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INVESTIGATION OF HOT FILM CALIBRATION FOR ENTROPY GENERATION RATE CALCULATIONS

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ABSTRACT

The objective of this paper is to investigate in detail the relationship between results obtained from flow over a circular cylinder in cross flow using Hot Film and Hot Wire Constant Temperature Anemometry (C.T.A.). The experimental results are compared with those obtained using numerical methods. The results obtained from Hot Wire Anemometry are used to attempt to calibrate the Hot Film Sensors for the purpose of evaluating entropy generation rates in the boundary layer of the cylinder.

INTRODUCTION

Flow past a bluff body, such as a circular cylinder, usually experiences boundary layer separation and very strong flow oscillations in the wake region behind the body. The flow past a cylinder can be divided into three regions. Far from the body the flow is essentially ideal, with viscous effects minimised. Near the body the fluid develops a boundary layer where viscous effects dominate; this boundary layer may or may not detach from the body depending on the value of the Reynolds number [1,2]. The oscillatory nature of the flow over the cylinder causes the shape and position of the boundary layer to change over time. This effect causes movement in both the stagnation and separation points on the cylinder [3]. Entropy may be defined as a loss due to heat or fluid flow, it is irrecoverable work done within certain surroundings. For the case of flow over a circular cylinder the entropy loss was assesed only from viscous effects as the flow was assumed to be isothermal and adiabatic.

NOMENCLATURE

A = Constant Coefficient
B = Constant Coefficient
C = Constant Coefficient
Kw = Correction Factor
Re = Reynolds Number
$\dot{S}''_{gen}$ = Entropy Generated per unit Area (W/m^2K)
$\dot{S}'''_{gen}$ = Entropy Generated per unit Volume (W/m^3K)
T = Absolute Temperature (K)
U = Free Stream Velocity (m/s)
u = X-direction Velocity (m/s)
V_O = Zero Flow Voltage(V)
V_S = Sensor Voltage(V)
x = X position (m)
Y = Distance from Wall (m)
μ = Viscosity (Ns/m^2)

ENTROPY GENERATION THEORY

In adiabatic and incompressible laminar flow the entropy generation rate [4,5] is defined as

$$\dot{S}'''_{gen} = \frac{\mu}{T}\left(\frac{\partial u}{\partial y}\right)^2$$

This equation can be applied where the flow is assumed to be moving in parallel streamlines. This allows its usage within attached boundary layers. In the case of a circular cylinder in cross flow this can only be applied up to the separation point on the cylinder surface. This equation can therefore be used to quantify entropy generated using results obtained from hot wire anemometry.

EXPERIMENTATION

Test Facility

All experimentation was carried out in a blow down wind tunnel. The test section area of the tunnel is 300mm x 300mm. The free stream air velocity used for all experimental testing was 16.1m/s equating to a corresponding Reynolds number of 50,000 for the cylinder used. The turbulence intensity measured at this particular velocity is 0.4%, this being calculated by means of a hot wire probe being placed in the section. The cylinder used in the experiments was manufactured from aluminium and had a highly polished surface.

Hot Wire CTA

The hot wire testing carried out on the circular cylinder involved the use of a Dantec 55p15 probe. The hot wire was coupled to a Dantec wheatstone bridge providing constant current output and varying the voltage, allowing the wire to hold constant temperature. The Dantec bridge was balanced in accordance with the Dantec user manual to provide an overheat temperature of 230° above the room temperature at that time. The hotwire traverse mechanism consisted of a stepper motor mechanism which provided movement of the hot wire probe and holder, a motion controller unit which provided the required voltages for the stepper motor and two coupled PC's used for monitoring and saving the data. When initialised the traverse PC sent a signal to the motion controller and also to the other PC as a trigger to capture the current voltage data. Prior to taking data the hot wire was positioned within 10 microns of the wall. When initialised the traverse moves incrementally out from the wall. The layout of the hot wire traverse is shown in figure2. The data was taken at a rate of 20kHz over a time period of 0.1 seconds, therefore yielding 2000 data points at each hotwire position.

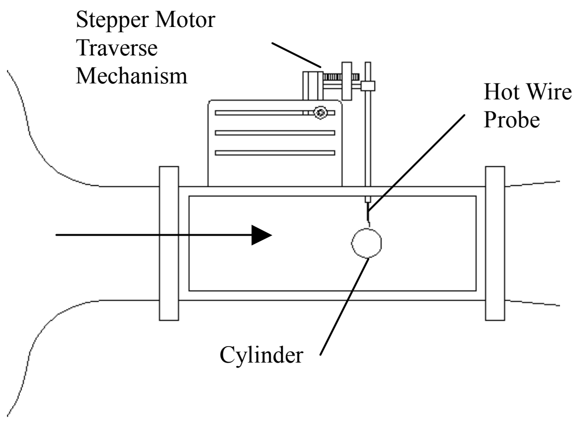

Figure 1 Hot Wire Traverse Layout

Calibration

The wire was placed in the test section of the medium speed wind tunnel and the voltage output from the bridge recorded on the PC for a range of velocities between 0 and 24.3 m/s. From the voltages obtained, figure 2, enables the direct calculation of velocity at any given bridge voltage provided the velocity was within the above range.

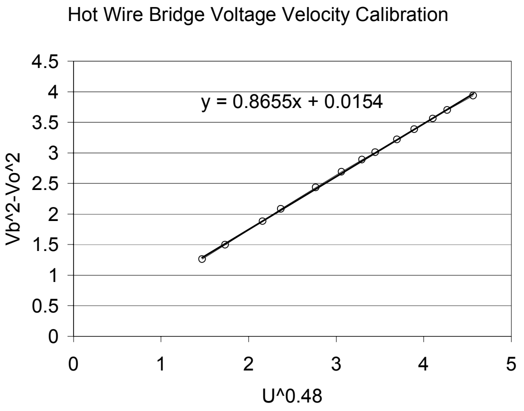

Figure 2 Velocity Calibration Chart

By curve fitting the data points it was possible to arrive at the equation

$$U = \left[\frac{V_s^2 - V_0^2 - 0.0154}{0.8655} \right]^{\frac{1}{0.48}}$$

This equation allows the direct calculation of velocity at any hot wire position from the voltages obtained.

Near Wall Correction

The temperature of the hot wire being 230° above ambient temperature causes conduction of heat onto the cylinder wall as it is approached by the hot wire. This has the effect of causing the bridge to automatically supply a higher voltage and therefore indicating that the velocity was higher than actual. Figure 3 shows the effect of the wall on the bridge voltage as it can be seen that the voltage does not continue to drop within the near wall region but in fact levels off and begins to rise slightly at the wall.

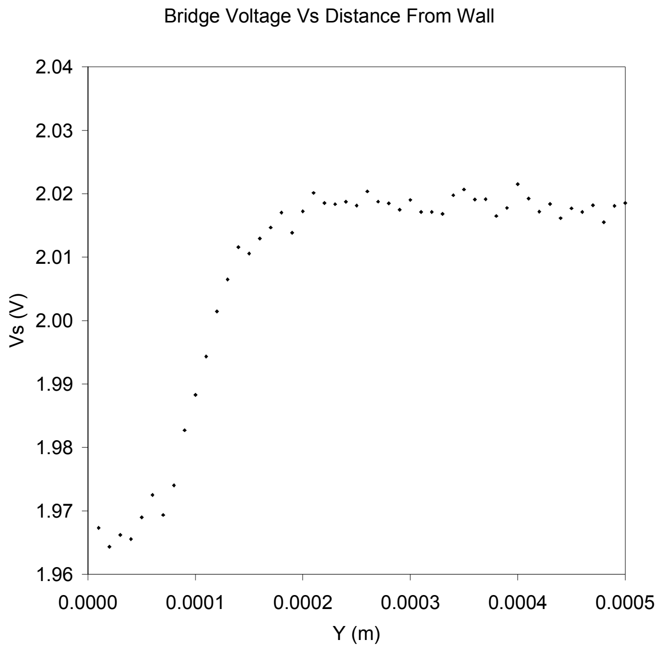

Figure 3 Uncorrected Bridge Voltage

To compensate for this higher voltage at the wall, a correction factor was used based on the hot wire Reynolds number. [6]. Figure 4 shows this correction factor and its variation as the wire moves out from the wall.

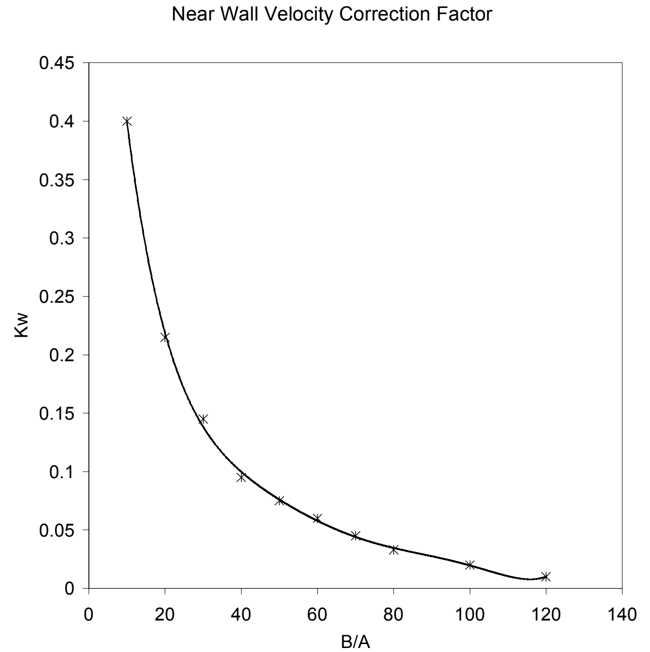

Figure 4 Kw Correction Factor

This correction factor was implemented using the equation,

$$V_s^2 - V_0^2 = A + Kw + B\,\mathrm{Re}_w^n$$

This equation is evaluated in terms of hot wire Reynolds number and is then converted back to yield actual velocity magnitude.

Hot Film CTA

The hot film array used was an MTU type, consisting of 30 sensors wrapped around the cylinder surface, as shown in figure 5. The sensor used was connected to the Dantec Wheatstone Bridge in the same manner as the hot wire. Voltage data points were taken at intervals of 10° by means of rotating the cylinder. The sampling rate used for the hot film was also 20kHz over 0.1 seconds. The equation used to quantify wall shear stress [7,8] from the hot film voltage is

$$\tau_w = C\left(V_s^2 - V_0^2\right)^3$$

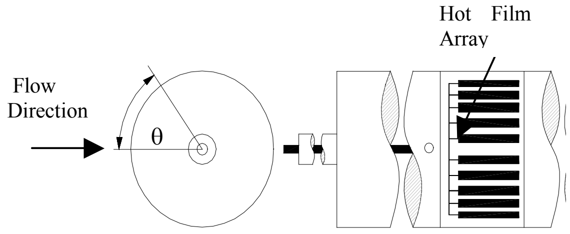

Figure 5 Circular Cylinder Layout

CFD METHOD

The computer software used for the numerical analysis of flow over the cylinder was Fluent Version 5.0, the mesh used was created in GAMBIT Version 1.0 .

The mesh created within GAMBIT was 2 dimensional and consisted of 40,000 cells, 100 in the radial direction of the cylinder, and 400 wrapped around the circumference.

A larger mesh was generated from the original 40,000 cell mesh with the use of grid adaption within Fluent V5.0. This allowed the mesh concentration at the wall to be greatly increased and in effect creating a larger quantity of data points within CFD at the area of most interest. This adaption created a mesh of 56,000 cells with the highest concentration of cells within a distance of 2mm from the wall.

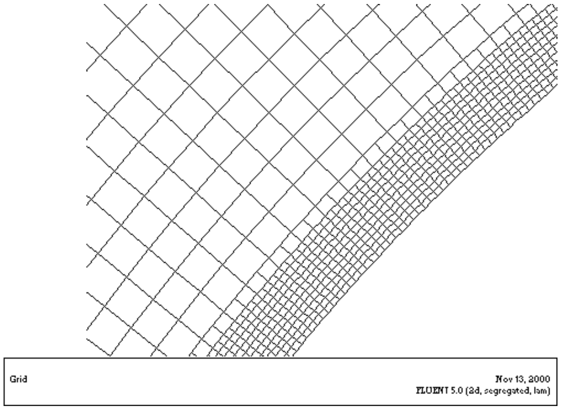

Figure 6 Cell Mesh: 56,000

A grid independence test was carried out to ensure that further increases in the actual mesh size would not cause any significant change in the data obtained from the previous solution. It was found that there were differences in the results obtained from the 40,000 and 56,000 cell meshes. It was decided to further adapt the 56,000 cell mesh by approximately a factor of 2. This resulted in a 120,000 cell mesh with the mesh only being refined in the near wall regions. Figure 6 and 7 show the grid layout of the 56,000 and 120,000 mesh respectively.

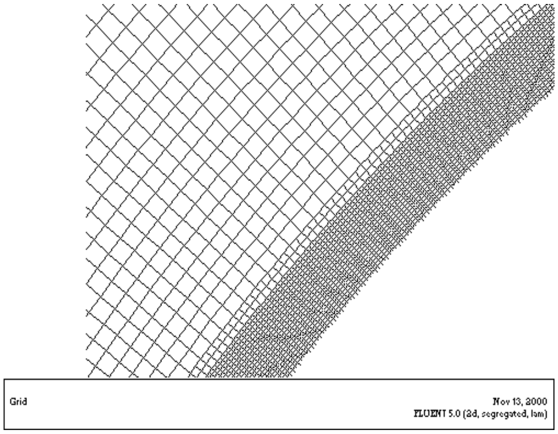

Figure 7 Cell Mesh: 120,000

RESULTS

Velocity Profiles

Figures 8 to 14 show the velocity profiles obtained from both the hot wire and CFD. These profiles were recorded from the stagnation point on the front of the cylinder (0°) to just after the separation point (90°). The angles specified are measured against the incoming flow direction. The Reynolds number of the flow was 50,000 for each of the profiles obtained.

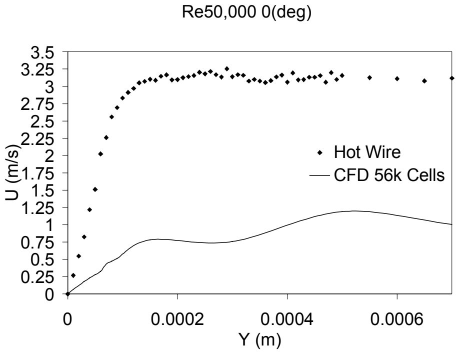

Figure 8 Velocity Profiles 0°

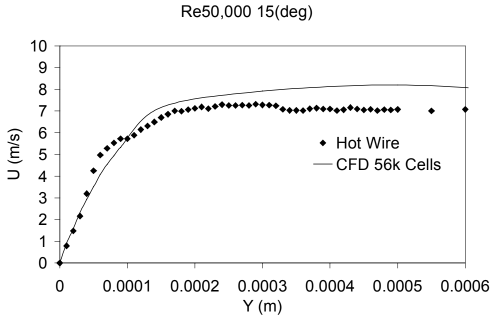

Figure 9 Velocity Profiles 15°

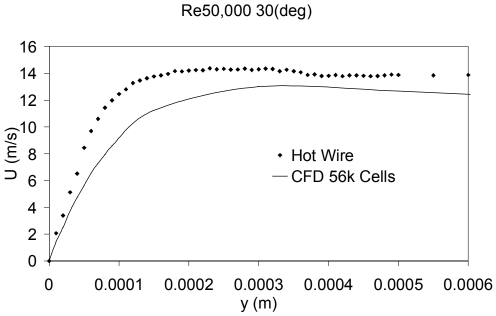

Figure 10 Velocity Profiles 30°

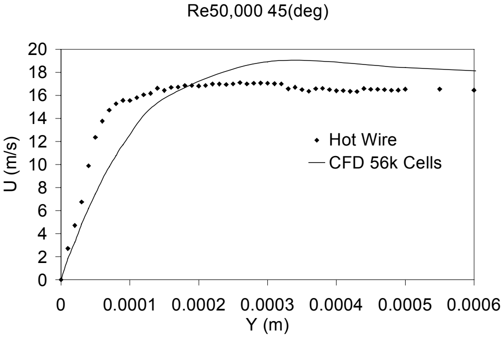

Figure 11 Velocity Profiles 45°

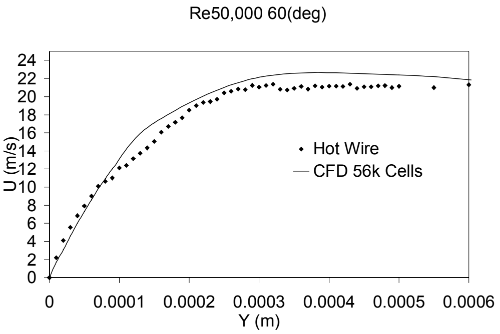

Figure 12 Velocity Profiles 60°

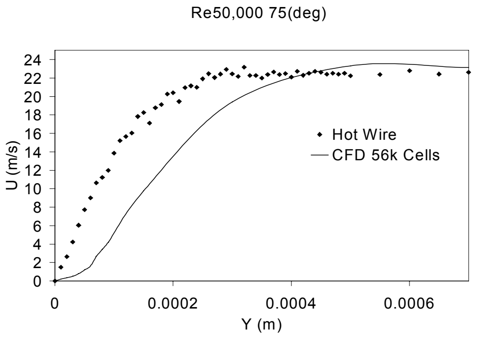

Figure 13 Velocity Profiles 75°

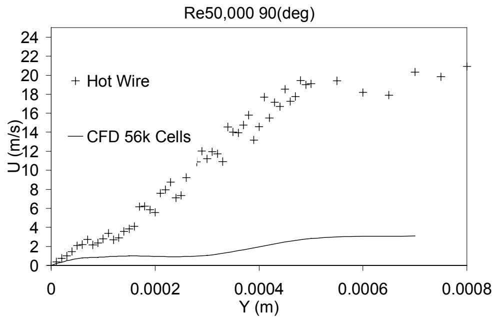

Figure 14 Velocity Profiles 90°

Entropy Generation Rates

Figures 15 to 20 show the entropy generation rates throughout each measured boundary layer on the cylinder. These are calculated directly from the velocity profiles shown in figures 8 to 14.

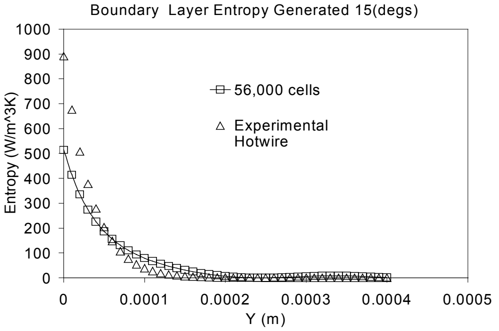

Figure 15 Entropy Profiles 15°

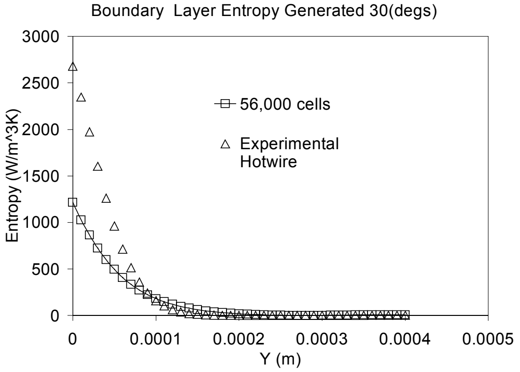

Figure 16 Entropy Profiles 30°

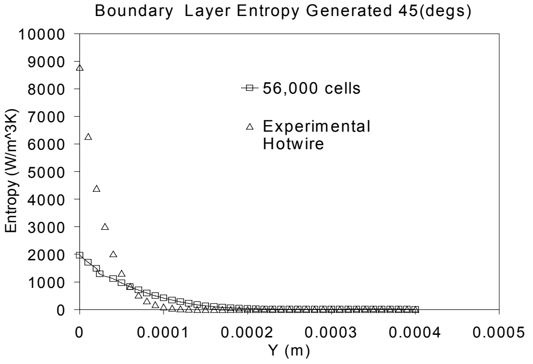

Figure 17 Entropy Profiles 45°

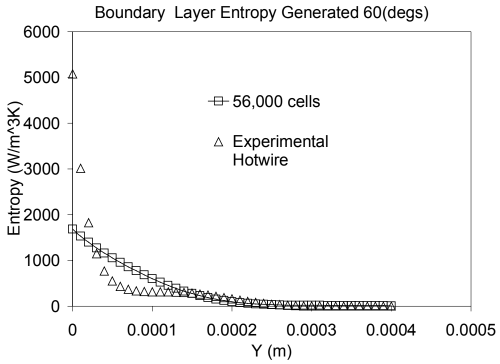

Figure 18 Entropy Profiles 60°

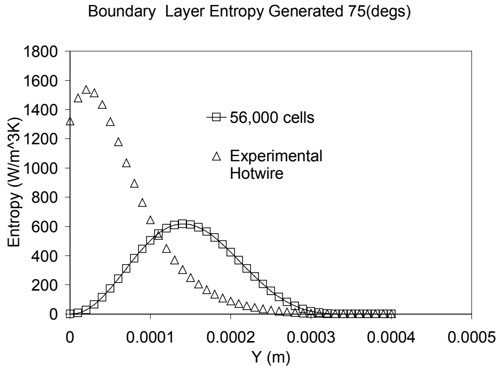

Figure 19 Entropy Profiles 75°

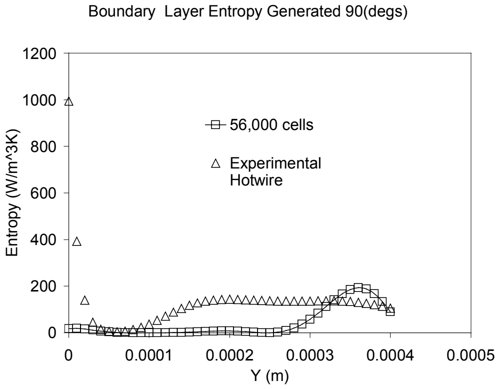

Figure 20 Entropy Profiles 90°

Total Entropy Generated

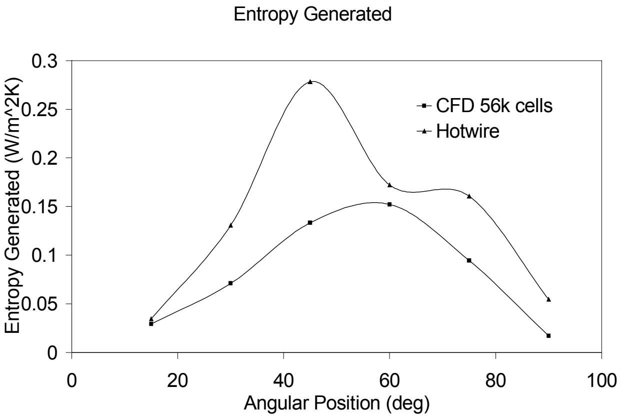

Figure 21 Overall Entropy Generated

Figure 21 shows the entropy generated per unit area from the 56,000 cell CFD model and from the hot wire test. The entropy is analysed throughout a sweep from 15° to 90° on the cylinder. The experimental data can be seen to rise rapidly from 15° to 45° and drop suddenly to 60°. It holds relatively level between 60° and 75° and then begins to drop towards 90°. The CFD solution shows gradually increasing entropy between 15 and 60° and from 60° onwards slowly reduces up until 90°. The maximum entropy values recorded for each method were 0.2781 W/m2K at 45° for the hot wire and 0.1521 W/m2K at 60° for the CFD model.

Wall Shear Stress

Figure 22 shows the wall shear stress obtained from experimental and numerical methods. In this case the wall shear stress is plotted firstly from CFD and the experimental hot wire results. A calibration factor was then substituted into the results from hot film testing to yield the closest values for wall shear stress to those obtained experimentally and numerically.

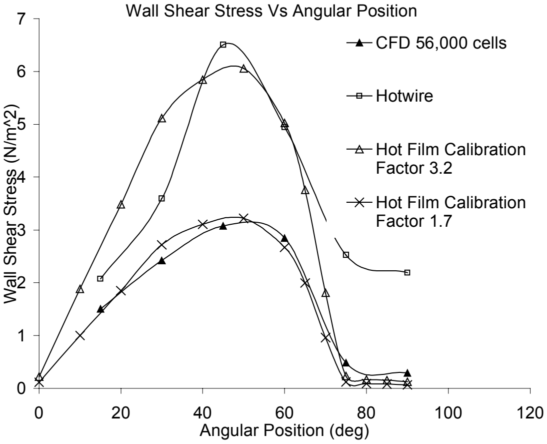

Figure 22 Wall Shear Stress Calibration

In the case of the hot wire test, the factor which yielded the most satisfactory result was 3.2 . With the use of this factor the hot film could predict wall shear stress most accurately between 50° and 65°. The same approach was used to give an indication of what factor would tie up with CFD and this yielded a value of 1.7.

DISCUSSION

Overall the results obtained from the hot wire, hot film and CFD yield relatively similar values. The experimental velocities obtained from single hot wires are not directional and therefore the flow direction has to be assumed to be parallel to the surface. In the case of the circular cylinder, this will not be true at all points, at stagnation point or 0° the profile obtained, Figure 8, will contain velocities travelling radially inward toward the cylinder surface. At the point of separation the flow comes away from the surface in an almost tangential direction to the actual point. If a measurement is being taken after the separation point , the flow outside the recirculation area will not be parallel to the surface. The other disadvantage with single hot wires is the way that it is impossible to determine flow in the opposite direction to that expected. This has a significant effect when the tested geometry is a cylinder, as the flow is highly time dependant and the stagnation and separation points move on the surface depending on the side which the vortex is being shed. If velocity at the stagnation point was considered, the expected velocity close to the wall would be expected to be close to zero, however the hot wire picks up velocities moving in opposite directions at different instants and cannot distinguish them. When an average is taken over time the end result is the average of absolute components which will give a much higher velocity that the true average of both positive and negative values. The hot films give similar data to that of the hot wire however the main problem being that they are not measuring at a point in space and are actually measuring a volume of undetermined size out from their surface. This leads to a problem of calibrating the films, and as they are sensitive to curvature and it is not possible to apply the same calibration to every geometry. The entropy generation rate per unit volume is proportional to the squared component of the velocity gradient therefore if velocity profiles do not match relatively well it will be impossible for entropy profiles to be similar. The entropy profiles obtained from experimental data seems to be much higher near the cylinder surface than that obtained from CFD, however the experimental values fall more rapidly moving out from the surface. The net result is that even though the experimental results have a higher maximum value, the integral of the entropy generated throughout the boundary layer with both results is more similar. The entropy generated between 15° and 90° on the cylinder from hot wire data is approximately two fold of the values from CFD except at 60° where there appears to be better comparison. Overall the entropy generation plots can be said to be highly dependant on any errors within the initial velocity profiles. The use of hotwire results to calibrate a hot film provided the closest comparison between 50° and 65° on the cylinder using a calibration factor of 3.2. CFD was also compared with the heated film and the calibration factor for this was 1.7. In this case the results tied up much better and using this calibration factor on film results one would expect to find a reasonable comparison with CFD. For the purpose of experimentally validating hot films, the CFD factor could not be taken into account.

CONCLUSIONS

The 56,000 cell CFD model is sufficiently large to obtain reasonably accurate results, as shown form the grid independence test.

The steady solution obtained from CFD fails to give comparable data to experimental at stagnation and separation points.

A calibration factor for the hot films tested of 3.2 would yield the closest approximation to the actual experimental wall shear stress.

The calibration obtained for heated films from hot wire experiments could be used only within the 50° to 65° range with reasonable accuracy.

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