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Effects of Free End and Turbulence Intensities on Triangular Prism

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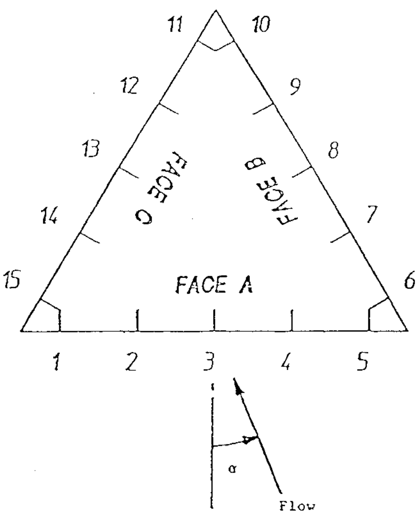
Introduction

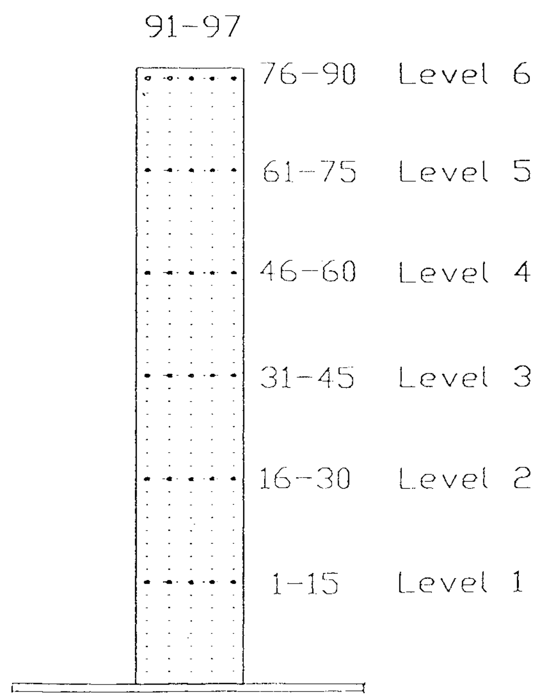
FOR three-dimensional prisms of finite length in natural wind environments, the influx of fluid from the top end of the prism can cause considerable alterations to the vortex-shedding process near the free end and hence variation of the loadings over the top end of the prism. It is thus desirable to know the extent of the wind loads variation at the free end of a prism due to changes in the incident turbulence characteristics of the natural wind for realistic wind-tunnel model tests. Flow patterns and pressure distributions around triangular prisms in smooth, uniform, two-dimensional flow without end effects were previously studied by El-Sherbiny[1] and Twigge-Molecey and Baines.[2] For finite length triangular prisms, however, no study on the effects of turbulence intensities on the surface pressures of the prisms has been cited in the literature. Finite length triangular prisms are now regularly being used as the main structural members of offshore oil rigs, telecommunication towers, etc. Some high-rise buildings are also of triangular shape.

Experiment, Results, and Discussion

The model (Fig. 1) used is an equilateral triangular prism with constant cross section. The width d of each side of the prism is 100 mm with an aspect ratio of 6. The prism was tested in the freestream of the wind tunnel without turbulence grid (turbulent intensity, $k \cong 0.5\%$) and with two different turbulence grids ($k \cong$ 10 and 30%). There are 97 pressure tapping points Fig. 1(b) on the prism. The distance between each level of the circumferential



a)



b)

Fig. 1 Pressure tapping locations: a) plan view: level 1 and b) elevations: levels 1–6.

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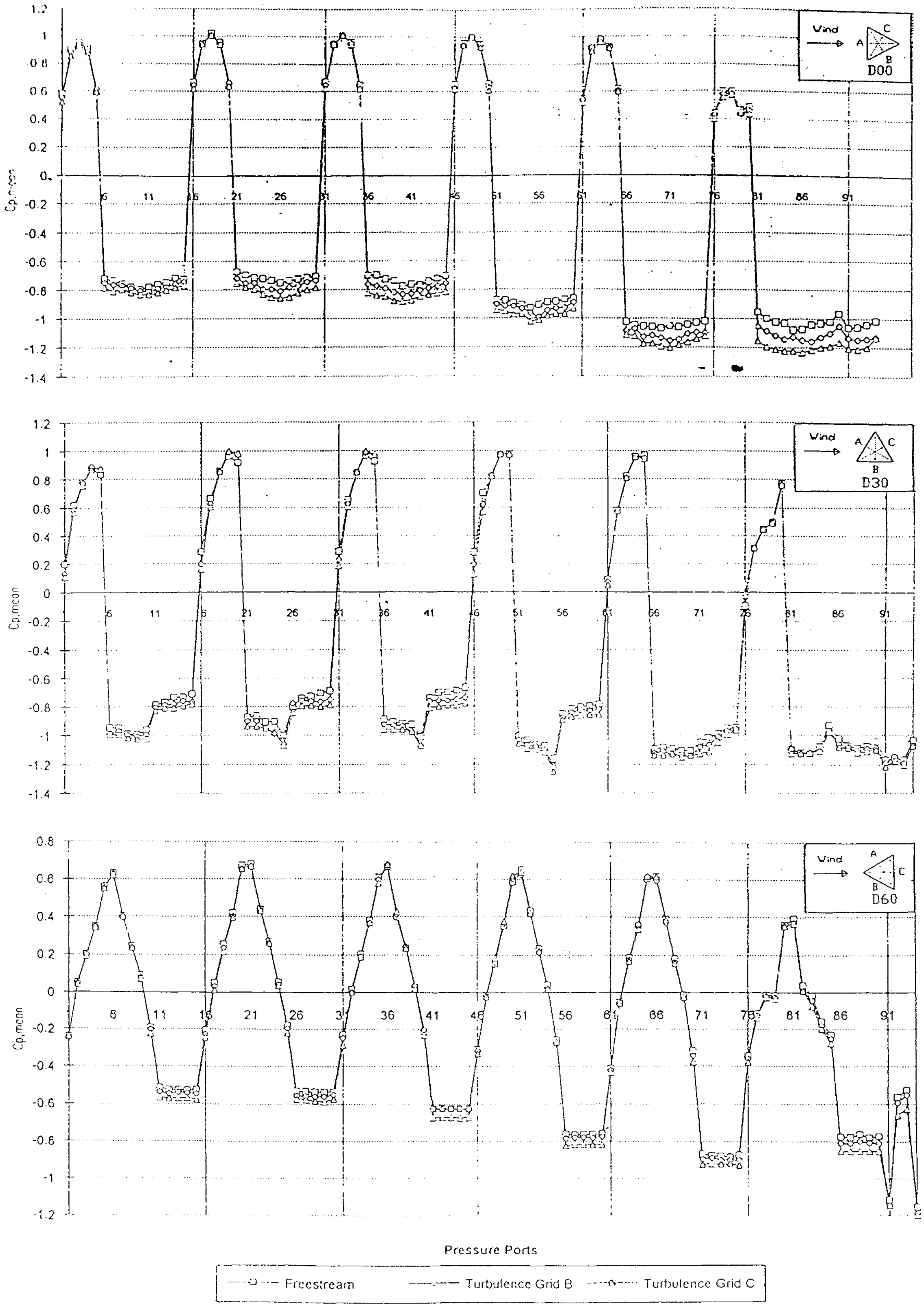


a)

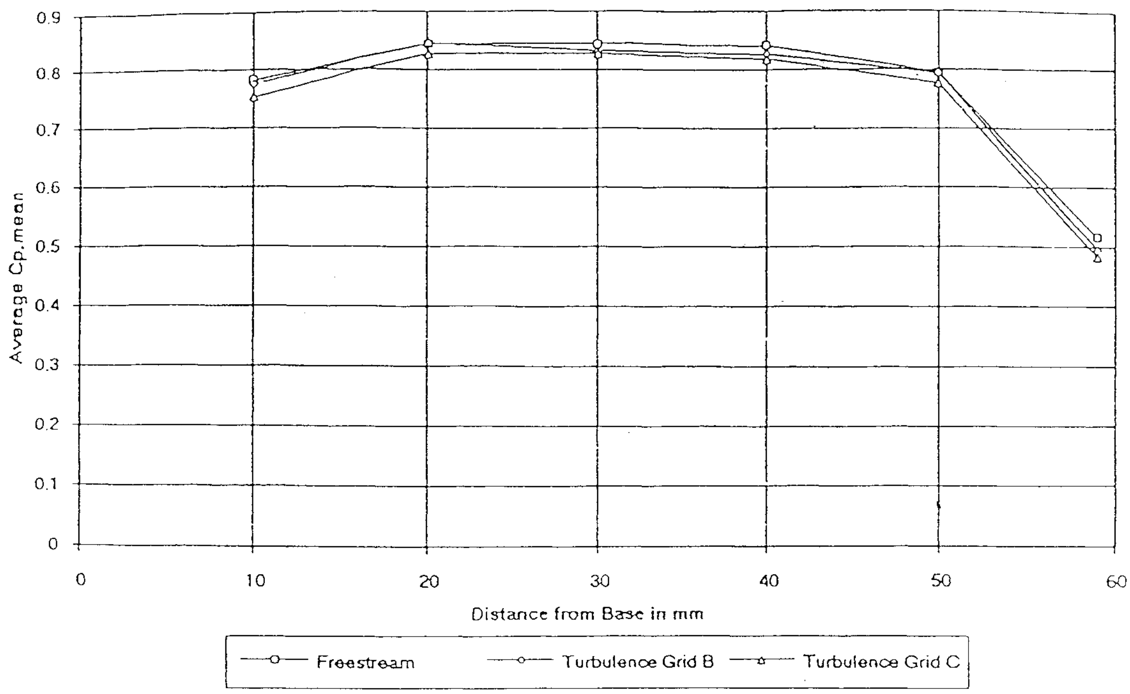
b)

c)

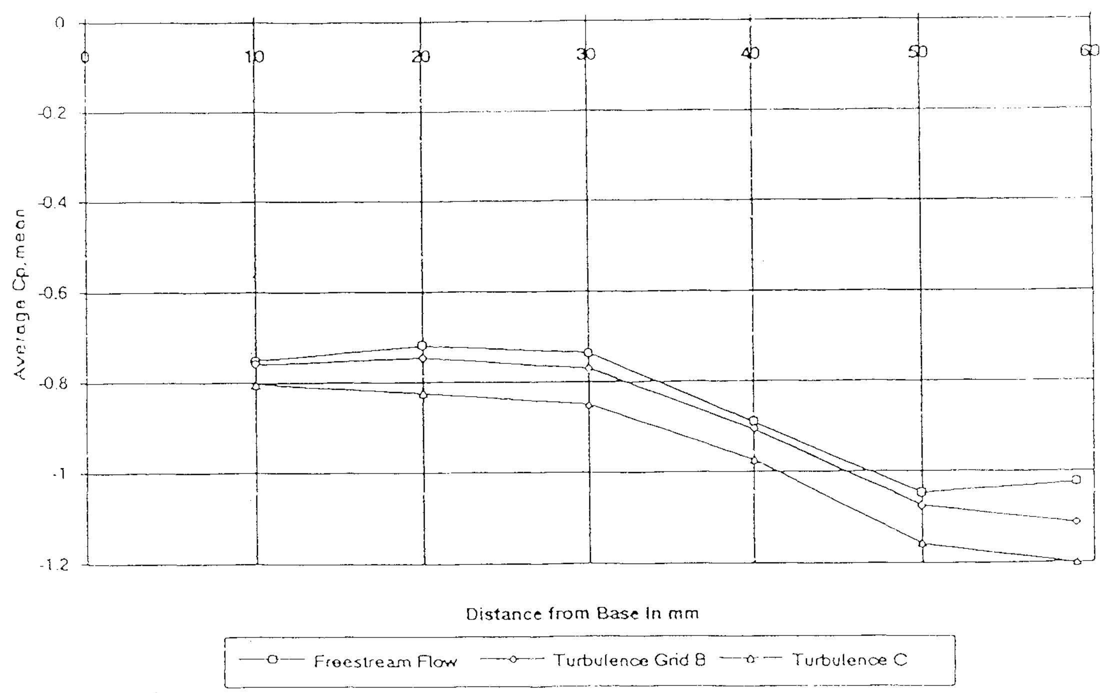
Fig. 2 Mean C_p in uniform flow of various turbulence intensities.

pressure tappings is 100 mm. For each pressure tapping port, the pressure coefficients were computed from measurements made at 500 Hz over a 36-s period. The experiments were conducted at a Reynolds number of 6×10^4 with flow directions at $\alpha = 0$–60 deg, in steps of $\Delta\alpha = 10$ deg.

Results of the aforementioned experiments show that, as the angle of incidence increases from $\alpha = 0$ (Fig. 2a) to $\alpha = 60$ deg (Fig. 2c), the stagnation point ($C_{p,\text{mean}} \cong 1.0$) moves from the centerline of the front face towards the edge of the front face nearest to the upstream of the flow. As α is increased from 0 to 30 deg, for the progressively windward face in the wake (face B), the average $C_{p,\text{mean}}$ becomes more negative due to wind glazing effects. When α is 30 deg, face B is parallel to the flow (Fig. 2b). For $\alpha > 30$ deg, there is a pressure recovery to positive $C_{p,\text{mean}}$ on face B due to the forward movement of the reattachment line of the separated flow towards the leading edge. For the progressively leeward face



a) Wind direction DOO-face A



b) Wind direction DOO-wake (faces B and C)

Fig. 3 Longitudinal C_p variation along triangular prism at α = 0 deg: a) prism face A and b) prism faces B and C.

in the wake (face C), the average $C_{p,\text{mean}}$ becomes less negative, though some local values of C_p become more negative towards the rear as the incidence angle gets larger. For an incidence flow angle of 60 deg (Fig. 2c), the pressure coefficients on the surface are symmetrical about the edge where faces A and B meet. The $C_{p,\text{mean}}$ is positive and at its maximum at this edge, getting more negative as it moves along the face towards the rear. The end effect of the "roof" of the triangular prism is to shift the position of the occurrence of the negative pressure region more towards the leading edge. Further analysis of the experimental results (Fig. 3) showed that the $C_{p,\text{mean}}$ values at each level on the front face of the prism collapse roughly to the same curves, except within the region of level 5 to level 6. Through other similar experiments at various incidence of flow, investigations show similarly that the end effects on the mean pressures on the front face of an equilateral triangular prism are limited to a region of $<1d$ from the free end. The other two sides facing away from the flow are immersed in the wake formed due to the separation of flow at the sharp edges of face A at small α. The pressure coefficients are negative and are fairly constant at each level, becoming more negative as the flow moves away from the sharp edges of face A. For the experimental results at all flow conditions, the $C_{p,\text{mean}}$ values at levels 1–3 on the faces immersed in the wake collapse fairly close together. The average $C_{p,\text{mean}}$ value at each level becomes more negative from level 4 upwards as the level gets nearer to the free end. Through these experiments at all other angles of incidence, it was noted that in the wake regions the end effects on the pressure coefficients are limited to a region of $3d$ from the free end. The effect of turbulence (Fig. 3) in the approach flow is to increase the turbulent mixing in the separated shear layer, thus increasing the separation shear flow thickness and the rate of entrainment of fluid from the wake. This results in greater streamline curvature around the prism and a decrease in radius of curvature of the shear layer. Increasing turbulence intensity thus results in earlier reattachment when compared with a similar flow situation with lower turbulence intensity. As the front wall face does not involve separation streamlines, it is thus not significantly affected by a higher turbulence intensity. This is evident from the average $C_{p,\mathrm{mean}}$ values at each level on the front face as shown in Fig. 3. For the sides immersed in the wake, however, the average $C_{p,\mathrm{mean}}$ values become markedly more negative in magnitude at higher turbulence intensities. The results do not show a pressure recovery that would imply a reattachment of flow. The absence of the pressure recovery on the leeward side of the prism is probably due to the sharp corners and short breadth of the prism.

Conclusions

Through this limited investigation, it was found that, for approaching uniform flow with various approaching turbulence intensities in the range of 05–30%, the effects of the free end of a triangular prism are limited to a region $<1d$ from the free end on the front face of the prism. On the faces immersed in the wake region, the end effects are limited to the region $<3d$ from the free end. The pressure coefficients on the surface facing the approaching flow do not appear to be significantly affected by the range of turbulence intensities investigated. For the sides immersed in the wake of the separation streamlines from the leading edges, the $C_{p,\mathrm{mean}}$ values become markedly more negative in magnitude at higher turbulence intensities.

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Experimental Investigation of Velocity Slip near an Arcjet Exit Plane

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Introduction

VELOCITY slip is a phenomenon associated with multicomponent flows in which species of different mass have different mean velocities. This phenomenon has been studied in molecular beam nozzles[1] and has been exploited for isotope separation.[2] Significant velocity slip has been measured in the plume of low-power arcjet thrusters.[3] These recent measurements, obtained by mass spectrometry of a molecular beam sampling probe, were limited to locations more than 10 diameters from the exit plane.

The determination of whether slip develops in the nozzle, near the exit plane, or in the expansion plume of an arcjet thruster, is important to both modeling efforts and to the interpretation of measurements. If velocity slip develops inside the nozzle, numerical models will need to include separate momentum equations for each neutral species or, at the very least, an appropriate model for multicomponent transport. These additions increase the complexity of an already difficult task. Measurements of exit-plane velocity in these devices have recently been made by laser-induced fluorescence (LIF),[4] a species specific technique. If significant velocity slip exists, then separate measurements for each species are necessary to completely characterize the flowfield.

We have previously reported LIF-based measurements of atomic hydrogen velocity and kinetic temperature in a hydrogen-fueled arcjet.[4,5] We recognize, however, that the flow consists of both atomic and molecular hydrogen (along with small fractions of ions and electrons). The most direct method to investigate velocity slip in the arcjet flowfield would be to measure, in addition to the velocity of atomic hydrogen, the velocity of molecular hydrogen under the same conditions. As with atomic hydrogen, absorption transitions from the ground state require vacuum-ultraviolet wavelengths. Owing to the low densities of excited-state molecules and the rovibrational distribution which reduces the density of any particular state, these transitions are difficult to probe.

A simpler approach, for the purpose of evaluating slip, is to seed the flow with a species that is accessible with the same laser used to probe atomic hydrogen. In the present study, helium was chosen as the seed species owing to its inertness (with respect to the arcjet nozzle), its relative mass (four times the mass of atomic hydrogen), and its convenient electronic transitions in the visible wavelength region. Velocity and temperature are measured by LIF of both helium and atomic hydrogen at the same arcjet operating condition. Absence of slip between helium and atomic hydrogen would suggest that slip is not a dominant mechanism in the nozzle or exit plane vicinity of our hydrogen arcjet.

Theory

In a multicomponent mixture, each species (denoted by i), may have its own mean velocity v_i, and the mean mass velocity v_m is defined by

$$v_m = \frac{\sum n_i m_i v_i}{\sum n_i m_i} \tag{1}$$

Here, n_i is the number density of species i and m_i is the mass. The simplified steady-state momentum equation for a single species in the axial direction z can be expressed as

$$n_i m_i v_i \frac{\partial v_i}{\partial z} + \frac{\partial p_i}{\partial z} = n_i m_i \sum_j k_{ij}(v_j - v_i) \tag{2}$$

where p_i is the partial pressure. The term on the right side of Eq. (2) represents the momentum exchange between species of different types due to collisions. The momentum exchange term formulated in this way assumes that the force per unit volume exerted on particles of species i, due to collisions with species of type j, is proportional to the difference between their respective mean velocities. The proportionality constant k_{ij}, which accounts for differences in mass of the colliding particles, can be considered a collision frequency for momentum transfer. This constant can be determined from kinetic theory.[6,7] The slip velocity v_{slip} is usually defined for a binary mixture as the difference in velocities,

$$v_{\mathrm{slip}} = v_j - v_i \tag{3}$$

If the density is high such that flow is in a continuum regime, the collision rate will be high, allowing efficient momentum exchange between species. Thus, the different species will be in equilibrium, and the slip velocity will be negligible. However, in an expanding flow, conditions can occur in the transition from continuum to free molecular flow, where velocity and pressure gradients are large and the collision rates are low. Insufficient collisions for momentum exchange between species allows a slip velocity to develop. The

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