Chapter 2

Design Features of a Low Turbulence Return Circuit Subsonic Wind Tunnel Having Interchangeable Test Sections

N. A. Ahmed

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/52989

1. Introduction

Wind Tunnels have played and are continuing to play a significant role in providing controlled test facilities in the aerodynamic research and development [1-43, 122-178].The present chapter describes in detail, the design features of a subsonic return circuit wind tunnel that is currently in operation at the Aerodynamics Laboratory of the University of New South Wales. It can be considered to be a general purpose low speed tunnel with a sufficiently large contraction ratio. It has a number of removable turbulence reduction screens to achieve low turbulence level. It also has the provision of removable principal test section and three alternative test section arrangements located at various parts of the wind tunnel circuit. The wind tunnel can provide a wind speed in the range of 0-170 ft/sec at the lowest turbulence level. The top speed can be 200 ft/sec, if a higher turbulence level and spatial non-uniformities produced by omission of the screens can be tolerated.

Floor space limitations of approximately of 65 ft x 12 ft have meant that the tunnel be vertical in the vertical plane. From such consideration and ease of wind tunnel experiments, the test section was placed at the laboratory floor level and the return circuit above the test section. The upper structure of the laboratory roof was too flimsy and inaccessible for satisfactory location of the fan and drive in that area so that the fan and the drive had to be at the floor level. The fan is, therefore, placed downstream of the test section and first diffuser and upstream of the first cascade corner. This unconventional arrangement is not, however, without precedent; similar layout has been used in the N.B.S. 4.5 ft low turbulence wind tunnel and Wichita University 10 ft x 7 ft wind tunnels [44-46].

Figure 1. Side View of the Subsonic Wind Tunnel of the University of New South Wales

2. General considerations

The configuration chosen presents several design advantages as well as disadvantages. These are detailed below:

Advantages:

1. Because the fan is located in a comparatively high speed portion of the tunnel, a favourable flow coefficient for a given tip speed may be more easily obtained, leading to high rotor efficiency
2. Except in the case of high lift or very bluff models, good inlet flow conditions to fan are obtained. This situation does not always occur in tunnels with the conventional fan location immediately after the second cascade corner. Maldistribution of flow may exist due to faulty turning vane performance or the need to pass the fan rotor drive shaft through the second cascade turning vanes. This, in turn, leads to reduced rotor performance and increased noise levels.
3. Flow disturbances created by the fan and its tail fairing in the conventional arrangement may adversely affect the performance of the main return circuit diffuser and hence the wind tunnel. The closed circuit type of diffuser is very sensitive to malfunctions in this diffuser [44,46-48]
4. The long flow return path between the fan and test section aids in achieving a low open tunnel turbulence level. This permits a reduction in the number of screens for certain types of test.

Disadvantages:

1. Since the fan is located in line of sight of the test section, care must be taken in the fan design to keep the noise level at the lowest possible value. Sound waves cause air motions which produce an effect similar to that of turbulence and this may place a lower limit on the tunnel turbulence level [44, 45, 49-51] In a tunnel with conventional fan location, the higher noise frequencies are partly attenuated by the two sets of turning vanes separating the fan and test section. Sound power transmitted to the test section from the fan may, however, be reduced by the tunnel breather slot or the use of ducts with acoustic absorbent inserts [49].

2. Since, for reasons of safety, the fan must be observed in the design of the screen to prevent its causing a high energy loss.

3. Care must be exercised in the design of the fan prerotator blades (if fitted) to render them comparatively insensitive to flow changes caused by the presence of high lifting or bluff models in the test section. The contraction ratio was approximately 7:1, similar to one employed in the N.B.S. 4.5 ft tunnel.

Considerable difficulties had to be overcome in the erection of the tunnel components, none the least of which were the strengthening of the comparatively light floor and roof structures of the laboratory so as to absorb lifting and installation stresses. In its present configuration, the tunnel has an overall length of 67.5 ft, an overall height of 27.5 ft and an overall length of 11.5 ft, excluding interchangeable test sections. Various components of the wind tunnel were built over a period, and the overall work from the start of design to manufacture of various components to final installation took about five years to complete.

3. Design of various components of wind tunnel

The detailed design of the tunnel components is described in the following sections of this report.

3.1. Test section design

The principal test section of 50 inch x 36 inch cross section has the normal value of its width to height, i.e., √2:1 [44]. Wall corrections are readily available for this configuration. The test section length of 9.75 ft is within the recommended range for general purpose work of 2.5 to 3 times the equivalent diameter (3.94 ft). Test section fillets, having a side of 5 inches are installed to prevent poor corner flow and accommodate the test section fluorescent lighting.

The test sections are tapered a total of 7/16 inch at the downstream and so as to compensate for the negative static pressure gradient associated with boundary layer thickness increase along the flow. This correction, which was found to be unattainable by tapering the test section fillets, as is sometimes recommended, is calculated to be approximately correct at a test section speed of 160 to 180 m/s. A filtered breather slot is located downstream of the test section.

When the original layout was developed, provisions were made to provide arrangements for removable test sections in various parts of the tunnel circuit. Four such test sections have been provided for. The possible configuration for each of the four is described below:

1. A principal test section having dimensions of cross section of 50 inch x 36 inch and 9.75 ft long and a speed range of 20 to 200 ft/sec.

2. A large test section can be inserted between the screen box/settling chamber assembly and the contraction, the latter being rolled back on a rail system after removal of the principal test section. This large test section is an octagon having maximum dimensions of 10 ft x 10 ft x 9.75 ft and a speed range of from 2 to 30 ft/sec. This test section is useful for a range of industrial aerodynamics tests.

3. An open jet test section, in conjunction with an appropriate removable collector, to be used if required, by removal of the principal test section.

4. A vertical test section which may be interposed in the tunnel circuit in place of the fourth diffuser. This test section permits testing in a vertical airstream and is of octagonal section having maximum dimensions of 5.1 ft x 5.1.ft and a speed range of from 10 to 100 ft/sec.

Of the above four, the first two have been constructed. The test sections were constructed of waterproof quality plywood of either ¾ inch or 1 inch thick, supported on angle from frames. Large viewing windows are provided from ½ inch and ¾ inch thick Perspex set in aluminium frames. The principal test section is provided with doors which open up one complete side over a length of 5 ft and extend two-thirds of the way across the top of the test section to improve accessibility. The tunnel floor is provided with a 3 ft diameter incidence change turntable mounted on a wire bearing race and controlled by a worm and piston drive. The principal test section is removed by means of an overhead travelling trolley and rail system. The large test section is traversed into position by means of a transverse floor rail system which aligns the walls and then by a set of translation tables which move the test section axially forward approximately 4 inches to close the pressure seal. Tapered dowel pins are used to secure accurate alignment of internal airline surfaces and over centre clamps are used to secure the vertical sections together.

3.2. Screen settling chamber design

Wind tunnel screens are required to perform at least two functions, that is, to reduce the:

1. test section turbulence level, and

2. airstream spatial non-uniformities before entrance into the contraction and test section

3.2.1. Turbulence reduction

It has been shown experimentally by Schubauer et al [52] that no turbulence is shed by a screen if the Reynolds number based on the wire material is less than 30 to 60, the exact value depending upon the mesh size and wire diameter. Thus to obtain a low test section turbulence level, the turbulence reduction screens must be placed in a low speed region well upstream of

http://dx.doi.org/10.5772/52989

the test section and contraction must consist of wires of the smallest diameter that are consistent with the strength required.

Batchelor [53] reports from experimental work that *'u'* and *'v'* turbulence components are reduced by factors of 0.36 and 0.54 respectively for wire screens having a resistance co-efficient of 2.0. According to additional experimental work by Dryden and Schubauer [B6), the mean turbulence intensity is reduced by the factor of 0.58 for k=2.0 screen and they propose the following relationship based on experiment but confirmed by appropriate theory:

$$U'_1/U'_3 = (1+k)^{-0.5}$$

U'_1 and U'_3 are the mean turbulence intensities before and after the screens respectively. The relationship between the screen open area ratio or porosity and resistance co-efficient is best found from the data of Annand [54].

The analysis of Batchelor and Drydoen and Schubaureer reveal that it is best to employ a number of screens in series and that of Batchelor indicates that it is the reduction of 'v' component which is most difficult. Relation of the 'v' component to the required level will automatically ensure that the 'u' component is reduced to a correspondingly low value.

3.2.2. Flow non-uniformity reduction

The screens are also required to reduce the flow spatial non-uniformities before the airstream enters the contraction.

A theoretical analysis by Batchelor [55] and an earlier analysis by collar [56] have shown that for steady non-uniform flow, the U component non-uniformities are reduced in the ratio:

$$(2-K)/(2+k)$$

This expression implies that if k=2, the non-uniformities are completely removed. The analysis by Batchelor [53] indicates that the reduction factor can be more accurately expressed as:

$$(1-\alpha+\alpha K)/(1+\alpha+K)$$

where α is the screen deflection coefficient defined as the ratio of (air exit angle)/(air entry angle)

Taking the approximate value of α [56], the reduction factor for k=2 and α =0.64 is seen to be 0.1. Batchelor gives the theoretical reduction for V or transverse velocity non-uniformity component as α or 0.64 for a screen of resistance coefficient 2.0.

3.2.3. Limitations on screen arrangement

Batchelor analysis indicates that the *'v'* component of turbulence is reduced by increasing k to a value of 4. However, screens having a resistance coefficient greater than 2 are not normally used, particularly for the final screen, for the following reasons:

1. Non-uniformity of weave of high resistance coefficient commercial screen materials produce flow disturbances which can have an adverse effect on test section flow distribution and turbulence level

2. Works by Bradshaw [57], Patel [58] and De Bray [59] have revealed that the final screen open-area ratios of less than 60% are likely to cause the development of flow instabilities of the type described by Morgan [60]. These instabilities produce small angular deviations in the flow downstream of the screens. De Bray suggests that a system of helical vortices originates at the screens and persists through the contraction and interacts with the test section boundary layers. The ultimate effect is to cause lateral variations in thickness and skin friction distribution in the test section boundary layers. Patel also reports that a similar effect is apparent if the screens are allowed to accumulate a build up of dust. Although a single screen resistance coefficient of 2.0 implies screen porosities of about 50%, it is necessary to use, at least for the final screen, a resistance coefficient of approximately 1.4 at 30 ft/sec in order to achieve a porosity of 57%. This is equivalent to a 20 mesh by 30 or 31 gauge wire screen.

There is also evidence to suggest that test section boundary layer disturbance of the type previously mentioned may be avoided by the use of a precision honeycomb located downstream of the last screen [B1,B9,B17]. However, such a device must have very small cell sizes, be of precision, and hence costly, construction and must be located in a very long settling length upstream of the contraction so as to reduce test section turbulence to a value equivalent to that obtained by the use of screen alone.

If screens are used, the attainment of a low turbulence level requires that use of several turbulence reduction screens each with a resistance co-efficient of less than 2. Following suggestion by Perry [B10], it appears reasonable to optimise the screen configuration by the selection of individual screen resistance coefficients which give the maximum reduction in turbulence intensity and spatial non-uniformity with the minimum overall loss. However, in this tunnel, four screens of equal porosity give almost the optimum performance

3.2.4. Screen spacing and settling length

Because of space limitations, it is not usual in wind tunnel design to allow the full length between the turbulence reduction screens required for complete decay of the turbulence introduced by the screen wires. Dryden and Abbott [45] suggest that the turbulence is of the order of the wire diameter wire at a distance of about 200 wire diameters downstream of a screen. A survey of various designs [51] indicates that inter-screen settling lengths to wire diameter ratios of as little as 250 are used. Dryden and Schubauer [62] found that no measurable effect on the test section turbulence level of the N.B.S. 4 ½ ft tunnel was observed when the inter-screen spacing was varied from 2 to 28 inches. Bradshaw and Pankhurst [44] suggest a distance of 500 wire diameters.

The parallel length after the last screen should, however, be as long as possible, consistent with the space available. Most designs for low turbulence wind tunnels appear to have minimum values of about 2000 to 3000 wire diameters [51]. Work of Manton and Luxton [63] shows that the final period of turbulent decay is reached after a distance of approximately 700 wire spacings.

The University of New South Wales 4 ft x 3 ft wind tunnel has a provision for four removable turbulence reduction screens which have an inter-screen settling length of 400 wire diameters and a final settling length of 2000 wire diameters based on the use of 30 gauge wire gauge. A larger final settling length could not be achieved due to inadequate allowance for the screens and turning vanes in the original aerodynamic layout. However, a removable screen facility permits a considerable variety in screen settling length arrangements. The final screen was 20 mesh by 30 or 31 gauge wire and the remaining screens were the same to reduce turbulence and spatial non-uniformities with minimum overall pressure loss.

Because of the long return path between the fan and test section and the closeness of the vane spacing in the fourth cascade, the empty tunnel turbulence level was of the order of 0.2 to 0.3 %, falling to 0.08 to 0.1% with four screens fitted. The similar N.B.S. tunnel had had a turbulence level of 0.26% without screens, decreasing to 0.04% with six screens fitted.

The screen box of the University of New South Wales tunnel is manufactured from ¾ inch waterproof quality plywood reinforced by steel angle iron frames. The wire screens are clamped by bolting between removable pairs of 3 inch x 2 inch Oregon frames which are a neat sliding fit between pairs of similar fixed frames. The movable frames are supported on overhead tracks by sets of small ball-bearing wheels. Ample space has been provided around the edges of the screen box to install spring loaded screen tensioners, or individual frame air seals. The removable frames are provided with adjustable transverse stops and quick acting clamps so as to ensure their accurate and rigid alignment. The screen box door is sealed by a refrigeration type hollow rubber seal and is locked in position by means of eight swing over bolts and large hand wheels. Extensions of the screen sliding tracks are provided outside the screen box to enable the screens to be removed easily.

4. Contraction design

A large contraction ratio is desirable for many reasons, some of which are:

1. A low air speed is obtained in the settling chamber thus permitting the installation of several low loss turbulence reduction screens without excessive power absorption

2. Because of the resulting low air speed in the settling chamber, turbulence generated in the last screen is lower for a given wire diameter

3. For a well designed contraction, the ratio of turbulence intensity to the mean speed will decrease as the mean speed increases at the test section entrance

4. A large contraction ratio, in conjunction with several damping screens, renders the tunnel test section characteristics least susceptible to disturbance in the tunnel circuit, such as those caused by high lift or bluff models [44].

In general, modern wind tunnels are designed for very low turbulence levels require contraction ratios of 12 to 16, in conjunction with up to six turbulence reduction screens. However, quite low turbulence levels may be obtained in wind tunnels with a contraction ratio of the order of 7:1, with four to six screens, and in conjunction with closely spaced vanes in the corner upstream of the settling chamber, as for example, in the N.B.S. 4 ½ ft tunnel [45].

The contraction ratio selected for the University of New South Wales tunnel produces reduction in the percentage longitudinal velocity non-uniformities by a factor of $1/n^2$ or 0.022 [B19] and of the mean RMS turbulence intensity by a factor of the order of [45] :

$$U'/U_T = \left[\left(2n/3+1/3n^2\right)^{0.5}\right]/n = 0.31$$

Taylor's alternative analysis suggests 0.4 to 0.8 [53]

There is as yet, no established exact design method for octagonal section wind tunnel contractions. Nevertheless, a design criterion common to all contraction is the avoidance of high wall curvature and large wall slope leading to possible adverse pressure gradients of strength sufficient to cause flow separation in either the contraction or test section.

This problem is particularly critical at the contraction entrance [43 and 46] and modern wind tunnels no longer use very small radius of curvature at the inlet end as was favoured before 1940 [44, 64 and 65]. It has been shown theoretically [66] that in order to obtain a uniform velocity distribution at exit, the velocity increase along the contraction must be monotonic but this condition is incompatible with the need for a finite contraction length. Most methods of design generally fall into of the five following categories:

1. Specification of an arbitrary contraction shape based on experience and/or the demands of the constructional material
2. A contraction shape given by the flow of a uniform stream about an arrangement of sources, sinks or vortex rings.
3. Specification of velocity distribution along the contraction axis leading to a derived contraction shape
4. Conformal transformation techniques
5. Specification of the contraction boundary velocity distribution in the hodograph plane and transformation to the x, r plane so as to derive the contraction shape in axisymmetric or two-dimensional flow.

Details of these methods can be found in References 64 to 84. The method employed for the University of New South Wales tunnel was to sketch in the shape, keeping in mind the demands of the constructional material techniques selected and the requirements for satisfactory performance [44, 46, 48, 64, 66, 69 and 85]. The contraction length was first estimated from the fact that, for contraction ratios of the order of 6 to 10:1, the ratio [51], the length to major inlet dimension, lies within 0.8 to 1.2.

The inlet and exit radii of curvatures are approximately 8 and 11 ft respectively for the University of New South Wales tunnel. The resultant contraction shape is very similar to that derived from an approximate theoretical solution by Cohen and Ritchie [64]. The contraction shape was approximately checked by the application of finite differences applied to the solution of the Laplace equation in radial symmetry [83]. A model was built and satisfactorily tested to confirm further the assumed design shape.

The contraction of the tunnel was manufactured from ¼ in marine ply, mitred and reinforced at the junction of the octagonal sides and built within accurately shaped frames of 3 inch x 2 inch Oregon. The Oregon frames were mounted at 1 ½ ft centres upon a base consisting of three longitudinal bearers of 6 inch x 4 inch Oregon. Flanged wheels and a rail system are mounted under the contraction to enable it to be moved axially along the tunnel centreline between the settling chamber and first diffuser.

5. Diffuser design

As mentioned in section 1, space limitation prevented the fitting of a controlled rapid expansion and the achievement of the optimum contraction ratio of 12 to 16:1. When it is possible to fit such an arrangement, a variety of flow stabilization methods of varying suitability are available for wide angle diffusers [86-94].

Considerable data is also available for the conventional diffuser design [98-104]. Unfortunately, however, little of this information has direct application to the design of three-dimensional octagonal section wind tunnel diffusers of any practical compact design must entail a certain amount of guess work or knowledge of previous experience in the selection of appropriate diffuser angles. For example, attempts to use the data of Ref D6 would indicate that for the large return diffuser of area ratio of 2.85:1, two-dimensional diffuser angles of up to 12^0 might be employed. However, experience with the square cross-section three-dimensional main return diffuser of the R.A.E. No. 2, 11 ½ ft x 8 ½ ft, wind tunnel1 indicated that equivalent cone angles of about 5^0 are satisfactory for this application. Shorter diffusers may employ somewhat larger angles and advantage has been taken of the fact in the design of the University of New South Wales tunnel where the equivalent cone angles used vary from 5.2^0 in the longest diffuser to a maximum of approximately 6 $¼^0$ in the shortest diffusers.

The first diffuser downstream of the test section is a particularly difficult design problem as the flow maldistribution caused by high lift and bluff models must be taken into account. Moreover, work by Willis [105] indicates that unsteady flow in the diffuser is responsible for a rise in a measured wall pressure spectra at low frequencies. The University of New South Wales tunnel has an essentially two-dimensional first diffuser with an included angle of 7 ¼ ^{0} and area ratio of 1.4:1 (equivalent cone angle of 3.4^0). Reference D6 indicates that a diffuser angle of up to 17^0 might be employed without separation for this diffuser.

Diffuser performance is also related to the inlet boundary layer thickness and free stream turbulence level [98, 99, 101-104). This makes the estimation of tunnel diffuser losses difficult. In the estimation shown in Table 1, the five diffusers contribute 37% of the tunnel loss, the first diffuser alone being about 14% of the tunnel loss. The design of the diffusion zone over the fan tail-fairing is a special problem and has been conveniently summarised by Russel and Wallis [106].

Diffuser numbers 4 and 5 of the University of New South Wales were built from ¾ inch thick exterior waterproof quality plywood with angle iron and 5 inch x 1 inch timber supporting frames. All sections are octagonal in shape as this permitted short length transitions to be made between the main components of the return circuit and circular fan ducting. The mitred sides of the octagons are constructed of 1/ inch ply mounted on 3 in x 2 in Oregon frames inside the main diffuser shell.

Diffuser No.1, the fan ducting and associated transitions are constructed from 16 gauge mild steel sheet which is reinforced with angle iron frames and rectangular bar steel frames and stringers.

Heavy Perspex windows and fluorescent lighting are fitted to enable easy visualisation of flow performance of the tunnel components. Each leg of the tunnel circuit between the turning vane cascades is provided with one or more quick opening doors for easy access. The doors are sealed with circular, foam rubber cord, formed into shape of an ‘O’ ring.

6. Turning vane design

It is well known that for abrupt rectangular corners, large aspect ratios and larges ratios of turning radius to inlet width are required to reduce the corner loss [107]. This has led to the post-second world war concept of closely spaced turning vanes to provide low loss, compact, wind tunnel corners.

In the past, it has been common to use thick profile aerofoil turning vanes because these can be designed to give air turning passages of approximately constant area, thus avoiding any expansion and possible flow separation around the passage between adjacent turning vanes. Such turning vanes are efficient in operation, but very difficult and expensive to construct. Winter [108] has shown that these thick vanes may be replaced by thin sheet metal turning vanes with little or no increase e in pressure loss at the corner. According to Winter[108], at a Reynolds number of 1.9×10^6 and for the same spacing to chord ratio (s/c) of 0.25, the thin sheet metal vanes reduced the vane loss to about 50% of that thick profiled turning vanes.

There is very little reliable information in the literature relating to turning vane losses for typical wind tunnel applications. The most extensive information is that reported by Salter [109] who obtained experimental data for both aerofoil profile and sheet metal circular arc turning vanes in the Reynolds number range of 6×10^4 to $1.9 \times 1.9 \times 10^5$. It must be noted that the data presented by Salter does not employ the conventional cascade definition of spacing to chord (s/c) ratio in which the vane spacing is measured normal to the line joining the vane trailing edges. Salter defines a gap to chord ratio based on the distance or gap between the vane trailing edges measured normal to the parallel trailing edge tangents. It would appear that this data has been either misinterpreted or not adequately clarified in most of the subsequent literature [44]. Salter's data has been recalculated according to the conventional cascade definition of s/c ratio

The thin circular arc vanes tested by Salter appear to have a minimum loss co-efficient at an s/c ratio of between 0.3 and 0.4. The difference in the magnitude of the loss co-efficient for the Salter type 2 and 3 vanes could be due to the slightly different camber angles, but it is most likely due to the threefold increase in Reynolds number for the type 3 vanes. The series of tests by Ahmed revealed a considerable variation in loss coefficient with Reynolds number up to a value of about 4×10^5 after which the loss coefficient remained essentially constant. The curves designated Salter 2 and 3 are mean loss coefficients for a cascade corner including losses due to boundary layer and secondary flow effects. Salter also measured the loss coefficient for the potential flow region alone. The greater relative difference can be attributed to the fact that the lesser number of vanes and lower aspect ratio of the type 3 vanes contributes to a larger secondary flow loss. Salter concludes that for 90^0, thin circular arc turning vanes, having 10% straight tangent extensions on the leading and trailing edges, the mean loss coefficient should not exceed 0.1 for Reynolds numbers in excess of 2×10^5. Salter recommends that, to ensure flow stability, the gap chord ratio should be about 0.2 with a vane aspect ratio greater than 3. This gap chord ratio of 0.2 corresponds to an s/c ratio of 0.28 by the conventional cascade definition. Also evident from Salter's results is that the optimum s/c ratio for thick aerofoil profile vanes is in the region of 0.5 to 0.6.

The types of thin sheet metal vanes tested by Silberman[110] have a minimum loss coefficient at an s/c ratio of 0.5 to 0.7 depending upon the vane shape. The curves shown represent the loss coefficients in the potential flow region only. Silberman's results for thick vanes indicate a minima at an s/c value of 0.5.

Since s/c is not the only parameter determining the turning vane design for wind tunnels, a choice must be made of either vane spacing 's' or chord 'c'. This apparent variation possible in this choice is exemplified by the values for the fourth cascade corners of two successful wind tunnels of roughly comparable size and performance, i.e., the R.A.E. 4 ft x 3 ft and N.B.S. 4 ½ ft tunnels. For the R.A.E. tunnel, an s/c ratio of 0.26 was selected using thick profiled turning vanes of 30 inch chord. For the N.B.S. tunnel, the s/c ratio was 0.52 with a chord of 2 7/8 inches, employing thin sheet metal vanes. These two designs represent opposite limits of cascade performance. The R.A.E. vanes appear to have been designed for low loss, whereas those of the N.B.S tunnel were designed for low turbulence. The large chord of the R.A.E. vanes implies high Reynolds numbers and lower loss coefficients. In the N.B.S. tunnel1, the smaller blade spacings selected (approximately 1 ½ inches) resulted in a lower turbulence level measured at the screen location. The 'u' turbulence component of the N.B.S. tunnel1 referred to the settling chamber velocity and, measured in the settling chamber downstream of the fourth cascade, was about 2.3% and about 60% greater than the 'v' or 'w' components. This is a favourable design situation as it is the 'v' and 'w' components which are least reduced by passage through the screens and contraction. In the R.A.E. tunnel, the turbulence level in the comparable location was about 5 % and roughly equal for all three components.

It, therefore, appears that wind tunnel turning vanes can be constructed from thin sheet metal circular arcs, having an s/c ratio in the region of 0.28 to 0.35 and a passage aspect ratio of 6 or more. It appears that vanes for more than 90^0 corners should have a camber angle of 86^0 to 87^0 and that they should be set initially at a positive angle of about 3^0 to 4^0 with trailing edge angle of zero relative to the tunnel centreline at exit. The selection of the value of blade spacing depends upon the application envisioned. Low turbulence tunnels require that small blade spacing be used, for example, a spacing dimension of 2 inch or 3 inch would be unreasonable. Tunnels not requiring a low 'open tunnel' turbulence level might employ spacing dimensions of 12 to 24 inches. Additional compromises to be effected are those of cost and structural integrity. Small vane spacings imply a large number of thin vanes of small chord with a resulting high cost and the possibility of vibration occurring due to relatively low vane natural frequency. Tunnels designed for low corner losses might be designed with a relatively large vane spacing and chord in order to ensure Reynolds numbers in excess of about 4×10^5. Salter suggests that a minimum of 20 turning vanes should be used in low loss corners.

The university of New South Wales tunnel employs s/c ratios of 0.25 and 0.27 for the first and the second cascade corners increasing to 0.31 for the third and fourth corners. Blade spacings vary from 2 to 5 inches and the number of turning vanes from 41 to 33 for the first and fourth cascade corners respectively. The maximum and minimum vane Reynolds numbers at design speed are approximately 5×10^5 and 2.4×10^5 for the first and fourth corners respectively. Turning vane t/c ratios vary between 0.7 to 1.5%.

Because the University of New South Wales wind tunnel cross section is octagonal at all cascade corners and the vane chord is an appreciable dimension, special care had to be taken in the design of the junction between the turning vanes and the octagonal fillet so as to prevent the airstream expanding and subsequently contracting in its passage around the junction zone. The problem was solved by the manufacture of special concave and convex cross sections which were fitted in the cascade corner fillets. The shape of these special corner sections was generated so as to provide a straight line intersection normal to the vane span at the junction of each turning vane and the corresponding corner fillet.

All turning vanes were produced from 10 gauge (1/8 inch) mild steel plate by brake pressing. The turning vanes are set in mild steel plate supporting frames which are reinforced with angle iron.

7. Fan and drive system design

The fan must, by reason of its location downstream of the test section, pose certain design problems as outlined before. These relate to noise level and sensitivity to flow maldistribution caused by high lift or bluff models in the test section.

In general, the design methods of Wallis have been employed [111-113], together with additional experimental data [114-115]. A design utilising 100% pre-rotation has been developed in conjunction with N.P.L. type flow straighteners so as to ensure good efficiency over a wide range of flows together with reduced possibility of stall of the cascade corner vanes immediately downstream of the fan nacelle fairing.

http://dx.doi.org/10.5772/52989

The location of the fan in a relatively high speed portion of the tunnel is associated with a mean rotor blade flow co-efficient of 0.56, which approaches the optimum range of flow coefficients for high fan rotor efficiency with the amount of pre-rotation employed. However, there are conflicting fan duty requirements due to the need for relatively high pressure rise and low fan noise level.

As may be calculated from the estimated tunnel pressure loss characteristic, the fan duty required is 3.8 in w.g. pressure rise at a flow of 1f 122,000 CFM. The tunnel coefficient utilisation is:

(test section energy)/ (Σ circuit losses) = 1.6 to 2.3

depending on the number of screens used.

These requirements have led to the selection of an 8-bladed fan rotor of 5 ft diameter, limited to a maximum tip speed of 315 ft/sec. The rotor blade chords vary from 9.9 inches at the root to 6.4 inches at the tip.

The noise spectrum from an axial flow fan can be described as consisting of two components: ‘broad band’ noise and ‘discrete frequency’ noise.

Broad band noise is attributed to two basic mechanisms: vortex shedding from blade boundary layers and interactions between the blading and random turbulence in the intake flow. The theoretical analysis of Refs 116 and 117 show that, for rotor blades operating at their design point, the vortex shedding component of broad band noise is proportional to blade relative velocity to the power 5.6 and that the intake turbulence interaction component is proportional to relative velocity to the power of 4. Reduction in broad band noise can thus be realized mainly by keeping flow velocities adjacent to solid boundaries and, specifically, blade tip velocities, to minimum values consistent with satisfactory aerodynamic performance.

Discrete frequency noise is caused by periodic aerodynamic interaction between fixed and moving blade rows. Like broad band noise, discrete frequency noise has two basic mechanisms. These are the force fluctuations on individual blades which arise from variations in mean velocity of the incoming flow. The data in Refs 116-118 indicate that interaction noise is strongly dependent upon pre-rotator-rotor axial spacing and the shape and size of the individual pre-rotator vanes. The axial spacing affects mainly the potential pressure field interaction mechanism and the vane shape, the mean velocity variation mechanism. As an example, the discussion to Ref 118 indicates that the pressure variation due to the wake persistence is still about 10% of the maximum theoretically possible at a distance equal to one stator chord downstream, for typical accelerating cascades. Experimental data seems to indicate that, consistent with satisfactory aerodynamics, interaction noise is considerably reduced by using separations between stator an rotor of three-quarters to one vane chord in conjunction with small vane areas and slender profiles.

Blade sections chosen for the pre-rotators and rotor are C4 compressor sections on circular arc camber lines [112,114-115 and 119]. These sections give high isolated aerofoil lift coefficients at angles of incidence of 3^0 to 4^0 and have a high stalling incidence. The straightener design is based on the use of the symmetrical NACA 0012 section which starts to stall at about $\pm 14^0$ in the isolated aerofoil condition. Pre-rotator blades of cambered plates were considered [117] because of their comparatively low cost but were abandoned in view of their relatively poor performance under off-design conditions when compared with C4 sections.

Another parameter requiring careful selection was the choice of boss ratio as this affects the overall efficiency of the fan and tail fairing diffuser assembly. Due to the proximity of the first cascade corner, this ratio was fixed at a value of 0.4 which is less than optimum for the rotor alone.

The fan rotor blades have been stressed for centrifugal loading, torsional loads and loads due to non-coincident profile centroids and estimates have been made of the blade natural frequencies [120-121]. The fan rotor was dynamically balanced to an effective centre of gravity displacement of 3 to 5 microns.

The fan design requires a power output of 90 HP at 1200 RPM and a variety of fan drive schemes were considered. Thus a 90 HP compound wound DC motor and ancillaries that included switchgear and speed variation equipment were purchased. The Ward Leonard type speed control system proposed presented considerable difficulty in providing tunnel automatic dynamic head control. In addition, aerodynamic problems were encountered in designing the drive arrangement. A conventional shaft drive through the first cascade was at first envisaged but abandoned when it was realised that the required fairing through the cascade turning vanes caused severe blockage of a component which was already heavily loaded aerodynamically. A direct mechanical drive through a right angle bevel gearbox was next considered. However, a large fairing was needed for the drive shaft and problems were encountered in a gearbox design due to high power transmission requirements in a confined space. Alternative drive systems such as eddy-current variable speed couplings and Thyristor controlled DC drives were also investigated. All these units were costly and suffered from the same basic disadvantage that the prime movers, being large, had to be located outside the tunnel and required some sort of drive shaft arrangement through the tunnel structure to the fan rotor.

Thus the feasibility of using a hydraulic drive system was studied. This system comprises an axial piston hydraulic pump driving similar motor unit and is of the same order of cost as the other systems. The system has many advantages, the main ones being:

1. The drive motor is only 10 inches in diameter and 20 inches long for maximum power output of 125 HP at 1200 RPM. It fits radially inside the fan nacelle fairing where the local diameter is 23 to 24 inches. This eliminates aerodynamic problems associated with a drive shaft through the tunnel structure.

2. Automatic tunnel dynamic head control can be obtained with conventional pneumatic control equipment to a repeatability of ± 0.4 %.

3. The motor speed is fully variable from 0 to 14oo RPM by means of a diaphragm actuator and conventional pressure regulator.

4. The hydraulic pump can be driven by a standard 415 volt, 3-phase induction motor, for which installed electrical capacity was available.

The system finally selected consists of a 150 HP induction motor of 92% efficiency, driving a 'Lucas' PM 3000 series, seven axial piston hydraulic pump fitted with servo-control of the swashplate angle. The servo is operated by a standard 3-15 psi diaphragm actuator. The pump provides high pressure oil at approximately 2300 psi which is supplied to, and returned from the motor by 1 ½ inch outside diameter high pressure tubes through the fan straightener and supporting vanes. Oil flow is approximately 3500 GHP and the overall efficiency of the combined pump and rotor unit is of the order of 82 to 85 %, over the complete speed range. The system also includes ancillary equipment such as a 70 gallon oil reservoir, an oil cooler, boost pump and oil filtration equipment. The main disadvantage of the arrangement is high noise level from the rotor. Provision was, therefore, included in the design for reducing noise transmission of both hydraulic pump and motor.

The fan and drive system and first cascade corner are mechanically isolated from the rest of the tunnel structure, and the laboratory floor, so as to prevent the possibility of any vibrations being transmitted to the test section or instrumentation.

The fan rotor is mounted on an overhung bearing assembly supported off the front of the straightener vane assembly. The straightener vanes are manufactured from ¼ inch mild steel plate with radial and longitudinal plate stiffeners which both provide torsional rigidity and define the aerodynamic profile of the straighteners. The front and the rear of the straightener vanes are attached to heavy steel diaphragm plates at the hub. The front diaphragm plate supports a rigid bearing assembly which carries the overhung fan rotor. The rear diaphragm plate carries another diaphragm plate to which is bolted the hydraulic motor. A flexible coupling connects the very short fan rotor drive shaft and the motor output shaft between the front and rear diaphragm plates. Provision is made in the rotor bearing design to absorb the 400 lb rotor thrust loading. The five straightener vanes have bolted-on cast aluminium nose and tail pieces with the sides sheathed in 16 gauge aluminium sheet.

The fan rotor is of built up construction with blades being held in split root fixings which are in turn clamped between mild steel shroud plates. The rotor blades are high quality aluminium alloy castings with large cylindrical root attachments which enable the blades to be adjusted to any angle by releasing the rotor shroud plate clamping bolts.

The pre-rotator vanes are aluminium alloy castings and are clamped between the shroud plates at the roots to form a rigid prerotator drum assembly. The nacelle nose and tail fairings are spun from 16 gauge aluminium alloy sheet. The nose fairing is bolted on to the front of the pre-rotator drum and the tail fairing to the rear diaphragm plate carrying the hydraulic motor.

Estimations have been made of the tunnel air temperature rise due to power dissipation around the circuit. It was found that without any form of tunnel air exchange or heat exchanger, the air temperature rose by as much as 10 to 15^0 C above ambient after a period of operation of about 10 minutes at a speed of 150 ft/s in the principal test section. This may be doubled for long periods of operation at 200 ft/sec.

The tunnel control system is reasonably straight forward. Instrumentation comprises an optical tachometer, electric drive motor anemometer and pressure gauges for hydraulic system. Electrical interlocks are provided against loss of hydraulic boost pressure and inadvertent starting of the hydraulic system with the hydraulic motor set at the maximum speed condition. Possible fan blade failures are provided for by a fan vibration cut-out switch.

8. Safety net design

For safe operation, a wind tunnel fan must have a suitable safety net located immediately upstream of it to prevent models, or tools, passing through the fan blades. The location of the fan in the University of new South Wales tunnel requires that the safety net be located in the relatively high speed portion of the tunnel circuit. This in turn, requires that considerable care is exercised in the aerodynamic design of the safety net.

It is not unusual to find the safety net located before the first cascade corner even in tunnels with conventional fan layout. It is also known that such safety nets can result in considerable tunnel power expenditure. It was found during experiments on the pressure losses in the ARL 9 ft x 7 ft tunnel that the safety screen which was located before the first corner, contributed 28 % to the total losses. This was the largest of any component. However, the safety net used in this case was relatively coarse, interlocked and 'cylcone' wire mesh.

The University of New South Wales tunnel safety screen is conical in shape and inclined at 45^0 to the free stream direction in order to reduce the velocity component normal to the screen. This configuration also ensures that any object stopped by the screen will be forced to the outside against the tunnel walls. The screen is constructed specially from fine gauge stainless steel wire so as to ensure a low pressure loss. One end of the screen is rigidly held whilst the other end is supported on an energy absorbing spring support.

9. Conclusion

A general purpose return circuit low speed wind tunnel has been designed for the Aerodynamics Laboratory of the University of New South Wales. A contraction ratio of 7:1 and four turbulence reduction screens are used. Low turbulence level is achieved with the assistance of some innovative design features. The fan is located upstream of the first corner. Corner cascade and screen configurations have received special attention.

Other unusual aspects of the design are three sizes of interchangeable test sections in the speed ranges of 0-25 ft/sec, 0-100 ft/sec and 0 -200 ft /sec.

The fan is driven by a hydraulic motor which considerably simplifies power transmission and control problems in this application.

Acknowledgements

The Author wishes to gratefully acknowledge the hard works and dedication of Barry Motson and the late Associate Professor Archer in the Design of this Wind Tunnel

Author details

N. A. Ahmed

School Of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney, NSW, Australia

References

[1] Findanis, N, & Ahmed, N. A. Wind tunnel 'concept of proof' investigations in the development of novel fluid mechanical methodologies and devices', invited Chapter, in 'Wind Tunnels and Experimental Fluid Dynamics Research', edited by J.C. Lerner and U.Boldes, published by In-Tech Organization, Austria, 978-9-53307-623-2July, (2011).

[2] Ahmed, N. A. Wind driven Natural-Solar/Electric Hybrid Ventilators', in 'Wind Power', Section D: The Environmental Issues", Chapter 21, edited by S.M.Muyeen Kitami, published by In-Tech Organization, Austria, 978-9-53761-981-7February, (2010).

[3] Lien, J, & Ahmed, N. A. Wind driven ventilation for enhanced indoor air quality', invited Chapter, in 'Chemistry, Emission, Control, Radiaoactive Pollution and Indoor Air Quality', edited by Nicholas A Mazzeo, published by In-Tech Organization, Austria, 978-9-53307-570-9June, (2011).

[4] Ahmed, N. A, Elder, R. L, Foster, C. P, Jones, J. D. C, & Novel, A. D Laser Anemometer for Boundary Layer Studies', ASME Conf, Boston, USA, 15th December (1987). Also in the 3rd International Symposium on Laser Anemometry, edited by A Dybs et al, ASME, The Fluids Engineering Division, , 55, 175-117.

[5] Ahmed, N. A, Elder, R. L, Foster, C. P, & Jones, J. D. C. Miniature Laser Anemometer for 3D Measurements', J of Measurement Sc Technol, (1990). , 1, 272-276.

[6] Ahmed, N. A, Elder, R. L, Foster, C. P, & Jones, J. D. C. Miniature Laser Anemometer for 3D Measurements', Engineering Optics, (1990). , 3(2), 191-196.

[7] Ahmed, N. A, Elder, R. L, Foster, C. P, & Jones, J. D. C. Laser Anemometry in Turbomachines', IMechE Proc, Part G, J of Aerospace Engineering, (1991). , 205, 1-12.

[8] Ahmed, N. A, Hamid, S, Elder, R. L, Foster, C. P, Jones, J. D. C, & Tatum, R. Fibre Optic Laser Anemometry for Turbo machinery Applications', Optics and Lasers in Engineering, nos 2 and 3, (1992). , 15, 193-205.

[9] Ahmed, N. A, & Elder, R. L. Flow Behaviour in a High Speed Centrifugal Impeller Passage under Design and Off-design Operating Conditions', Fluids and Thermal Engineering, JSME International series B, February, (2000). , 43(1), 22-28.

[10] Simpson, R. G, Ahmed, N. A, & Archer, R. D. Improvement of a Wing Performance using Coanda Tip Jets', AIAA Journal of Aircraft, (2000). , 37(1), 183-184.

[11] Gatto, A, Ahmed, N. A, & Archer, R. D. Investigation of the Upstream End Effect of the Flow Characteristics of a Yawed Circular Cylinder',The RAeS Aeronautical Journal, March, (2000). pp125-128, 104(1033), 253-256.

[12] Gatto, A, Ahmed, N. A, & Archer, R. D. Surface Roughness and Free stream Turbulence Effects on the Surface Pressure over a Yawed Circular Cylinder', AIAA Journal of Aircraft, September, (2000). , 38(9), 1765-1767.

[13] Ahmed, N. A, & Archer, R. D. Performance Improvement of a Bi-plane with Endplates', AIAA Journal of Aircraft, March-April, (2001). , 38(2), 398-400.

[14] Gatto, A, Byrne, K. P, Ahmed, N. A, & Archer, R. D. Pressure Measurements over a Cylinder in Crossflow using Plastic Tubing', Experiments in Fluids, (2001). , 30(1), 43-46.

[15] Ahmed, N. A, & Archer, R. D. Post-Stall Behaviour of A Wing under Externally Imposed Sound', AIAA Journal of Aircraft, September-October, (2001). , 38(5), 961-963.

[16] Ahmed, N. A, & Archer, R. D. Testing of a Highly Loaded Horizonatal Axis Wind Turbines designed for Optimum Performance', International Journal of Renewable Energy, January, (2002). , 25(4), 613-618.

[17] Simpson, R. G, Ahmed, N. A, & Archer, R. D. Near Field Study of Vortex Attenuation using Wing Tip Blowing', The Aeronautical Journal, March, (2002). , 102

[18] Ahmed, N. A, & Goonaratne, J. Lift augmentation of a low aspect ratio thick wing at a very low angle of incidence operating in ground effect", AIAA Journal of Aircraft, March-April (2002). , 39(2)

[19] Ahmed, N. A. Implementation of a momentum integral technique for total drag measurement', International Journal of Mechanical Engineering and Education, (2002). , 30(4)

[20] Pissasale, A, & Ahmed, N. A. Theoretical calibration of a five hole probe for highly three dimensional flow', International Journal of Measurement Science and Technology, July, (2002). , 13, 1100-1107.

[21] Pissasale, A, & Ahmed, N. A. A novel method of extending the calibration range of five hole probe for highly three dimensional flows", Journal of Flow Measurement and Instrumentation, March-April, (2002). , 13(1-2), 23-30.

[22] Ahmed, N. A, & Wagner, D. J. Vortex shedding and transition frequencies associated with flow around a circular cylinder", AIAA Journal, March, (2003). , 41(3), 542-544.

[23] Rashid, D. H, Ahmed, N. A, & Archer, R. D. Study of aerodynamic forces on rotating wind driven ventilator', Wind Engineering, (2003). , 27(1), 63-72.

[24] Ahmed, N. A. An acoustic energy concept for the design of a flow meter', International Journal of Vibration and Acoustics, March (2003). , 8(1), 52-58.

[25] Pissasale, A, & Ahmed, N. A. Examining the effect of flow reversal on seven-hole probe measurements', AIAA Journal, (2003). , 41(12), 2460-2467.

[26] Pissasale, A, & Ahmed, N. A. Development of a functional relationship between port pressures and flow properties for the calibration and application of multi-hole probes to highly three-dimensional flows', Experiments in Fluids, March, March, (2004). , 36(3), 422-436.

[27] Shun, S, & Ahmed, N. A. Utilizing wind and solar energy as power sources for a hybrid building ventilation device', Renewable Energy, June (2008). , 33(6), 1392-1397.

[28] Findanis, N, & Ahmed, N. A. The interaction of an asymmetrical localised synthetic jet on a side supported sphere', Journal of Fluids and Structures, (2008). , 24(7), 1006-1020.

[29] Longmuir, M, & Ahmed, N. A. Commercial Aircraft Exterior Cleaning Optimization', AIAA, Journal of Aircraft, Jan-Feb issue, (2009). , 46(1), 284-290.

[30] Lien, S. J, & Ahmed, N. A. (2010). Numerical simulation of rooftop ventilator flow. Building and Environment, , 45, 1808-1815.

[31] Lien, S. J, & Ahmed, N. A. (2011). Effect of inclined roof on the airflow associated with a wind driven turbine ventilator. Energy and Buildings, , 43, 358-365.

[32] Lien, J, & Ahmed, N. A. An examination of the suitability of multi-hole pressure probe technique for skin friction measurement in turbulent flow', in press, Journal of Flow Measurement and Instrumentation, (2011). , 22, 153-164.

[33] Wu, C, & Ahmed, N. A. Numerical Study of Transient Aircraft Cabin Flowfield with Unsteady Air Supply, AIAA Journal of Aircraft, Nov-Dec issue, (2011). , 48(6), 1994-2002.

[34] Findanis, N, & Ahmed, N. A. Three-dimensional flow reversal and wake characterisation of a sphere modified with active flow control using synthetic jet', Advances and Applications in Fluid Mech, (2011). , 9(1), 17-76.

[35] Behfarshad, G, & Ahmed, N. A. Effect of unsteady and sinusoidally varying free stream on turbulent boundary layer separation', Advances and Applications in Fluid Mechanics, (2011). , 10(2), 79-98.

[36] Shun, S, & Ahmed, N. A. Airfoil Separation Control using Multiple Orifice Air Jet Vortex Generators', AIAA Journal of Aircraft, Nov-Dec issue, (2011). , 48(6), 1994-2002.

[37] Ahmed, N. A. Engineering solutions towards cost effective sustainable environment and living' Journal of Energy and Power Engineering, February (2012). , 6(2), 155-167.

[38] Behfarshad, G, & Ahmed, N. A. Investigation of Newtonian liquid jets impacting on a moving smooth solid surface', Advances and Applications in Fluid Mechanics, (2012). , 12(1)

[39] Ahmed, N. A. Novel developments towards efficient and cost effective wind energy generation and utilization for sustainable environment', Renewable and Power Quality Journal, 0217-2038X, April issue, (2012). (10), PL4.

[40] Zheng, Y. Y, Ahmed, N. A, & Zhang, W. Impact Analysis of Varying Strength Counter-flow Jet Ejection on a Blunt Shaped Body in A Supersonic Flow, (in press) Advances and Applications in Fluid Mechanics,(2012), 12(2), 119-129

[41] Yen, J, & Ahmed, N. A. Parametric Study of Dynamic Stall Flow Field with Synthetic Jet Actuation', Journal of Fluids Engineering, Transactions of the ASME, (2012), 134 (7), 2012,45-53.

[42] Yen, J, & Ahmed, N. A. Synthetic Jets as a Boundary Vorticity Flux Control Tool', AIAA Journal, (2013), 51(2),510-513

[43] Wu, C, & Ahmed, N. A. A Novel Mode of Air Supply for Aircraft Cabin Ventilation', Building and Environment,(2012), 56, 47-56

[44] Bradshaw, P, & Pankhurst, R. C. The Design of Low Speed Wind Tunnels', NPL Aero Report 1039, (1962).

[45] Dryden, H. L, & Abbott, I. H. The Design of Low Turbulence Wind Tunnels', NACA Report 940, (1949).

[46] Razak, K. The University of Wichita 7 ft x 10 ft Wind Tunnel', University of Wichita Engg Report 022, April, (1950).

[47] Squire, H. B, & Winter, K. G. The RAE 4 ft x 3 ft Experimental Low Turbulence Wind Tunnel, Part I: General Flow Characteristics', ARC R&M 2690, February, (1948).

[48] MacPhailD.C., et el., 'The ft x 8 ½ ft Wind Tunnel at RAE, Farnborough', ARC R & M 2424, August, (1945). (2)

[49] Schun, H. The RAE 4 ft x 3 ft Experimental Low Turbulence Wind Tunnel, Part IV: Further Turbulence Measurements', ARC R&M 3261, June, (1953).

[50] Bradshaw, P. Measurements of Free Stream Turbulence in some Low Speed Tunnels at NPL', R & M 3317, (1962).

[51] Ferris, D. H. Measurements of Free Stream Turbulence in the RAE Bedford 13 ft x 9 ft Wind Tunnel', RAE Aero Report 1066, July, (1963).

[52] Schubauer, G. B. et el 'Aerodynamic Characteristics of Damping Screens', NACA TN (2001).

[53] Bachelor, G. K. Homogenous Turbulence', Cambridge University Press, (1953).

[54] Annand, P. The Resistance to Air Flow of Wire Gauges', J Royal Aero Soc, March, (1953). , 141-146.

[55] Bachelor, G. K. On the Concept and Properties of the Idealised Hydrodynamic Resistance', ACA Report ACA-13, (1945).

[56] Collar, A. R. The Effect of a Gauge on Velocity Distribution in a Uniform Duct', ARC R&M 1867, (1939).

[57] Bradshaw, P. The Effect of Wind Tunnel Screens on 2 D Boundary Layers', NPL Aero Report 1085, December, (1963).

[58] Patel, N. P. The Effects of Wind Tunnel Screens and Honey Combs on the Spanwise Variation and Honeycombs on the Spanwise Variation of Skin Friction in 2D Turbulent Boundary Layers', McGill University Mech Engg Tech Note October, (1964). , 64-7.

[59] De Baray, B. G. Some Investigations into the Spanwise Non-uniformity of nominally 2D Incompressible Boundary Layers Downstream of Gauge Screens', ARC Fluid Memo, FM 3863, ARC 29271, July (1967).

[60] Morgan, P. G. The Stability of Flow Through Porous Screens', J of Roy Aero Soc, June (1960). , 359-362.

[61] Lumley, J. L. Passage of a Turbulent Stream Through Honeycomb of Large Length-to Diameter Ratio', Tran ASME, Series D, June (1964). , 218-220.

[62] Dryden, H. L, & Schubauer, G. B. The Use of Damping Screens for the Reduction of Wind Tunnel Turbulence', J of Aero Sci., April (1947). , 221-228.

[63] Manton, M. J, & Luxton, R. E. Note on the Decay of Isentropic Turbulence', Inst of Engineers Austr. Conf. On Hydraulics and Fluid Mechanics', November, (1968). , 93-97.

[64] Cohen, M. J, & Ritche, N. J. B. Low Speed 3D Contraction Design', J of Roy Aero Soc, April, (1962). , 66, 232-236.

[65] Batchelor, G. K, & Shaw, F. S. A Consideration of the Design of Wind Tunnel Contractions', Aust Council Aeronautics Report, ACA-4, (1944).

[66] Cohen, I. A. An Experimental Comparison of the Flow Induced in the Working Section of a Wind Tunnel by Contractions having 2D and 3D Flow Characteristics', Monash Univ Report, MME/65/1, August, (1965).

[67] Thwaites, B. On the Design of Contractions for Wind Tunnels', ARC R & M 2278, March, (1946).

[68] Cheers, F. Notes on Wind Tunnel Contractions', R & M 2137, March, (1945).

[69] Gibbins, J. C, & Dixon, J. R. D Contracting Duct Flow', Quarterly J of Mech and Applied Maths', (1957). , 10, 24-41.

[70] Stanitz, J. D. Design of 2D Channels with prescribed Velocity Distribution along the Channel Walls', Part I: Relaxation Solutions, NACA TN 2593, 1952, Part II: Solutions by Green's Function, NACA TN 2595, (1952).

[71] Smith, A. M. O, & Pierce, J. Exact Solutions of the Newmann Problem: Calculation of Non-Circulatory Plane and Axially Symmetric Flows about or Within Arbitrary Boundaries', Douglas Aircraft Co. Inc Report ES26988, April (1958).

[72] Gibbins, J. C. Design of an Annular Entry to a Circular Duct', Aero Qtly, (1959). , 10, 361.

[73] Libby, P. A, & Reiss, H. R. M. The Design of 2D Contraction Sections', QAM, vol IX, April (1951).

[74] Jackson, J. D. A Description of some Wind Tunnel Contraction Design Data which has been obtained using the Ferranti Mercury High Speed Digital Computer', ARC Report 23, (1962).

[75] Harrop, R. A Method of Designing Wind Tunnel Contactions', J of Roy Aero Soc., (1951). , 55, 169-180.

[76] Smith, R. H, & Wang, C. T. Contracting Cones giving uniform Throat Speeds', J of Aero Sc, October, (1944). , 11

[77] Jordinson, R. Design of Wind Tunnel Contractions', Aircraft Engg, October, (1944). , 33, 294-297.

[78] Whitehead, L. G, Wu, L. Y, & Waters, M. H. L. Contracting Ducts of Finite Length', Aero Qtly, February (1951). , 2, 254-271.

[79] Tsien, H. S. On the Design of the Contraction Cone for a Wind Tunnel', J of Aero Sci., (1943). , 10, 68-70.

[80] Szczeniowski, B. Contraction Cone for a Wind Tunnel', J of Aero Sci., (1943). , 10, 311-313.

[81] Lighthill, M. J. A new Method of 2D Aerodynamic design', ARC R & M., 2112, (1945).

[82] Lilley, G. M. Some Theoretical Aspects of Nozzle Design', M.Sc. Thesis, UL, (1945).

[83] Woods, L. C. A new Relaxation treatment of Flow with Axial Symmetry', Qtly J of Mech and Appl Maths, Part 3, (1951). , 4, 358-370.

[84] Lau, W. T. F. An Analytical Method for the Design of 2D Contactions', J of Roy Aero Soc, January, (1964). , 68

[85] Salter, C, & Raymer, W. C. The NPL 7 ft Wind Tunnel: Sundry Notes and Comments following Measurements of Flow Distribution, Wall Pressures etc.,' NPL Aero Note 1023, October (1963).

[86] Schubauer, G. B, & Spangenberg, W. G. Effect of Screens in Wide Angle Diffusers', NACA Report 949, (1949).

[87] Squire, H. B, & Hogg, h. Diffuser Resistance Combinations in Relation to Wind Tunnel Design', RAE Report Aero 1933, ARC Report &628, April (1944).

[88] Feir, J. B. The Effects of an Arrangement of Vortex Generators Installed to Eliminate Wind Tunnel Diffuser Separation', UTIAS TN june (1965). (87)

[89] Feil, O. G. Vane Systems for Very Wide Angle Subsonic Diffusers', Trans ASME Series D, J of Basic Engg, December, (1964). , 759-764.

[90] Moore, C. A, & Kline, S. J. Some Effects of Vanes and of Turbulence in 2D Wide Angle Subsonic Diffusers', NACA TN 4080, June (1958).

[91] Cochran, D. L, & Kline, S. J. Use of Short Flat Vanes for Producing Efficient Wide Angle Subsonic Diffusers', NACA TN 4309, June (1958).

[92] Fox, R. W, & Kline, S. J. Flow Regime Data and Design Methods for Curved Subsonic Diffusers', Tans ASME, Series D, (1962). , 84, 302-316.

[93] Kline, S. J, Moore, C. A, & Cochran, D. L. Wide Angle Subsonic Diffusers of High Performance and Diffuser Flow Mechanisms', J of Aero Sci, June (1957). , 24(6), 469-470.

[94] Migay, V. K. Investigations of Finned Diffusers', USAF Systems Command,FTD-TT-October, (1962). , 63-86.

[95] Wollett, R. R. Preliminary Investigation of Short 2D Subsonic Diffusers', NANA RM E56CO2, May, (1956).

[96] Raju, K. N, & Rao, D. M. Experiments on the Use of Screens and Splitters for Flow Control in Wide Angle Diffuser', Indian N.A.L., TN-AE-April (1964). , 24-64.

[97] Rao, D. M, & Raju, K. N. Experiments on the use of Splitters for Control in Wide Angle Diffusers', Indian N.A.L. TN-AE-December (1964). , 26-64.

[98] Henry, J. R, et al. Summary of Subsonic Diffusers', NACA L56F05, October (1956).

[99] Cockrell, D. J, & Markland, E. A Review of Incompressible Diffuser Flow', Aircraft Engg, October, (1963). , 286-292.

[100] Patterson, G. N. Modern Diffuser Design', Aircraft Engg, September, (1938). , 267-273.

[101] Cockrell, D. J, & Markland, E. The Effects of Inlet Conditions on Incompressible Fluid Flow in Conical Diffusers', Int J of Mech Sci, (1966). , 8, 125-139.

[102] Kline, S. J, Abbott, D. E, & Fox, R. W. Optimum Design of Straight walled Diffusers', Tans ASME J of Basic Engg, Paper (1959). (58-A)

[103] Winternitz, F. A. L, & Ramsay, W. J. Effects of Inlet Boundary Layer on Pressure Recovery, Energy Conversion and Losses in Conicl Diffusers', J of Roy Aero Soc, February, (1957). , 61, 116-124.

[104] Waitman, B. A, Reneau, R. L, & Kline, S. J. Effect of Inlet Conditions on Performance of 2D Subsonic Diffusers', Trans ASME J of Basic Engg, Paper (1960). (60-WA)

[105] Wills, J. A. B. Spurious Pressure Fluctuations in Wind Tunnels', NPL Aero Report 1237, July (1967).

[106] Wallis, R. A. Axial Fans', Newnes, London, (1961).

[107] Patterson, G. N. Corner Losses in Ducts', Aircraft Engg', August (1937). , 205-208.

[108] Winter, K. G. Comparative Tests of Thick and Thin Turning Vanes in the RAE 4 ft x 3 ft Wind Tunnel', ARC R & M 2589, August, (1947).

[109] Salter, C. Experiments on Thin Turning Vanes', ARC R& M 2469, October, (1946).

[110] Silberman, E. Importance of Secondary Flow in Guide Vane Bends', Tech Paper Series B, 3rd Mid Western Conf on Fluid Mechanics, Univ of Minnesota, (1953). (14)

[111] Wallis, R. A. A Rationalised Approach to Blade Element Design', Conf on Hydraulics and Fluid Mechanics, Inst of Engineers, Aust, (1968).

[112] Wallis, R. A. Optimisation of Axial Flow Fan Design', Ins of Engineers, Aust, M & C Trans, May (1968).

[113] Russel, B. A, & Wallis, B. A. A note on Annular Diffuser Design', CSIRO Int Rep July (1969). (63)

[114] Ruglen, N. Low Speed Wind Tunnel Tests on a series of C4 section Aerofoils', ARC Note ARL/A 275, July (1966).

[115] Edmunds, H. G, & Bartlett, W. J. Section Data of C4 Aerofoils', Power Jets Memorandum April, (1940). (M1090)

[116] Myles, D. J. et el., '' The Design of Axial Flow Fans, Part II: Blade geometry for the Rotor and the Stator', DSIR, NEL Report 181, April (1965).

[117] Sharland, I. J. Sources of Noise in Axial Flow Fans', J Sound Vibrations, (1964). , 1(3), 302-322.

[118] Sharland, I. J. Intake Noise from Axial Flow Turbochargers and Compressors', Proc Inst of Mech Engineers', (1968). , 182(3), 73-77.

[119] Garter, A. D. S. Blade Profiles for Axial Flow Fans, Pumps' compressore', Proc I Mech E, (1961). , 175(15), 775-806.

[120] Schilhans, M. J. Bending Frequency of a Rotating Cantilever Beam', Trans ASME J Applied Mech and Maths, March (1958). , 28-30.

[121] RoxbeeCox, H., (ed) 'Gas Turbine principles and Practice', Chapter 12: Vibrations', G. Newnes, London, (1955).

[122] N.A.Ahmed, 'Investigation of dominant frequencies in the transition Reynolds number range of flow around a circular cylinder Part I: Experimental study of the relation between vortex shedding and transition frequencies', Journal of CSME, vol.19, No.2, 2006, pp159-167

[123] N.A.Ahmed, 'Investigation of dominant frequencies in the transition Reynolds number range of flow around a circular cylinder Part II: Theoretical determination of the relationship between vortex shedding and transition frequencies at different Reynolds numbers', Journal of CSME, vol.19, No.3, 2006, pp 317-326

[124] G.Behfarshad and N.A.Ahmed, 'Vortex flow asymmetry of slender Delta Wings', International Review of Aerospace Engineering, Vol.4, No.3, 2011, pp 184-188

[125] G.Behfarshad and N.A.Ahmed, 'Reynolds Stress Measurement Over Four Slender Delta Wings', International Review of Aerospace Engineering, Vol.4, No.4, 2011, pp 251-257

[126] N.A.Ahmed, 'Detection of Separation bubble using spectral analysis of fluctuating surface pressure', International review of Aerospace Engineering', International Review of Aerospace Engineering', vol.4, no. 4, June, 2011

[127] G.Behfarshad and N.A.Ahmed, 'Experimental Investigations of Sideslip Effect on Four Slender Delta Wings', International Review of Aerospace Engineering, Vol.4, No.4, 2011, pp 189-197

[128] N.A.Ahmed and J.R.Page, 'Real-time Simulation as a new tool in Future Advanced Aerospace Project Design and Manufacturing Processes', Advanced Materials Research, Vols. 317-319 , 2011, pp 2515-2519

[129] N.A.Ahmed and J.R.Page, 'Developing and integrated approach to advanced aerospace project design in tertiary education', Advanced Materials Research, Vols. 317-319 , 2011. pp 2520-2529

[130] H. Riazi, and N.A. Ahmed, 'Numerical investigation of four orifice synthetic jet actuators, International Review of Aerospace Engineering', Vol.4, No. 5, 2011, pp 272-276

[131] S. Shun and N.A. Ahmed, 'Airfoil Separation Control using Multiple Orifice Air Jet Vortex Generators', AIAA Journal of Aircraft, vol 48, no.6, Nov-Dec issue, 2011, pp 1994-2002

[132] N.A.Ahmed, 'Engineering solutions towards cost effective sustainable environment and living' Journal of Energy and Power Engineering, Vol 6, No.2, February 2012, pp155-167

[133] S. Shun and N.A. Ahmed, 'Design of a Dynamic Stall Test Rig', Applied Mechanics and Materials Vols. 215-216 (2012) pp 785-795, © (2012) Trans Tech Publications, Switzerland

[134] G.Behfarshad and N.A.Ahmed, 'Investigation of Newtonian liquid jets impacting on a moving smooth solid surface', Advances and Applications in Fluid Mechanics, vol. 12, no.1, 2012

[135] S. Shun and N.A. Ahmed, 'Rapid Prototyping of Aerodynamics Research Models', Applied Mechanics and Materials Vols. 217-219 (2012) pp 2016-2025, © (2012) Trans Tech Publications, Switzerland

[136] N.A.Ahmed, 'Novel developments towards efficient and cost effective wind energy generation and utilization for sustainable environment', Renewable and Power Quality Journal, ISSN 2172-038X, No. 10, April issue, pp PL4, 2012

[137] Y.Y.Zheng, N.A.Ahmed and W.Zhang, 'Feasibility Study of Heat Transfer with Fluidic Spike', International Review of Aerospace Engineering, vol. 5, no.2, 2012, pp 40-45.

[138] N.A.Ahmed, 'New Horizons of Applications of the 21st Century Aerodynamic Concepts from Aerospace to Power Generation and Utilization', Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 338-347

[139] S. Shun and N.A. Ahmed, "Wind Turbine Performance Improvements Using Active Flow Control Techniques", Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 83-91

[140] Matsoukas, G., and Ahmed, N.A., 'Experimental Investigation of Employing Asymmetrical Electrodes in Propulsion of Vehicles', Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 247-253

[141] G.Behfarshad and N.A.Ahmed, 'Splash measurement of Newtonian Liquid Jets Impacting on a Moving Solid Surface' International Conference on Mechanical Engineering and Mechatronics, Ottawa, August 16-18, 2012

[142] Y.Y.Zheng, N.A.Ahmed and W.Zhang, 'Heat dissipation using minimum counter flow jet ejection during spacecraft re-entry', Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 271-279

[143] Wu, C., and Ahmed, N.A., 'Application of Flow Control Technique for Indoor Ventilation' Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 135-141

[144] Riazi, H., and Ahmed, N.A., 'Effect of the ratio of specific heats on a small scale solar Brayton cycle', Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 263-270

[145] Yen. J., and Ahmed, N.A., 'Improving the Safety and Performance of Small-Scale Vertical Axis Wind Turbine', Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 99-106

[146] Wongpanyathaworn, M., and Ahmed, N.A., 'Optimising louver locations to improve indoor thermal comfort based on natural ventilation', Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 169-178

[147] Findanis, N., and N.A. Ahmed, 'Control and Management of Particulate Emissions using Improved Reverse Pulse-Jet Cleaning Systems', Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 338-347

[148] T.G.Flynn, G.Behfarshad and N.A. Ahmed, 'Development of a Wind Tunnel Test Facility to Simulate the Effect of Rain on Roof Ventilation Systems and Environmental Measuring Devices', Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 239-246

[149] J. Lien and N.A. Ahmed, Numerical evaluation of wind driven ventilator for enhanced indoor air quality', Procedia Engineering, Elsevier Publications, vol. 49, 2012, pp 124-134

[150] N.A. Ahmed, 'Diverse Applications of Active Flow Control', Commissioned for publication in 'Progress in Aerospace Sciences', a commissioned paper by invitation of Journal board, expected publication, 2013

[151] J. Lien and N.A. Ahmed, 'Indoor Air Quality Measurement with the Installation of a Rooftop Turbine Ventilator', Journal of Environment Protection', Vol.3, No.11, November 2012, pp1498-1508

[152] J.Yen and N.A.Ahmed, 'Enhancing Vertical Axis Wind Turbine Safety and Performance Using Synthetic Jets', Journal of Wind and Industrial Engineering, vol.114, 2013, pp12-17

[153] I.H. Salmom and N.A.Ahmed, "Delaying Stall by Acoustic Excitation Using a Vibrating Film Wing Surface", AIAA 22nd Applied Conference and Exhibit, 16-19 August 2004, Providence, Rhode Island, AIAA Paper No. 2004-4962

[154] N.A.Ahmed, "Turbulent Boundary Layer Analysis of Flow in a Rotating Radial Passage", 2nd BSME-ASME International Conference on Thermal Engineering, 2-4 January, 2004, Dhaka, pp 325-333

[155] T.G.Flynn and N.A.Ahmed, 'Investigation of Rotating Ventilator using Smoke Flow Visualisation and Hot-wire anemometer', Proc. of 5th Pacific Symposium on Flow Visualisation and Image Processing, 27-29 September, 2005, Whitsundays, Australia, Paper No. PSFVIP-5-214

[156] N.Findanis and N.A.Ahmed, 'Wake study of Flow over a sphere', 25th AIAA Applied Aerodynamics Conference, San Francisco, USA, 8-10 June, 2006, AIAA-2006-3855

[157] S.J. Lien and N.A. Ahmed, 'Skin friction determination in turbulent boundary layers using multi-hole pressure probes'25th AIAA Applied Aerodynamics Conference, San Francisco, USA, 8-10 June, 2006, AIAA-2006-3659

[158] N.Findanis and N.A.Ahmed, 'A Flow Study Over a Sphere with Localised Synthetic Jet', 12th Australian International Aerospace Congress/12th Australian Aeronautical Conference19-22 March 2007, Melbourne, Victoria Australia

[159] S.J. Lien and N.A. Ahmed, 'A novel method for Skin friction determination using multi-hole pressure probes', 12th Australian International Aerospace Congress/12th Australian Aeronautical Conference19-22 March 2007, Melbourne, Victoria Australia

[160] B. Ahn and N.A. Ahmed, 'Internal Acoustic excitation to enhance the airfoil performance at high Reynolds number', 14th International Conference on Sound and Vibration, 9-12 July, 2007, Cairns, Australia

[161] N.A.Ahmed, 'The Study of Spectral Properties of a Separation Bubble on a Circular Cylinder under the effects of free stream)turbulence 4th BSME-ASME International Conference on Thermal Engineering, 27-29 December, 2008, Dhaka

[162] N.Findanis and N.A.Ahmed 'Active Flow Control Over a Bluff Body Utilising Localised Synthetic Jet Technology , 13th Australian International Aerospace Congress/ 13th Australian Aeronautical Conference, 9 - 12 March 2009, at the Melbourne Convention Centre, Melbourne, Australia

[163] J.Lien and N.A.Ahmed 'Prediction of Turbulent Flow Separation with Pressure Gradient , 13th Australian International Aerospace Congress, 13th Australian Aeronautical Conference, 9 - 12 March 2009, at the Convention Centre, Melbourne, Australia

[164] N.A.Ahmed and J.R.Page, 'An Improved Approach for Future Aerospace Design process', 13th Australian International Aerospace Congress/13th Australian Aeronautical Conference, 9 - 12 March 2009, at the Convention Centre, Melbourne, Australia

[165] N.A.Ahmed, 'Engineering solutions towards cost effective sustainable environment and living', International Conference on Mechanical, Industrial and Energy Engineering, 22-24 December, 2010

[166] T.J.Flynn and N.A.Ahmed, 'An Investigation of Pitot Tube and Multi Hole Pressure Probe Performance Using a Wet Weather Wind Tunnel Test Section'14th AIAC, Melbourne, 28 Feb-3rd March, 2011

[167] C.Wu and N.A.Ahmed, 'Using Pulsed Jet of Fresh Air to Control CO2 Concentration in an Air Cabin', 14th AIAC, Melbourne, 28 Feb-3rd March, 2011

[168] C.Wu and N.A.Ahmed, 'Aircraft cabin flow pattern under unsteady air supply', 29th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii, USA. 27 June 2011

[169] H. Riazi and N.A. Ahmed, 'Numerical investigation on two-orifice synthetic jet actuators of varying orifice spacing and diameters', 29th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii, USA. 27 June 2011

[170] G.Behfarshad and N.A.Ahmed, 'Turbulent Boundary Layer Separation in Adverse Pressure Gradient', Proceedings of the 23rd Canadian Congress of Applied Mechanics, 5-9 June, 2011, pp 557-560

[171] N.A.Ahmed, 'Novel developments towards efficient and cost effective wind energy generation and utilization for sustainable environment', Plenary Paper, International Conference on Renewable Energies and Power Quality ICREPQ'12, Santiago de Compostela, Spain, 28-30 March, 2012

[172] S. Shun and N.A. Ahmed, "Utilizing Vortex Acceleration to Improve the Efficiency of Air Jet Vortex Generators", 6th AIAA flow control conference, New Orleans, 25-28 June 2012

[173] H. Riazi and N.A. Ahmed, 'Efficiency enhancement of a small scale closed solar thermal Brayton cycle by a combined simple organic Rankine cycle', Proceedings of the ASME 2012 International Mechanical Engineering Congress & Exposition, IMCE2012, November 9-15, 2012, Houston, Texas, USA

[174] J. Olsen, J.R.Page and N.A. Ahmed, 'A Hybrid propulsion system for a light trainer aircraft', *15th Australian International Aerospace Congress*, 25-28 February 2013.

[175] Y.Y.Zheng, N.A. Ahmed and W.Zhang, 'A Feasibility Study of Bow Shock Wave Heat Dissipation using Counter-Flow Jet Activation', *15th Australian International Aerospace Congress*, 25-28 February 2013.

[176] S.Shun and N.A. Ahmed, 'Experimental Investigation of the Effects of Fluid Acceleration upon Air Jet Vortex Generator Performance', *15th Australian International Aerospace Congress*, 25-28 February 2013.

[177] C.Wu and N.A. Ahmed, 'Vectoring of Wall bounded Planar Ventilation Jet with Synthetic Jet Actuator', *15th Australian International Aerospace Congress*, 25-28 February 2013.

[178] J.Yen and N.A. Ahmed, "Parametric study of synthetic jet on dynamic stall flow field using Computational Fluid Dynamics", *15th Australian International Aerospace Congress*, 25-28 February 2013.