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ANALYSIS OF TEST SECTION FLOW CONDITIONS OF LOW SPEED WIND TUNNEL

JI Abeygoonewardene[1#], DR Caseer[1], and K Wickramasinghe[1]
[1]Department of Aeronautical Engineering, Kotelawala Defence University, Sri Lanka
 # jabeygoonewardene@kdu.ac.lk

Abstract - Low speed wind tunnels are preferred in experimental aerodynamics due to their ability of including the full complexity of real fluid flow while providing accurate, reliable data in the most economical manner. Determination of basic flow characteristics of a wind tunnel will lead to precise fluid measurement of more complex flows to be generated in the test section. Proper understanding of the distribution of fundamental flow properties along with turbulence level will lead to precise data interpretation and subsequent flow calculations.

The focus of the research is in determining pressure distribution and flow velocity through the test section of the low speed wind tunnel available at Kotelawala Defence University. This is done using a pitot static tube and boundary layer mouse connected to a liquid manometer. Test section is calibrated for speed setting by measuring static and total pressures. The longitudinal pressure gradient is obtained in order to make required buoyancy corrections. Dynamic pressure variation throughout the rectangular test section is obtained to include approximate survey of the walls as well. Generated results serve as a basis or reference in future experimentations in the low speed wind tunnel to make necessary corrections/ allowances to assure precision.

Keywords - Boundary Layer mouse, Low speed wind tunnel, pitot static tube, pressure variation, test section calibration.

I. INTRODUCTION

Wind tunnels serve as a powerful means of providing experimental information to solve aerodynamic and hydrodynamic problems. The primary activity of a majority of these experiments involve use of scale models which in turn effectively predict the behaviour of the full-scale scenario.

Further small wind tunnels have proven to provide valuable information with regard to flow physics in many instances. Their simplicity and low cost in both construction and operation have made them attractive to users. In the study of flow patterns and how geometric parameter parametric variations affect them the low speed small wind tunnel is a useful tool (Barlow, et al., n.d.).

When air enters to the inlet section of the wind tunnel, the friction is developed in the wall of the wind tunnel. As a result a boundary layer is developed near the walls. Due to boundary layer development, the free stream pressure variation is created along the stream wise direction of the test section. When a body is tested in the wind tunnel, actual phenomenon of the flow properties around the body cannot be attained due to the free stream pressure variation in the developing zone. A study on boundary layer correction factors have been done in a wind tunnel having a 30 inch test section (Van Schielstett, 1934) while pitot-static tubes have been calibrated in even small tunnels (Spaulding & Marriam, 1935). It has been demonstrated that the effect of sidewall boundary layers as causing changes in both test Mach number and airfoil thickness that the latter effect is dominant at low speeds (Murthy, 1985). As difficult as it may seem at times to obtain a certain Reynold's number in small tunnels, the importance of having proper understanding of this similarity parameter cannot be understated (Donnelly & Streenivasan, 2012). Even though the experiment results may not be accurate at higher Reynold's numbers, devices such as hand thrown sports objects, small aircraft models and various instrumentation devices can be successfully tested (Tsuji, 2009).

In order to understand and estimate the flow properties, flow visualization through simple means such as smoke, tufts, or china clay can be accomplished. Since the pressure distribution over a given airfoil does not have drastic changes dependent on Reynold's number at angles of attack well below stall, pressure measurements yield useful results in tunnels of this nature. As per Barlow, et al many experiments concerning wind tunnel wall corrections are suitable for the small low speed tunnel as they are least affected by the Reynold's number. Separation and transition points indicate Reynold's number effects. However if both are fixed by virtue of natural shape of the object or through manipulation, then it is unlikely that there will be significant changes in Reynold's number.

II. METHODOLOGY/ EXPERIMENTAL DESIGN

For steady, inviscid flow having a uniform velocity field far from any object that may be in the flow, it can be taken that the time derivatives of the Navier-Stokes equations for incompressible flow are equal to zero. The Reynold's number will be infinity and the curl of the velocity field must be equal to zero everywhere. Then the Navier-Stokes equation can be written as,

$$\hat{\nabla}\left(\frac{\hat{V}^2}{2}\right) = -\frac{1}{2}\hat{\nabla}C_p \qquad (1)$$

Where symbols in carets are dimensionless variables, V is the nondimensionalized velocity which is equal to 1 and C_p is the dimensionless form for pressure with the reference value shifted according to standard practice. Thus it can be stated that

$$\hat{V}^2 + C_p = 1 \qquad (2)$$

Or equivalently,

$$p + \tfrac{1}{2}\rho V^2 = p_\infty + \tfrac{1}{2}\rho V_\infty^2 \equiv p_{\text{tot}} \qquad (3)$$

Is the classical Bernoulli equation which is the base for low-speed wind tunnel experiments and for most speed-setting systems (Ristic, Isakovic, Ilic, & Ocokoljic, 2004). Thus the velocity could be obtained through pressure difference measurement,

$$V_\infty = \sqrt{2(p_{\text{tot}} - p_\infty)/\rho} \qquad (4)$$

In real flows, the effect of shearing or viscosity is to be taken into account, especially in case of flow adjacent to solid boundaries. When fluid elements pass over a solid surface (such as test section walls) fluid elements right adjacent to the wall will be in the 'no-slip' condition, whereas fluid elements immediately above will be at a retard state until such time that they are able to overcome the shearing effect induced by the wall. Thus a boundary layer will be created where fluid elements will be at lower velocity than the free stream flow (Schlichting & Gersten, 2017). The velocity of fluid increases from zero velocity on the stationary boundary to the free stream velocity of the fluid in the direction normal to the boundary. Fluid elements at the outer edge of the boundary layer will be almost close to potential flow velocity (Anderson, 2007). Assuming zero pressure gradient along the plate and uniform external velocity, the shearing stress is given by the Von Karman integral momentum equation,

$$\tau = \frac{d}{dx}\int_0^\delta (Vu - u^2)dy \qquad (5)$$

where δ is the boundary layer thickness and u is the local velocity. Distance along and perpendicular to the surface are given by x and y respectively. For laminar boundary layers over a flat plate, Blasius solution to the flow governing equations give that boundary layer thickness,

$$\delta = \frac{5x}{\sqrt{Re_x}} \qquad (6)$$

The retarded flow inside the boundary layer acts as a partial obstruction to the free stream flow thus deflecting the streamlines external to the boundary layer by the displacement thickness,

$$\delta^* = \frac{1.72x}{\sqrt{Re_x}} \qquad (7)$$

An index that is proportional to the decrement of momentum flow due to the presence of the boundary layer is given by the momentum thickness,

$$\delta^* = \frac{1.72x}{\sqrt{Re_x}} \qquad (8)$$

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It is the height of a hypothetical stream tube which is carrying the missing momentum flow at freestream conditions.

III. RESULTS AND DISCUSSION

The experiment is conducted in the Educational Wind Tunnel at the Department of Aeronautical Engineering of Kotelawala Defence University. It is a open circuit, low speed wind tunnel with a speed range of 4.5 m/s to 65 m/s. The test section dimensions are 30.5 cmx 30.5 cmx 60 cm. The four major duct components are the contraction, the test section, diffuser and fan housing. The 8.3:1 contraction ratio of the tunnel is a major contributor to its high performance and low turbulence level. The test section side wall has a divergence of 0.159 mm to compensate for boundary layer development (Aerolab LLC, 2013).

A. Speed Setting

When calibrating the low speed tunnel for speed setting, the experiment set up consists of the tunnel mounted with a pitot static tube. The test section is otherwise empty since the presence of pitot static tube and model will cause induced flow. The pitot static tube used in this experiment reaches 6.6 cm forward of the bend, extending 33 cm to the bend. It consists of a rounded-tip total-pressure tap and six static ports. The fan speed is controlled via a Variable Frequency Drive (VFD) and pressure readings are obtained for speeds ranging from 500 to 1500. The experiment was repeated four times and the results are shown in figure 1.

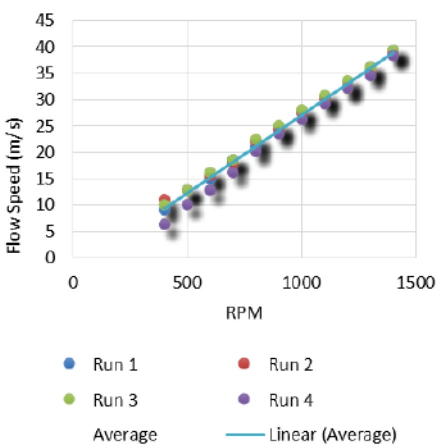

Figure 1. Variation of Velocity with Fan speed

B. Pressure Variation

The next step in the experimental procedure is to analyse the flow uniformity through the cross section of the test section. As per Barlow, et al (1999) the local dynamic pressure should not deviate more than 0.5 % from the mean dynamic pressure at the cross section of interest. Thus it is important to understand the interferences that the measurement device, in this case the pitot static tube, pose on the accuracy of results (Assato, Fico Jr, & Girardi, 2003). In the present experiment pressure variation in the direction perpendicular to the flow was measured via the pitot tube. The variation of dynamic and static pressure from mid-point of the test section towards the side walls is shown in figures 2 and 3 respectively.

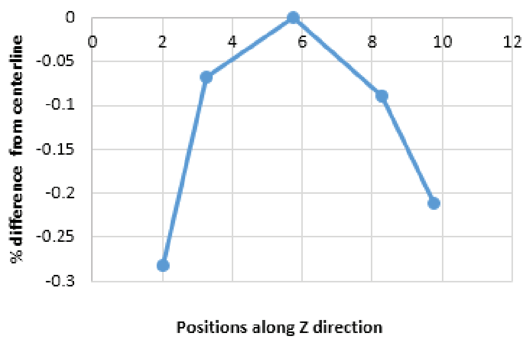

Figure 2. Dynamic pressure variation

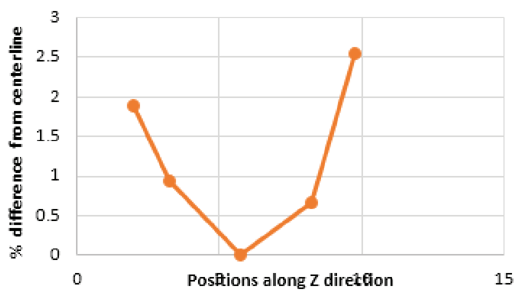

Figure 3. Static pressure variation

It is seen that the deviation of static and dynamic pressure in the direction perpendicular to flow at tunnel midsection does not exceed 0.3 %.

C. Wall Boundary Layers

Wall and surface boundary layer profiles were generated by obtaining readings through a boundary layer mouse.

The mouse has 10 total pressure probes that ascend on an angle and cover a width of 25.4 mm and a height of 6.1 mm. The probes are approximately 1.22 mm apart along the diagonal. Readings were taken for 6 equally spaced positions along the wall and 9 positions along the surface (base) of the test section for fan speeds ranging from 500 to 1500. The boundary layer velocity profiles for three points measured along the base of the test section in the direction of the flow for a fan speed of 500 rpm are shown in figure 4.

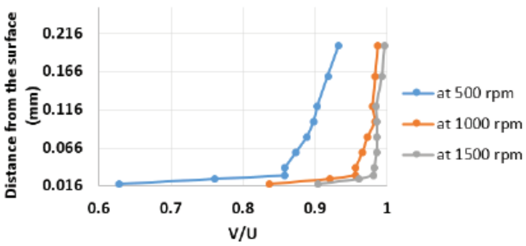

Figure 4. Boundary layer profiles of the start of the test section base

Velocity in the boundary layer at a constant height above the surface is shown in figure 5. The height of consideration is 0.06 mm above the base of the test section. The transition region for the three speed settings occurs around the same region: immediately aft of mid test section.

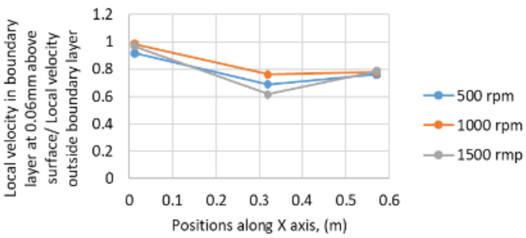

Figure 5. Velocity in the boundary layer at a constant height above the surface

The variation of boundary layer properties for the three different speed settings for the wall and surface (base) is illustrated in figures 6 to 11.

1. Variation of boundary layer thickness on the wall and surface:

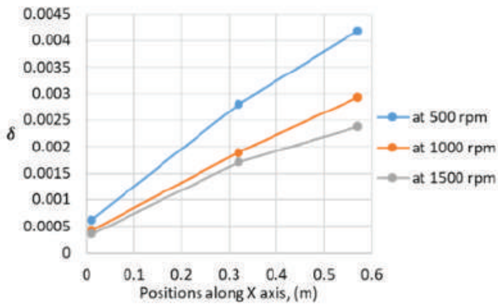

Figure 6. Variation of boundary layer thickness on the surface

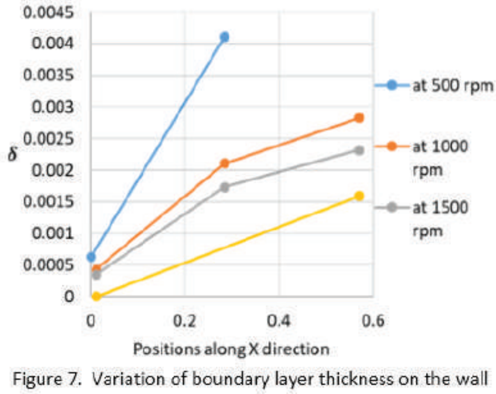

Figure 7. Variation of boundary layer thickness on the wall

2. Variation of displacement thickness on the wall and surface:

The variation of boundary layer properties along with wall and surface of the test section are inspected. The divergence of the side wall is taken into account and represented as a correction factor.

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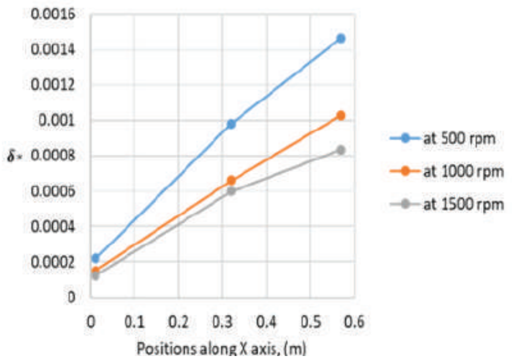

Figure 8. Variation of displacement thickness on the surface

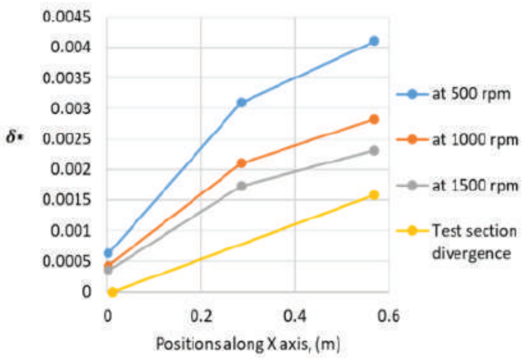

Figure 9. Variation of displacement thickness on the wall

3. Variation of momentum thickness on the wall and surface:

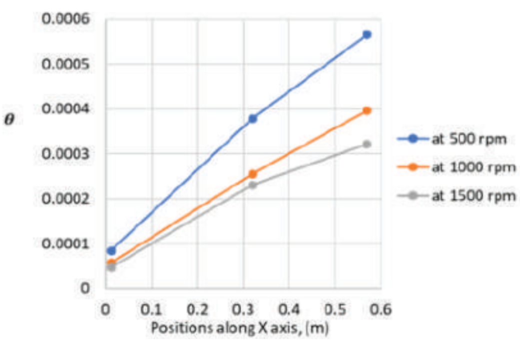

Figure 10. Variation of momentum thickness on surface

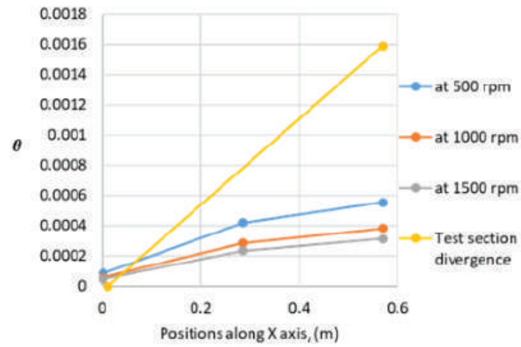

Figure 11. Variation of momentum thickness on the wall

The percentage reduction in the stream tube downstream of the test section is summarized in table 1 for the surface and table 2 for the side walls taking into consideration the divergence of the test section.

Table 1. Percentage reduction in the stream tube downstream of the test section for the surface

Setting	% Due Boundary Layer Thickness	% Due Displacement Thickness	% Due Momentum Thickness
500 rpm	1.2	0.4	0.16
1000rpm	0.86	0.29	0.12
1500 rpm	0.65	0.24	0.092

Table 2. Percentage reduction in the stream tube downstream of the test section for side walls

Setting		500 rpm	1000rpm	1500 rpm
% Due Boundary Layer Thickness	Measured	2.62	1.86	1.46
	Corrected	0.84	0.4	0.24
% Due Displacement Thickness	Measured	2.74	1.86	1.52
	Corrected	0.84	0.4	0.24
% Due Momentum Thickness	Measured	0.32	0.24	0.2
	Corrected	-0.36	-4	-0.43

It is seen that at low flow speeds the reduction of the undisturbed stream tube downstream of the test section due to boundary layer formation on the surface is approximately 1 %. For the side wall the effect is minimized by the inbuilt divergence of the test section.

III. CONCLUSION

Three basic characteristics including speed settings and boundary layer properties of air flow in the test section of a low speed wind tunnel were analysed. As per the results obtained it is seen that the wind tunnel free stream velocity along the stream wise direction is constant, and is accelerated in the downstream direction. The reduction in flow area due to boundary layer formation was observed in the downstream direction as well.

With existing limitations in control and measurement, the results show that even though the flow parameters are subject to time dependent fluctuations, they can be neglected for educational purposes for which the tunnel is used presently. Boundary layer development is present but not significant so as to interfere with primary measurements which are obtained at mid height and width of test section at present use. When utilizing to its full potential however, adequate turbulence and wall corrections need to be incorporated to ensure accurate results.

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