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Generating high freestream turbulence levels

K. A. Thole, D. G. Bogard, J. L. Whan-Tong

Abstract This paper presents a method of generating a highly turbulent freestream flow, up to levels of 20% with a relatively uniform mean velocity field. This method was developed as a result of a combined water channel and wind tunnel study. The method for generating these high turbulence levels includes using high-velocity jets issuing into a mainstream cross-flow. A range of turbulence levels can be generated, using this same flow geometry, by adjusting the jet-to-mainstream velocity ratio or the Reynolds number of the flow.

List of symbols

b	Grid bar width
D	Turbulence generator jet hole diameter
$E_u(f)$	Spectral energy for streamwise velocity fluctuations
f	Frequency
H	Channel height
L_u^ε	Dissipation length scale, $L_u^\varepsilon \equiv -\dfrac{\overline{(u'^2)}^{3/2}}{U_\infty \dfrac{d\overline{(u'^2)}^{3/2}}{dx}}$
m	Exponent for length scale growth
M	Grid mesh size
n	Exponent for turbulence decay
Re_D	Reynolds number based on jet hole diameter
Re_T	Turbulent Reynolds numbers, $u'\lambda_g/\nu$
S	Lateral spacing between the jet holes
T	Integral time scale of turbulence
Tu	Streamwise turbulence intensity, u'/U
u'	RMS velocity in streamwise direction
U	Mean local velocity in streamwise direction
U_∞	Freestream velocity in streamwise direction
v'	RMS velocity in normal direction
x	Streamwise distance measured from the turbulence generator jets
y	Vertical distance from the wall
z	Spanwise distance
δ	Boundary layer thickness ($U = 0.99\, U_\infty$)
Λ_x	Longitudinal integral length scale of turbulence

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1 Introduction

High freestream turbulence levels such as those found in gas turbines are discussed throughout the literature as one of the factors which cause large discrepancies between measured and predicted surface heat transfer. The turbulence levels found in gas turbines, as measured by Kuotmos and McGuirk (1989), are in the range of 20–30%. However, many freestream turbulence studies have used turbulence generated by some type of bar-grid arrangement which is inherently limited to levels of 7% or less for uniform flow. This paper discusses a new technique for generating a range of turbulence levels and, in particular, turbulence levels as high as $Tu = 20\%$.

Only recently have there been attempts to study freestream turbulence levels with devices other than grids. MacMullin, Elrod and Rivir (1989), Maciejewski and Moffat (1989), and Ames and Moffat (1990) have all reported studies with relatively high turbulence levels. MacMullin, Elrod, and Rivir (1989) used a wall-jet to generate turbulence levels up to 20%. Maciejewski and Moffat (1989) used a free jet to generate a range of turbulence levels up to 60% by positioning their test plate at various angles relative to the free jet. Although both of these flow configurations produced high turbulence levels, the mean velocity profiles for these wall jet flows are inherently highly non-uniform. Ames and Moffat (1990) were able to achieve turbulence levels up to 19% by simulating an annular combustor where flow was injected through a series of wall slots and jet holes upstream of their wind tunnel contraction.

Since the turbulence present in a gas turbine is a result of that generated in the upstream combustor, it is not surprising that the design for the turbulence generator described here has similar characteristics to that of a combustor. The basic idea for the generator described here is to use high-velocity, normal jets issuing into a mainstream crossflow. In principle, the design of this turbulence generator is based on the combustor just as Ames and Moffat's (1990) generator was. However, one of the differences is that this generator is placed in the test section downstream of the contraction. From a construction standpoint, implementing this design into a wind tunnel is simpler. This paper briefly describes the design and the capabilities of the generator.

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Turbulence generator design

The turbulence generator was to be used in an existing closed-loop, boundary layer wind tunnel facility located in the Turbulence and Turbine Cooling Research Laboratory (TTCRL) at the University of Texas. Some preliminary studies for the generator development took place in a water channel facility also located in the TTCRL. The criteria set forth in developing this turbulence generator included: achieving turbulence levels representative of what may be found in a gas turbine ($10\% < Tu < 20\%$) with slow decay rates; to have a relatively uniform mean velocity field; and to have turbulent length scales on the order of the boundary layer thickness.

Velocity fields were measured in both the water channel and the wind tunnel tests with either a single- or two-component laser Doppler velocimeter (LDV). A hot-wire (hot-film in the water channel) anemometer system was used to measure the velocity fluctuations which were then used to obtain integral time scales and energy spectra. The energy spectra were determined through the use of a spectrum analyzer. The integral time scales, T, were calculated directly from correlations of the digitized hot-wire measurements, or from the power spectrum extrapolated to zero frequency using the following relation (Hinze, 1975):

$$T = \frac{1}{4u'^2} \lim_{f \to 0} [E_u(f)] \quad (1)$$

The integral length scales were deduced from the measured integral time scales and mean velocities invoking Taylor's hypothesis.

Preliminary design of the turbulence generator was conducted in a water channel facility using a single row of jets on the bottom wall as shown in Fig. 1. These tests, described in detail by Whan-Tong (1991) and Bogard, Thole, and Crawford (1992), used only a portion of the water channel test section to conduct the testing of the jets-in-crossflow concept. For these tests, 14 jet holes were used with hole diameters of $D = 6.35$ mm and a spacing between holes of $S/D = 1.5$. As shown in Fig. 1, a side wall was positioned at a width of 13.3 cm to confine the flow through the row of jets, and the jets were also confined by a top wall placed at a height of 7.0 cm. The flow was provided from the stilling tank and was driven by a 0.25-hp pump. The flowrate to the jets was measured using a rotameter.

These preliminary water channel tests showed that turbulence levels greater than 20% could be achieved with jet-to-

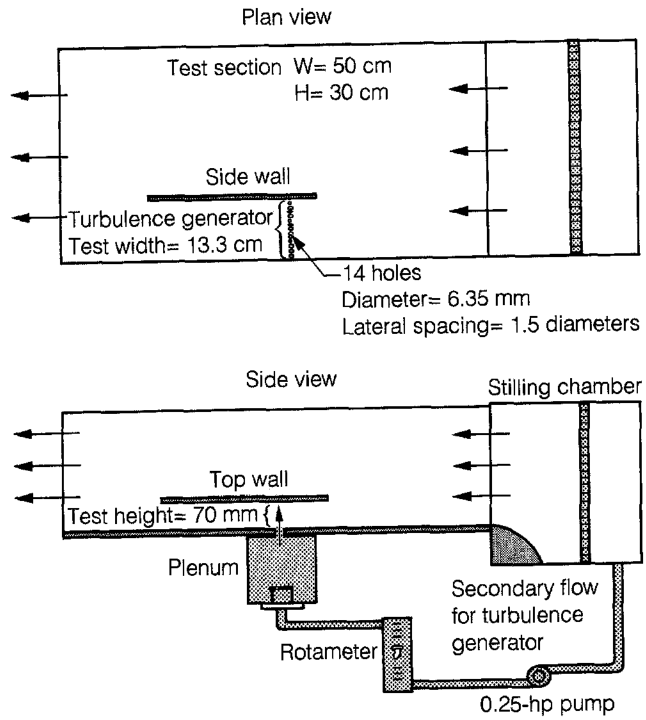

Fig. 1. Plan view (top schematic) and side view (bottom schematic) of the water channel facility used for the initial development of the turbulence generator

mainstream velocity ratios (VR) greater than $VR = 3.7$, as shown in Fig. 2. Turbulence levels were found to increase significantly as the velocity ratio was increased from $VR = 3.7$ to $VR = 7.8$. Although the turbulence levels were much higher, the decay rate was faster at the higher velocity ratio. Significantly better uniformity of the mean velocity profiles was found to occur when the jets were directed into a confined channel with a channel height of $H/D = 11$ (70 mm) rather than a channel with an open top. At a velocity ratio of $VR = 5.3$, the mean and rms velocity profiles across the height of the channel were found to be uniform within $\pm 10\%$ at a distance of $x/D = 87$ downstream of the jets. The turbulence level at this downstream position was $Tu = 22\%$.

After the preliminary water channel tests, the jets-in-crossflow turbulence generator was implemented in the closed-loop wind tunnel facility. A schematic of the wind tunnel, including a secondary flow loop for the turbulence generator, is shown in Fig. 3a. The flow for the wind tunnel facility was driven by a variable speed 5-hp fan allowing a range of freestream velocities in the test section from 0.5 m/s to 40 m/s. The mainstream flow was conditioned downstream of the fan with a honeycomb section followed by a series of four screens. Downstream of these screens was a two-dimensional 9:1 tunnel contraction which was then followed by the working test section. The test section had dimensions of 244 cm in length, 61 cm in width, and 15.2 cm in height.

The flow was provided for the high-velocity, normal jets through a secondary flow loop that was driven by a 7.5-hp blower. The design flowrate/pressure drop characteristics for the secondary loop blower were 28″ of water at 700 scfm. The air supply for this blower was removed upstream of the wind tunnel

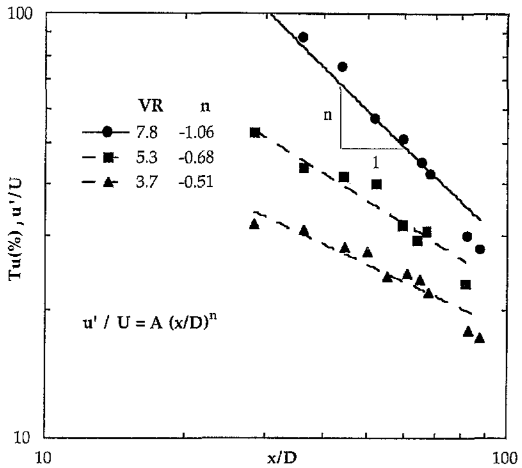

Fig. 2. Streamwise turbulence intensity decay as measured in the water channel tests comparing velocity ratios

fan. After exiting the blower, the secondary flow was cooled, crudely yet effectively, by injecting low-temperature nitrogen into the flow to remove the extra heat addition from the blower.

As shown schematically in Fig. 3b, the secondary flow was then piped to two plenums positioned above the top wall and below the bottom wall of the wind tunnel test section. At the exit of both of these plenums, the jets were exhausted into the mainstream crossflow through holes which were 5.08 mm in diameter with a lateral spacing of $S/D = 3$. The jets were exhausted directly into the initial region of the test section, downstream of the contraction. The streamwise location of the jets was 130 jet diameters upstream of the region of interest on the test plate. Testing in the wind tunnel indicated that shorter streamwise distances between the generator and the test plate resulted in non-uniform mean velocities.

To prevent the jets from interacting after exiting the holes, a thin splitter plate having a thickness of 1.6 mm was placed parallel to the flow at the mid-height of the tunnel. The splitter plate spanned the entire width of the tunnel and extended 15 cm upstream of the jet holes and 10 cm downstream. The splitter plate was used to prevent the jets from interacting where the velocity gradients were extremely high. Without the splitter plate, the interaction of these jets produced bulges in the lateral mean velocity profiles further downstream (Thole, 1992). It was also critical that the row of jet holes fully extended to the lateral edges of the tunnel. Initially, there were side gaps having a width of 57 mm which resulted in poor spanwise uniformity with the main flow being directed towards the lateral edges. Additional holes were added which extended to the lateral edge and resulted in better uniformity.

The required jet-to-mainstream velocity ratio, indicated from the water channel tests to achieve turbulence levels of $Tu = 20\%$, was nominally a $VR = 5$. However, after implementing the design into the wind tunnel, a larger velocity ratio was needed to achieve the same turbulence levels. This is, in part, due to a Reynolds number effect which will be discussed further in the next section. The Reynolds number based on the jet diameter for the water channel tests were $Re_D = 500$ whereas for the wind tunnel tests the Reynolds number was $Re_D = 1700$. As the

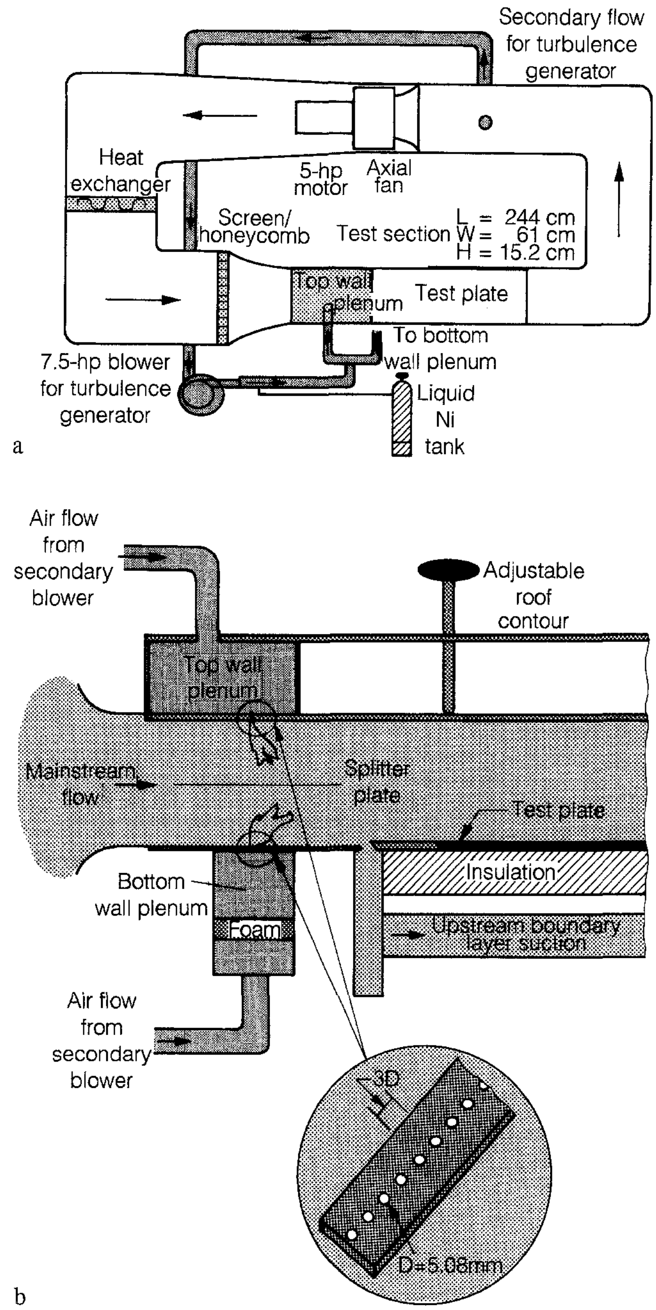

Fig. 3. a Plan view of the closed-loop wind tunnel including the secondary flow loop for the turbulence generator; b schematic of the wind tunnel test section including the turbulence generator

Reynolds number increases, higher jet-to-mainstream velocity ratios are required to give similar turbulence levels. The final design used a ratio of $VR = 17$ to achieve turbulence levels of $Tu = 20\%$ at a streamwise distance measured from the jet holes of $x/D = 130$. This velocity ratio resulted in a mass flowrate addition to the crossflow at the start of the test section of nominally 20%.

The resulting lateral uniformity of the mean velocity and the turbulence level profiles are shown in Fig. 4. These velocities were measured in the mid-height of the tunnel at an $x/D = 130$ and were representative of the flow core. The streamwise mean velocity was uniform across the span to within $\pm 4\%$ while the rms velocities were uniform to within $\pm 9\%$ within the center

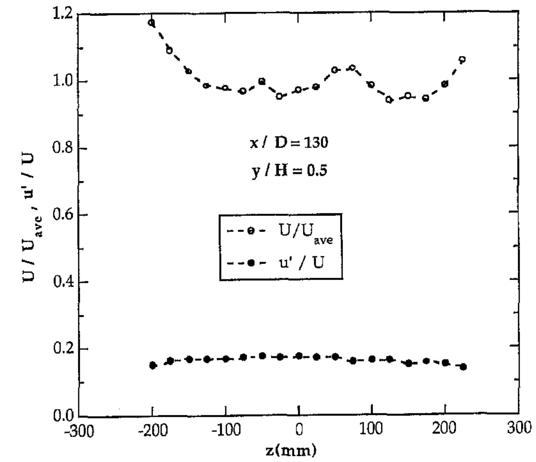

Fig. 4. Spanwise uniformity of highly turbulent flowfield at the mid-height of the tunnel and at a downstream distance measured from the jets of $x/D = 130$

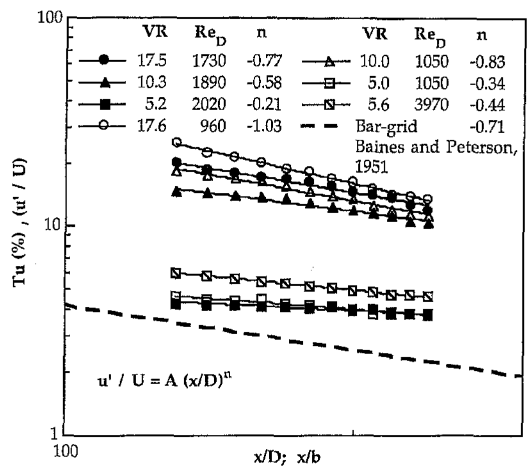

Fig. 5. Streamwise decay of turbulence levels as a function of jet-to-mainstream velocity ratio and jet Reynolds number as compared with grid-generated turbulence

300 mm of the tunnel. The streamwise mean velocity was uniform in the vertical direction to within $\pm 5\%$ as measured at an $x/D = 130$ and at the mid-span of the tunnel ($z/D = 0$).

3 Highly turbulent flowfield characteristics

The turbulence levels generated with the jets-in-crossflow configuration were dictated by both velocity ratio and Reynolds number based on the upstream crossflow velocity and jet hole diameter (Re_D). Figure 5 shows the decay rates for different velocity ratios and Reynolds numbers measured in the mid-height ($y/H = 0.5$) and lateral centerline ($z/D = 0$) of the wind tunnel test section. As the velocity ratio decreased, the turbulence levels which could be achieved also decreased, where as the Reynolds number decreased, the turbulence levels increased. Similar to the water channel studies, as the turbulence levels increased so does the rate of streamwise decay.

Also shown in Fig. 5 is the typical decay for grid-generated turbulence. The very high turbulence levels generated with

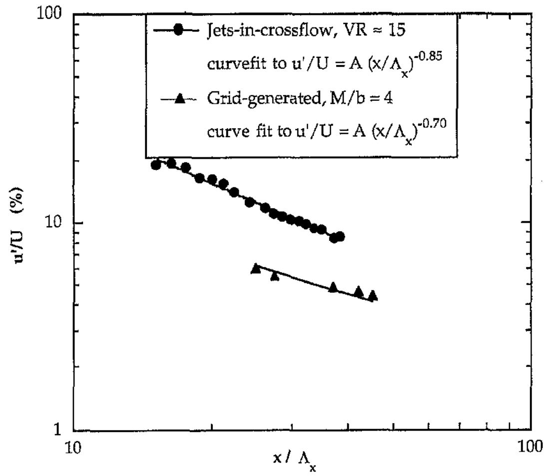

Fig. 6. Streamwise decay of turbulence compared with grid-generated turbulence. Streamwise distance is normalized by the integral length scale

jet velocity ratios of $VR > 10$ had decay rates similar to grid-generated turbulence, but the lower turbulence levels obtained with $VR \sim 5$ had noticeably slower decay rates. As shown in Fig. 5, the exponents of the decay rates for $VR = 5$ range between $-0.44 < n < -0.21$ which is significantly slower than bar-grid generated turbulence which has an exponent of nominally $n = -0.7$.

For comparisons of turbulence generated by the jets-in-crossflow and by bar-grids as presented in Fig. 5, the streamwise distance was normalized with the jet diameter and the bar width, respectively. However, there is no assurance that these are comparable normalizing scales. To resolve this ambiguity, the measured turbulent integral length scale was used to normalize the streamwise distance as shown in Fig. 6. The grid turbulence was generated by a bi-planar bar-grid located at the entrance of the wind tunnel test section. The grid had a square bar width of $b = 6.35$ mm and a square mesh size of $M = 25.4$ mm. As evident in Fig. 6, the jets-in-crossflow had much higher turbulence levels even though the downstream distance relative to the turbulent integral length scales was similar to that of the grid-generated turbulence.

To achieve the turbulence levels of interest, the jet-to-mainstream velocity ratio and Reynolds number used were $VR = 17$ and $Re_D = 1700$, respectively. This velocity ratio required that the blower be operated at full capacity with a nominal freestream velocity of 8 m/s downstream of the jet holes. Although, as indicated in Fig. 5, the lower Reynolds number flow ($Re_D = 960$ and $VR = 17.6$) gave even higher turbulence levels, these conditions were not chosen because the vertical mean velocity profile was not as uniform as for the $Re_D = 1700$ case.

The decay of u' and v' velocity components for these conditions is shown in Fig. 7. The v' component was about 30% lower than the u' component, and the relative difference remained the same for the length of the test section. These results are in contrast to the turbulence generated by the combustor simulator of Ames and Moffat (1990) for which the v' levels were 20% to 30% higher than the u' levels.

In principle, according to the results of Whan-Tong (1991) and Baines and Peterson (1951), turbulence levels of $Tu = 20\%$ can be generated by a bar-grid at a streamwise distance of $x/b = 10$

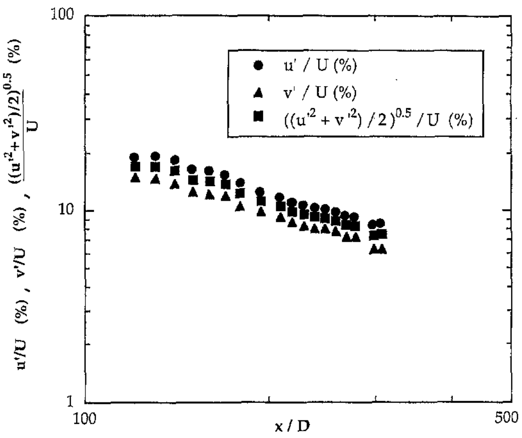

Fig. 7. Streamwise decay of turbulence for streamwise, vertical, and combined fluctuating velocities

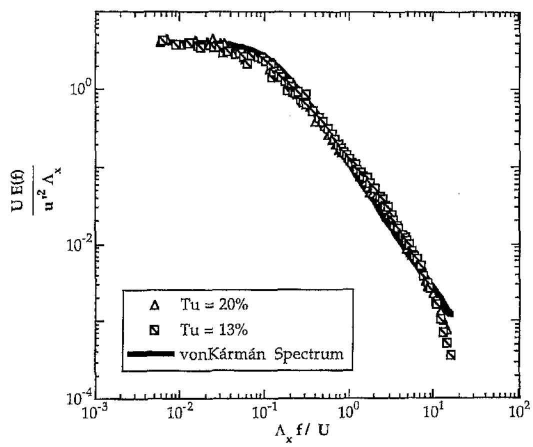

Fig. 9. Energy spectra of freestream turbulence as compared with the vonKármán Spectrum

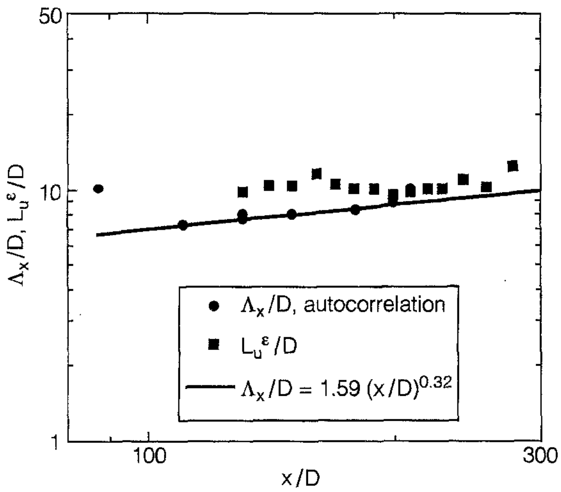

Fig. 8. Streamwise integral and dissipation turbulent length scales for the high turbulent flow field

measured downstream from the grid location. However, the flow uniformity at this location would be quite poor. Grid-generated turbulence would decay to a turbulence level of $Tu=12\%$ at $x/b=20$. For the present jets-in-crossflow turbulence generator the turbulence level decays from $Tu=20\%$ to $Tu=12\%$ over a distance of about 50 cm. Consequently, in order to have a similar decay length of 50 cm from a bar-grid, bar widths of 5 cm must be used. Considering that the height of our wind tunnel test section was 15 cm, only one large bar in a grid could be used; hence, resulting in a very non-uniform flow.

The integral turbulent length scales, deduced from the integral time scales, were calculated using both the autocorrelation and energy spectra, as discussed in the previous section. The dissipation and integral length scales, normalized by the jet diameter, are shown in Fig. 8. The growth rate of the integral length scales was quite similar to the growth rate of integral scales resulting from grid turbulence as reported by Comte-Bellot and Corrsin (1966). The growth rate exponent for the jets-in-crossflow turbulence generator was $m=0.32$ whereas Comte-Bellot and Corrsin report exponents ranging from $m=0.30$ to 0.35.

Relative to the height of the wind tunnel, the integral length scales were $\Lambda_x/H=0.26$ at $x/D=130$ growing only slightly to $\Lambda_x/H=0.30$ at $x/D=200$. The dissipation and integral length scales, as shown in Fig. 8, were comparable for this highly turbulent flowfield. The dissipation to integral length scale ratio ranged from $1.1<L_u^\varepsilon/\Lambda_x<1.4$ over the streamwise distance of $x/D=130$ to $x/D=200$.

Figure 9 shows the energy spectra of the streamwise velocity fluctuations measured at two different streamwise locations which had turbulence levels of $Tu=20\%$ and $Tu=13\%$. The energy spectra agreed very well with the classic von Kármán spectra. The turbulent Reynolds numbers for these two locations were $Re_T=271$ for a $Tu=20\%$ and $Re_T=159$ for a $Tu=13\%$. The turbulent Reynolds numbers were somewhat larger than those for grid-generated turbulence which is typically $Re_T<100$ (Hinze, 1975).

4
Conclusions

The high-velocity jets-in-crossflow is a viable technique for generating high freestream turbulence levels ($10\%<Tu<20\%$) that are representative of what may be found in a gas turbine environment. Although the intent of this turbulence generator was to achieve high freestream turbulence levels, we found that a range of turbulence levels could be achieved depending on both the Reynolds number and jet-to-mainstream velocity ratio. For high velocity ratios, the jets-in-crossflow generate much higher turbulence levels than bar-grids, but turbulence decay rates, length scale growth rates, and energy spectra are very similar to grid-generated turbulence. For lower velocity ratios the turbulence decay rates are significantly slower than for grid-generated turbulence. Moreover, it would not be possible to use a bar-grid arrangement to produce turbulence levels of this magnitude and have a relatively uniform flowfield.

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Announcements

EUROMECH Colloquia 1995

EUROMECH Colloquia are informal meetings on specialized research topics. Participation is restricted to a small number of European research workers actively engaged in the field of each Colloquium. The organization of each Colloquium, including the selection of participants for invitation, is entrusted to a Chairman. Proceedings are not normally published. Those who are interested in taking part in a Colloquium should write to the appropriate Chairman. Number, Title, Chairman or Co-chairmen, Dates and Location for each Colloquium in 1995, and an advance notice for a Colloquium in 1996, are given below.

329. *Methods for nonlinear stochastic structural dynamics*
Prof. G. I. Schueller, Institute of Engineering Mechanics, University of Innsbruck, Technikerstrasse 13, A-6020 Innsbruck, Austria
13–17 March 1995, Innsbruck, Austria

330. *Laminar/turbulent transition of boundary layers influenced by free-stream disturbances*
Dr. P. Jonás, Institute of Thermomechanics, Academy of Sciences of the Czech Republic, Dolejskova 5, CZ-182 00 Praha 8, Czech Republic
Prof. F. Pittaluga, Genova
10–12 April 1995, Prague, Czech Republic

331. *Flows with phase transition*
Prof. G. E. A. Meier, Institut für Strömungsmechanik der DLR, Bunsenstrasse 10, D-37073 Göttingen, Germany
Prof. G. H. Schnerr and Prof. J. Zierep, Karlsruhe
13–16 March 1995, Göttingen, Germany

332. *Drag reduction*
Prof. P. Luchini, Dipartimento di Progettazione Aeronautica, Università di Napoli Federico II, P. Le Tecchio, I-80125 Napoli, Italy
Dr. D. Bechert, Berlin
19–20 April 1995, Ravello (near Naples), Italy

335. *Image techniques and analysis in fluid dynamics*
Prof. A. Cenedese, Department of Mechanics and Aeronautics, University "La Sapienza", Via Eudossiana 18, I-00184 Roma, Italy
Prof. F. T. M. Nieuwstadt, Delft
5–7 June 1995, Rome, Italy

336. *Flows dominated by centrifugal and Coriolis forces*
Prof. H. Andersson, Applied Mechanics, The Norwegian Institute of Technology, N-7034 Trondheim, Norwar
21–23 June 1995, Trondheim, Norway

337. *Plastic flow instabilities at high rate of strain*
Prof. C. Fressengeas, L.P.M.M./I.S.G.M.P., Université de Metz Ile du Saulcy, F-57045 Metz Cédex 01, France
Dr. B. Dodd, Reading
10–13 July 1995, Metz, France

338. *Atmospheric turbulence and dispersion in complex terrain*
Dr. F. Tampieri, FISBAT CNR, Via Gobetti 101, I-40129 Bologna, Italy
4–6 September 1995, Bologna, Italy

339. *Internal waves, turbulence and mixing in stratified flows*
Dr. C. Staquet, Ecole Normale Supérieure de Lyon, Laboratoire de Physique, 46, allée d'Italie, F-69364 Lyon Cédex 07, France
6–8 September 1995, Lyon, France

340. *Statistical properties of turbulent gaseous flames*
Prof. D. Roekaerts, Heat Transfer Section, Faculty of Applied Physics, Delft University of Technology, Lorentzweg 1, NL-2628 CJ Delft, The Netherlands
Dr. Th. van der Meer, Delft
30 August–1 September 1995, Delft, The Netherlands

342. *Aerothermodynamics*
Dr. G. Eitelberg, Aerothermodynamics Branch, Institute for Fluid Mechanics, DLR, Bunsenstrasse 10, D-37073 Göttingen, Germany
Dr. H. Legge, Göttingen, and Prof. R. Brun, Marseille
26–29 September 1995, Göttingen, Germany