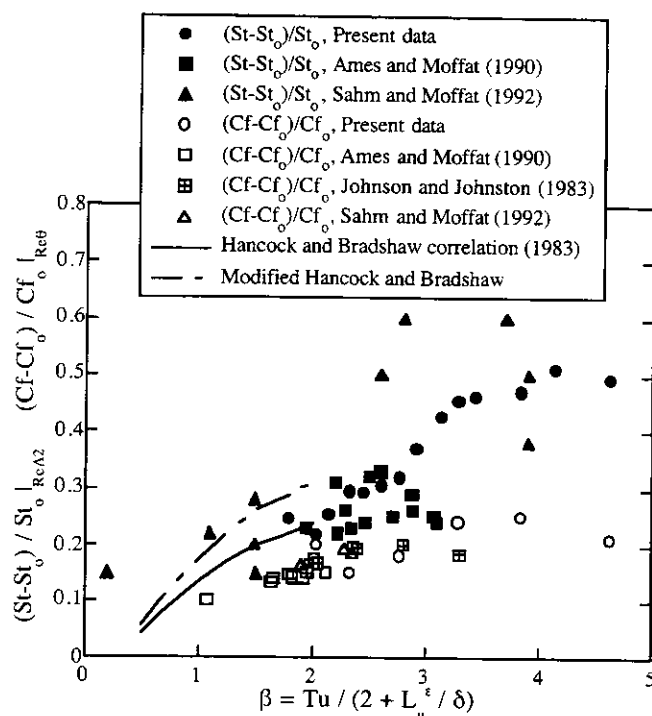


Fig. 12 Comparison of heat transfer and skin friction enhancements.

$1\% < Tu < 28\%$ , while the dissipation length scale to boundary layer thickness ratio ranged over two orders of magnitude. The results of this study show that the TLR parameter is slightly more successful in scaling the heat transfer enhancement and the  $\beta$  parameter is slightly more successful at scaling the skin friction enhancement.

The simpler  $St'$  correlation is particularly good at very high freestream turbulence levels ( $Tu > 20\%$ ) for two reasons. First, at  $Tu = 20\%$  the peak streamwise rms velocity in the near-wall region is the same as the freestream rms velocity which makes the correlation relatively easy to apply. Second, at high turbulence levels there does not appear to be any Reynolds number or length scale effects. At  $Tu < 20\%$ , there is more scatter in the  $St'$  data which is in part due to a Reynolds number effect.

A new parameter,  $C_f'$ , was introduced to scale the skin friction.  $C_f'$  is inversely proportional to the square of  $u'_{\max} / u_\tau$ .  $C_f'$  remains constant until  $Tu \approx 12\%$  and then begins to decrease as freestream turbulence levels increase.

All of the data presented here indicate higher heat transfer enhancements relative to skin friction enhancements independent of the correlation that is used. The skin friction enhancement does not continue to increase at high turbulence levels because large scale turbulent eddies from the freestream penetrate into the boundary layer. These large eddies, which are non-stress producing and are also known as inactive motions, replace what would typically be smaller-scale stress-producing motions. These same large-scale eddies are, however, effective in removing heat and, hence, thermally active. This is particularly evident in comparing  $St'$  and  $C_f$ .  $St'$  remains constant as freestream turbulence levels continue to increase because the large scale motions present from the freestream are continuing to remove heat. Hence, at high turbulence levels the heat transfer coefficient scales with the maximum streamwise rms level. Alternatively,  $C_f$  decreases as freestream turbulence levels increase because inactive motions penetrate into the boundary layer from the freestream and do not contribute to the wall shear stress.

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