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The Influence of Jet-Grid Turbulence on Heat Transfer from the Stagnation Region of a Cylinder in Crossflow

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THE INFLUENCE OF JET-GRID TURBULENCE ON HEAT TRANSFER FROM THE STAGNATION
REGION OF A CYLINDER IN CROSSFLOW

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ABSTRACT

An experimental study has been performed to determine the effect of high-intensity turbulence on heat transfer from the stagnation region of a circular cylinder in crossflow. The work was motivated by the desire to be able to more fully understand and predict the heat transfer to the leading edge of a turbine airfoil. In order to achieve high levels of turbulence with a reasonable degree of isotropy and homogeneity, a jet-injection turbulence grid was used. The jet grid provided turbulence intensities of 10 to 12 percent, measured at the test cylinder location, for downstream blowing with the blowing rate adjusted to an optimal value for flow uniformity. In contrast, if flow uniformity is to be maintained, the maximum achievable turbulence intensities behind a conventional passive square-bar, square-mesh grid were found to be 7 to 8 percent. Heat transfer augmentation above the zero-turbulence case ranged from 37 to 53 percent for the test cylinder behind the jet grid for a cylinder Reynolds number range of 48 000 to 180 000, respectively. The level of heat transfer augmentation was found to be fairly uniform with respect to circumferential distance from the stagnation line. Stagnation point heat transfer results (expressed in terms of the Frossling number) were found to be somewhat low with respect to previous studies, when compared on the basis of equal values of the parameter $Tu \, Re^{1/2}$, indicating an additional Reynolds number effect as observed by previous investigators. Consequently, for a specified value of $Tu \, Re^{1/2}$, data obtained with a relatively high turbulence intensity (such as those of the present study) will have lower value of the Frossling number.

NOMENCLATURE

A_j single jet exit area, cm^2

b square bar width, cm

J_{opt} optimal jet grid blowing ratio

$\dot{m}_{grid}$ total grid injection flow rate, kg/s

$\dot{m}_{Tot}$ total wind tunnel flow rate, kg/s

M grid bar spacing distance, cm

Nu Nusselt number

Re Reynolds number based on free-stream conditions and cylinder diameter

Re_b Reynolds number based on free-stream conditions and grid bar diameter

Tu turbulence intensity

$\overline{U}$ time-averaged free-stream velocity, m/s

$\overline{U}_{AV}$ spanwise and time-averaged free-stream velocity, m/s

x streamwise coordinate, cm

y cross-stream coordinate normal to cylinder axis, cm

θ angle from stagnation line, deg

INTRODUCTION

One of the most critical heat transfer areas on a turbine airfoil is the blunt leading edge. This region, usually of circular cross section, is subjected to a complex, highly turbulent flow of hot combustion gases. The augmentation of heat transfer from a circular cylinder due to the presence of free-stream turbulence has been well documented; however, it is still not possible to accurately predict heat transfer to the stagnation region of a turbine blade in a new engine design.

Various means exist for generating turbulence in laboratory wind tunnels. The most common of these is the use of a passive grid, which produces turbulence by acting simply as an obstacle to the flow. At high Reynolds numbers far downstream of such a grid, the turbulence is found to be isotropic, with a reasonable degree of homogeneity in the mean velocity. It is

difficult, however, to achieve by means of a passive grid the high levels of turbulence characteristic of turbomachinery, while maintaining isotropy and homogeneity. This difficulty is due to the manner in which turbulence decays behind a passive grid, which necessitates proximity to the grid for achieving high turbulence. However, gradients in the mean velocity profile dominate the flow field at near-downstream stations and assumption of homogeneity is thus inappropriate.

An alternate method for generating wind tunnel turbulence is through the use of a jet grid. Such a grid consists of an array of hollow rods or pipes through which air is forced and delivered to small holes or jets in the rods. The jets can be oriented to blow in the upstream or downstream direction with controllable flow rates. The possibility of generating high levels of jet-grid turbulence (10 to 15 percent), while maintaining isotropy and homogeneity, and of measuring the influence of these high levels of turbulence on stagnation point heat transfer from a circular cylinder were the main focus of this project.

Previous studies by Gad-El-Hak and Corrsin (1) and by Tassa and Kamotani (2) were aimed primarily at characterizing the turbulent flow field behind a jet grid. Intensity, decay rates, pressure drop, homogeneity, isotropy, spectra, and scales of turbulence were documented for both upstream and downstream blowing and as a function of jet injection rate. The jet-grid turbulence was found to be nearly isotropic in both studies but other results of these studies are contradictory. No previous studies of heat transfer for an object downstream of a jet grid have been made.

With regard to cylinder stagnation region heat transfer, several analytical and experimental studies have been made. The classical analytical work of Frossling (3) for stagnation region heat transfer in a laminar boundary layer washed by a zero-turbulence free stream provides a baseline for experimental work. More recent experimental work (4-8) has demonstrated the marked effect of turbulence intensity on stagnation region heat transfer. Smith and Kuethe (5) developed a theoretical relation for heat transfer and skin friction near the stagnation point and supported their theory with experimental data. Their data exhibited a Reynolds number effect for Re < 10^5 that is not accounted by the theory.

Several recent studies (9-13) have been aimed at identifying the mechanisms responsible for stagnation region heat transfer augmentation in a turbulent flow. Reference 14 provides a review of this work. The primary mechanism for heat transfer augmentation is thought to be vortex stretching. Vortices with components of their axes normal to the cylinder stagnation line and normal to the free stream flow direction are stretched and tilted due to divergence of streamlines and acceleration around the body. Conservation of angular momentum causes the vorticity to be amplified. The extent of amplification was found to be scale-dependent in Ref. 10 and a so-called most amplified scale was identified in Ref. 11. In Refs. 12 and 13, vortex formation and heat transfer in a cylinder stagnation region downstream of an array of parallel wires were studied. In Ref. 12, downstream distance from the wire grid and Reynolds number were found to be the critical factors in determining whether vortex formation and corresponding heat transfer enhancement occurred at the cylinder. Local combined heat transfer and flow visualizations in Ref. 13 revealed that the spanwise locations of maximum heat transfer corresponded to the region between vortex pairs where the velocity induced by the vortices was toward the cylinder surface.

The primary focus of the present study was the generation of a high-intensity homogeneous isotropic turbulent flow field by means of a jet grid and the determination of its effect on stagnation region heat transfer for a cylinder in crossflow. The results are compared to several previous related studies.

APPARATUS AND PROCEDURE

The experiments were carried out in the open-circuit wind tunnel depicted schematically in Fig. 1. Air was drawn from the laboratory and passed through some straw flow straighteners and turbulence damping screens before entering the 4.85:1 contraction. The rectangular test section measured 15.2 wide by 68.6 cm high in cross section. Air flow in the test section was characterized by an extremely flat velocity profile and turbulence intensities on the order of 0.6 percent. The maximum attainable air velocity in the wind tunnel was 45 m/s, corresponding to a maximum Reynolds number of 1.88×10^5 for flow across the 6.60 cm diameter test cylinder.

After leaving the 96.5 cm long test section, the air flow passed through a converging transition section and into a 25.4 cm diameter pipe in which a flow-measuring orifice plate (19.1 cm diam) was located. Air then passed through a butterfly valve which was used to control the tunnel flow rate and then to the building altitude exhaust system.

The temperature of the air entering the wind tunnel was measured by four exposed-ball Chromel-Alumel thermocouples located around the perimeter of the inlet. These four temperatures were averaged to yield the total or stagnation temperature.

Wind tunnel turbulence was generated by means of a jet grid consisting of 13 parallel copper tubes (1.59 cm o.d.) spaced 5.08 cm center-to-center, as shown in Fig. 2. Each tube spanned the 15.2 cm width of the wind tunnel. The open area of the jet grid was 68.7 percent. Small circular holes, 1.59 mm in diameter, were drilled in the copper tubes at 3.05 cm intervals. The jet grid could be oriented such that the holes would point upstream or downstream, as desired. Air was supplied to the jet grid from 5.08 cm o.d. service line (maximum pressure 850 kPa). The flow rate of air to the jet grid was controlled by a remote valve and measured by means of a turbine flowmeter, which provided a frequency signal proportional to the volume flow rate. The air pressure and temperature at the turbine flowmeter measuring station were also monitored, allowing for determination of the total mass flow rate of injected air.

As a basis for comparison, turbulence was also generated by means of two conventional square-mesh, square-bar, bi-plane, passive grids. One grid was formed by 0.653 cm square stock spaced 2.86 cm apart center-to-center in a square array, yielding an open area of 60.5 percent. The second passive grid was formed similarly with 1.27 cm square stock and 5.62 cm spacing, again yielding an open area of 60.5 percent.

Cylinder stagnation region heat transfer measurements were made utilizing the specially instrumented test cylinder shown in Fig. 3. The instrumented portion of the test cylinder was divided circumferentially into eight separate copper (0.318 cm thickness) segments, each 6.6 cm long and spanning 10° of arc. The average gap between the segments was 0.10 cm and was filled with epoxy. Each segment was individually heated by a strip heater located beneath the cylinder surface. The temperatures of each segment were measured by means of Chromel-Alumel thermocouples embedded beneath the surface of each segment. Of the eight circumferential segments, only six were used for

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obtaining convective heat transfer information. The remaining two segments were utilized as guard heaters. In addition, guard heaters were located spanwise-adjacent to the circumferential segments and beneath each strip heater. The temperature of all the segments and guard heaters were set and maintained at a specified uniform value by a specially-designed, fast-response thermocouple control circuit, which allowed for the attainment of steady-state in a matter of a few minutes following any adjustment in the experimental conditions. The heat transfer cylinder and the temperature control circuit are described more fully in Ref. 15. In addition, the data reduction and error analysis techniques used for the heat transfer cylinder are detailed in Ref. 15. The data reduction includes corrections for conduction and radiation losses. The conduction losses, which occurred mainly on a result of the presence of the small (0.10 cm) unheated gaps between the heated copper segments, averaged about 15 percent. Radiation losses averaged about 2.5 percent.

The heat transfer cylinder described above provided circumferentially, local heat transfer information, spanwise-averaged over each segment. In order to visually verify that the heat transfer coefficients were uniform in the spanwise direction, an additional heat transfer cylinder was used. This cylinder was uniformly heated and wrapped in a liquid crystal sheet which permitted visual observation of the local temperature distribution on its surface. The liquid crystal technique is fully described in Ref. 16.

Measurements of mean and rms fluctuating velocities were made using a hot wire (4×10^{-6} m diam tungsten) and constant temperature anemometer (DISA electronics model 55M10). Calibration and linearization of the hot wire was performed using a calibration jet at the same temperature (± 1 °C) as the wind tunnel flow prior to each wind tunnel test. The hot wire was mounted on a remotely controlled and monitored traversing mechanisms, which permitted translational movement of the hot wire in all three coordinate directions as well as rotational movement.

Turbulence scale was estimated using an autocorrelation of the hot wire signal. The autocorrelation was obtained on a dual channel fast Fourier transform (FFT) spectrum analyzer. The area under the autocorrelation function yields an integral time scale which when multiplied by the mean velocity provides an integral length scale.

EXPERIMENTAL RESULTS AND DISCUSSION

The objectives of these experiments were the generation in the wind tunnel of high-intensity homogeneous, isotropic jet grid turbulence and the determination of the effects of this turbulence on heat transfer from the stagnation region of a cylinder in cross flow. The experiments encompassed the characterization and optimization of the jet-grid turbulence field as well as the heat transfer measurements.

Grid Turbulence

Preliminary experiments with the jet grid were carried out in order to determine the best orientation (upstream or downstream blowing) and the optimal jet grid flow rates for attainment of a uniform mean velocity profile in the wind tunnel test section. Initially, the jet grid was pointed upstream and measurements of velocity profiles were made at various distances downstream of the grid. In particular, the profiles at a distance of 25 cm downstream from the grid (16 grid tube diameters) were of interest since this measuring station corresponded to the future location of the test cylinder.

The results of these measurements are shown in Fig. 4. In this figure, three representative cross-stream (vertical) velocity profiles measured 25 cm downstream from the grid are shown. The average free stream velocity, $\overline{U}_{AV}$, was 19 m/s for these measurements. The first profile is a baseline which represents the effect of the presence of the grid with no blowing. The wakes of the individual tubes which make up the jet grid are clearly visible and periodic in nature, as would be expected. The normalized cross-stream coordinate, y/M, used in these profiles takes on values ranging from -2 to +2, representing a traverse of four jet-grid tube spacings.

The second profile shown in Fig. 4 resulted from upstream blowing at an intermediate blowing rate. The shape of this profile is typical of the upstream-blowing cases studied. The nonuniformities visible in the profile do not correspond to tube wakes, but may have resulted from instabilities in the interaction of the counter-current jets with the main flow.

The third profile shown in Fig. 4 resulted from a downstream-blowing situation in which the jet flow rate had been adjusted to an optimal value, yielding a nearly flat profile. Profiles of rms fluctuating velocities were obtained simultaneously during the vertical traverses and were similarly flat. No such optimal jet flow rates were found for the upstream-blowing orientation. The turbulence intensities (measured with no test cylinder in place) for downstream blowing were lower than for upstream blowing, consistent with the findings of Ref. 1. In addition, the turbulence intensities (measured 25 cm downstream from the grid) associated with optimal downstream blowing, which are listed in Table I, were found to be lower than those for nonoptimal downstream blowing rates. That is, the intensities exhibited a minimum with respect to blowing rate at the optimal blowing condition. Nevertheless, the optimal-blowing Tu values listed in Table I are still within the desired range (10 to 15 percent) associated with gas turbine blades. Values for the optimal jet-grid injection ratio, J_{opt}, defined as the ratio of the flow rate of injected air at optimum downstream blowing to the total wind tunnel flow rate are also listed in Table I. Horizontal (z-direction) cross-stream traverses were also obtained behind the jet grid. These profiles (of both mean and rms velocities) were consistently flat to within ± 1 percent, regardless of blowing rate, as would be expected since the bars which make up the jet grid are horizontal.

Isotropy of the jet-grid turbulence was verified by several experiments in which a hot wire was rotated $\pm 45°$ from the normal to the flow direction. These measurements were made 25 cm downstream from the grid. A representative result is shown in Fig. 5. In the figure, the mean velocity is seen to vary sinusoidally as the wire is rotated, while the fluctuating component is independent of wire angular orientation.

Turbulence measurements were also made behind two conventional square-bar, square-mesh grids in order to provide a basis for comparison to the jet-grid results. Decay of turbulence behind these two grids and also behind the jet grid is shown in Fig. 6 for several values of Reynolds number based on bar size, Re_b. The turbulence decay behind the square bar grids agrees fairly well (± 20 percent) with the curve fit of Baines and Peterson (17) for flow behind screens. It should be noted, however, that for values of x/b less than about 40 (which corresponds to the test cylinder location for the 0.635 cm bar size grid), significant non-uniformities in the mean velocity profile were observed behind the square bar grids due to proximity to the grids. It appears that if flow homogeneity is desired,

the maximum turbulence intensity achievable behind a passive grid is about 7 to 8 percent, regardless of Reynolds number. However, turbulence intensities higher than ten percent were achieved at the same streamwise coordinate behind the jet grid with flow homogeneity, as previously mentioned.

Also shown in Fig. 6 is a representative plot of the decay of turbulence behind the jet grid. These data were obtained at a free-stream velocity of 19 m/s, yielding a bar-size Reynolds number of 18 900. When fitted to a power law, the jet grid turbulence decay exponent, n, is 1.11, which agrees quite well with previous jet-grid studies.(1,2)

Integral length scales of turbulence were measured in the clear tunnel behind each of the grids using the autocorrelation technique. At an intermediate tunnel free-stream velocity of 23 m/s, the length scales at the test cylinder (25 cm downstream of the grids) were found to be 0.61 and 0.91 cm for the 0.635 and 1.27 cm square-bar grids, respectively, and 0.63 cm for optimum downstream blowing from the jet grid. These values of integral length scale were found to be insensitive to free-stream velocity. Detailed length-scale studies were not made due to the limited range of scale values and the fact that length scale has been generally found to influence heat transfer results only slightly for a specified turbulence intensity.(6)

Heat Transfer

The heat transfer cylinder of Fig. 3 provides spanwise-average heat transfer coefficient for the 10°-wide circumferential segments near the cylinder stagnation line. In order to verify spanwise uniformity of heat transfer coefficients, the liquid-crystal heat transfer cylinder was placed in the wind tunnel and observed visually. This same heat transfer cylinder had been successfully utilized in a previous study (13) in order to visualize the spanwise local variations in heat transfer coefficients downstream of an array of parallel wires oriented perpendicular to the test cylinder. Observations were made over the entire Reynolds number range available in a clear tunnel (no grid in place, $Tu \approx 0.6$ percent) and with the jet grid in place and set for optimum downstream blowing. The visualizations revealed equivalent levels of heat transfer spanwise uniformity for the clear tunnel and with the blown grid, reflecting the previously verified spanwise uniformity of the flow fields in both cases.

Circumferentially local heat transfer results are listed in Table II and shown in Fig. 7. The results were corrected for radiation and conduction losses, as detailed in Ref. 15. In Fig. 7 the Frossling number, $Nu/Re^{1/2}$, is plotted as a function of angle from the cylinder stagnation line. Data are presented for three Reynolds numbers and three basic turbulence conditions: no grid, 0.635 cm square-bar grid, and jet-grid with optimal blowing. Data are not presented for the larger square-bar grid since significant nonuniformities in the mean velocity were present behind this grid at the test cylinder location. The solid line in the figure represents the classical Frossling theoretical (zero-turbulence) calculation for a laminar boundary layer.(3)

The experimental results shown in Fig. 7 reveal the important trends associated with stagnation region heat transfer in a turbulent free stream. The tests with the highest Reynolds number and highest turbulence intensities resulted in the highest Frossling numbers. The data from the low-turbulence ($Tu \approx 0.6$ percent) clear-tunnel experiments agree with the Frossling solution within ten percent. Relatively low stagnation line ($\theta = 0$) heat transfer results for the

low-turbulence case were consistently observed for several different Reynolds numbers and angular orientations of the heat transfer cylinder in which successively different heated copper segments were located on the stagnation line. The level of heat transfer augmentation above the Frossling solution associated with the turbulence generated by the passive square-bar grid ($Tu \approx 7.3$ percent) ranges from an average of 27 percent of the lowest Reynolds number shown to an average of 46 percent for the highest Reynolds number. The augmentation associated with the high-intensity jet-grid turbulence ($Tu \approx 11$ percent) ranges from an average of 37 to 53 percent for the lowest and highest jet-grid Reynolds numbers. In all cases, the level of augmentation is fairly uniform with respect to circumferential distance from the stagnation line.

Stagnation point heat transfer results (see Table II) are shown in Fig. 8 using the correlation parameters of Ref. 5 as coordinate axes. Also shown in the figure are the theory of Smith and Kuethe (5) and correlations of Kestin and Wood (6) and Lowery and Vachon (7). The present data agree most closely with the correlation of Ref. 7, which, except for a single data point, generally overpredicts the data by 10 to 15 percent. Comparison of the present data with the theory of Smith and Kuethe reinforces the apparent inadequacy of the theory to predict Frossling numbers when the value of $Tu Re^{1/2}$ exceeds 20. Smith and Kuethe did propose, however, an empirical modification to their theory which accounts for Reynolds number effects and which is significant for Re values <100 000. When this modification is used, the theory agrees much more closely with the low Reynolds number data of the present work.

A similar Reynolds number effect is evident from the present results. For a specified value of the $Tu Re^{1/2}$ parameters (e.g., $Tu Re^{1/2} \approx 30$), the experiments with the highest Reynolds numbers yield the highest Frossling numbers. This behavior at least partially explains the fact that the present data is somewhat low with respect to the Kestin and Wood correlation since their data were obtained with relatively low values of Tu (2.5 to 7.3 percent). Additional experiments will be required to fully resolve the Reynolds number effect.

CONCLUDING REMARKS

The work described herein represents the first definitive study of heat transfer from a bluff body placed downstream of a jet-injection turbulence grid. The experiments were performed with the goal of determining the effect of high-intensity, homogeneous, isotropic turbulence on heat transfer from the stagnation region of a circular cylinder in crossflow.

The turbulent flow field downstream of the jet grid was found to be very nearly homogeneous and isotropic for downstream (co-current) injection at an optimal blowing rate, which depended on the main wind tunnel flow rate. Turbulence intensities measured at the test cylinder location (with no cylinder in place) ranged from 10 to 12 percent for optimal downstream blowing. Maximum turbulence intensities achievable behind a conventional square-bar, square-mesh grid at the same location were found to be 7 to 8 percent if a flat profile of mean velocity is to be maintained. Turbulence decay rates behind the jet grid and two square-bar grids were found to agree reasonably well with the results of previous investigators. (1,2,17)

Heat transfer measurements were made in the turbulent flow fields produced by the grids utilizing a specially instrumented isothermal test cylinder which yielded spanwise-average, circumferentially local heat

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transfer coefficients. Spanwise uniformity of the heat transfer results was verified visually by means of a separate uniformly heated test cylinder which was wrapped with a liquid crystal sheet. Heat transfer augmentation above the zero-turbulence case, expressed in terms of the Frossling number, ranged from 37 to 53 percent for the test cylinder behind the jet grid ($Tu \approx 11$ percent) for a cylinder Reynolds number range of 48 000 to 180 000, respectively. The level of heat transfer augmentation was found to be fairly uniform with respect to circumferential distance from the stagnation line.

Stagnation point heat transfer results were compared to the results of previous studies (5,7) and found to be somewhat low. In particular, the results were 10 to 15 percent lower than the correlation of Lowery and Vachon.(7) This behavior is probably due to a Reynolds number effect as observed by Smith and Kuethe.(5) Namely, for a specific value of $Tu \, Re^{1/2}$, the data obtained with a relatively high turbulence intensity and thus lower Reynolds number (such as those of the present study) will have a lower value of the Frossling number.

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TABLE I. - TURBULENCE INTENSITIES AND BLOWING RATES FOR OPTIMAL DOWNSTREAM JET-GRID INJECTION

$\dot{m}_{Tot}$, kg/s	Tu, percent	$J_{opt} = \dot{m}_{grid}/\dot{m}_{Tot}$
1.36	11.9	0.0110
2.27	11.1	.0124
3.18	11.1	.0128
3.63	10.8	.0130
4.08	10.5	.0136
4.54	10.4	.0137
5.22	10.1	.0138

TABLE II. - HEAT TRANSFER RESULTS SUMMARY

(a) Clear tunnel (Tu ≈ 0.6 percent)

Re	Tu $Re^{1/2}$	$Nu/Re^{1/2}$					
		$\theta = 0°$	10°	20°	30°	40°	50°
48 800	1.33	0.917	0.968	0.958	0.952	0.924	0.833
79 300	1.69	.904	.960	.949	.934	.912	.833
110 400	1.99	.907	.986	.958	.943	.926	.841
141 500	2.26	.912	.980	.968	.957	.932	.859
156 400	2.37	.912	.978	.967	.954	.933	.868
180 000	2.55	.898	.982	.963	.951	.932	.885

(b) Jet grid (Tu ≈ 11 percent)

Re	Tu $Re^{1/2}$	$Nu/Re^{1/2}$					
48 000	26.1	1.29	1.27	1.26	1.23	1.18	1.14
78 800	31.2	1.36	1.33	1.32	1.27	1.21	1.16
110 300	36.9	1.38	1.37	1.35	1.29	1.24	1.19
125 800	38.3	1.41	1.40	1.40	1.31	1.27	1.21
141 400	39.5	1.44	1.41	1.40	1.34	1.27	1.23
156 800	41.2	1.45	1.43	1.39	1.35	1.28	1.25
178 700	42.7	1.46	1.44	1.40	1.35	1.29	1.24

(c) 0.635 cm square-bar grid (Tu ≈ 7.3 percent)

Re	Tu $Re^{1/2}$	$Nu/Re^{1/2}$					
37 700	14.6	1.18	1.15	1.17	1.14	1.09	1.06
95 600	22.6	1.28	1.27	1.26	1.21	1.16	1.11
178 800	30.9	1.40	1.38	1.35	1.28	1.23	1.17

(d) 1.27 cm square-bar grid (Tu ≈ 14 percent)

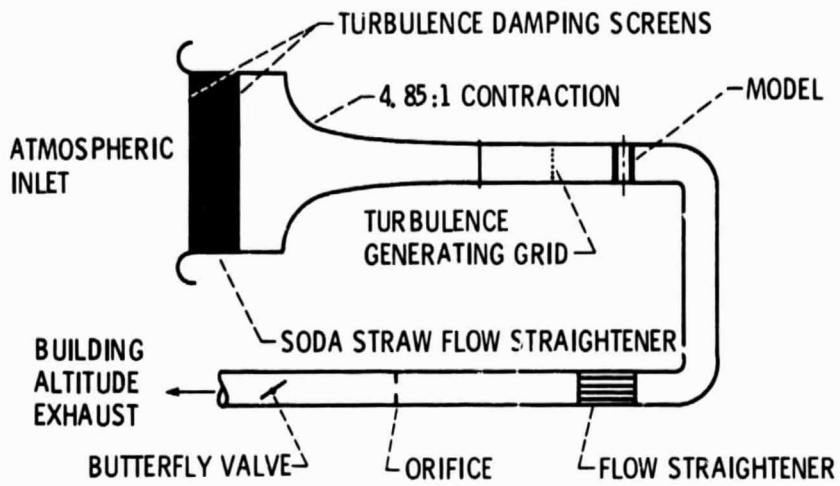| Re	Tu $Re^{1/2}$	$Nu/Re^{1/2}$					
40 300	28.1	1.27	1.25	1.27	1.22	1.18	1.14
94 500	43.0	1.40	1.36	1.36	1.31	1.26	1.22
178 700	57.1	1.51	1.48	1.47	1.41	1.36	1.31

Figure 1. - Schematic of wind tunnel.
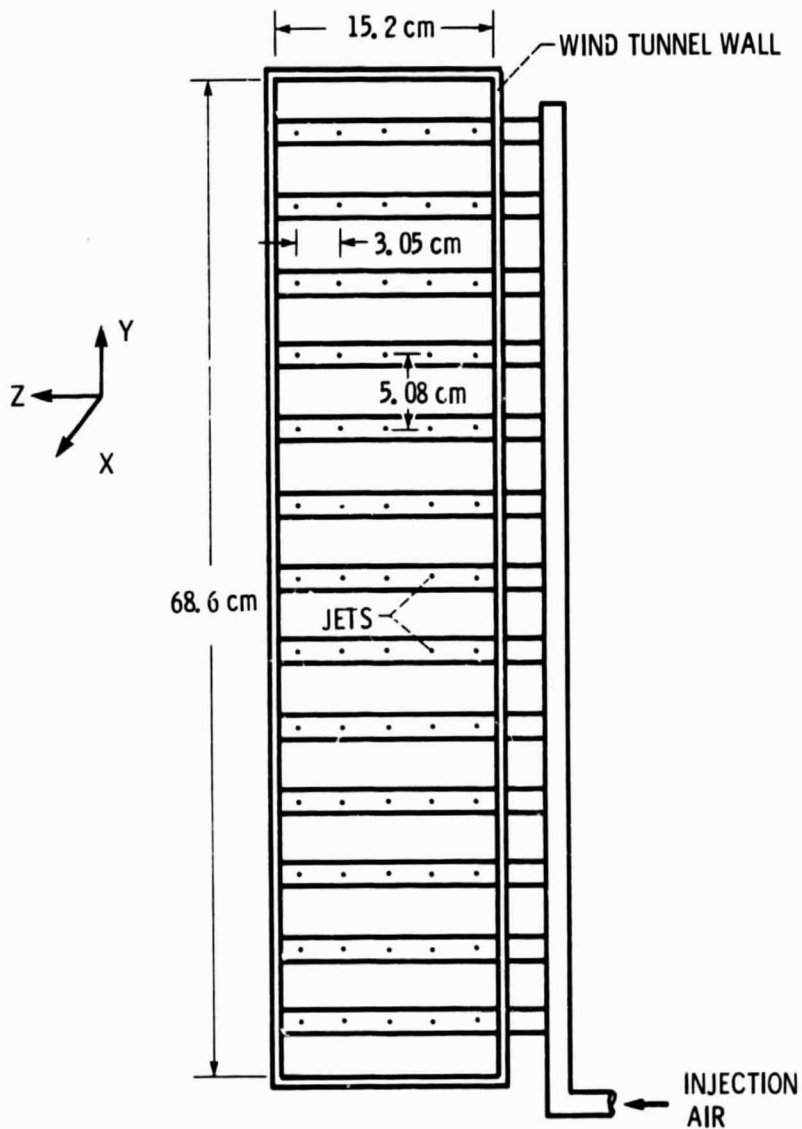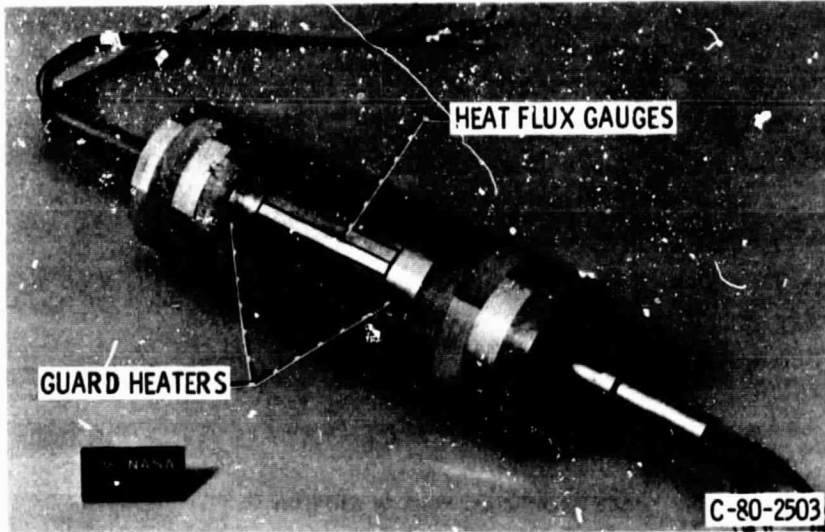

Figure 2. - Jet injection turbulence grid.

Figure 3. - Spanwise average heat transfer model.

(a) No blowing.

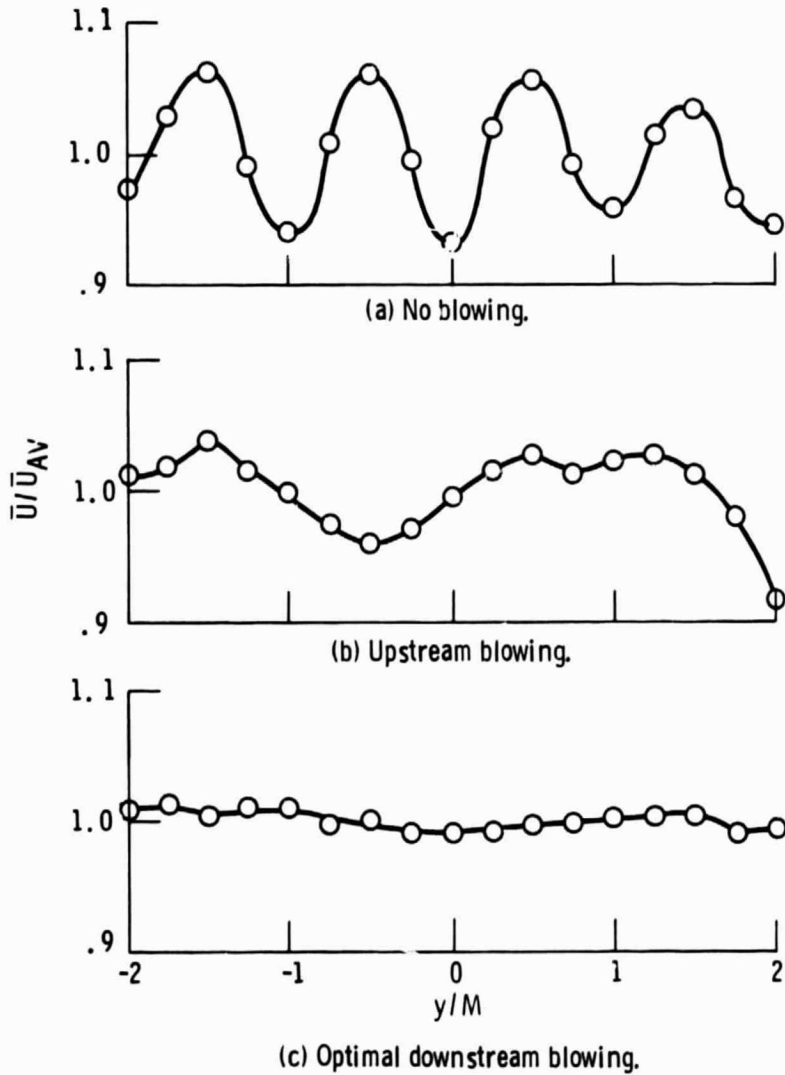(b) Upstream blowing.

(c) Optimal downstream blowing.

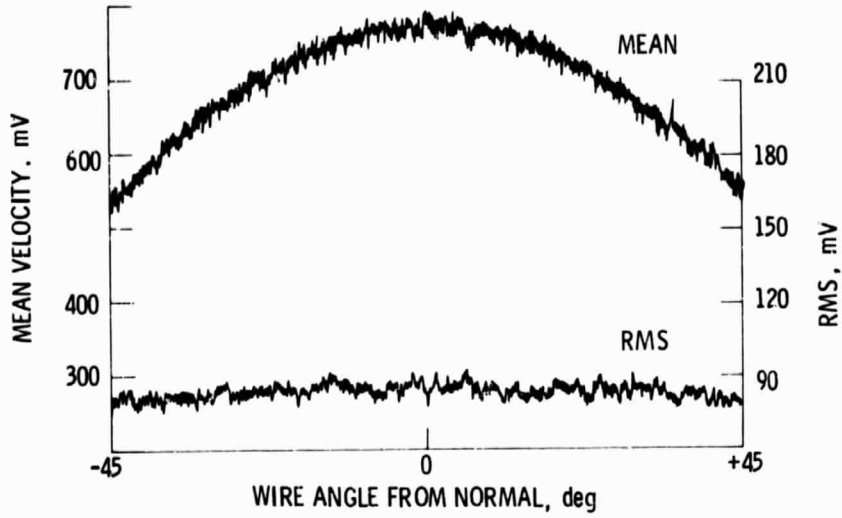Figure 4. - Mean velocity profiles downstream of jet grid.
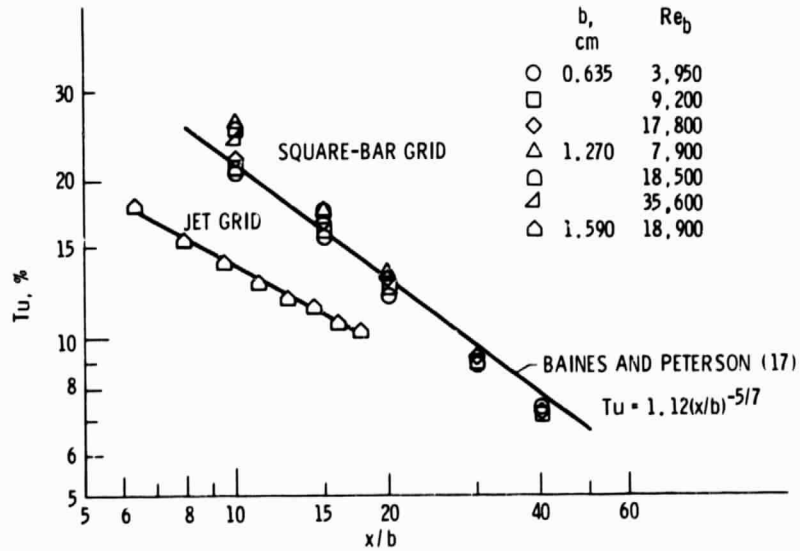
Figure 5. - Isotropy of jet-grid turbulence.
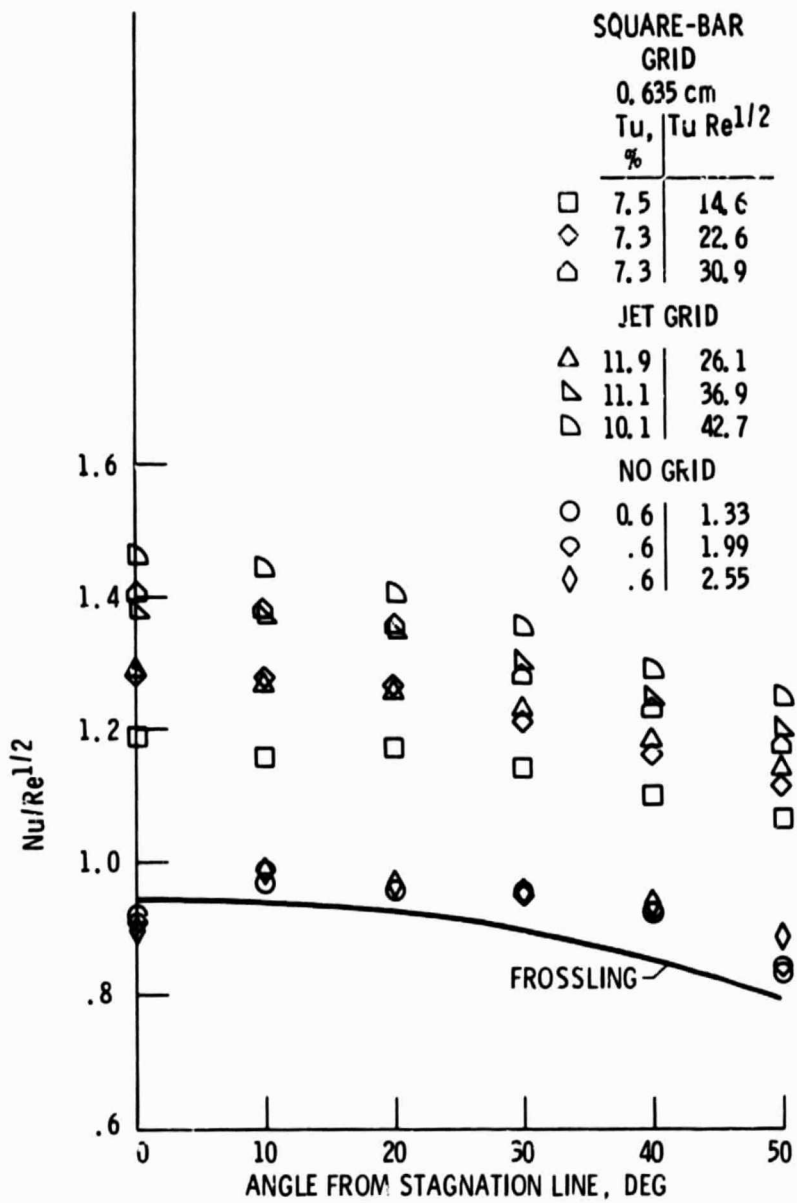

Figure 6. - Decay of turbulence behind grids.
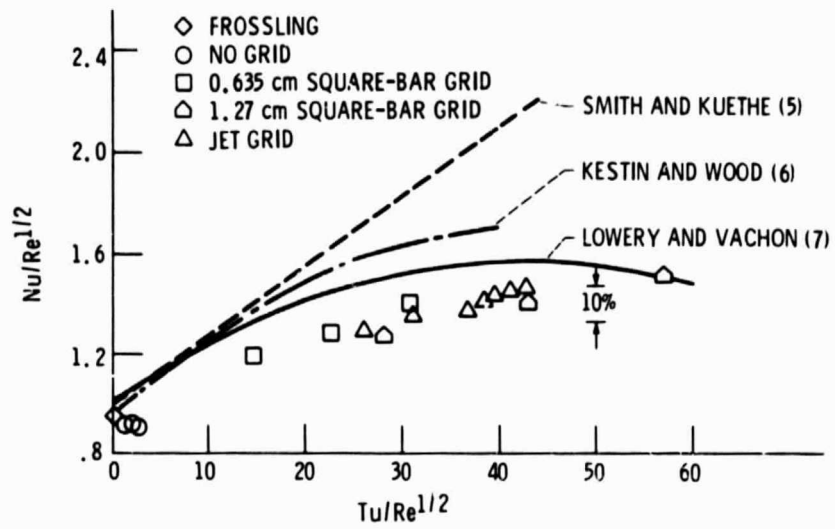
Figure 7. - Local heat transfer results.

Figure 8. - Stagnation point heat transfer results.

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16. Abstract

An experimental study has been performed to determine the effect of high-intensity turbulence on heat transfer from the stagnation region of a circular cylinder in crossflow. The work was motivated by the desire to be able to more fully understand and predict the heat transfer to the leading edge of a turbine airfoil. In order to achieve high levels of turbulence with a reasonable degree of isotropy and homogeneity, a jet-injection turbulence grid was used. The jet grid provided turbulence intensities of 10 to 12 percent, measured at the test cylinder location, for downstream blowing with the blowing rate adjusted to an optimal value for flow uniformity. In contrast, if flow uniformity is to be maintained, the maximum achievable turbulence intensities behind a conventional passive square-bar, square-mesh grid were found to be 7 to 8 percent. Heat transfer augmentation above the zeroturbulence case ranged from 37 to 53 percent for the test cylinder behind the jet grid for a cylinder Reynolds number range of 48 000 to 180 000, respectively. The level of heat transfer augmentation was found to be fairly uniform with respect to circumferential distance from the stagnation line. Stagnation point heat transfer results (expressed in terms of the Frossling number) were found to be somewhat low with respect to previous studies, when compared on the basis of equal values of the parameter $Tu\,Re^{1/2}$, indicating an additional Reynolds number effect as observed by previous investigators. Consequently, for a specified value of $Tu\,Re^{1/2}$, data obtained with a relatively high turbulence intensity (such as those of the present study) will have lower value of the Frossling number.

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