EIGHTH SYMPOSIUM ON
TURBULENT SHEAR FLOWS
Technical University of Munich
Munich, Germany
September 9 - 11, 1991

Generation of Very High Freestream Turbulence Levels and the Effects on Heat Transfer

by

Karen A. Thole, Janine Whan-Tong, and David G. Bogard

Mechanical Engineering Department
The University of Texas at Austin
Austin, TX 78712

ABSTRACT

Attempts at establishing reliable correlations for the effects of high freestream turbulence on heat transfer have been hampered by the relatively low turbulence levels used in most studies, or the complex flow fields when using free jets to obtain high freestream turbulence. In the present study a new freestream turbulence generator was developed which produced a freestream turbulence field with larger turbulence levels and significantly smaller length scales than have been previously possible in a uniform flow test section. Significant enhancement of heat transfer was found to occur due to high freestream turbulence levels. The effect on heat transfer was found to correlate best using a parameter based on the turbulence level, integral length scale, and the enthalpy thickness Reynolds number.

NOMENCLATURE

C_f	Friction coefficient
C_{fo}	Friction coefficient for a standard boundary layer
HB	Hancock/Bradshaw parameter
L_u^{ε}	Dissipation length scale
Re_{Δ}	Enthalpy thickness Reynolds number
Re_{θ}	Momentum thickness Reynolds number
St	Stanton number
St_o	Stanton number for a standard boundary layer
St'	Stanton number based on u'_{max}
TLR	Turbulence scaling parameter
$T\Lambda_xR$	Turbulence scaling parameter
Tu	Turbulence intensity, u'/U_{∞}
u'	Fluctuating velocity in streamwise direction
U_{∞}	Mainstream velocity in streamwise direction
v'	Fluctuating velocity in normal direction
x	Streamwise distance measured from virtual origin
x_h	Streamwise distance measured from the start of the heater plate
y	vertical distance
β	Low Re_{θ} function
Δ	Enthalpy thickness
δ_{99}	Velocity boundary layer thickness
δ_{th}	Thermal boundary layer thickness
Λ_x	Integral turbulent length scale
θ	Momentum thickness

INTRODUCTION

The goals of this study were to develop a highly turbulent freestream flowfield (turbulence levels of nominally 20%) and then study the effects of this highly turbulent freestream on heat transport. The development of the turbulent boundary layer with a highly turbulent freestream is relevant in predicting convective heat transfer in many flow geometries. High freestream turbulence levels have dramatic effects on heat transfer in such devices as heat exchangers, combustors, and gas turbine blades. For example, typical freestream turbulence levels which occur in gas turbines have been measured by Koutmos and McGuirk (1989) to be greater than 20%. Dunn et al. (1986) compared the heat transfer data taken in a real turbine to those predictions based on turbulent heat transfer correlations. They reported the correlations underpredicted their measured heat transfer by as much as 100 percent on the blade pressure side and 30 percent on the suction side.

There are several heat transfer correlations reported throughout the literature which have been developed to account for the enhancement of high freestream turbulence effects on both the wall shear stress and wall heat transfer. These correlations have been developed from both grid-generated turbulence, where the levels are 7% or lower, and high freestream turbulence studies, where the highest levels, to date, have been reported at 60% by Maciejewski and Moffat(1989a). The enhancement of heat transfer is typically measured by a ratio of Stanton numbers, St/St_o where St_o is for a standard boundary layer at either the same momentum or enthalpy thickness Reynolds number as for the measured high freestream turbulence St. These correlations, as will be discussed below, are typically based on either the velocity boundary layer characteristics, such as thickness (δ_{99}), momentum thickness (θ), and momentum Reynolds number (Re_{θ}); or thermal boundary layer characteristics, such as thickness (δ_{th}), enthalpy thickness (Δ), and enthalpy thickness Reynolds number (Re_Δ). In addition, some of the correlating parameters include the turbulence levels (Tu), the integral length scale (Λ_x), and the dissipation length scale (L_u^ε) defined by Simonich and Bradshaw (1978) as

$$L_u^\varepsilon = -\frac{(\overline{u'^2})^{\frac{3}{2}}}{U_\infty \frac{d(\overline{u'^2})^{\frac{3}{2}}}{dx}} \qquad (1)$$

Most of the heat transfer data reported in the literature is for grid-generated turbulent freestreams where levels are typically less than 7%. Early grid-generated turbulence studies showed that the only effect that grid-generated turbulence had was to move the transition location upstream (Kestin et al. (1961)). Later, Simonich and Bradshaw (1978), showed that heat transfer enhancement increases with increasing turbulence intensities. Simonich and Bradshaw found a relatively weak dependence on the $L_u^\varepsilon/\delta_{99}$ ratio, with a decrease in heat transfer enhancement as $L_u^\varepsilon/\delta_{99}$ increased. Simonich and Bradshaw evaluated the St/St_o ratio at a constant Re_θ.

Hancock and Bradshaw (1983) studied the effect of grid-generated turbulence only on velocity boundary layers. They correlated their skin friction coefficient ratio (C_f/C_{fo}), where C_{fo} is for a standard boundary layer at the same Re_θ,. with a parameter they defined as,

$$HB = \frac{Tu}{\left(\frac{L_u^\varepsilon}{\delta_{99}} + 2\right)} \qquad (2)$$

Hereafter, we will refer to this parameter as the HB parameter. They found the C_f/C_{fo} ratio was a nonlinear function of the HB parameter. The range of the HB parameter which they investigated was between HB = 0.5 and HB = 2.

Blair found a low Re_θ effect where the skin friction enhancement is dampened. Blair developed an empirical relation, $\beta = (3\, e^{-Re_\theta/400} + 1)$ to account for this damping. This damping term is significant at low Re_θ, i.e. at Re_θ = 700, $\beta = 1.5$, but asymptotes to unity near Re_θ = 2000 where $\beta = 1.02$. Later, Blair (1983) applied the Hancock/Bradshaw correlation to evaluate whether it would also collapse the enhancement of grid-generated turbulence on heat transfer, namely St/St_o, evaluated at the same Re_θ. Blair modified the Hancock/Bradshaw correlation by using Reynolds analogy factor, $2St/C_f = 1.3$ and also applied β to the heat transfer results.

Baskaran, Abdellatif, and Bradshaw (1989) also applied the Hancock/Bradshaw correlation to their grid-generated turbulence results between HB = 0.2 and 1 where they evaluated St/St_o at a constant Re_θ. Their measured heat transfer enhancement was significantly underpredicted. Baskaran et al. suggested changing the denominator of the HB parameter which would give a better fit to their data.

The very high freestream turbulence studies to date, where the turbulence production used techniques other than a grid (studies where turbulence levels greater than 7%), include MacMullin, Elrod and Rivir (1989), Maciejewski and Moffat (1989a,b), and Ames and Moffat (1990a,b). MacMullin et al. generated turbulence levels up to 20% using a wall jet with a characteristic highly non-uniform vertical mean velocity. Maciejewski and Moffat were able to achieve turbulence levels up to 60% using a free jet facility with a constant temperature plate positioned off-axis and several jet diameters downstream of the jet exit plane. Similar to MacMullin et al., Maciejewski and Moffat also had a highly nonuniform mean flowfield. Ames and Moffat achieved high turbulence levels (up to 16%) by simulating an annular combustor by injecting the flow through a series of wall slots and jet holes prior to the wind tunnel contraction.

MacMullin et al. applied the HB scaling parameter using the integral length scale as opposed to the dissipation length scale and evaluated the St/St_o ratio at a constant Re_θ. Even though they applied Blair's low Re_θ function, there was a large scatter in the data. For example at an HB = 3.25, the St/St_o ratio ranged from 1.48 to 1.8.

Maciejewski and Moffat (1989b) found that their data best scaled with a parameter they defined as St' which uses the maximum fluctuating streamwise velocity component as the velocity scale. They proposed that St' was a function of turbulence level alone with a maximum St' occurring near a turbulence level of 11%. Maciejewski and Moffat were able to collapse their data and some of the data available in the literature at lower turbulence levels, such as Blair, to within ± 15% of their correlation.

Ames and Moffat (1990a) compared their St data to the Hancock/Bradshaw correlation using the thermal boundary layer thickness and comparing the St/St_o ratio at a constant Re_Δ. Ames and Moffat found that their St/St_o ratio agreed well with the original correlation (not corrected using the Reynolds analogy factor). They also proposed a scaling parameter (Ames and Moffat, 1990b) which they call TLR, defined as

$$TLR = Tu \left(\frac{\Delta}{L_u^\varepsilon}\right)^{0.33} \left(\frac{Re_\Delta}{1000}\right)^{0.25} \qquad (3)$$

The TLR parameter showed promise in scaling both their own data as well as the data from Maciejewski and Moffat. However, Λ_x instead of L_u^ε was used for Maciejewski and Moffat's data. In addition, the TLR parameter uses enthalpy thickness as opposed to boundary layer thicknesses which, as Ames and Moffat point out, are difficult to measure in highly turbulent fields.

As indicated above, in evaluating the different scaling parameters for high turbulence heat transfer and the correlations that have been proposed in the literature, we have found that these correlations have been applied in a variety of different and sometimes contradictory ways. For instance, the integral length scale and dissipation length scales have been interchanged as well as interchanging whether the Stanton number ratio, St/St_o, is evaluated at a constant Re_θ or Re_Δ. In particular, the ratio of integral length scale to dissipation length scale is quite different for different turbulence fields, e.g. $L_u^\varepsilon/\Lambda_x = 1.1$ for Simonich and Bradshaw (1978) and $L_u^\varepsilon/\Lambda_x = 1.5$ for Blair (1983). Based on these variations in the $L_u^\varepsilon/\Lambda_x$ ratio for different flowfields, it is imperative in applying scaling parameters based on a turbulence length scale that a consistent length scale be used. The interchanging of these parameters throughout the literature has confounded the interpretation of the correlations and may well contribute to the large scatter in the existing data.

In this paper, we have addressed generating high freestream turbulence levels of nominally 20% and the effects on heat transfer. We were particularly interested in determining which of the turbulence length scales, that is the dissipation or the integral scale, serve as a better scaling parameter for high freestream turbulence effects. We have used the thermal boundary layer parameters in evaluating the HB and TLR scaling parameters. The remainder of the paper discusses the experimental facility and data acquisition techniques used; quantifies the highly turbulent flowfield; and gives the surface heat transfer results for the highly turbulent case.

EXPERIMENTAL FACILITIES AND DATA ACQUISITION

This section of the paper describes the experimental facilities which includes the wind tunnel, the turbulence generator, and constant heat flux plate as well as the instrumentation used to measure the velocity and surface temperatures. Details of the facility and instrumentation were presented by Whan-Tong (1991).

Experiments were conducted in a closed-loop boundary layer wind tunnel driven by a 5 Hp fan. Heat exchangers, located downstream of the fan, maintained the mainstream flow temperature. The test section was 180 cm long, 61 cm wide and 15.2 cm high. A suction loop was added to the tunnel to remove the upstream boundary layer.

High freestream turbulence levels were produced by normal jets injected from both the floor and roof of the wind tunnel at the inlet of the test section. The turbulence generator, shown in figure 1, consisted of a top and a bottom row of opposing jets, each with a row of 35 holes having a diameter 5.08 mm and spaced 3 diameters apart. The test plate was located 40 cm downstream of the jet holes. Flow for the turbulence generator was diverted from upstream of the wind tunnel fan and was driven by a 7.5 Hp blower. The temperatures of the wind tunnel mainstream and turbulence generator jets were matched by cooling the turbulence generator flow loop by injecting small amounts of low temperature nitrogen. After being cooled, the flow was equally split between two plenums located on the roof and floor of the wind tunnel. The velocity ratio of the jets-to-mainstream dictated the turbulence level. For these experiments, a velocity ratio of 11 was used with a mainstream velocity of nominally 8 m/s.

Downstream of the suction slot, shown in figure 1, was an unheated, sharp leading edge followed by a constant heat flux test surface. The unheated sharp leading edge was 12 cm long with a 2.4 mm trip wire mounted 2 cm from the start of the plate. The constant heat flux plate which consisted of a serpentine, monel heating element was sandwiched between two Kapton films. The length and width of the plate were 1.4 m and 0.6 m, respectively. The heater plate was bonded to a 12.7 mm thick fiberglass composite (G-10). Below the plate were several layers of insulation to minimize conduction losses.

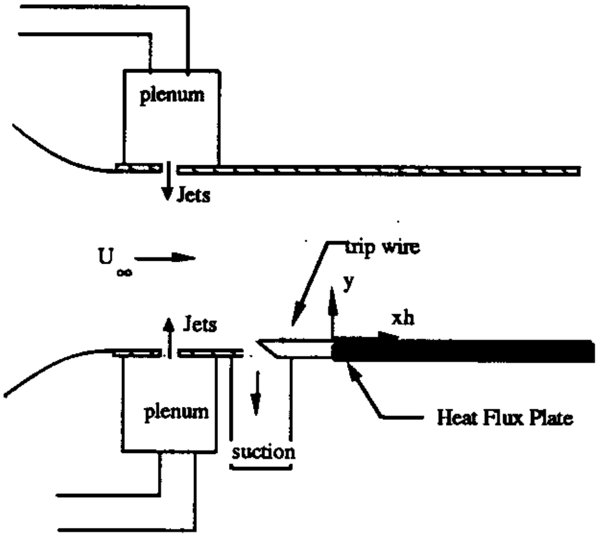

Figure 1. Schematic of the turbulence generator and heat flux plate assembly.

The total heat flux for these experiments was approximately 260 W/m^2 which resulted in a temperature differential of nominally 10°C. Low temperature differentials were used to avoid property variation effects. A DC power supply was used as the supply to the resistive heater. A significant radiation correction was required to obtain the net convective heat flux. The radiation correction was based on the radiation exchange between the heat flux plate and the wind tunnel roof. Surface temperatures of the wind tunnel roof were measured so that an accurate measure of the surrounding radiative temperatures could be made. The radiative heat flux was at most 17% of the total heat flux.

A two-component laser Doppler velocimeter (LDV) was used to measure the streamwise and vertical velocity components. The signal was processed by counters and then input to a computer. Velocity bias corrections were done using residence time weighting. The flow was seeded using smoke which was generated from burning incense sticks. The tar from the smoke was filtered out by using steel wool and then cooled before being injected into the tunnel.

Single sensor hot-wire measurements were made to determine the integral scales. Integral length scales, Λ_x, were deduced from the integral time scales based on Taylor's hypothesis of "frozen turbulence". The integral length scales discussed in this paper were measured at a lower freestream velocity (~ 4 m/s) but at the same turbulence levels, the same physical turbulence generator configuration, and the same ratio of jet-to-mainstream velocity.

The surface temperatures were measured using Type E surface thermocouple ribbons, described by Sinha et al. (1991) that were glued to the constant heat flux plate. Output from 63 thermocouples was multiplexed into a data acquisition computer where it was processed on-line to indicate Stanton number distributions.

TURBULENCE FIELD

The streamwise decay of u'/U_∞ and v'/U_∞ is shown in figure 2 with respect to the streamwise distance measured from the start of the heater plate. At 25 cm downstream of the start of the heater plate, at which point where the unheated starting length affects are negligible, $Tu = u'/U_\infty = 21\%$. Tu decays to 11% at 90 cm downstream which was the furthest point at which heat transfer effects were evaluated.

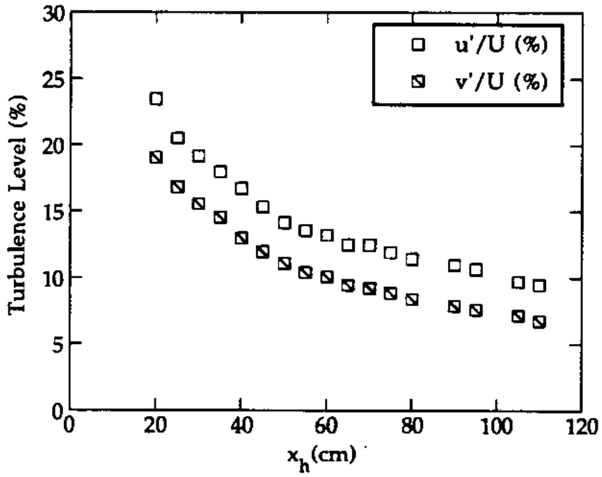

Figure 2. Streamwise turbulent decay for the highly turbulent flowfield along the heat flux plate.

The turbulent dissipation length scales, Lu^{ε}, were deduced from the u'^2 decay and the u' and U_∞ measurements. The ratio of dissipation to boundary layer thickness decreased from $Lu^{\varepsilon}/\delta_{99} = 3.4$ at $x_h = 25$ cm downstream to $Lu^{\varepsilon}/\delta_{99} = 3.0$ at $x_h = 90$ cm downstream. The Λ_x/δ_{99} ranged from 1.8 at $x_h = 25$ cm to 1.4 at $x_h = 90$ cm. Integral scales were only measured at a nominal freestream velocity of $U_\infty = 4$ m/s. The ratio of the dissipation scale to the integral scale was a relatively constant value of $Lu^{\varepsilon}/\Lambda_x = 3.1$.

Inherent in generating very high turbulence levels is the difficulty of maintaining a uniform mean flowfield. The mean flow uniformity of the highly turbulent field in the streamwise, lateral, and vertical directions were measured. The streamwise variation of freestream velocity increased by 4.5 % between $x_h = 25$ cm and 70 cm but then remained within ± 1.5% beyond $x_h = 70$ cm. The lateral variation in the mean velocity was nominally ± 10% at $x_h = 25$ cm downstream, but improved further downstream. The vertical non-uniformity at $x_h = 25$ cm was ± 2.5%. Although this does not appear to be large, the vertical velocity profile had a continuous gradient which made defining the boundary layer edge difficult. In order to identify the boundary layer edge at this location, the boundary layer was heated and the air temperature profile was measured and then used to identify the boundary layer edge. Further downstream, at 60 cm and 75 cm, the vertical profile was flat within ± 1%.

HIGH TURBULENCE HEAT TRANSFER RESULTS

The enhancement of heat transfer for the highly turbulent flowfield as compared with the standard boundary layer benchmark data and correlation (given by Kays and Crawford, 1980) is shown in figure 3. The Stanton number distributions are given as a function of Reynolds number based on streamwise distance, Re_x, where x is measured from the virtual origin located 0.36 m upstream of the heat flux plate. The virtual origin was deduced from the measured momentum thickness. The Stanton numbers shown in figure 2 for both the standard boundary layer and the high freestream turbulence cases show the effect of the unheated starting length. To avoid the unheated starting length effect, only the Stanton number data downstream of this region ($Re_x > 3\times10^5$, x_h = 25 cm), and in the centerline of the plate, were analyzed in this study. For the highly turbulent case, the spanwise variation of surface temperature and freestream velocity was ±6% and ±10%, respectively which resulted in a ±9% variation in Stanton number. Further downstream at 50 cm, where the velocity field was more uniform, the spanwise variation in surface temperature reduced to ±4%.

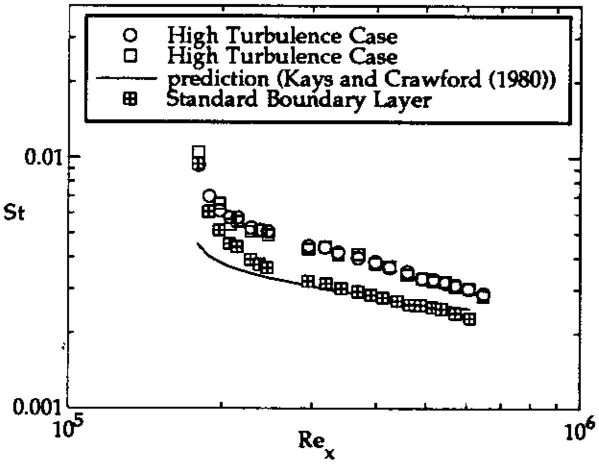

Figure 3. Stanton number distribution for both the standard boundary layer benchmark test and high freestream turbulence case.

In applying the Hancock and Bradshaw correlation as well as the Ames and Moffat correlation, St/St_o is found at a constant enthalpy thickness Reynolds number, Re_Δ. The enthalpy thickness, Δ, can be quantified by either measuring both the velocity and temperature profiles directly or can be found by using an energy balance which results in $\Delta = St \cdot x_h$ where x_h is the distance along the heater plate. The velocity and temperature profiles were measured at 25 cm and 60 cm downstream of the start of the heater. The enthalpy thicknesses deduced from the profiles were 36% and 52% lower than those calculated using the $St \cdot x_h$. This discrepancy was attributed to the difficulty of accurately measuring the enthalpy thickness for the thin boundary layer, and to effects due to the additional energy flux by turbulent fluctuations which become significant at high turbulence levels. Similar difficulties in directly measuring enthalpy thickness were encountered by Ames and Moffat (1990b) who found deviations as much as 30% from the $St \cdot x_h$ value. Ames and Moffat attributed this result to the spanwise variation of enthalpy thickness. Because of the difficulty in directly measuring the enthalpy thickness, in this study the enthalpy thickness was deduced from $St \cdot x_h$ values.

The measured Stanton number distribution for the standard boundary layer shown in figure 3 follows the correlation for the most part, but decreases at a greater rate resulting in a 7 % deviation at an $Re_x = 6.1x\ 10^6$. Also shown in figure 3 are two experimental data sets, under nominally the same conditions, for the high freestream turbulence showing the enhancement of heat transfer with the high freestream turbulence. The freestream velocity for the standard boundary layer was 7.8 m/s while the freestream velocity for the highly turbulent case ranged from 7.6 m/s at x_h = 25 cm to 8.2 m/s at the end of the plate, x_h = 90 cm. The experimentally measured Stanton numbers were used as the reference St_o in evaluating freestream turbulence effects. The experimentally measured Stanton numbers were used rather than the values from the correlation so than any experimental bias errors would be nullified.

Figure 4 shows the measured St/St_o ratio based on the same streamwise location. Also shown in figure 4 is the Ames and Moffat(1990a) data. Although our data shows a larger effect on the heat transfer enhancement, between x = 25 cm and 70 cm, both sets of data are asymptotically approaching $St/St_o|_{xh} = 1.25$ beyond x = 70 cm.

Of particular interest in figure 4 is the reduced enhancement of the heat transfer at the start of the heat flux plate. Our data, as well as the Ames and Moffat data, show that at the start of the heat flux plate, where the turbulence levels are the highest, there is essentially no enhancement of the heat transfer. This suppression of the enhancement effect could be due to either a low Re_Δ affect or a large ratio of turbulence length scale to thermal boundary layer thickness, Λ_x/Δ. In both data sets the enhancement increases in the downstream direction until there is a peak in the enhancement. If we assume that the suppression of the heat transfer has become negligible at this peak, it is of interest to contrast Re_Δ and Λ_x/Δ for the two data sets at the peak. These values are Re_Δ = 520 and 1960, and Λ_x/Δ = 29 and 36 for our data and Ames and Moffat, respectively. Clearly, the Re_Δ values are quite different, but the Λ_x/Δ are very close indicating that the suppression of the heat transfer enhancement at the beginning of the plate is due to a length scale ratio effect.

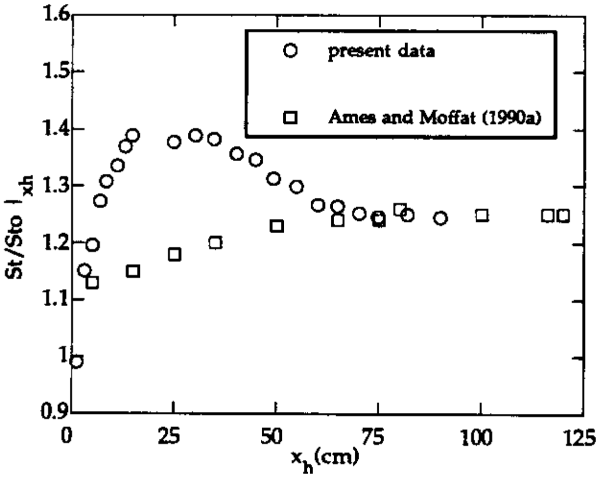

Figure 4. Ratio of high freestream turbulence St to the standard boundary layer St_o at the same streamwise locations.

Figure 5 compares our data as well as the Ames and Moffat data with the Hancock/Bradshaw correlation originally developed to scale C_f/C_{fo} as well as the Reynolds analogy modified Hancock/Bradshaw correlation. Data taken by Ames and Moffat agree reasonably well for 1.25 < HB < 2 with the original Hancock/Bradshaw correlation. Beyond HB = 2, which is also beyond the original correlation, the Ames and Moffat St/St_o continues to follow the same trend. Our data extends between 1.9 < HB < 3.8, but is significantly above both the Ames and Moffat data, as well as an extrapolation of the original Hancock/Bradshaw and modified correlations.

Our data was taken at relatively low Re_θ, i.e. 704 < Re_θ < 1054, which suggests the use of Blair's (1983) low Re_θ correction. However, the low Re_θ correction reduces the HB parameter which leads to worse agreement with the correlation.

The Stanton number correlation, given by Maciejewski and Moffat (1989b), based on the fluctuating streamwise velocity component is shown in figure 6. Our data shows a consistent trend in this format and falls on the lower bounds of the correlation with a maximum value near a turbulence level of 10%. However, there are clear differences in terms of the St' parameter between our data and that of Ames and Moffat (1990b) and the Maciejewski and Moffat (1989b) correlation.

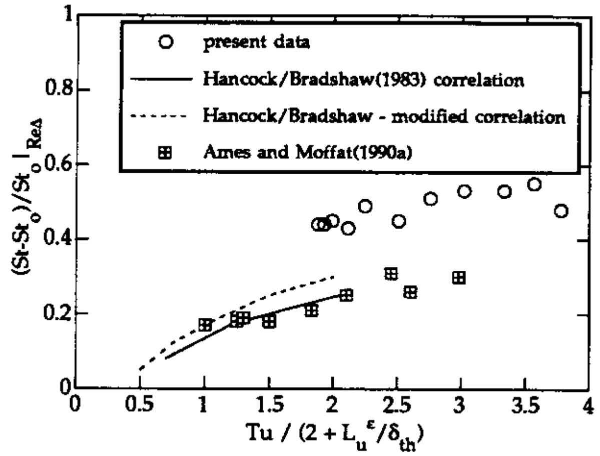

Figure 5. Comparison of present data with the Hancock/Bradshaw(1983) correlation.

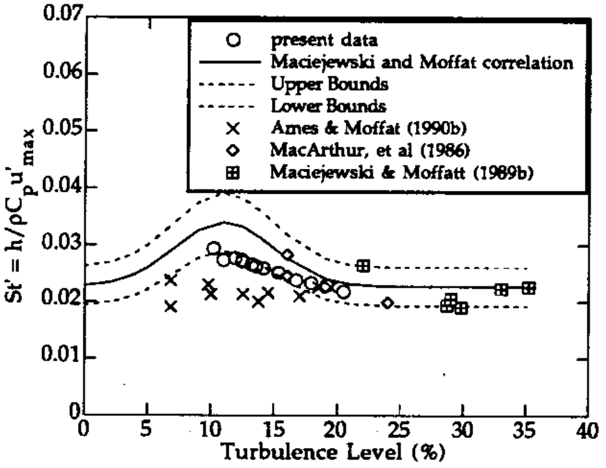

Figure 6. Comparison of present data with the Maciejewski and Moffat (1989b) correlation.

A new parameter for correlating high turbulence effects on heat transfer was suggested by Ames and Moffat (1990b) as described in the introduction. The Ames and Moffat TLR parameter is based on the turbulence level, dissipation length scale, and Re_Δ. Figure 7 shows our data compared to that of Ames and Moffat. As is evident from figure 7, there is still a distinct difference between the two data sets in terms of the TLR parameter.

In an attempt to better collapse the data, we evaluated the TLR parameter using the integral length scale, $T\Lambda_xR$, as opposed to the dissipation length scale. For this analysis we assumed that the $L_u^\varepsilon/\Lambda_x$ ratio measured at 4 m/s was valid at 8 m/s. Figure 8 shows results in terms of the $T\Lambda_xR$ parameter for our data, the data of Ames and Moffat (1990b), and the data of Maciejewski and Moffat (1989b). In using the $T\Lambda_xR$ parameter our data has been significantly shifted relative to Ames and Moffat's data such that all three data sets fall nominally in line. This shift occurred because of the significant differences in the ratio of the dissipation length scale to the integral length scale for our experiments, $L_u^\varepsilon/\Lambda_x \approx 3.1$, compared to Ames and Moffat, $L_u^\varepsilon/\Lambda_x = 2.2$. The $T\Lambda_xR$ parameter is the best parameter that has been investigated in this paper for collapsing all three high freestream turbulence data sets.

CONCLUSIONS

The new freestream turbulence generator developed as part this study produced a freestream turbulence field with larger turbulence levels and significantly smaller length scales than have been previously possible in a uniform

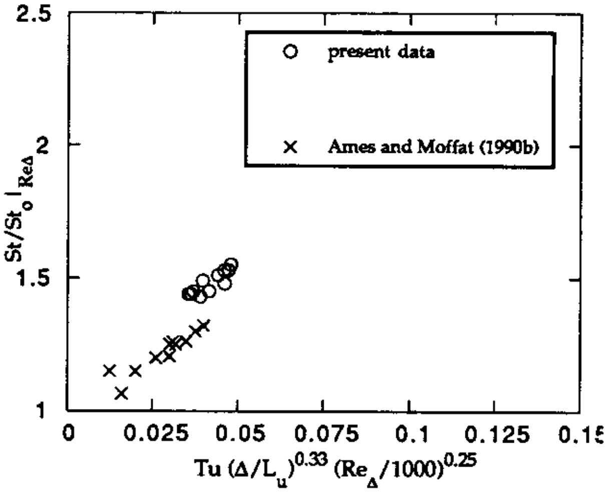

Figure 7. Comparison of present data to the Ames and Moffat (1990b) correlation using the turbulent dissipation scale.

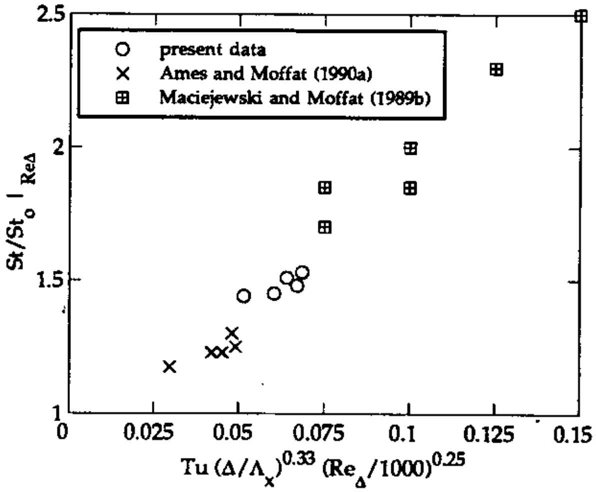

Figure 8. Comparison of present data to the Ames and Moffat (1990b) correlation using the turbulent integral scale.

flow test section. Effects of this high freestream turbulence on heat transfer were evaluated in terms of a variety of different correlations that have been published in the literature. Large enhancements to heat transfer were found at relatively low Re_θ which was somewhat contrary to the damping effect at low Reynolds number found for C_f by Blair (1983). However, significant suppression of the freestream turbulence effects was found to occur at the start of the heated surface which was attributed to the large turbulence length scale to thermal boundary layer thickness ratio at this location. Comparisons to the data of Ames and Moffat (1990b) were particularly revealing because similar turbulence levels were used, but the turbulence length scales were quite different. The TLR parameter suggested by Ames and Moffat was modified by using the integral length scale rather than the dissipation length scale. This TA_xR parameter was the best parameter investigated in this paper for collapsing all three high freestream turbulence data sets.

ACKNOWLEDGEMENTS

We gratefully acknowledge the support of the Wrigth-Patterson Research and Development Center and Allied-Signal Aerospace Corporation. We would also like to thank Dr. Michael Crawford for his helpful discussions.

REFERENCES

Ames, F.E. and Moffat, R.J., (1990a) "Effects of Simulated Combustor Turbulence on Boundary Layer Heat Transfer," AIAA/ASME Thermophysics and Heat Transfer Conference, Seattle,pp. 11-17.

Ames, F.E. and Moffat, R.J., (1990b) "Heat Transfer with High Intensity, Large Scale Turbulence: The Flat Plate Turbulent Boundary Layer and the Cylindrical Stagnation Point," Stanford University Report No. HMT-44.

Baskaran, V., Abdellativ, O.E., and Bradshaw, P. (1989) "Effects of Free-stream Turbulence on Turbulent Boundary Layer with Convective Heat Transfer," Seventh Symposium on Turbulent Shear Flows, Stanford University, paper 20.1.

Blair, M.F. (1983) "Influence of Free-Stream Turbulence on Turbulent Boundary Layer Heat Transfer and Mean Profile Development," Part I - Experimental Data, ASME J Heat Transfer, Vol. 105, pp. 33-40.

Dunn M.G., Martin, H.L., Stenek, M.J. (1986) "Heat Flux and Pressure Measurements and Comparison with Prediction for a Low Aspect Ratio Turbine Stage," ASME Gas Turbine Conference, 86-GT-79, Dusseldorf, West Germany.

Hancock, P.E. and Bradshaw, P. (1982) "The Effect of Free-Stream Turbulence Boundary Layer Development," ASME J Power Engineering.

Kays, W. M.; Crawford M. E. (1980) *Convective Heat and Mass Transfer, Second Edition*, McGraw-Hill, New York.

Kestin, J., Maeder, P.F. and Wang, H.E. (1961) "Influence of Turbulence on the Heat Transfer from Plates with and without a Pressure Gradient," International Journal of Heat and Mass Transfer, Vol. 3, p. 133.

Koutmos, P. and McGuirk, J. J., (1989) "Isothermal flow in a Gas Turbine Combustor — a Benchmark Experimental Study," Experiments in Fluids, Vol. 7, p. 344.

MacArthur, C.D. (1986) "Fluid Dynamics and Heat Transfer of the Circular Tangential Wall Jet," Ph.D. Thesis, University of Dayton, Dayton, Ohio.

Maciejewski, Paul K. and Moffat, Robert J. (1989a) "Effects of Very High Turbulence on Heat Transfer," Seventh Symposium on Turbulent Shear Flows, Stanford University, August 21-23, 1989.

Maciejewski, P. K. and Moffat, R. J. (1989b) "Heat Transfer with Very High Free Stream Turbulence," Stanford University, Report HMT-42.

MacMullin, R., Elrod, W., and Rivir, R. (1989) "Free-Stream Turbulence From a Circular Wall Jet on a Flat Plate Heat Transfer and Boundary Layer Flow," Transactions of the ASME, Vol. 111, pp. 78-86.

Simonich, J.C., Bradshaw, R. (1978) "Effect of Free Stream Turbulence on Heat Transfer through a Turbulent Boundary Layer," ASME J of Heat Transfer, Vol. 100, pp. 671-677.

Sinha, A.K., Bogard, D.G., and Crawford, M.E. (1991) "Film Cooling Effectiveness Downstream of a Single Row of Holes with Variable Density Ratio," ASME Journal of Turbomachinery, Vol. 113, No.3.

Whan-Tong, J. (1991) "The Development of a Very High Freestream Turbulence Generator for Use in Gas Turbine Studies," Master's Thesis, University of Texas at Austin, Turbulence and Turbine Cooling Research Laboratory.