Development of a Subsonic Wind Tunnel in UTP - Selection of the Flow Visualization Device

by

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CERTIFICATION OF APPROVAL

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Approved by,

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Jan 2004

CERTIFICATE OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

AHMAD KHAIRUDIN ZAINON

ABSTRACT

The report is written to present the work done on the Final Year Project entitled 'Development of a Subsonic Wind Tunnel in UTP - Selection of the Flow Visualization Device'. The main objective of the project is to perform research and develop a subsonic wind tunnel in UTP and also to study and perform the flow visualization experiments on the developed wind tunnel. Without a wind tunnel, the learning and understanding process on topics related to flow behavior become more difficult. Also, since the wind tunnel's working medium, air is not visible under normal conditions, flow visualization method is essential to make the flow visible. Those are the problems that trigger the idea to initiate this project. This project will cover scope of works on the research of the available wind tunnel design criteria, research on flow visualization methods, the selection of the most suitable design recommendation on wind tunnel, selection of most suitable flow visualization method, the design and fabrication of the wind tunnel and model to be used, the experimental procedure of the selected flow visualization method, materials required to perform the experiments and also results and findings from the performed flow visualization experiments. Various methods used in undertaking this project in order to obtain the best results, which include project planning, researching, weekly meetings with supervisor and technicians, and performing the experiments. A lot of findings have been obtained from this project. The findings obtained are in term of wind tunnel dimensions and final design, materials to fabricate the wind tunnel, fan selection result for designed wind tunnel, flow visualization experiment procedures, materials required for experiments, model and test section design, findings from both flow visualization experiments, coat estimation and conceptual design of a smoke generator. From the designed wind tunnel, the air speed inside test section is 12 m/s with test section cross sectional area of 30cm x 30 cm. By proper work, this project can yield a great output. This project can bring a lot of benefit to all parties involved if done successfully.

ACKNOWLEDGEMENT

First of all, deepest gratitude goes to the supervisor, Pn Azuraien Japper @ Jaafar for the guidance and patience in ensuring that the author accomplishes the objective of this project. Greatest thanks to the Head of Mechanical Engineering Department, Associate Professor Dr Fakhruldin Mohd Hashim and other mechanical lecturers, as well as technicians from Mechanical Engineering Department and from other department, and also the rest of UTP staffs whoever have provided guidance.

The gratitude is extended to the author's parents who have encouraged the author throughout the education. The author will always be grateful for their sacrifices, sincerity and love. Finally, special thanks to colleagues for the understanding and support towards project completion.

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CHAPTER 1 INTRODUCTION

1.1 Background of Study

The title of the Final Year Project is 'Development of a Subsonic Wind Tunnel in UTP - Selection of the Flow Visualization Device'. As the title sounds, the background of this project is mainly about developing a small scale subsonic wind tunnel in UTP for educational purposes and also about selecting and develops the most suitable flow visualization method to be applied to the fabricated wind tunnel. This project will be divided into two phases, which the first phase is the development of the wind tunnel and the second phase is the development of the flow visualization device. The whole general process that are involved in performing this project is from project planning, research, design, material preparation, devices selection, fabrication, conceptual design, experiment preparation and conducting experiment.

1.2 Problem Statement

The wind tunnel is a very important device in analyzing and observing the flow behaviors around a model, whether a car or even an airplane. The small scale wind tunnel can be used in testing the design of any small scale model whether it has good drag and lift coefficient or not, through experiments. So, without a wind tunnel, the learning and understanding process on topics related to flow visualization become more difficult. This problem actually triggers the idea to initiate this project. Also, the main problem associated in studying air flow behavior using wind tunnel is that the working medium, air, is not visible under normal conditions. The physical features and behaviors of the air flow can contribute a lot of information about its conditions if observer can see the flow pattern using bare eyes or using other recording devices. Besides only for observations, under certain condition, the information from the flow pattern also can be manipulated to make quantitative measurement.

This project is to develop a small-scale open-circuit subsonic wind tunnel in UTP that can be used in learning and understanding purposes and also to select and develop the most suitable flow visualization methods that are available and apply the selected method to the developed wind tunnel.

Students that involve with subjects or courses that are related to flow behaviors can use the wind tunnel and the flow visualization devices to get more understanding on the subject matter. They can get a better picture of what they have learnt theoretically in class.

1.3 Objective and Scope of Study

For the first phase of the project, which is the design and development phase, the main objective is to develop a small-scale open-circuit subsonic wind tunnel in UTP, by practicing all theoretical knowledge earned during study period at this university so far. The scope of work ranges from research, design, materials preparation to fabrication. The main objective of second phase of the project is to study the flow visualization methods that available which can be used to visualize the air flow pattern inside the developed wind tunnel, or more specifically, inside the test section. Besides studying the available methods, the second phase of the project also will cover the selection of which methods is most suitable to be applied to the wind tunnel, as well as the development of the selected method. A solid model will also be designed and fabricated to be placed inside the test section as the study model. The conceptual design of certain flow visualization device will also be a part of the project. The scope of study will covers project planning, research, materials and substances preparation, model preparation, conceptual design and conducting experiment. The summary of the scope of tasks for second phase is presented below:

i) Detail research on the selected flow visualization method
ii) Fabricate a model to be used in the flow visualization experiment
iii) Redesign the test section sides for model attachment

iv) Conduct the flow visualization experiments using the tuft and surface oil method

v) Perform the conceptual design of the smoke generator for wind tunnel

The implementation of this project is really relevant now since all the Mechanical Engineering students at UTP, especially for those who are taking subjects like Fluid Mechanics, mostly involve with the flow characteristic study. This project obviously will be a great opportunity for Mechanical Engineering students to get better understanding on the topics related with fluid mechanics that involves flow characteristics around a body. The outcome of this project can also be used by the lecturers as a new teaching tool. The time frame given to accomplish this project quite reasonable and the objectives of the project can be achieved according to the scope of project.

CHAPTER 2 LITERATURE REVIEW AND THEORY

2.1 Wind tunnel theory

Developing a small scale wind tunnel is not a new project conducted in UTP. A few similar projects have already been conducted before. However, due to some problems, such as the design features of wind tunnel, the performances of the wind tunnel produced were not good enough. The problems related with the previously built wind tunnel were due to the improper selection of contraction ratio and also due to the fan selection problem. Therefore, this project is conducted once again to get a wind tunnel that satisfies a few requirements such as the wind velocity inside the test section and the size of the test section.

The wind tunnel is a device used to study the flow characteristic over an object. Wind tunnel also can be defined as an instrument which its purpose is to measure aerodynamic properties of the body installed inside the test section. It is also can be used to study the force and friction over that body under certain velocity, which are then manipulated to determine the drag and lift characteristic of the object. The flow visualization testing also can be done by conducting experiments using the wind tunnel.

Throughout the world, wind tunnels have been widely used in engineering field, like in automobile and aircraft manufacturers, where wind tunnels are used to test the design of their products in terms of aerodynamic feasibility and other engineering aspects. Not only used by the automobile industry, wind tunnels also been used by other engineering fields like civil engineering, in determining the flow characteristics around a solid object, like a building or house. Besides research, wind tunnels also have been widely used in most universities in the world as learning tools. Students can conduct experiments relating to their field of study by using wind tunnels.

There are actually two main types of wind tunnel, which are the open circuit wind tunnel and the close circuit wind tunnel. The open circuit wind tunnel is the one which air passes straight through the tunnel and is not re-circulated (refer Figure 2.1). It has no passage that will return the exhaust air back into its inlet section. After air has been exhausted from the diffuser, it will be released to the atmosphere and newly fresh air will be drawn into its inlet section.

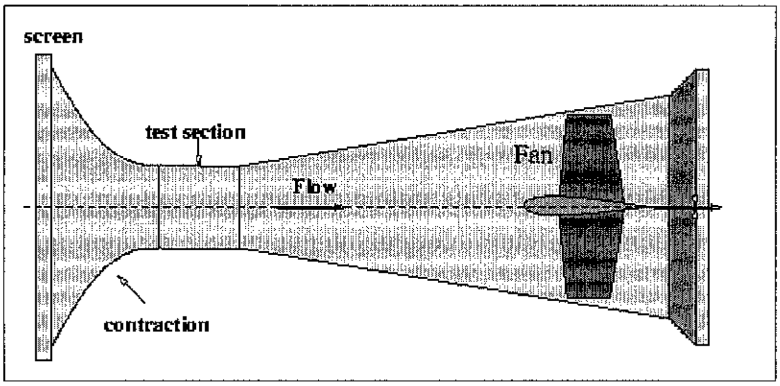

Figure 2.1: The open circuit wind tunnel

On the other hand, the close circuit wind tunnel is in which the same air is re-circulated within the tunnel (refer Figure 2.2). It has a return path for the air to deliver the exhaust air back into its inlet section. This means that in close circuit wind tunnel, there may be little or no exchange of air within its passages.

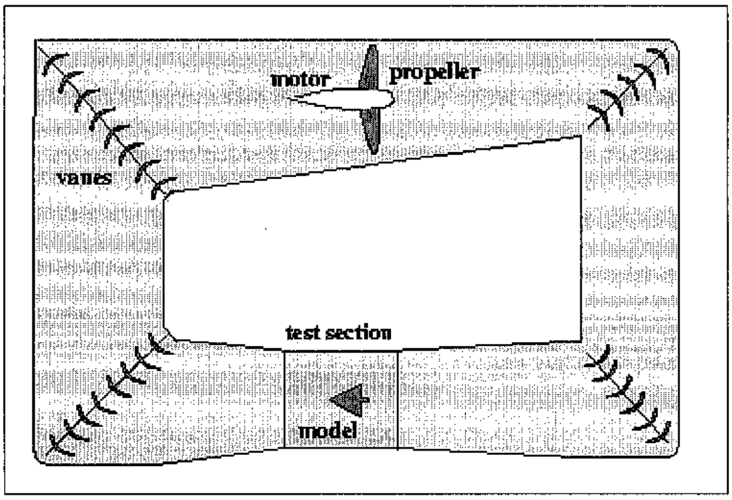

Figure 2.2: The close circuit wind tunnel

The advantages and disadvantages between open circuit and closed circuit wind tunnel are tabulated in Table 2.1.

Table 2.1: Advantages and disadvantages between open circuit and closed circuit wind tunnel

Types of wind tunnel	Advantages	Disadvantages
Open circuit wind tunnel	Less expensive to build.	Not accurate - subjected to variables changes in atmosphere (temperature, pressure) and can require more power
Closed circuit wind tunnel	Some energy is recovered due to constant ambient condition	Much more expensive to build
	Completely enclosed, and so are shielded from rain and cold weather	Air inside the wind tunnel is full of dust and debris from clothing, cushions, etc due to constant circulation of air

2.2 Wind tunnel design criteria

In developing the wind tunnel, there are a few basic criteria that must be followed based on constrains outlined by the supervisor. The design criteria that need to be met in designing the wind tunnel are:

i) The wind tunnel must be an open circuit wind tunnel

ii) The velocity of air flowing inside the test section must be between 10m/s – 15m/s

iii) The cross sectional area of the test section must be 30 cm x 30 cm

Besides that, it will be necessary to design and develop the wind tunnel during the first semester of the project. By the end of the first semester, the preliminary research for the second semester individual topic, which is the further work on the first semester topic, must be initiated.

2.3 Parts of a wind tunnel

For this project, it has been decided to proceed with the open circuit wind tunnel. This selection is done prior to the outlined constrains. The schematic diagram of an open circuit wind tunnel is shown in Figure 2.3.

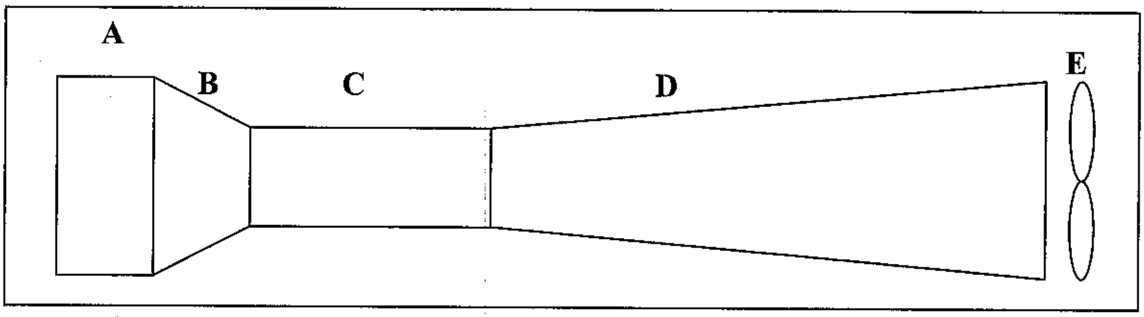

Figure 2.3: The schematic side view of an open circuit wind tunnel

There are a few basic parts that a wind tunnel must have. The parts are the settling chamber (consist of screens and honeycomb), contraction cone, test section, diffuser and drive section (consist of fan and motor). These are the main features of the parts (refer Figure 2.3).

2.3.1 Settling chamber (A)

The settling chamber is the first part of the wind tunnel. As it name implies, the settling chamber is a part where outside air being 'settled down' in term of "turbulence" ness. The settling chamber smoothens and straightens the flow of intake air and filter out all undesired turbulence. This objective can be achieved by means of using the screens and honeycombs inside the chamber. Honeycomb is used to straighten flow and reduce swirl while the screens will be used to smooth turbulence, some of which will be caused by the honeycomb.[1]

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[1] Dr Matthew R. Evans, 2003, Design and construction of a wind tunnel.

2.3.2 Contraction cone or nozzle (B)

The second part of a wind tunnel is the contraction cone. The working principle of the contraction cone is same as the normal nozzle. It uses Venturi effect to compress low velocity, large volume air into smaller volume and higher velocity air. The effectiveness of the contraction cone is depends on the contraction lengths, contraction ratio and cross sectional shape.

2.3.3 Test section (C)

The test section is where the test models are placed. Usually, for better flow visibility, the wall is made of Plexiglas or Perspex. Sensors also mounted within the test section to measure the flow quality of air inside it. The flow within the test section is the most important parameter that needs to be controlled.

2.3.4 Diffuser (D)

Diffuser is located between the test section and drive section. The purpose of a diffuser is as a part where the flow velocity decrease as the pressure rises back. A diffuser enables the use of a fan of greater cross sectional area than that of the test section.[2]

2.3.5 Drive section (E)

Drive section is the part on the wind tunnel that uses energy to suck outside air into the entrance of the wind tunnel. Drive section consist of motor that rotates the fan, where air is drawn through the tunnel into the test section.

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[2] Dr Matthew R. Evans, 2003, Design and construction of a wind tunnel.

2.4 Design rules for wind tunnel

Before beginning the detail design process for the wind tunnel, there are a few design parameters for each part of the wind tunnel that must be considered first.

2.4.1 Settling Chamber

As mentioned earlier, a settling chamber consists of a honeycomb, which their functions are to straighten flow and reduce swirl and then followed by screens, which is installed to smooth turbulence. Besides that, extra screen also can be installed in front of the honeycomb to reduce the flow angles. In designing the settling chamber, the recommended length is must be half of the inlet diameter.

2.4.2 Honeycombs and screens

Since the purpose of the honeycomb is to straighten flow and reduce swirl, so it is better to place it at front of the entry section, and screens be placed behind it. The honeycomb requires a longer settling length since it produces eddies of larger scale than the screens.[3] To get the best result, it is better if the cell length is about 6 to 8 times of its diameter, while the cell size is roughly consist of 150 cells per settling chamber diameter, i.e. 25000 total cells are adequate.[4]

Screens are normally made whether from metal wire, polyester or nylon woven into meshes and placed after the honeycomb. The purpose is to smooth turbulence, some of which will be caused by the honeycomb. But, one extra screen can also be placed ahead of the honeycomb to reduce flow variation angle that might stall the honeycomb. In designing the screens, the recommended spacing of the screens is whether 510 times the diameter of the wires in the screen or 0.2 times the diameter of the entry section.[3]

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[3] Dr Matthew R. Evans, 2003, Design and construction of a wind tunnel

[4] RD Mehta and P Bradshaw, Nov 1979, "Design Rules for Small Low Speed Wind Tunnels", The Aeronautical Journal of the Royal Aeronautical Society (pg 447)

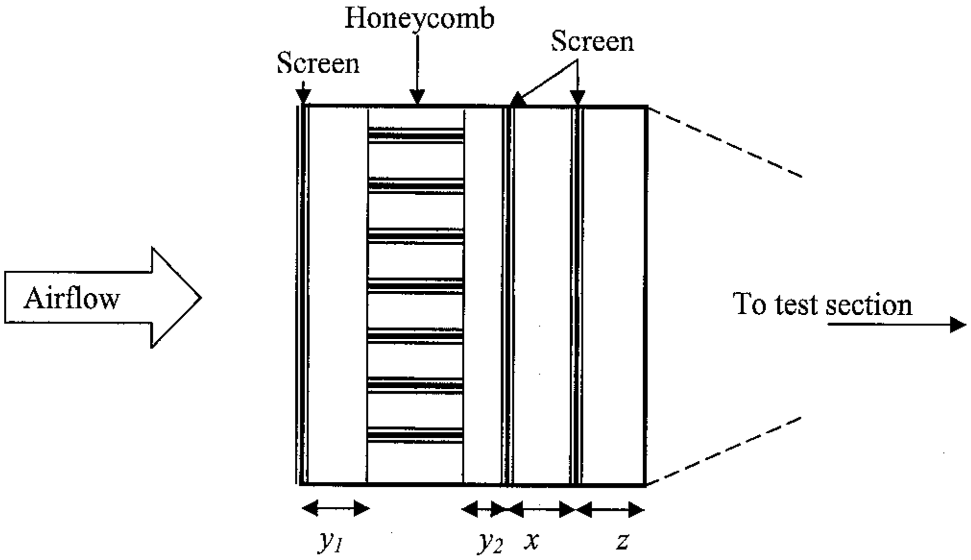

Figure 2.4: The arrangement of honeycomb and screens within the settling chamber

According to Mehta and Bradshaw (1979), the screen spacing (x) that is equivalent to about 0.2 of the settling chamber diameter performs successfully (refer Figure 2.4). The distance between last screen and the contraction entry (z) has also been found to be about 0.2 of the cross sectional diameters. The spacing between screens and honeycomb (y_1 and y_2) will be determined after obtaining the suitable length of the honeycomb.

2.4.3 Contraction Cone

Basically, the quality of air flow inside the test section heavily depends on the profile of the contraction ratio. According to Lam and Pomfret, 1984; Gibbings, 1993; Gordon, 1997, a well-designed contraction should have:

i) No flow separation,

ii) A uniform and parallel flow at the exit, and

iii) Should minimize the unsteadiness and degree of turbulence in the test section

So, in order to achieve those criteria of a well designed contraction cone, it is recommended to use a square cross section in order to obtain the best result. However, Mehta and Bradshaw (1979) suggest adding small 45^0 corner fillet. The contraction length should also be reasonably long to avoid separation in the contraction area. The most important parameter in deciding the flow quality inside the test section is the contraction ratio. Contraction ratio is the ratio of entrance cross sectional area of the section to its exit cross sectional area. The contraction area ratio should be "as large as possible", to reduce the total-pressure loss through the screens.[5] The actual recommendation for the value of contraction ratio is between 6 and 9, and according to Mehta and Bradshaw (1979), the minimum recommended value is 6. On the other hand, the recommended length of the nozzle is,

$$\text{Nozzle length, } l_n = 1 \text{ x inlet radius} \qquad \text{(Eq. 2.1)}$$

2.4.4 Test Section

The requirement for the test section already outlined by the supervisor, where the air velocity inside the section must be between 10 – 15 m/s and the cross sectional area must be 30 cm x 30 cm. From the outlined constrains, all the variables needed in designing the wind tunnel can be determined, according to recommendations from literature research. For the test section design, the recommended length to diameter ratio for the test section is 2.

2.4.5 Diffuser

Diffuser is a part where the flow velocity decrease as the pressure rises back. The basic design rule for diffuser in a subsonic wind tunnel is that the diffuser should not expand at an equivalent cone angle of greater than 7°. The preferable total inclination angle of the diffuser should not exceed 5^0. In designing the diffuser, the length of the diffuser should be 3 or 4 times of the test section length.

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[5] RD Mehta and P Bradshaw , 16th August 2003, <http://vonkarman.stanford.edu/tsd/pbstuff/tunnel/contraction.html>

2.5 Fan selection method

In determining the specification of needed fan and motor, the author did perform calculation on the volume flow rate of air inside the test section of wind tunnel, Q_{ts}. From the calculation (refer Appendix 1) it turned out that the flow rate inside the test section is 1.35 m^3/s or 81.0 m^3/min. From a meeting with lecturer from Mechanical Engineering Department to get the opinion on determining the right method to perform the fan selection, the lecturer did recommend to include the pressure loss within the diffuser in the calculation. Although the diffuser length is only 2.4m, where the pressure loss is not significant, but to get better result and higher efficiency of the wind tunnel, it is better to improve the calculation method. The lecturer also recommended to use the fan capacity diagram (refer Figure 2.5), which can be obtained from the manufacturer of the fan, and use the relationship between total pressure and air velocity to plot the system total pressure curve. After obtaining the curve, it will be necessary to compare the curve with the manufacturer's fan capacity diagram.

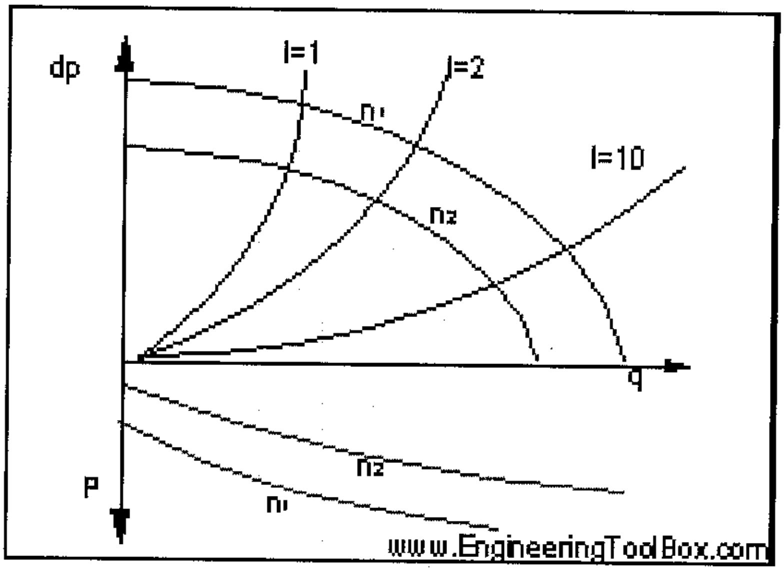

Figure 2.5: The fans pressure head as a function of the air volume[6]

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[6] The Engineering ToolBox, 5 October 2003, http://www.engineeringtoolbox.com/37_143.html

2.6 Introduction to flow visualization

The main problem associated in studying air flow behavior using wind tunnel is that the medium which the study focuses is air, which is not visible under normal conditions. The physical features and behaviors of the air flow can contribute a lot of information about its conditions if observer can see the flow pattern using naked eyes or using other recording devices. Besides only for observations, under certain condition, the information from the flow pattern also can be manipulated to make quantitative measurement.

The flow visualization techniques in air can generally be divided into two main categories; surface flow visualization and off-the-surface visualization. Surface flow visualization consists of tufts method, surface oil method and China clay method and off-the-surface visualization involves the use of tracers as smoke particles, Particle Image Velocimetry (PIV) or helium-filled soap bubbles.

2.7 Surface flow visualization

Information about the flow characteristic on the surface of a model is usually most critical. For the surface flow visualization, the visualization methods involve using tufts, surface oil and China clay. The surface flow visualization techniques are only used to visualize the flow pattern on the surface of model and can provide a lot of information on the state of boundary layer, transition regions, and as well as the regions of separated flow.

2.7.1 Tufts

The first method for surface flow visualization is using tufts. The tuft method is the simplest and most often used. The tuft is basically made of flexible thread, or wool. The tuft must be lightweight and the length must suitable with the model's size, but must not exceed 2 inches in any event to avoid 'flag-waving'. Tufts are usually attached to the model's surface by using the cellophane tape. The distance between tufts varies depending on the model's size and shape, but the suitable distance is about 2 inches to 4 inches, with the tuft's length from 1.5 inches to 2 inches. The tuft's diameter also varies, and also depends on the model's size, about 0.5 mm. After installing the tufts, the experiment can be started, and the flow pattern can be observed and recorded using camera. A problem might arise where ordinary camera's shutter speed will unable to take a clear picture of the tuft pattern due to the movement of the tufts that results from unsteady flow over it. Figure 2.6 shows the example of setup for the tufts method.

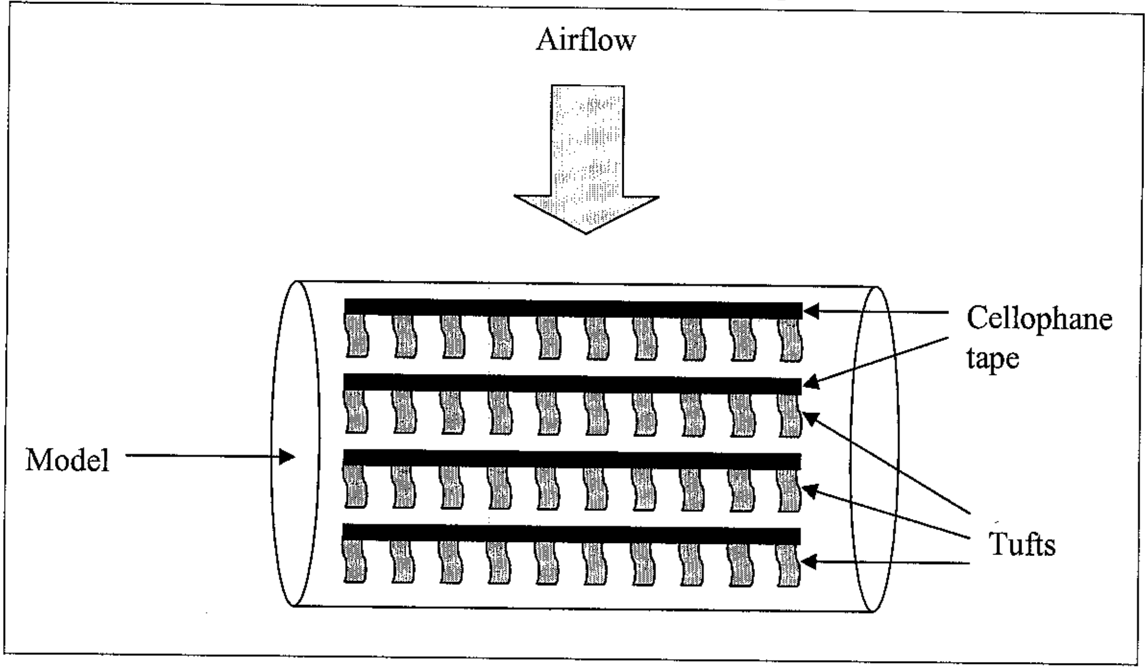

Figure 2.6: Example of setup for the tufts method

2.7.2 Surface oil method

The second flow visualization method that under the surface flow visualization category is the surface oil method. For the surface fluorescent oil technique, it was found to be effective, inexpensive, and fast for low speed testing with relatively small models. The surface fluorescent oil method was introduced to investigate flow pattern by DL Loving and S Katzoff. Fluorescent oil method is based on shear stress variation. Because shear stress dramatically varies between laminar, turbulent, and transition regions, transition location can be readily observed from visualization of patterns of shear stress. Visualization is accomplished via a solution of fluorescent dye and "carrier" oil, known as the fluorescent-oil solution. A thin layer of the fluorescent-oil solution is applied to the model surface. In areas of relatively high shear stress, oil is swept away from the surface. At areas of low shear stress, such as a laminar separation bubble, the oil collects and pools. The application of a fluorescent substance dramatically improves visibility. The fluorescing dye washes out extraneous reflections and it can be made more visible as necessary by increasing the intensity of incident ultraviolet light. The fluorescent oil solution can be applied to metal models with no special preparation or technique. The dye that can be used in this experiment, as referred to the experiment conducted at the Son of BART wind tunnel facility at the University of California, Davis, is called A-680 Plus and is the product of a company called Ultra-Violet Products (UVP). After the fluorescent solution has been applied to the model's surface, the flow pattern on the model's surface can be recorded whether by using still camera or by video camera. However, in order to make the fluorescent solution visible, it will be necessary to use the ultra violet light. This ultraviolet illumination can be obtained by using blacklight blue (BLB) light. For maximum effect, at the time of observation and photography, all normal lights in the wind tunnel building suppose to be turned off.

In the surface fluorescent oil method, the fluorescent solution is used to enhance the surface flow visibility. However, if this solution is used, there will be needs for the ultra violet light in order to make the fluorescent visible. So, to make the experiment more feasible, another method to make the oil visible is searched. It found out that the "carrier" oil, which is petroleum lubricating oil, can be made white by mixing titanium dioxide into it. This solution then can be applied to a black model and ordinary light can be used for observation and photography. This methods seems more preferable since there will be no need in installation of blacklight blue (BLB) light and other requirement on lighting management.

2.8 Off-the-surface flow visualization

This is the second type of flow visualization techniques, and off-the-surface visualization techniques uses medium that must follow the pattern of flow in order to convey correct information about the flow. Off-the-surface visualization involves the use of tracers such as smoke particles, Particle Image Velocimetry (PIV), oil droplets and helium-filled soap bubbles.

2.8.1 Smoke particle method

The smoke particle method uses smoke, which is known as a very small and very light particle, and these properties enables them to follow the motion of the flow faithfully. In the early days, rotten wood was the popular source of smoke. However, smoke produced by the burning wood was an eye irritant and caused an accumulation of tars. So, now there is an invention to produce a better quality smoke, known as the smoke generator. The working principle of the smoke generator is actually to force oil through a small diameter tubing which is heated by electric current. The oil vaporizes in the tubing and quickly condenses to form a visible "smoke," as it comes out of the open end. The substance that used to produce the smoke usually made from the vaporized kerosene, cleaning solvent, Carnea oil, and paint thinner. However, from an experiment produced by Shojiro Shindo and Otto Brask from Department of Aeronautics & Astronautics, College of Engineering, University Of Washington, they discovered that the best substance to be used is the "Type 1964 Fog Juice", which will produce non-toxic, non-corrosive and dense smoke. The schematic diagram of a smoke generator is shown in Figure 2.7.

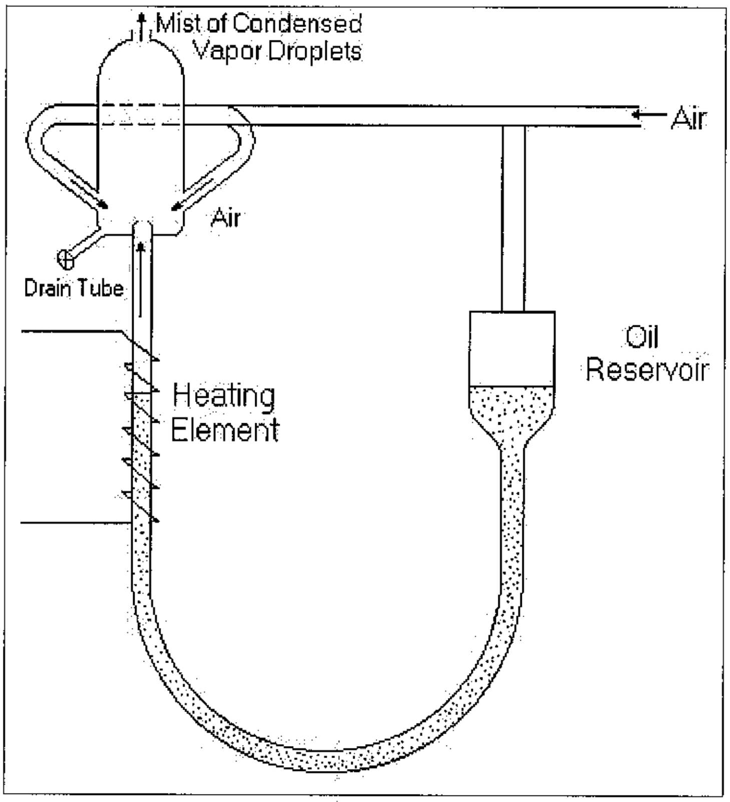

Figure 2.7: Schematic diagram of a smoke generator (Preston-Sweeting Mist Generator)[7]

2.8.2 Particle Image Velocimetry (PIV)

The second flow visualization method that falls under the off-the-surface flow visualization category is the Particle Image Velocimetry (PIV) method. PIV is a method whereby velocities of fluids can be measured by photographing particles within the flows in two positions a short time distance apart. This is achieved by running the model as for flow visualization but instead of using a continuous sheet of laser light, the laser is flashed twice over a known period of time. Storing the image as a PC graphics file, special software is used to identify the particle pairs and plot velocity vectors for each particle movement. This is then analyzed and displayed as a colored vector map. This

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[7] WJ Devenport and WL Hartwell, 2 February 2004, www.aoe.vt.edu/~devenpor/aoe3054/manual/expt1/text.html#F4

colored vector map can then be compared with computational studies which give an output in a similar format.[8]

2.8.3 Helium-filled soap bubbles

To trace pathlines, which are also streamlines if the flow is steady, the helium filled soap bubbles that have neutral buoyancy can be used. The bubbles are released inside the test section ahead of the model, and photographed with a plane of high-intensity light that passes through the test section. With proper photographic exposure time, the bubble will appear as a streak. This can be done with usage of bubble generators.

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[8] VisEng Ltd, 28 January 2004, http://www.viseng.com/consult/flowvis.html

CHAPTER 3 METHODOLOGY/ PROJECT WORK

3.1 Procedure Identification

In performing this project, there are procedures that need to be followed in order to get this project runs smoothly and produce great results. The first procedure is to line up a proper planning of the project. This includes producing a Gantt Chart (refer Appendix 2 and Appendix 3) that will be used throughout the project duration as guidance in term of time management. In order to get more information on the wind tunnel and the flow visualization field, research plays an essential role. A few books that are related to this project have been referred to and all important data recorded. The internet also contributes a lot in obtaining needed sources. A few associated websites have also been visited. Besides that, thesis and reports about this project that associates with flow visualization devices have also been used as the references.

In order to get things done properly, weekly meeting with the supervisor is conducted. This meeting is really essential for presenting all of the findings throughout the week, and also to report all of the progress on the project, by present it on the weekly report. During the meeting, any troubles and difficulties faced can be confronted to the supervisor and seek for advice and guidance to solve these arising problems.

In the final stage of the project, which is the flow visualization experiments, the usage of the equipment in the laboratory is needed. Due to that, a few formal procedures needed to be followed in order to get permission to use the facilities. The application procedure involves a lot of parties and departments and permission from all respective departments must be obtained before proceeding with the experiments.

3.2 Tool Required

In completing this project, correct tools that will be used must be selected wisely. These tools include hardware, equipment, as well as software. So far, computer is the most important tool in performing this project in order to seek information through the internet, writing the reports and to analyze design calculation. Besides that, software like Microsoft Words also necessary in smoothens the progress of this project. Another important software that has a big impact on this project is the CATIA Solutions. The software is required to produce the technical drawing of the wind tunnel and to produce the technical drawing of the model that is going to be designed.

However, during the fabrication and development phase of the wind tunnel project, the usages of certain hardware like carpenter tools and workshop tools are really important. This is because the fabrication process requires building up the wind tunnel from drawings and will be based on the materials that will be used to build the wind tunnel. Examples of the process that can be implemented on constructing the wind tunnel are sheet metal process or carpentry process.

During the second phase of the project also, the usages of additional tools like chemical substances, tuft materials and machining tools are really important. This is because during the final stage of the project, it is required to conduct the flow visualization experiments using certain materials and chemical substances. The materials needed are the model (with and without tuft attached), titanium dioxide and petroleum lubricating oil. On the other hand, the machining tools will be necessary during the fabrication phase of the designed model.

CHAPTER 4 RESULTS AND DISCUSSIONS

4.2 Findings and discussion

So far, this project has produced a lot of findings. The findings are in form of calculated values of wind tunnel dimension, materials selection and technical drawing of the wind tunnel itself. Besides that, other findings includes experimental procedures that need to be followed for both the tuft experiment and the surface oil experiment and also the materials and substances required in completing this project also been obtained. Another outcome of the project is the completion of fabrication of the model to be used and also the results of the flow visualization experiments.

4.1.1 Wind tunnel dimension

From the research done on a wind tunnel, a few rules that must be attended in designing a wind tunnel have been obtained. All the recommendations done are based on previously built wind tunnel. After obtaining the design rules and recommendations, simple calculation is performed and resulting the values and dimensions for the wind tunnel design.

All the calculation shown is based on recommendations from the research. The main important criterion that has been selected is the contraction ratio, Cr, which is 9.

a) Settling Chamber

For the settling chamber, the recommended length is must be half of the inlet diameter (refer to Section 2.4.1). So first, need to determine the inlet hydraulic diameter (since the inlet is noncircular).

Contraction ratio, Cr = 9

Inlet area, A_{in} = Cr x (test section area)

$= 9 \times 0.09\ m^2 = 0.81\ m^{2`}$

So, hydraulic diameter, $D_h = \frac{4A}{P}$

$$= \frac{4(0.81)}{3.6} = 0.9 \text{ m}$$

Settling chamber length, $l_{sc} = 0.5 \times 0.9 \text{ m} = 0.45 \text{ m}$

b) Contraction Region or Nozzle

Basically, the recommended length of the nozzle is, $l_n = 1 \times$ inlet radius (refer Section 2.4.3).

Since inlet $D_h = 0.9$ m,

So, inlet radius, $r_{in} = 0.45$ m

Thus, nozzle length, $l_n = 1 \times 0.45$ m

$= 0.45$ m

c) Test Section

The recommended length to diameter ratio for the test section is 2 (refer Section 2.4.4).

Also, D_h for test section = 0.3 m

So, $\frac{l_{ts}}{D_h} = 2$

Thus, $l_{ts} = 2 \times 0.3$ m

$= 0.6$ m

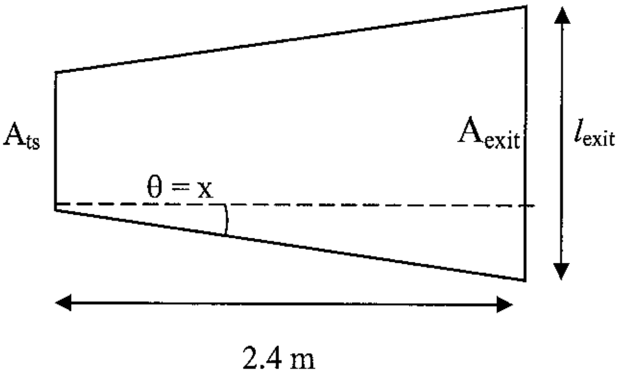
d) Diffuser

For the diffuser, the lengths suppose to be 3 or 4 times of the test section length (refer Section 2.4.5), which produce;

Diffuser length, $l_d = 4 \text{ x } 0.6$ m

$= 2.4$ m

Selected area ratio for diffuser, $A_r = 3$



Thus, $A_{exit} = 3 \text{ x } A_{ts}$

$= 3 \text{ x } 0.09 \text{ m}^2$

$= 0.27 \text{ m}^2$

to find contraction angle, θ,

$l_{exit} = \sqrt{0.27} \text{ m}^2$

$= 0.52$ m

$$\text{So, contraction angle, } \theta = \tan^{-1}\left[\frac{(0.52 - 0.3)/2}{2.4}\right]$$

$$= 2.62^{\circ}$$

The sketch of the basic dimension for the wind tunnel is shown in Figure 4.1

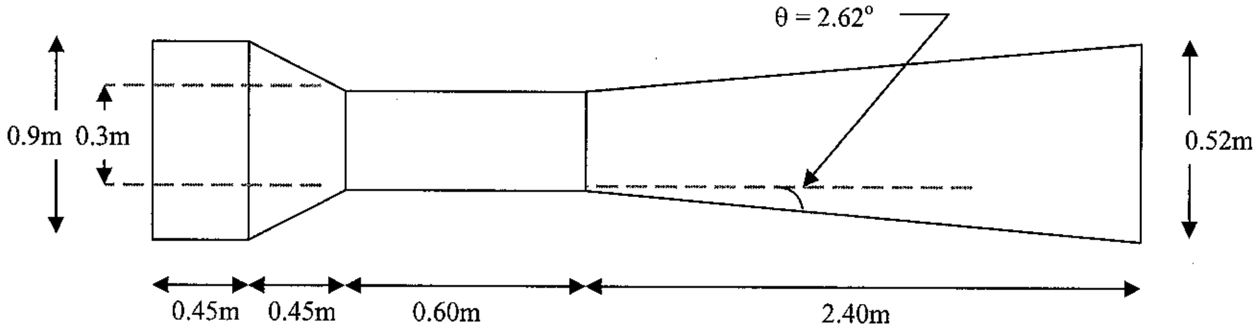


Figure 4.1: The sketch of the basic dimension for the wind tunnel

Besides performing calculations for determining the dimension of the wind tunnel, it was also necessary to consider the arrangement inside the settling chamber. All the rules for arrangement have been revised (refer Section 2.4.2) and also from simple calculation, the arrangement inside the settling chamber has been produced.

From recommendations on Section 2.4.2, the screen spacing (x) that equivalent to about 0.2 of the settling chamber diameter performs successfully. Also, the distance between last screen and the contraction entry (z) has also been found to be about 0.2 of the cross sectional diameters.

So, spacing between screens, $x = (0.2) \times 0.9\text{m}$

$= 0.18$ m

Also, known $z = x$

Thus, $z = 0.18$ m

Also, for maximum overall benefit the cell length should be about 6 – 8 times its diameter.

Obtained cell size is 6mm, so cell length, $y_2 = 8 \times 6\text{mm}$

$= 48\text{mm}$

$\cong 50\text{mm}$ or 0.05 m

Then, spacing between honeycomb and the first screen, $y_1 = 0.02$ m

The sketch of the arrangement inside the settling chamber is shown in Figure 4.2.

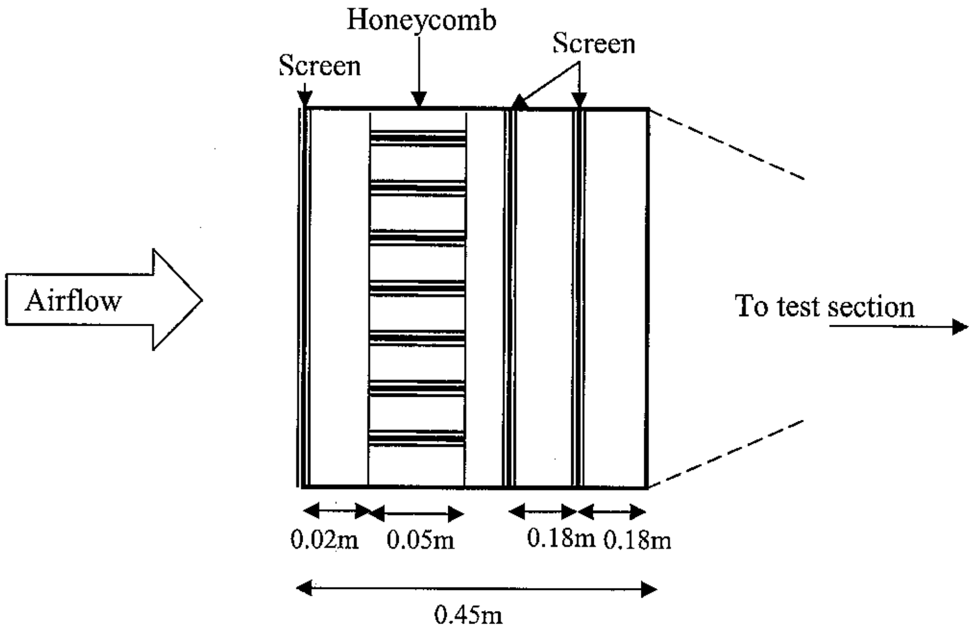


Figure 4.2: The dimension of arrangement of honeycomb and screens within the settling chamber

4.1.2 Materials selection for wind tunnel

Basically, there are 4 general criteria that need to be considered in selecting appropriate material for the wind tunnel (Dieter, 2000), which are:

a) performance characteristics, which selecting materials with suitable properties
b) processing characteristics, such as finding suitable process to form the material
c) environmental profile
d) budgets, in term of material cost and processing cost

Initially, the main material that suitable to construct the wind tunnel with is actually the wood. Overall frames and walls of the wind tunnel will be made of wood, including the contraction's walls and diffuser's walls. But, after discussion with the technicians, one more options besides wood is considered, which is metal sheet. The metal sheet is considered since it has better surface smoothness than wood and the fabrication process for metal sheet is easier than wood.

Besides that, the material for the honeycomb also requires consideration. From previous research, it turn out that honeycomb is very rare to find in the market. Based from discussion with the technicians, it was discovered that the market price for the fiber glass honeycomb is quite expensive and is not affordable financially. In addition, from research also, the market price for the aluminum honeycomb is higher than the fiber glass, which automatically make aluminum is not an option. However, since the cell size for the honeycomb is 6mm, it seems better to build up the honeycomb instead of buying it. The possible material that can be used is the normal drinking straw since it satisfy the size needed.

The summary for materials that have been selected respectively to the parts within the settling chamber and test section are in Table 4.1:

Table 4.1: Materials selected for constructing wind tunnel

Parts	**Materials**
Wind Tunnel Wall	Metal sheet
Honeycomb	Straw
Screens	Metal Mesh
Sides, Top And Bottom Panels For Test Section	Plexiglas

4.1.3 Drawing of wind tunnel

The drawing of the wind tunnel had been produced according to the actual dimension that obtained from previous calculations. The drawing of the wind tunnel was done using CATIA Solutions software. There are a few drawings have been produced, which are the isometric drawing (refer Figure 4.3), technical drawing and standard drawing with material applied. The drawings of the wind tunnel are attached in the Appendix 4 and Appendix 5.

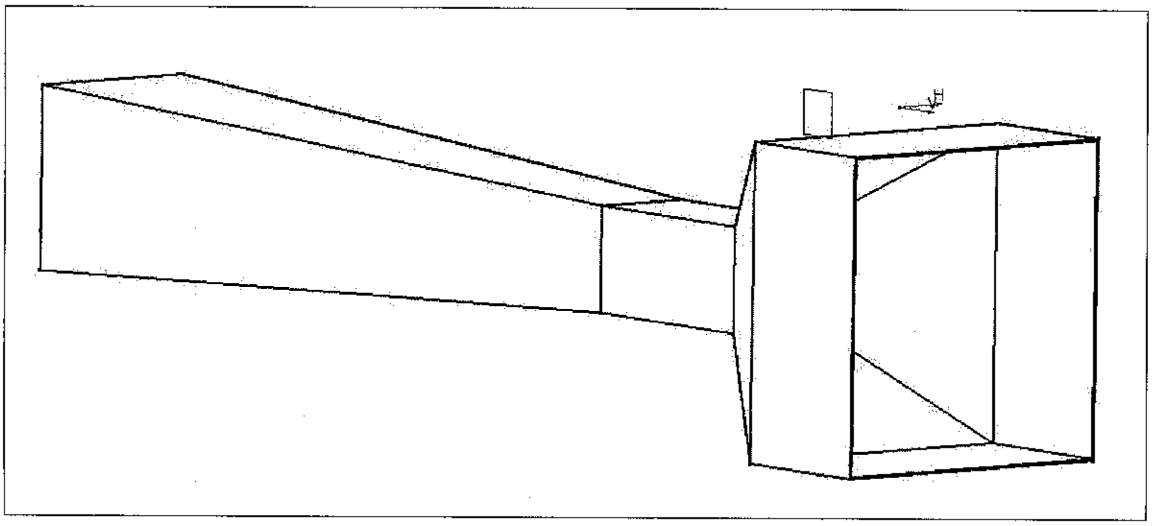


Figure 4.3: Isometric view of the subsonic wind tunnel

4.1.4 Fan specification selection

From the flow rate of the air in the test section, a system curve that the fan must comply with has been developed. Taking the intersection of the system curve and the fan capacity diagram, the fan's horsepower and fan efficiency are able to be determined. From calculation (Appendix 6), the system curve obtained is in Figure 4.4.

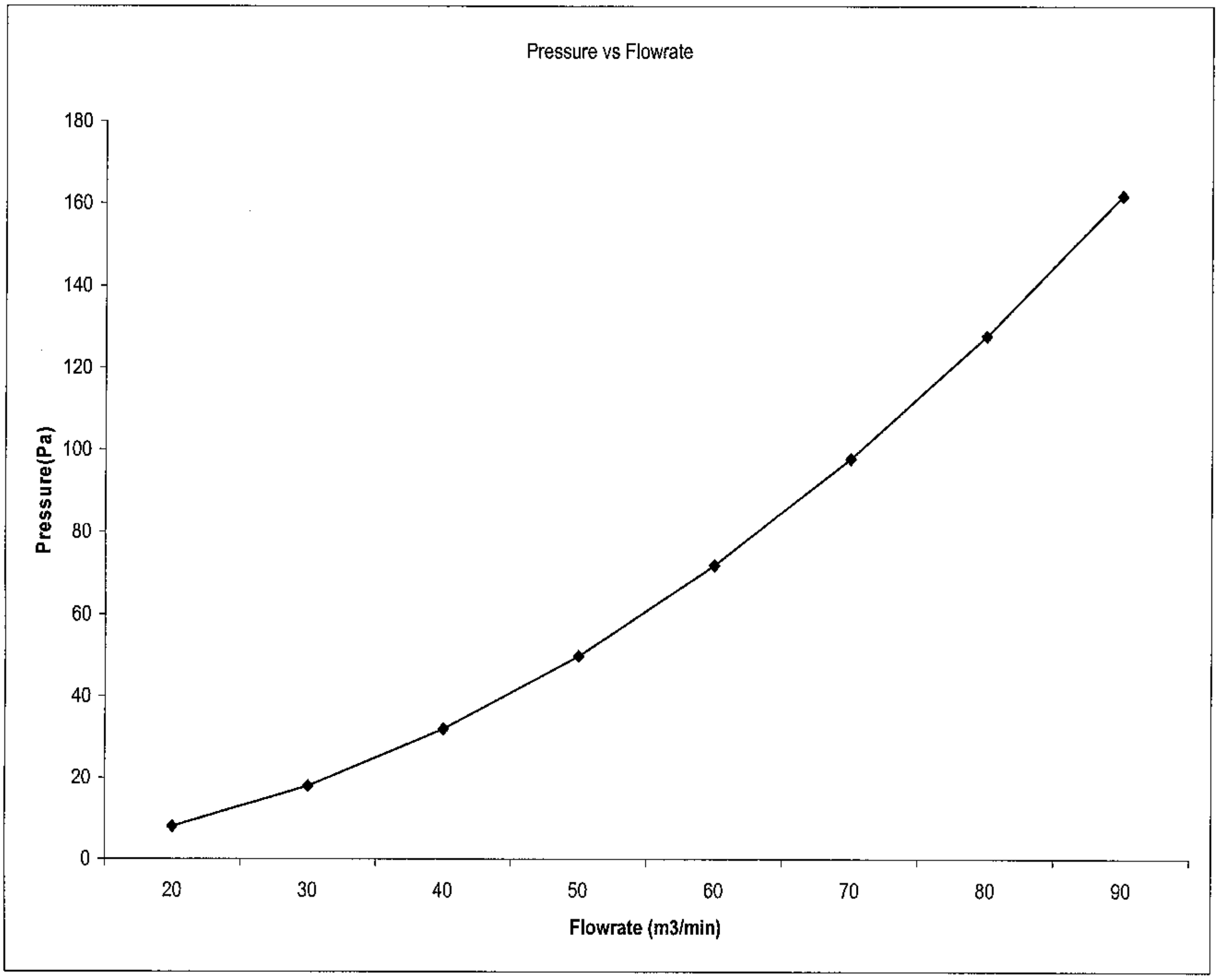


Figure 4.4: System curve for the fan operating condition

4.1.5 The developed wind tunnel

From all the recommendations, wind tunnel's dimension and design, the wind tunnel finally has been developed. The developing process took about 1 month. The initial budget for developing the wind tunnel needs to be exceeded due to its fabrication process and material's price. The fabricated wind tunnel is shown in Figure 4.5.

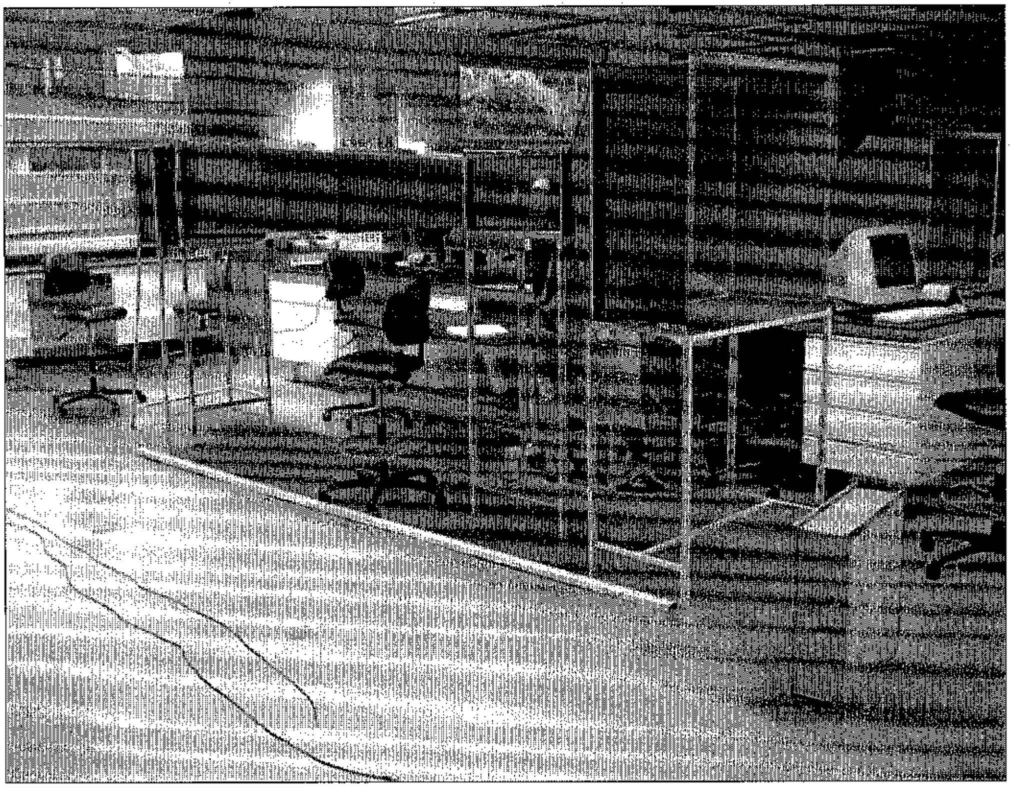


Figure 4.5: The developed small scale subsonic wind tunnel in UTP

4.1.6 Conceptual design of smoke generator

One of the work scopes for this project is to perform the conceptual design of a smoke generator. In designing the smoke generator, firstly designer must know the working principle of a smoke generator. The working principle of a smoke generator;

i) pressure will force oil to pass through a small diameter tubing
ii) the tube is heated by electric current
iii) oil will vaporize in the tube
iv) as it come out of tube, oil will condensate and form visible smoke

There is also another recommendation in designing the smoke generator. In order to produce a higher quality and more dense smoke, it would be better if the condensed smoke is accumulated first inside the tube before being released. This method is able to produce a consistent amount and constant density of smoke throughout the flow visualization experiment.

From research, the schematic diagram of a smoke generator has been produced. The diagram is shown in Figure 4.6.

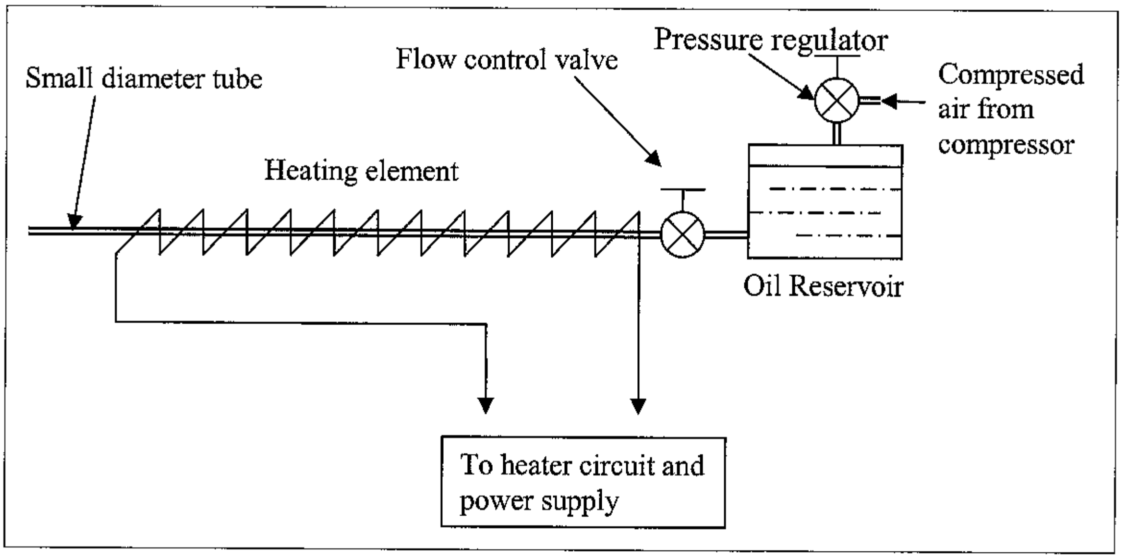


Figure 4.6: Schematic diagram of the smoke generator

From the schematic diagram, a conceptual designed has been produced. The conceptual design is shown in Figure 4.7.

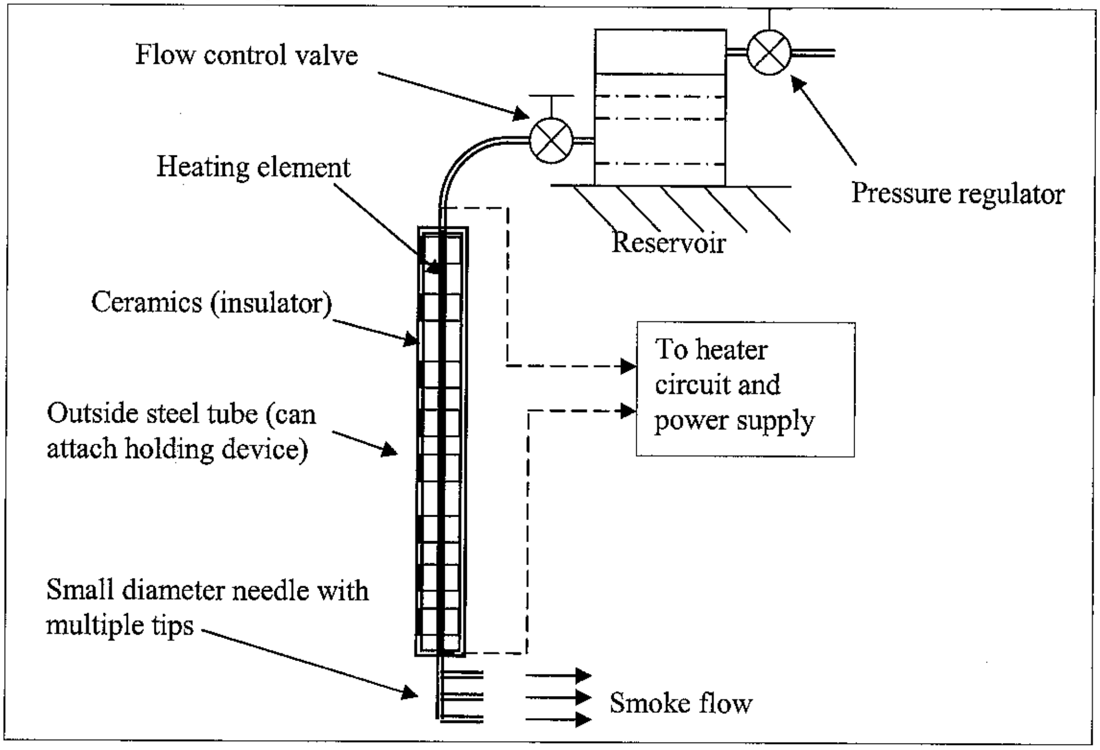


Figure 4.7: Conceptual design of the smoke generator

4.1.7 Tuft flow visualization experiment procedure

As mentioned earlier, the main task for the second phase of the project is to conduct the flow visualization experiments using the tuft and surface fluorescent oil method. The procedure for tuft flow visualization experiment is actually in applying tuft to the model's surface, there are actually two methods available, by using cellophane tape or glue. In this project, the using cellophane tape is more preferable since it is more convenient, faster and less chemical substance required. In using tape, before attaching tuft to the model's surface, it is necessary to make the tuft first. To make the tuft with correct length, a board known as the tuft board is often used. The tuft material, in this case is lightweight wool, will be strung back and forth around pins, then the tape is applied to the wool and the wool is cut at the edge of the tape. This gives a length of tape with tuft, and readily to be applied to the model. The distance between tufts are vary, depends on the model's size and shape, but the suitable distance is about 2 inches to 4 inches, with the tuft's length from 1.5 inches to 2 inches. The tuft's diameter also varies, and also depends on the model's size, about 0.5 mm. After installing the tufts, the experiment can be started, and the flow pattern can be observed and recorded using camera. Figure 4.8 shows the procedure of tuft preparation.

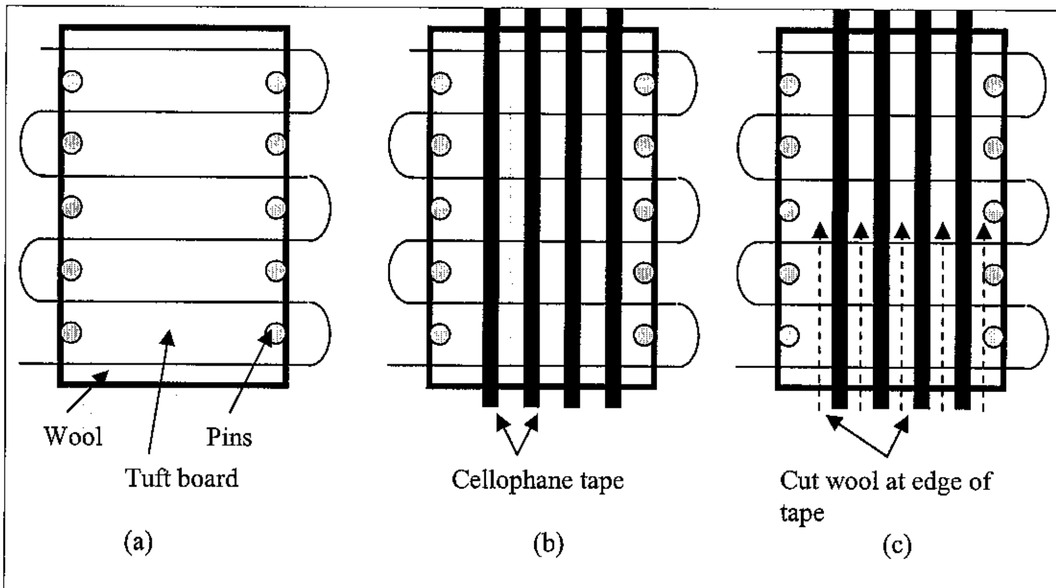


Figure 4.8: Procedure of preparing tuft, (a) strung wool around pins, (b) apply tape to the wool, and (c) cut wool at edge of tape.

4.1.8 Surface oil flow visualization experiment procedure

Meanwhile, for the surface oil experiment, it found out that the "carrier" oil, which is petroleum lubricating oil, can be made white by mixing titanium dioxide into it. This solution then can be applied to a black model and ordinary light can be used for observation and photography.

The issue arise concerning the usage of the titanium dioxide is about its availability. The availability of the chemicals and its purchase price (if purchase required) need to be determined and a meeting with technician from the Chemical Engineering Department have been held. The status of the experiment using the titanium dioxide depends on the availability and price of the substance, due to the financial status of this project. From the meeting with the technicians, it is known that the chemical, titanium dioxide is available at the Chemical Engineering Laboratory. However, due to the price of the titanium dioxide that is too expensive, they only can give maximum of 50 grams of the chemicals. This amount seems enough, since the experiment will not require too much amount of the substance. There was also no formal procedure in getting the substance.

Applying the surface oil solution on the model is simple and straight forward. No special care is really needed in applying an even coat, although some caution is in order to prevent making a mess with the oil. A camel hair brush or sponge brush can be used for application. When using a camel hair brush, care must be taken to not leave any hairs on the model as they will prematurely trip the boundary layer. The model should be completely covered from the leading edge to the trailing edge. As soon as a coat of the oil solution has been applied, the tunnel should be run immediately in order to prevent premature drying and to minimize dripping on the force balance plate. In general, very little of the oil solution are going to be used. Then, still photography process can be started as the method of recording data of the surface oil flow visualization experiments.

4.1.9 Materials required for experiments and model

In this project, the experiments involved require several chemicals substances and special materials. The list of materials, chemical substances and machining tools required is tabulated in the Table 4.2.

Table 4.2: Summary of materials, chemical substances and machining tools required

Project phase	Materials, chemical substances or machining tools required
Tufts experiment	White lightweight wool
	Cellophane tape
	Polystyrene board (to be used as tuft board)
	Pins
Surface oil experiment	"Carrier" oil (petroleum lubricating oil)
	Titanium dioxide
Model fabrication	Raw materials; rectangular steel tubes, bolt and nuts
	Machining tools

4.1.10 Model fabrication and redesign test section

In designing the model, it is necessary to determine the shape of the model. Initially, the shape of the model is quite hard to be decided due to complexity of its fabrication process. In this case, there are two possible shapes, which are cylindrical shape or aerofoil (wing) shape, since the purpose of the experiments is only to demonstrate the flow visualization method. However, it has been decided to design a shape which has wider top surface area, to make the flow visualization more visible. The initial design of the model is shown in Figure 4.9, and the technical drawing of the initial model is on Appendix 7. But, after consulting the project supervisor on selecting the model's shape, the most feasible shape to be used is any basic shape, like normal circular or rectangular. During the early stage of model design and fabrication, the material that can be used to produce the model most probably is the solid aluminum block, and then converted into the desired shape using machining method. After machined, the model can be paint into black, since the flow visualization method that mentioned earlier uses white indicators (white wool and white oil) for better visibility.

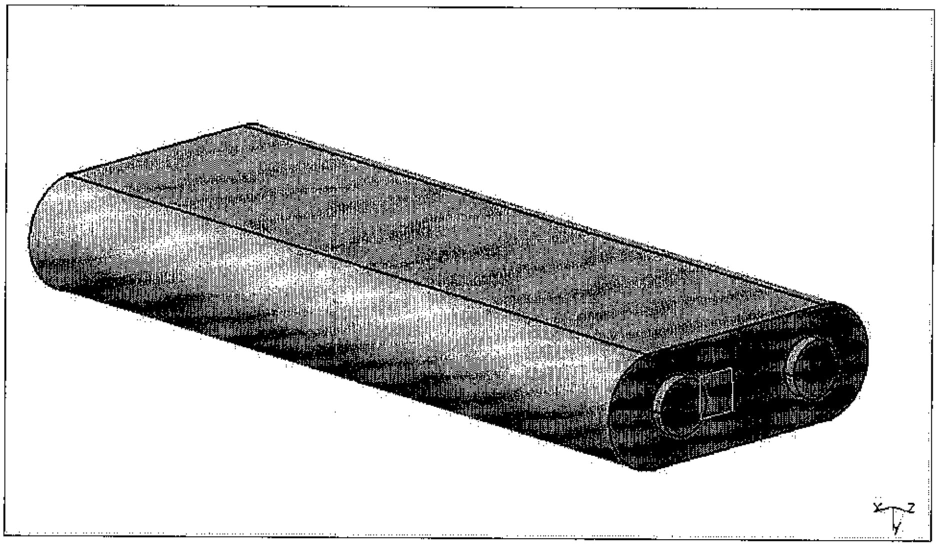


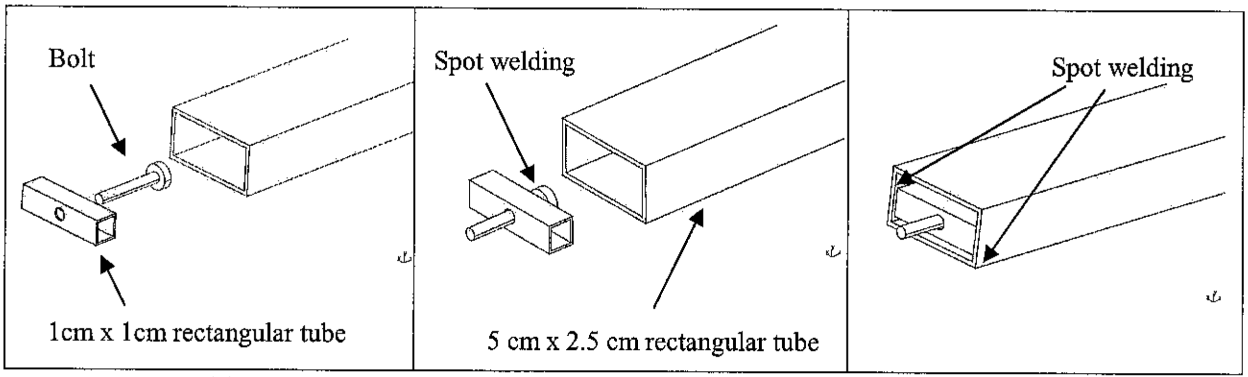
Figure 4.9: The initial design of the model

However, there are a lot of problems associated with the determined method. The raw materials required, which is aluminum block, is not available for the time being since the size of the material is quite large (5.5 cm x 33 cm x 2.5 cm) compared to available raw materials at the laboratory. The technicians from Mechanical Engineering Department suggest buying the aluminum from a company based in Shah Alam, known as Maju Saintifik Sdn. Bhd. But still, there are a few problems arise concerning buying the raw materials:

- The exact price of the mentioned size aluminum block is unknown, since the company was unable to be contacted
- The probability of insufficient in budget allocated for this project, in case the price is too expensive

As an alternative, another method and material which is less expensive have been searched to build the model. The new fabrication method has been selected. The model will be made of various sized rectangular steel tube, the 5 cm x 2.5 cm rectangular tube and 1cm x 1cm rectangular tube, which is less expensive than the aluminum block.

The fabrication steps are shown in Figure 4.10 (a) to (c).



(a) (b) (c)

Figure 4.10: The part required to built the model are (a) assembled together and (b) the bolt will be inserted to the 1cm x 1cm rectangular tube before (c) attached to the 5cm x 2.5cm rectangular tube using spot welding process.

The drawing of final product of the model is shown in Figure 4.11, and the actual fabricated model is shown in Figure 4.12. The technical drawing is attached on Appendix 8.

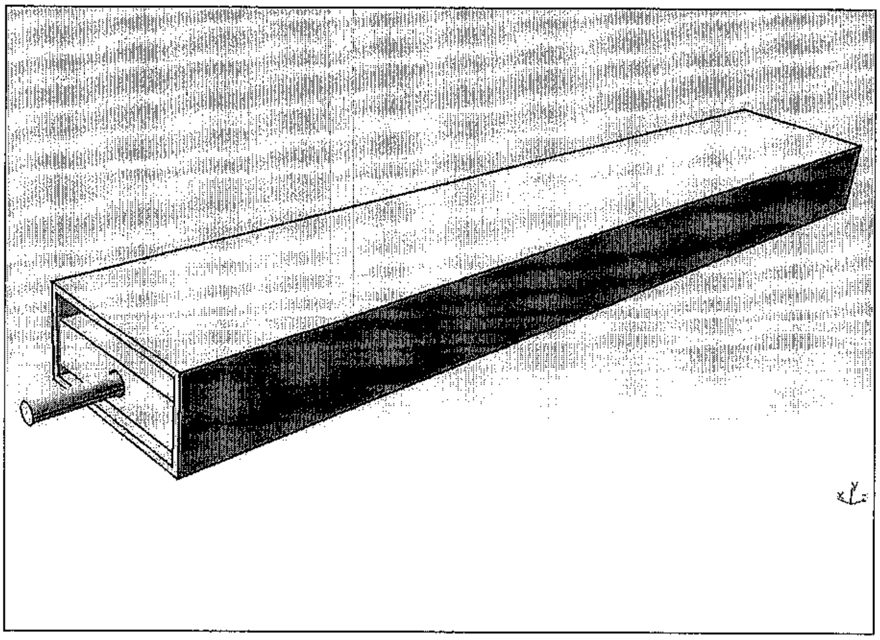


Figure 4.11: The final drawing of fabricated model

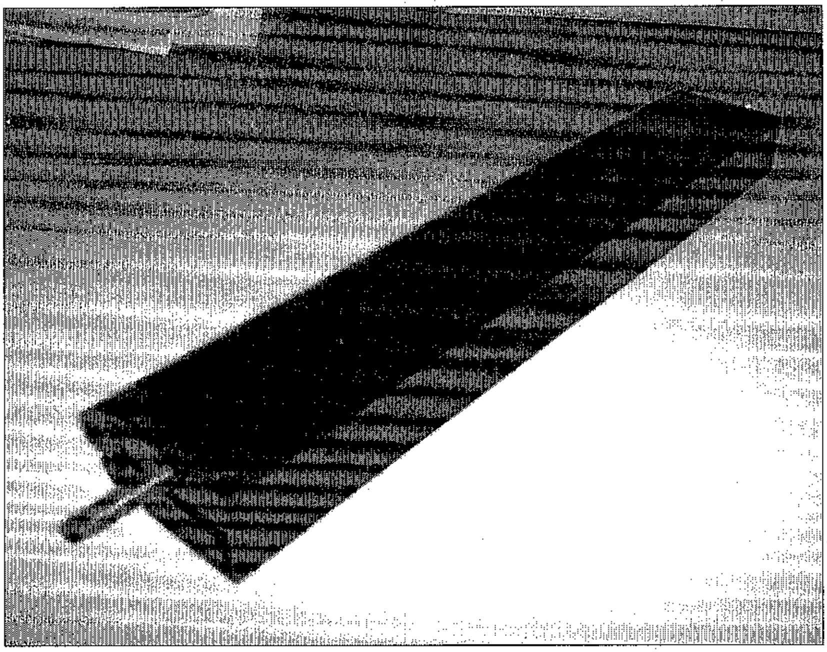


Figure 4.12: Actual model that is going to be used

Besides designing the model, the side panels of the wind tunnel's test section also need some modifications. The modifications only involve drilling holes on the panels as the holder for the model. The model then will be attached to the side panels. The modified side panel is shown in Figure 4.13.

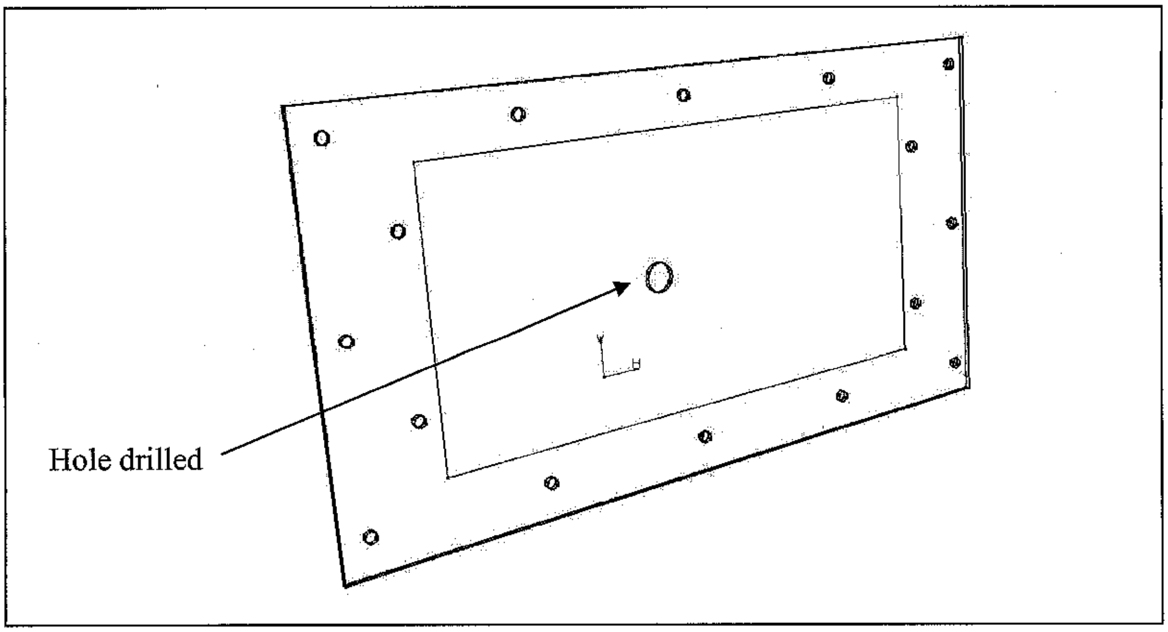


Figure 4.13: The modified side panel (Perspex) of the test section

4.1.11 Conducting flow visualization experiment: Tuft flow visualization

The first flow visualization experiment that has been conducted is the tuft flow visualization experiment. Before proceeding with the experiment, there are preparation procedures that need to be completed. The preparation for the tuft flow visualization experiment involves the installation of the tuft to the model's surface. Since there are two models that had been fabricated, the tuft will remain attached to the one of the model, and the other model will be prepared for surface oil flow visualization experiment. From the research, the placement of the tuft and the tuft size must follow some recommendations. The recommended distance between tufts varies, depends on the model's size and shape, but the suitable distance is about 2 inches to 4 inches, with the tuft's length from 1.5 inches to 2 inches. The tuft's diameter also varies, and also depends on the model's size, about 0.5 mm. However, in this case, since the model's size is quite small, a new approach has been used. The distance between tufts has been changed from 2 inches to 2 cm and the length of the tuft has been set as 1.5 cm. This value is to ensure the same ratio between tuft's distances and tuft's length. Figure 4.14 shows the model with the tuft attached to it.

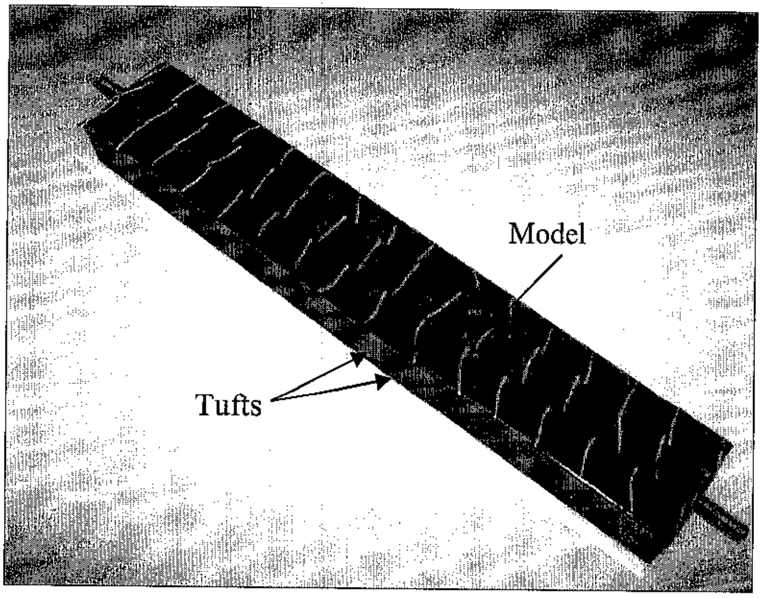


Figure 4.14: Model that is going to be used in the wind tunnel with tuft attached

After installing the tuft on the model's surface, the model is now ready to be used in the experiment. The model is then placed inside the test section. During the experiment, the velocity of air inside the test section is approximately 12 m/s. The flow pattern of air on the surface of the model can be observed and recorded. The recording device that has been selected is the digital still camera. The pictures of surface flow pattern has been taken and shown in Figure 4.15.

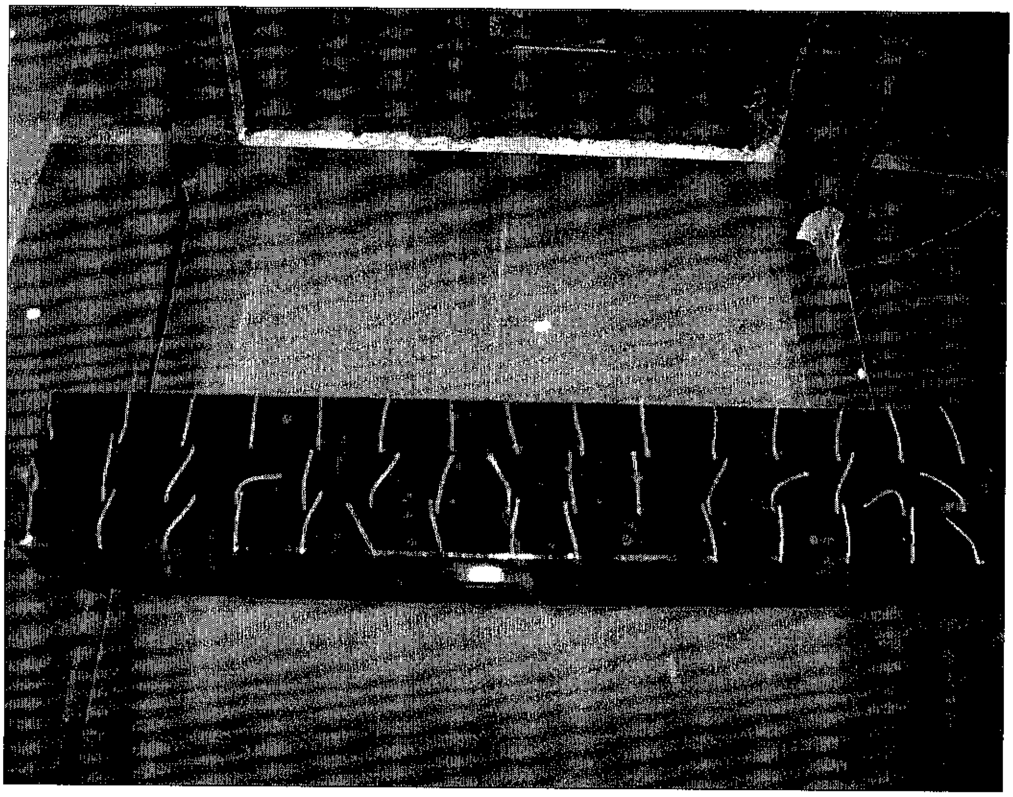


Figure 4.15: Tuft flow visualization experiment using rectangular model

From the figure, it is obvious that the flow pattern on the surface of the model is not too steady. Also, from the figure above, it can be seen that the tuft method works well in order to visualize the flow pattern on the surface of the model. Note how well the white tufts photographed against black model. The color selection is also one of the important criteria that need to be emphasized in doing the tuft flow visualization experiments.

4.1.12 Conducting flow visualization experiment: Surface oil flow visualization

In conducting the surface oil experiment, the first procedure is to prepare the surface oil solution. The solution is made by mixing the petroleum lubricating oil and titanium dioxide. The petroleum lubricating oil that been used in the experiment was Petronas Sprinta 2XT (Semi Synthetic). The purpose of mixing titanium dioxide into the oil is to make the oil white, so that it will improve the visibility of the oil against a black model. Figure 4.16 shows the material that has been used in this experiment.

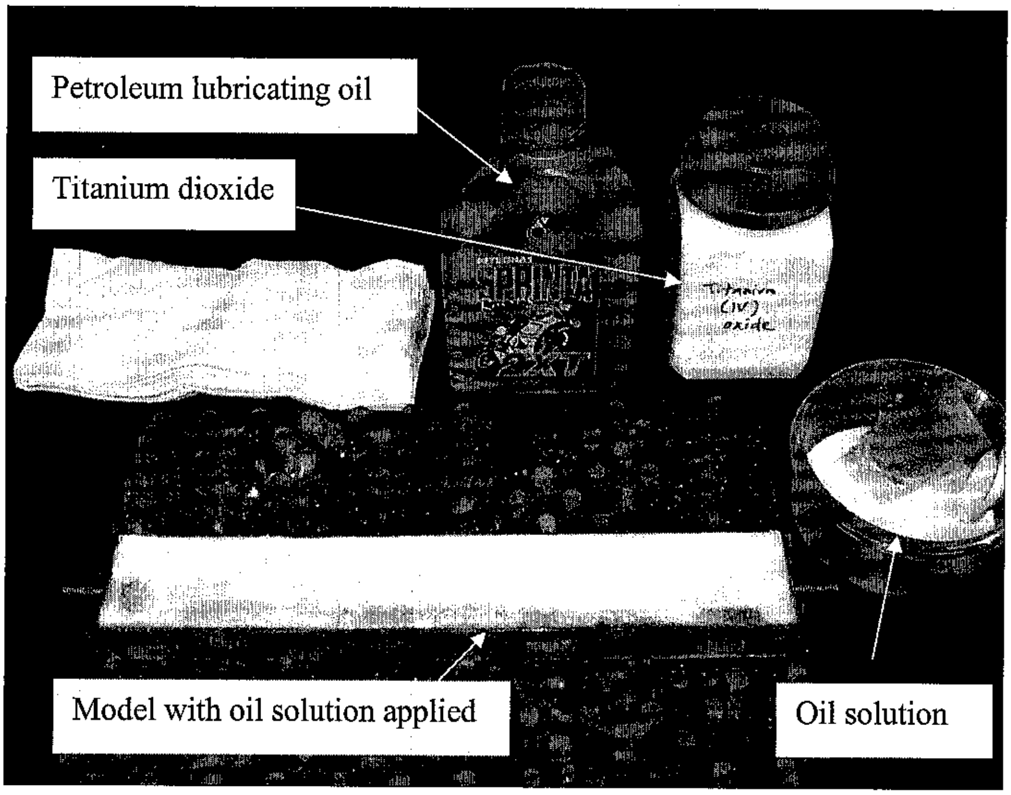


Figure 4.16: The materials for surface oil flow visualization experiment

After the oil solution has been prepared, a thin layer of oil was applied to the entire surface of the model. The application process is done by using sponge to get uniform thickness of oil layer. Then, the model was attached to the inside the test section for the experiment. The air velocity inside the test section during surface oil experiment is approximately 12 m/s. A digital camera has been used as the recording device for the surface oil experiment. The picture of surface flow pattern made visible by surface oil method is shown in Figure 4.17.

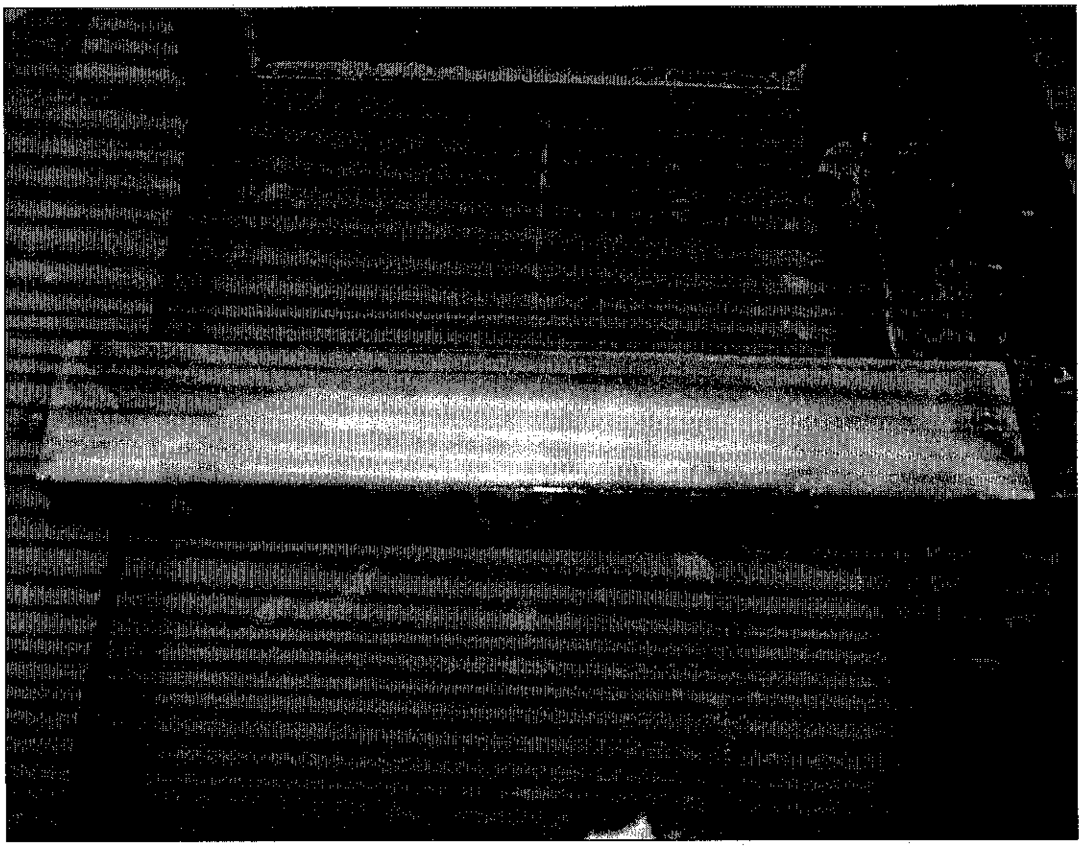


Figure 4.17: The surface oil method experiment to visualize flow pattern

From the photograph of the surface oil experiment, it was obvious that the usage of titanium dioxide to make the oil white against black model was very effective. The flow pattern on the model's surface has better visibility at relatively simple method, compared to using fluorescent oil which requires special lighting management. In conclusion, the surface oil method proved to be a simple, safe, inexpensive, and effective mean of visualizing subsonic flow patterns and transition areas.

4.1.13 Analysis on visualization experiments

From the results of the flow visualization experiment conducted, note how the differences in shear stress between laminar, turbulent, and transition regions, can be readily observed from visualization of patterns using the surface oil solution. As mentioned before, in areas of relatively high shear stress, oil is swept away from the surface. At areas of low shear stress, such as a laminar separation bubble, the oil collects and pools. All these conditions can be observed from Figure 4.17 and 4.18. From Figure 4.18, at area A, the oil solution collects and tends to pools. This shows that the oil solution experiences low shear stress which indicates laminar flow at area A. However, at the rest of the model's surface, the oil solution tends to swept away, which indicates the flow over it is has high shear stress. This shows that, the flow over the rest of model's surface is turbulent flow.

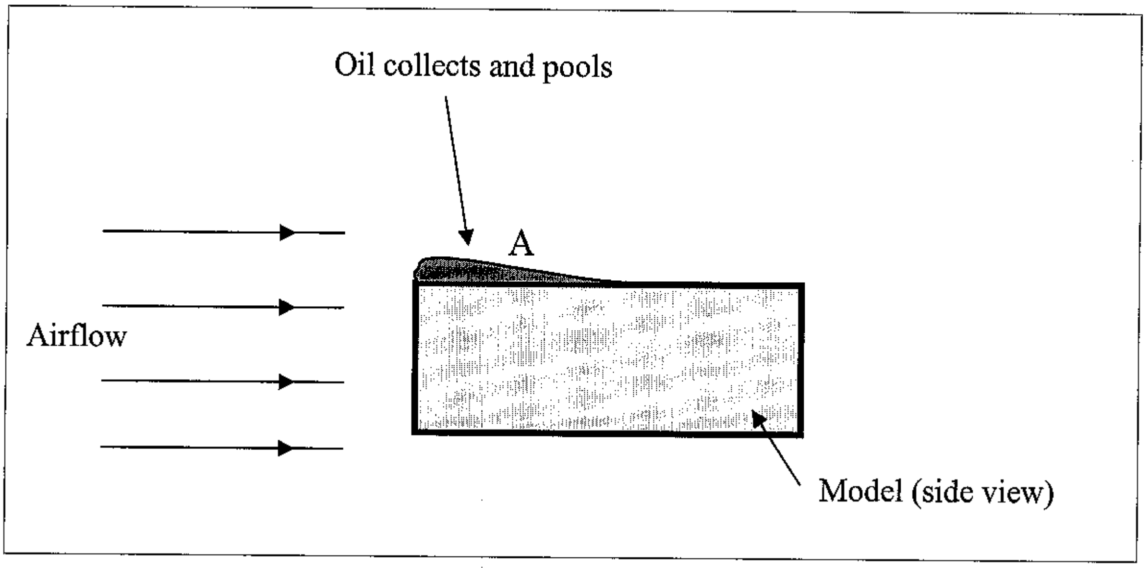


Figure 4.18: Surface oil pattern on the rectangular model

CHAPTER 5 CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The development of a small scale wind tunnel is very important in UTP. Besides that, the study the flow visualization methods that can be used to visualize the air flow pattern inside the developed wind tunnel is also important as the continuation of the project Development of a Subsonic Wind Tunnel in UTP. The wind tunnel will be a great teaching tool to the students. It can also be used as a research tool. This project really has a lot of benefits to both the students and UTP itself.

The project has achieved its pre-defined objectives which are to study, design and develop a subsonic wind tunnel in UTP for learning purpose, and also to develop the studied flow visualization experiments, design and redesign the model and test section, and also conceptual design of a smoke generator. There are also a lot of other useful findings that had been obtained from this project.

This project has been made reality since the efforts poured into it are sufficient and cooperation from every party is achieved. The first phase of the project, the design and fabrication phase had ended, as well as the second phase, the selection of flow visualization device. Good project planning and diligent work is very important along with supervision from supervisor in charge. These are among the key factors that have lead to the success of this project.

5.2 Recommendations

It is recommended that further work should be carried out to optimize the usage of this wind tunnel. The further study on the flow produced within the test section should be initiated. This is essential since the wind tunnel is fully designed based on the recommendations from experts and never simulated before. The study should cover the velocity analysis within the test section, the flow characteristics produced within the test section and also the pressure analysis inside the test section. This study will help in determining the effectiveness of the wind tunnel, as well as locating the possible defects on the wind tunnel, if any, and finds appropriate solution to improve the flow quality.

There is also another improvement that can be made to enhance the results of the project. The project needs to widen its scope to perform the off surface flow visualization experiments, instead of only performing the surface flow visualization experiment. This is because there are going to be a lot of benefits that can be gained from the off surface flow visualization experiments. This is due to certain limitations that occur from surface flow visualization experiments since it only involves visualizing flow pattern on the model's surface. There are several off-surface flow visualization method that can be implement, which are the smoke particle method and by using 'black pepper' seeding method. For the smoke particle method, the continuation work on the conceptual design of the smoke generator should be carried out. After the smoke generator design is complete, it can be used in the smoke particle experiment. As for the 'black pepper' method, it can be done by doing seeding simulation using black pepper seeds. Certain amount of black pepper seeds will be released into the wind tunnel from entrance section, and by using a high speed camera to capture the pattern of the seeds, user can observe the flow pattern around the model. This method is applicable at UTP since the Mechanical Engineering Department can provide the high speed camera for this purpose.

CHAPTER 6 REFERENCE

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APPENDIX 1

In determining the specification of needed fan and motor, we perform calculation on the volume flow rate of air inside the test section of wind tunnel, Q_{ts}.

Volume flow rate, $Q_{ts} = A_1 V_1$

Where A_1= cross sectional area of the test section

V_1 = velocity of air pass through the test section, varies from 10m/s to 15m/s

From calculation, $Q_{ts(max)} = (0.09\text{m}^2)(15\text{m/s})$

$= 1.35\ \text{m}^3/\text{s}$

$= 81.0\ \text{m}^3/\text{min}$

$Q_{ts(min)} = (0.09\text{m}^2)(10\text{m/s})$

$= 0.90\ \text{m}^3/\text{s}$

$= 54.0\ \text{m}^3/\text{min}$

APPENDIX 2

Planned Gantt Chart for 1st semester of Final Year Project (Development of a Subsonic Wind Tunnel in UTP)

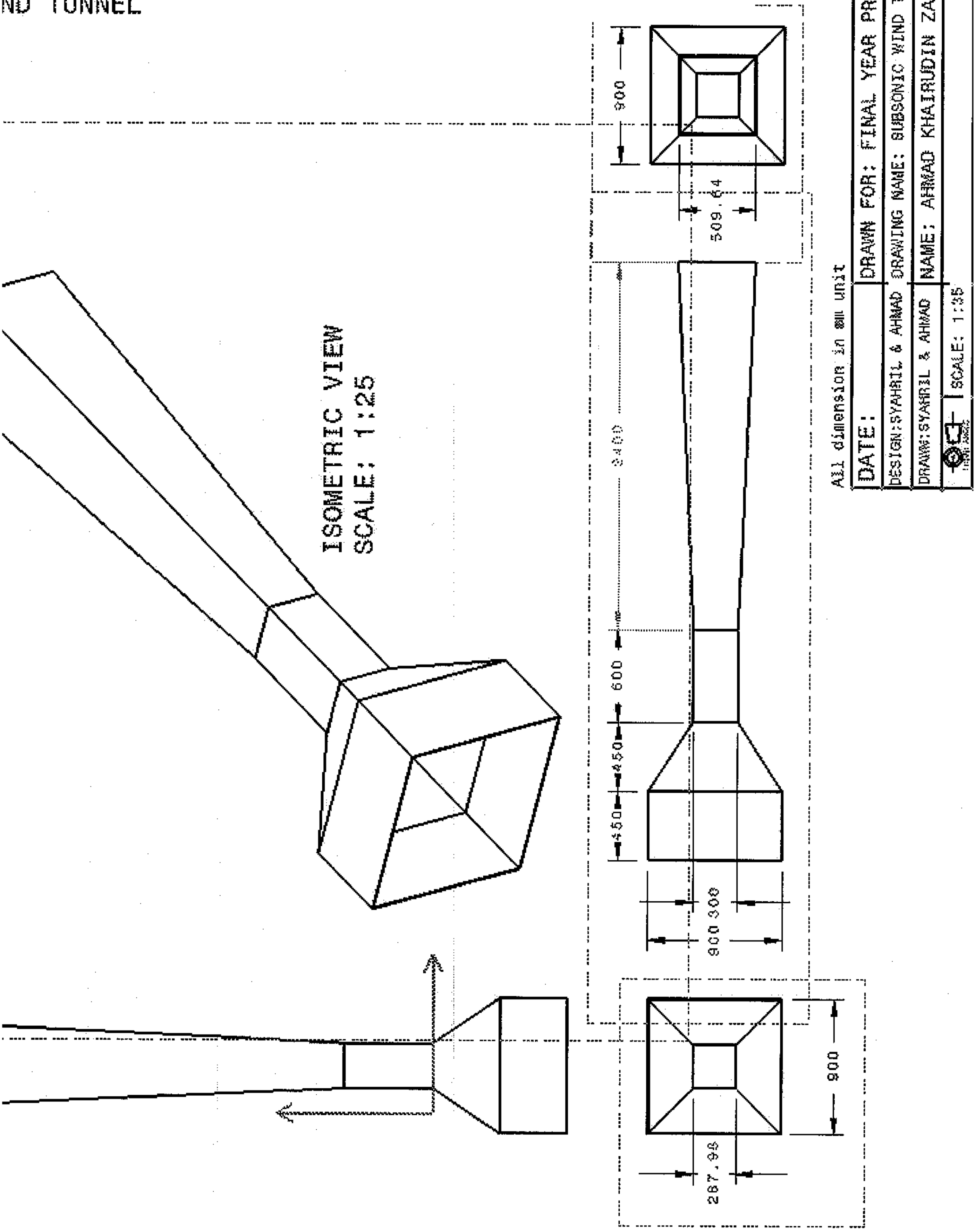
No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	SW	EW
Selection of Project Topic																
Propose topic	▨	▨														
Topic assigned to student		●														
Prelimary Research Work																
Introduction		▨	▨													
Objective and scope			▨	▨												
Project planning			▨	▨												
List of references/literature				▨												
Submission of Prelimary Report				●												
Project Work 1																
Literature research					▨	▨	▨	▨	▨	▨	▨					
Research and application of calculation methods					▨	▨	▨									
Conceptual design (Produce technical drawing)						▨	▨									
Submission of Progress Report									●							
Project Work 2																
Materials selection and preparation								▨	▨							
Fabrication and development										▨	▨	▨				
Submission of Interim Report Draft													●			
Oral Presentation														▨	▨	▨
Submission of Interim Report																●

PPENDIX 3

Planned Gantt Chart for 2nd semester of Final Year Project (Development of a Subsonic Wind Tunnel in UTP - Selection of the Flow Visualization Device)

No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	SW	EW
Preliminary Research Work																
Project planning	▨	▨														
Introduction (Flow visualization methods)	▨	▨	▨													
Selection of most appropriate method and further study on selected method			▨	▨												
Submission of progress report 1				●												
Project work continue																
Initial development of selected method (redesign test section) and model preparation					▨	▨	▨									
Preparation of surface flow visualization experiment						▨	▨	▨	▨							
Submission of progress report 2										● 22/3						
Project work continue																
Run the flow visualization experiment (tuft and fluorescent oil)									▨	▨						
Conceptual design of the smoke generator										▨	▨	▨	▨			
Poster submission													12/4			
Submission of Dissertation Final Draft														● 20/4		
Oral Presentation															▨ ●	▨
Submission of project dissertation																● 31/5

PENDIX 4: TECHNICAL DRAWING OF THE SUBSONIC ND TUNNEL



APPENDIX 5

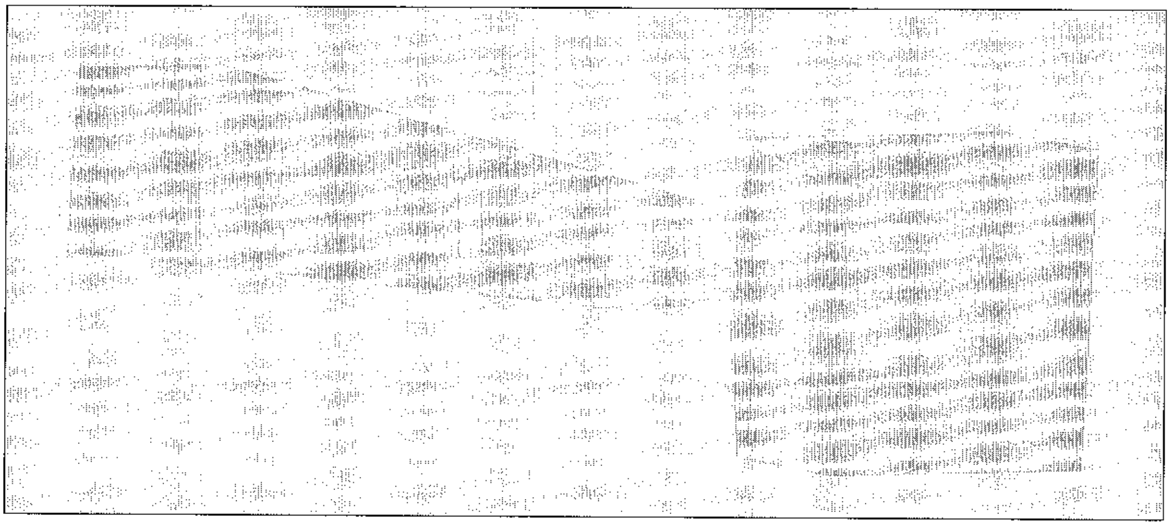


Figure A-5: The isometric view of the wind tunnel

APPENDIX 6

The plotted system curve is the plot of pressure P_1 versus flow rate Q_1 by using the relationship;

$$P_1 = P_2 \left(\frac{Q_1}{Q_2} \right)^2 ,$$

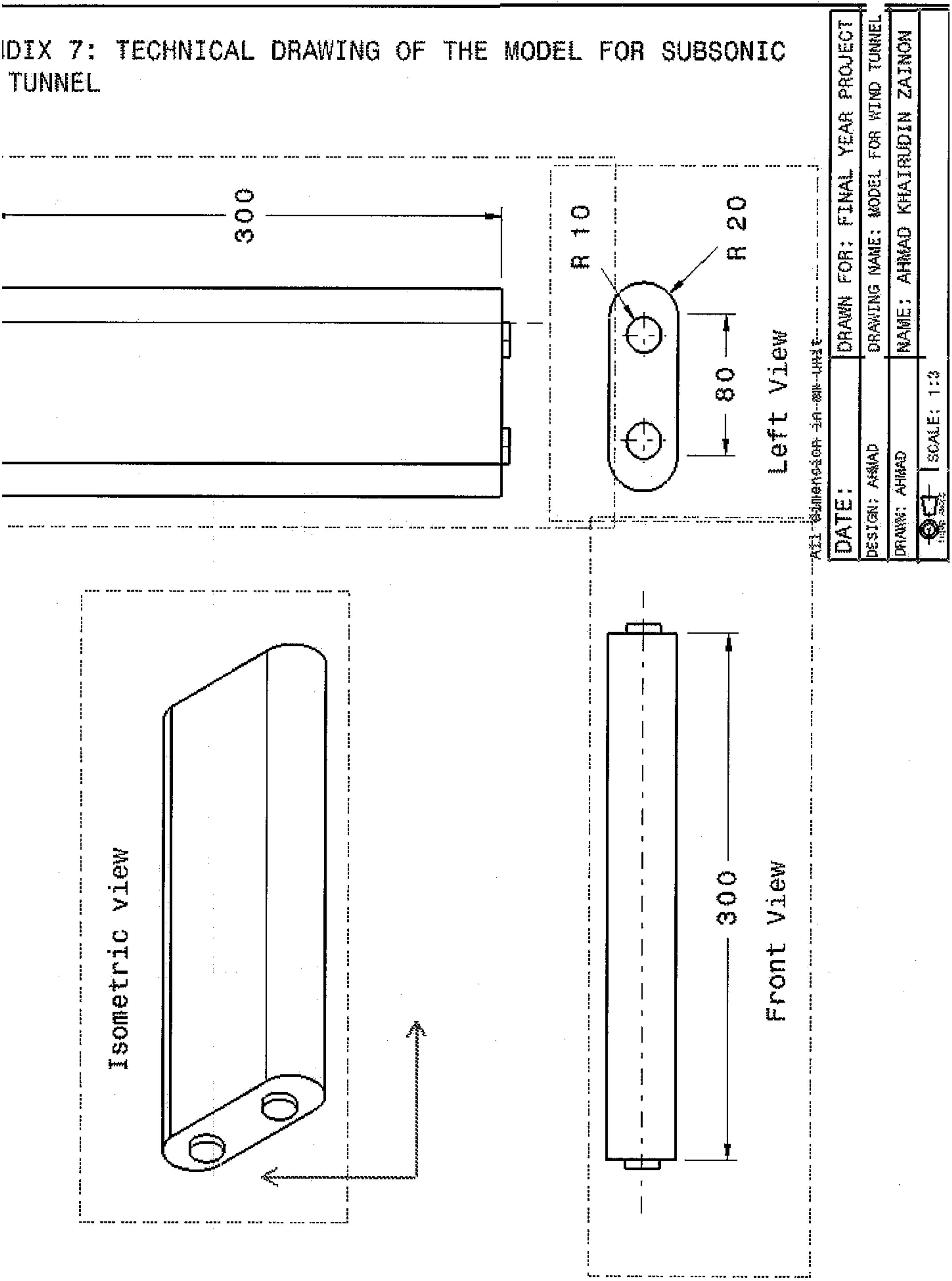
where, $P_2 = \frac{1}{2} \rho V_2^{\,2}$ and $V_2 = 15 m/s$,

from V_2, we obtained $Q_2 = 81 m^3/min$

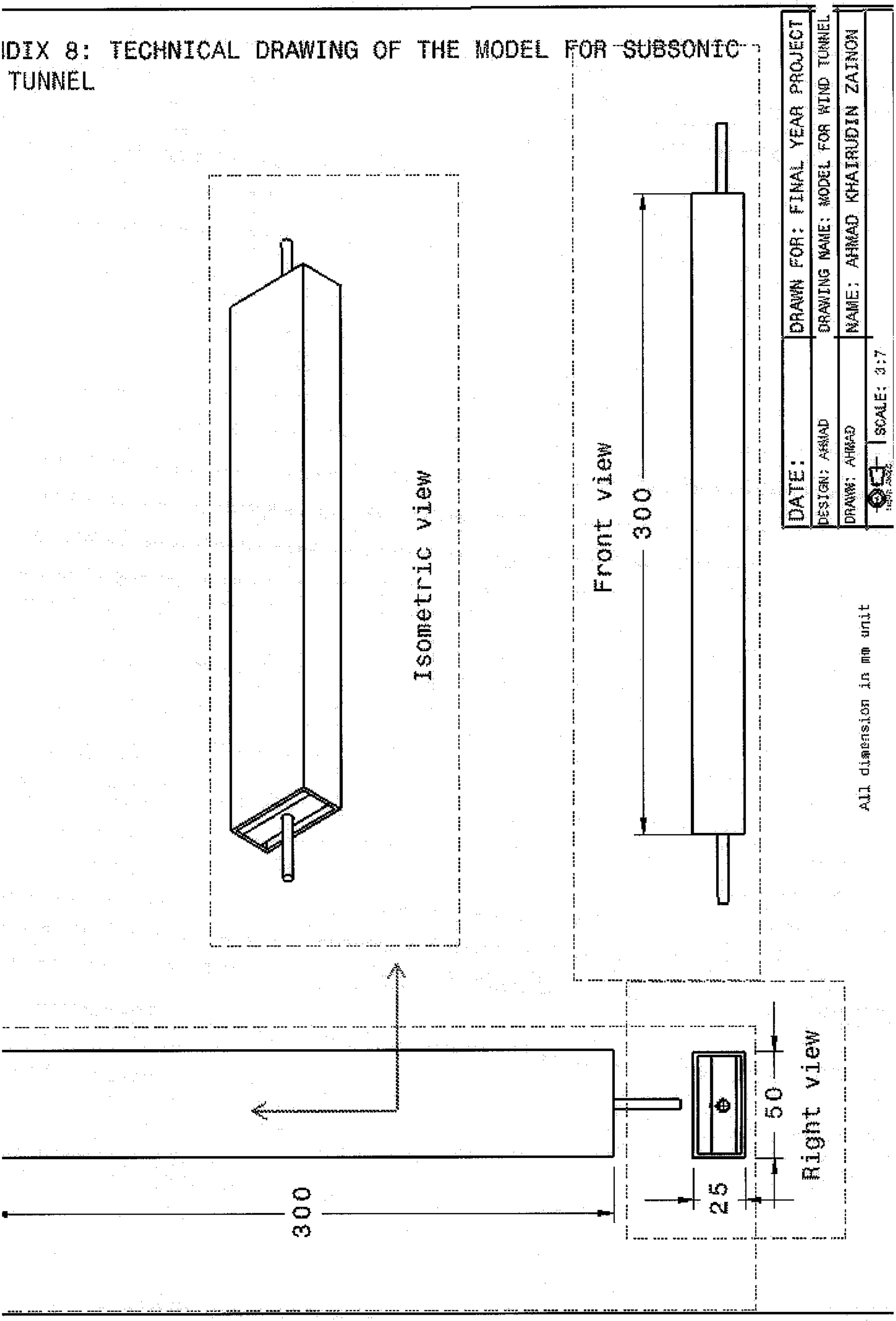
The values tabulated below:

Flow rate	Pressure
20	7.990245
30	17.97805
40	31.96098
50	49.93903
60	71.91221
70	97.88051
80	127.8439
90	161.8025

IDIX 7: TECHNICAL DRAWING OF THE MODEL FOR SUBSONIC TUNNEL



IDIX 8: TECHNICAL DRAWING OF THE MODEL FOR SUBSONIC TUNNEL



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Technical Notes

Design rules for small low speed wind tunnels

R. D. MEHTA and P. BRADSHAW

Design rules for small low speed wind tunnels

R. D. MEHTA and P. BRADSHAW

INTRODUCTION

ı with today's computers, a wind tunnel is an essential in engineering, both for model tests and basic re-h. Since the 1930s, when the strong effect of free-m turbulence on shear layers became apparent, hasis has been laid on wind tunnels with low levels ırbulence and unsteadiness. Consequently most high ormance wind tunnels were designed as closed-circuit s (Fig. 1(*a*)) to ensure a controlled return flow. How-, as will be seen below, it is possible with care to eve high performance from an open-circuit tunnel, saving space and construction cost. 'Blower' tunnels ı the fan at entry to the tunnel, Fig. 1(*b*)) facilitate changes in working section arrangements; to cope the resulting large changes in operating conditions, ntrifugal fan is preferable to an axial one. For ease hanging working sections the exit diffuser is often ted from small blower tunnels, at the cost of a power or greater than unity. This paper concentrates on the gn of *small blower* tunnels but most of the infor-on is applicable to wind tunnels in general.

large open-circuit tunnel would be of rather incon-ent dimensions, mainly in length. Also, an open-ıit tunnel requires enough free room around it so the quality of the return flow is not affected signifi-ly (remember that an open-circuit tunnel in a room is y a closed-circuit tunnel with a poorly-designed re-leg). The choice may also be restricted by the maxi-n available blower size. A working section Re per e of more than about 3×10^6 (a speed of about ns^{-1}) is rare in blower tunnels of whatever size, and mercial blowers capable of producing such a speed in ction more than about 1 m^2 in area are also rare.

The main advantage of open-circuit tunnels is in the ng of space and cost. They also suffer less from perature changes (mainly because room volume $\gg$ ıel volume) and the performance of a fan fitted at upstream end is not affected by disturbed flow from working section. One disadvantage of any open-ıit tunnel with an exit diffuser is that the pressure is ıys less than atmospheric and so spurious jets issue n holes left unpatched, although this can be remedied obstructing the tunnel outlet and creating an over-sure in the working section. The main advantage of ntrifugal blower, as distinct from an axial fan, is that erforms well over a large range of loads (the whole le being at the same incidence and hence operating he same lift coefficient). The only advantage of a ion tunnel, with a centrifugal or axial fan at exit, is dubious one that air coming from the tunnel room be less disturbed than that coming from a fan.

It is difficult and unwise to lay down firm design rules nly because of the wide variety of requirements and cially the wide variety of working-section configura-s. An attempt is made here to present design guidelines for the main components of a wind tunnel—the fan, wide-angle diffuser, corner vanes, settling chamber, contraction and exit diffuser (Fig. 1)—based on data from successful designs and some original experiments. For details of the data correlations see Mehta (1977) and for complete details of the experiments and design procedure see Mehta (1978).

2. FANS

2.1. Axial flow fans

The usual arrangement in a closed-circuit tunnel is a stator ('pre-rotation vanes') upstream of the rotor (the fan proper), designed so that the swirl at exit is zero. In the case of an open-circuit tunnel, swirl present in the flow out of the fan *may* be dissipated before the flow reaches the intake, but a remaining advantage of pre-rotation vanes is that the flow velocity relative to the fan blades is larger than if the stator is absent or located downstream of the fan.

2.1.1. *Fan solidity*

The design procedure outlined by Bradshaw and Pankhurst (1964) is still an adequate guide. The only serious problem found in fan design that is not found in the design of wings for low-speed aircraft is the interference between the flow fields of the blades. This interference depends mainly on the 'solidity', the ratio of blade chord to the gap between blades (measured around the circumference). Providing that the solidity is less than unity approximately, interference is small enough to be treated as a small correction to the performance of an isolated aerofoil; for higher solidities the flow cannot be accurately related to that round an isolated aerofoil, and data for 'cascades' (rows of aerofoils arranged in the same manner as corner vanes) must be used instead. The solidity varies with radius, and in order to use the same

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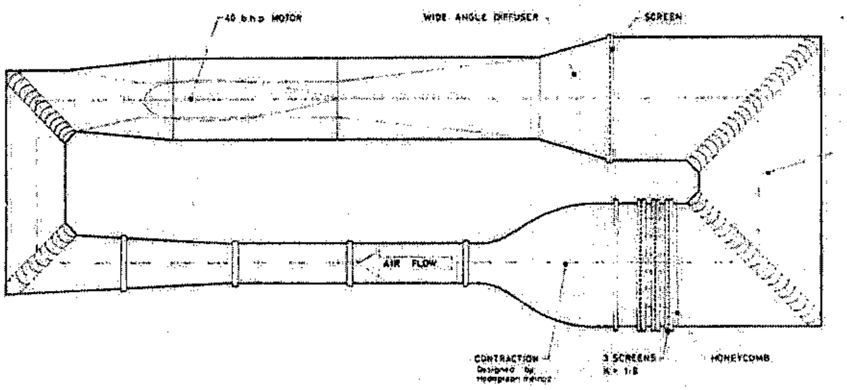
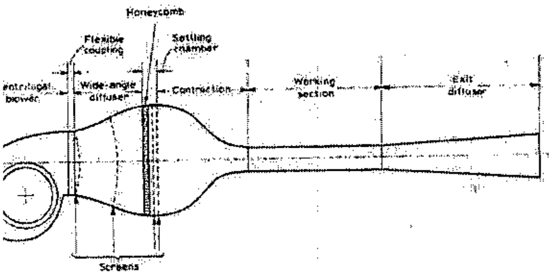


Figure 1(a). The main components of a typical closed-circuit wind tunnel.



e *1(b).* The main components of a typical blower tunnel. (Not to scale.)

ı procedure for the whole length of the blade it is ıble to keep the solidity at the root below unity by ıting the fan on a central nacelle whose maximum eter is roughly half the fan diameter.

Blade design

fan efficiencies are of the order of 90% so that nisation of losses is not usually important, and the procedure is to choose the blade lift coefficient to high as is safe, irrespective of lift/drag ratio; values 7 to 0·9 are typical.

Pre-rotation vanes

otation vanes should be run at a lift coefficient not ar above that for maximum lift/drag ratio because wakes pass through the fan; to limit the resulting the axial distance between the trailing edge of the otation vanes and the leading edge of the fan blades d be at least 20% of the vane chord and the number n blades should be different from the number of . Pre-rotation vane solidities usually fall into the le range.

ı alternative to pre-rotation vanes for a lightly d fan is a set of straightener vanes downstream of ın.

or detailed design rules for pre-rotation vanes, fan s and straighteners *see* Bradshaw and Pankhurst).

Centrifugal blowers

ifugal blowers are normally used to drive open- t tunnels from the upstream end: a blower could stalled at the exit instead but this has no particular tage. Single-inlet blowers could also be used to return-circuit tunnels by installing them in one of orners. Single-inlet blowers are found to produce a -type flow (due to the asymmetric positioning of npeller) which would aid wall flow attachment in the ıngle diffuser. This compensates for the non-uniformity of the flow (which is also improved by the screens in the wide-angle diffuser and the settling chamber).

2.2.1. Advantages over other fans

Centrifugal blowers run with reasonable steadiness and efficiency over a wide range of flow conditions (i.e. varying tunnel power factor) because the whole blade span operates at nominally the same lift coefficient. The noise and pulsations generated by a centrifugal blower are adequately low, even at off-design conditions, and the uniformity of flow varies less with advance ratio, $U/\omega r_2$ in the notation of Fig. 2. The swirl (exit vortex) produced by a single-inlet blower is also independent of advance ratio (dependent on the ratio of rotor to casing width).

2.2.2. Types of impeller

The most common type of blading is the backward-facing aerofoil-type (Fig. 2); forward-facing is less efficient. If the blower efficiency is not too important, these blades could be designed in the same way as corner vanes or cascades by choosing a leading edge angle of 4-5° and a zero trailing edge angle, but a more efficient blade shape is that of a cambered aerofoil with finite thickness. In the present authors' tests on blowers with aerofoil-type impellers it was found that the flow uniformity deteriorated with increasing loading. However, with backward-facing 'S' shaped blades (Fig. 2) the flow uniformity was found to *improve* with loading, presumably because these blades stall relatively early, leading to increased mixing. The cost is a higher turbulence level in the outlet flow and a reduced blower efficiency.

2.2.3. Splitter plate (tongue)

This is an important component which affects the outlet flow uniformity and blower noise characteristics. For minimum interference with the flow uniformity, the ratio of tongue height to casing height needs to be small ($<0·3$) and the angle and shape carefully designed. The gap between the rotor and tongue needs to be a minimum for aerodynamic reasons but optimised for minimum interaction with the outgoing flow and thus minimum noise level. The tongue design on most commercially available blowers is adequate. A badly angled tongue could be improved upon by adding a cusped fairing downstream, as shown dotted in Fig. 2.

2.2.4. Other features and suggestions

An inlet bellmouth helps to produce a uniform flow and reduces inlet losses, and an inlet filter (helping to reduce inlet swirl) is essential to reduce contamination of hot-wire probes. Large blowers should be mounted on antiation mountings and connected to the tunnel with a ble coupling to reduce vibration.

ouble-inlet blowers (air entering the impeller from sides) tend to produce a uniformly inclined flow out a vortex) which takes a longer distance to re- h to the bottom wall downstream of the tongue. should therefore be more conservative in designing -angle diffusers for double-inlet blowers.

n the whole, commercially available single-inlet rifugal blowers with backward-facing impellers are uate for driving blower tunnels.

nce the maximum required fan static pressure and me flow rate have been estimated, the makers' per- nance charts can be consulted. Optimisation between efficiency, rpm and required power leads to the ver choice (*see* section 10).

SCREENS

d tunnel screens are normally made of metal wires woven to form square or rectangular meshes. ens woven from nylon or polyester threads are also being used when the wind loads are not expected to ery high (UTS of nylon ~ 70, steel ~ 1100, bronze 0–1100 MNm^{-2} and E of nylon $\not> 3$, steel~ 200, ze ~ 100 GNm^{-2}). The action of the gauze is ribed in terms of two parameters: the pressure drop ficient, $K = f_1(\beta, R_e, \theta)$ and the deflection coefficient, $f_2(\beta, K, \theta)$, where β is the screen open-area ratio and the flow incidence angle, measured from the normal e screen.

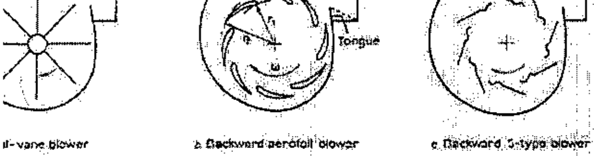
Main effects

(for detailed explanations *see* Mehta 1978)

ens make the flow velocity profiles more uniform by sing a static pressure drop proportional to (speed)^2 thus reduce the boundary layer thickness so that the ty to withstand a given pressure gradient is increased. creen with a pressure drop coefficient of about 2 oves nearly all variation in the longitudinal mean city. A screen also refracts the incident flow towards local normal and reduces the turbulence intensity in whole flow-field. For a given open-area ratio, it is r to have a smaller mesh for the reduction of *existing* turbulence. Plastic screens tend to yield a uniform flow beyond the boundary layer edge, ly due to the weaving properties, and produce an rshoot' in the velocity profile near the edge, mainly ed by screen deflection angle which is a maximum e wall. In terms of tackling a given pressure gradient voiding separation, this overshoot could be beneficial.

Open-area ratio (β)

l screens with very low β ($\sim 0{\cdot}3$) also produce an shoot but this is caused by streamline inclination near boundary layer edge. Low β ($<0{\cdot}57$) screens also luce instabilities resulting from a random coalition of jets and presumably amalgamating to form longitudinal vortices which persist through the contraction. The coalition process is enhanced by variations in β (i.e. non-uniform weave) and by irregularities in the screen shape (i.e. wrinkles). It is therefore essential to inspect and clean wind tunnel screens regularly.



l-vane blower   b Backward aerofoil blower   c Backward S-type blower

gure 2. Different impeller types used in centrifugal blowers.

3.3. Determination of K

(ratio of pressure drop to dynamic pressure)

Although there is no *wholly satisfactory* method, Wieghardt's (1953) formula $\{K = 6{\cdot}5\,[1-\beta/\beta^2]\,[Ud/\beta\nu]^{-1/3}\}$, where d is wire diameter, predicts the right trend; K decreases with increasing speed up to about $Ud/\beta\nu = 600$, after which it is independent of Re. Collar's (1939) formula $\{K = 0{\cdot}9\,(1-\beta/\beta^2)\}$ usually over-estimates K in the high Re limit. One needs to be more careful in predicting K-values for plastic screens since,

$$K = f\,(\beta,\ \mathrm{R_e},\ \theta\ \ldots\ \text{co-planarity}\ \ldots).$$

where θ is angle of screen to incident flow. For $\theta \neq 0$ use

$$K_\theta = K \cos^m \theta, \text{ with } m = 1{\cdot}0 \text{ for screens with } \beta \sim 0{\cdot}6 \text{ and } m \sim 1{\cdot}4 \text{ for } \beta \sim 0{\cdot}3.$$

3.4. Determination of α

(ratio of outlet angle to inlet angle)

For α the form:

$$\alpha = A + \frac{B}{\sqrt{(1+K)}}$$

where A, B are empirical constants, is a better fit than the generally accepted form:

$$\alpha = \frac{1{\cdot}1}{\sqrt{(1+K)}}$$

Note that the refractive index of a screen (μ) defined as in optics is equal to $1/\alpha$ for small θ. For larger θ use

$$\alpha_\theta = \frac{1}{\theta}\tan^{-1}\left\{\tan\theta - \frac{\theta}{2}\sec^2\theta\left[C - \frac{D}{\sqrt{(1+K_\theta)}}\right](E+F\theta)\right\}$$

C, D, E and F are empirical constants.

Values suggested for the empirical constants by some limited experiments (Mehta, 1978) are: $A = 0{\cdot}66$, $B = 0{\cdot}31$, $C = 0{\cdot}68$, $D = 0{\cdot}62$, $E = 1{\cdot}0$, $F = 1{\cdot}5$.

A more complete analysis of the flow through screens can be found in Mehta (1978).

4. DIFFUSERS

The flow through a diffuser depends on its geometry defined by the area ratio (A), diffuser angle (2θ), wall contour and diffuser cross-sectional shapes. Other parameters like the initial conditions, boundary layer control method and the presence of separation could also affect the flow thus making it very difficult to predict. Almost all knowledge acquired about diffusers is empirical. There are two main types:

4.1. Exit diffusers

These are fitted downstream of the working sections and have gentle expansions with a diffuser included angle usually not exceeding 5° (for best flow steadiness, although best pressure recovery is achieved at about 10°) and an area ratio not exceeding about 2·5. It is important to have a reasonable degree of flow steadiness in the exit diffuser, since otherwise the pressure recovery tends to fluctuate with time, and, therefore, so does the tunnel speed if the input power is nearly constant. The design hese diffusers is well catered for by existing methods Cockrell and Markland, 1974).

Wide-angle diffuser

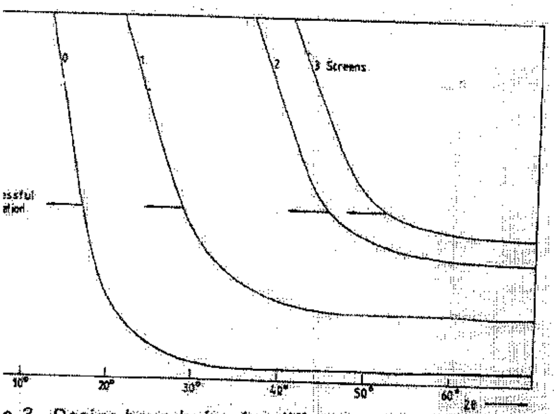
type is normally installed between the blower and ing chamber or between the fourth corner and settling nber of a closed-circuit tunnel; the cross-sectional increases so rapidly that separation can be avoided by boundary layer control. A wide-angle diffuser is eans of reducing the length for a given area ratio ɛr than effecting a pressure recovery; generally the pressure rise through a screened wide-angle diffuser gative but small.

Boundary layer control methods

most popular means of boundary layer control is ıstalling gauze screens. A screen, besides removing lirect effects of layer growth and incipient separa- gives the layer a new lease of life. In a wide-angle ier it is better to use several screens of relatively K (less than about 1·5) because increasing K at station has little effect on the skin friction at a n much further downstream. Other types of iary layer control methods include splitters, suction trapped vortices, vortex generators and vanes and ɔe preferable in diffusers with very severe geometries 5, $2\theta > 50°$). For a review *see* Mehta (1977).

Design charts

four most important parameters in a wide-angle ɛr are A, 2θ, K and n, where n is the number of s *within* the diffuser—this includes the screens in- l at the inlet and outlet. Data were collected from a hundred wide-angle diffuser designs, mostly ssful' (no separation, and uniform outlet flow with ceptable turbulence level), and charts were plotted levant parameters, from which design rules have derived. In Fig. 3, A is plotted against 2θ; the enclosing successful configurations have an ap- nately hyperbolic shape. As n increases, the vertex to a higher value of 2θ and, to a lesser extent, to er value of A, thus implying a stronger dependence uired n on 2θ. Figure 4 is a plot of the sum of ɛe drop coefficients of all the screens, $K_{sum} \equiv \Sigma$, vs A. The straight line EF ($A = 1 \cdot 14\, K_{sum} + 1 \cdot 0$) ɛd the maximum number of successful configura-



e 3. Design boundaries for diffusers with screens.

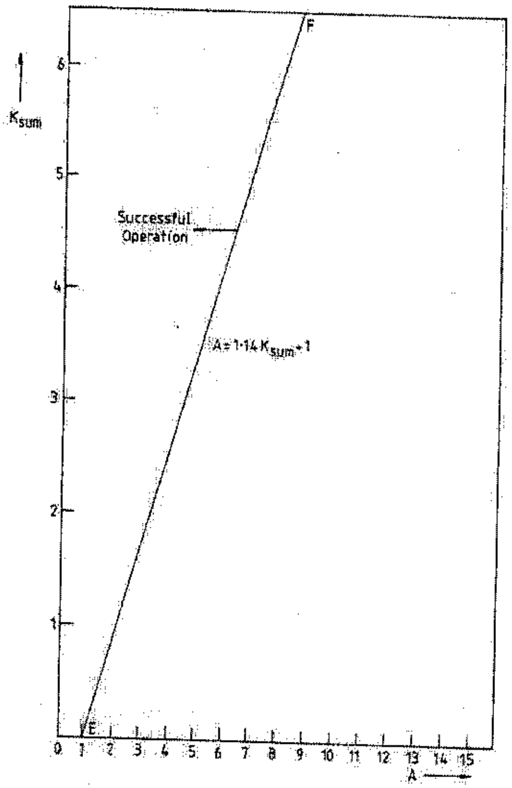


Figure 4. Overall pressure drop coefficient requirements for a diffuser with screens.

Overall design procedure

diffuser design to operate successfully it must lie to t of the relevant curve in Fig. 3, giving the mini- ıumber of screens required in the diffuser, and A must be less than ($1 \cdot 14\, K_{sum} + 1 \cdot 0$), giving the minimum required overall pressure drop coefficient. A diffuser configuration satisfying both these curves should perform successfully *provided that* certain other design factors are kept in mind:

(*i*) *Inlet conditions*: Thin boundary layers and steady flow at the inlet are obviously beneficial.

(*ii*) *Screen Positioning*: The basic rule is to place screens where the diffuser wall angle changes suddenly, since these are the points where the flow is most likely to separate. In diffusers where no obvious location is indicated screens should be equally spaced, remembering that a screen at the diffuser entry (with a relatively high resistance) is desirable because the angle changes suddenly there.

(*iii*) *Wall shape*: The number of screens required in a diffuser could well be reduced, and the efficiency increased, by employing curved walls. Potential flow methods are sometimes used to determine wall shapes but it is often easier to design wall shapes by eye. Straight-walled diffusers (often with curved screens) are, however, often employed, because they are easier and cheaper to construct.

(*iv*) *Screen shape*: It is an advantage for the screen to intersect the diverging walls and streamlines at right angles, so that the refraction of the flow by the screens does not itself induce separation. Curved screens can be held in metal frames pressed into circular arcs and lined with wooden strips so that the gauze may be firmly embedded between two frames. It could be more difficult to dish the more flexible plastic screens (*see* section 3) which may also tend to flutter. Another alternative is to use a plane, 'variable-K' screen comprising of one screen concentrically superimposed on another.

Cross-sectional shape: Most wide-angle diffusers have either rectangular or square cross-sections for ease of construction and since pressure recovery is not too important. It is advisable to fillet the corners in small tunnels, whose designs are likely to be more adventurous, to reduce the risk of large regions of flow separation.

4. Comparison and verification of design rules

ese design rules compare well with those proposed by ne *et al* (1957), Schubauer and Spangenberg (1948) and iire and Hogg (1944). This is to be expected because ny designers have used these rules; evidently the rules successful, but they may be conservative. The present es also compare well with some experiments and test es, details of which can be found in Mehta (1977), ough there is evidence that the rules are not inflexible.

CORNER VANES

en some open-circuit tunnels have corners, say to lect the efflux from a horizontal tunnel upwards to uce draughts. Rules for the design of vanes for 90° ners are uncontroversial and probably rather conservative. Thin sheet metal vanes are used on all but the gest tunnels and, even in the latter, thick aerofoil-tion vanes are used for strength rather than aeroamic advantage. The ratio of the gap, h, between es (measured from leading edge to leading edge) to chord, c, should not exceed about 0·25; the vane lift fficient is $2h/c$. Usual practice is to make the vane as ircular arc, with short straight extensions at leading and lling edges for ease of rolling or pressing. The trailing e is aligned parallel with the axis of the downstream and the leading edge is set at a positive 'angle of idence' of 4° to the axis of the upstream leg. This angement has superficial logic but differs from established cascade-design practice, and recently Ermshaus and udascher (1977) have successfully used a hodographution design which has a *negative* angle of incidence the leading edge and over-turns at the trailing edge so t the included angle is 105° instead of the convenal 86°. It is not clear whether a significantly higher can be used with this design.

The pressure drop through thin vanes of standard °) design is estimated by Bradshaw and Pankhurst 64) to be about 1·2 $(Uc/\nu)^{-1/5}$ times the dynamic ssure.

HONEYCOMBS

neycombs are effective for removing swirl and lateral an velocity variations, as long as the flow yaw angles not greater than about 10°. Large yaw angles cause honeycomb cells to 'stall' which reduces their effectives besides increasing the pressure loss.

Reduction of turbulence

incidental effect of honeycombs is to reduce the bulence level in the flow. Essentially, the lateral nponents of turbulence, like those of mean velocity, inhibited by the honeycomb cells and almost complete ihilation is achieved in a length equivalent to about 0 cell diameters. Honeycombs themselves shed small le turbulence, the level of which is found to be higher en the cell flow is laminar than when it is turbulent; is attributed to a basic instability of the laminar near kes. Note that the cell flow in most wind tunnel eycombs is *laminar* and so Lumley and McMahon's 57) analysis, which assumes turbulent flow, will *not* ly. With a laminar cell flow the *net* reduction is atest for the shortest honeycomb (Loehrke and Nagib, 1976). It turns out that the shear layer instability in the near wake has a strength proportional to the shear layer thickness and so for the longest honeycomb, the ratio of turbulence generated to that suppressed is greatest.

6.2. Optimum cell size

For maximum overall benefit the cell length should be about 6–8 times its diameter. The cell size should be smaller than the smallest lateral wavelength of the velocity variation (roughly 150 cells per settling chamber 'diameter', i.e. 25 000 total, are adequate). The cross-sectional shape of the honeycomb cells is usually hexagonal, but sometimes square or triangular, the shape being chosen mainly for ease in construction. Impregnated paper honeycombs are adequate for small tunnels. Aluminium honeycombs made for aircraft sandwich construction have more precise dimensions than paper honeycombs and are to be preferred for high performance tunnels and large tunnels where the wind loads may be expected to be high. The cells of all honeycombs are often partly obstructed by burrs which can be fatigued off with an air hose.

7. SETTLING CHAMBERS

7.1. General arrangement

The usual arangement consists of a honeycomb (with about 25 000 cells) followed by screens, the number and K-value depending on the turbulence level requirements. If severe yaw or swirl is expected in the flow from the wide-angle diffuser, it is advisable to install one screen upstream of the honeycomb, so that the flow angles are reduced. A screen with $K = 1{\cdot}5$ reduces yaw and swirl angles by a factor of about 0·7 for swirl angles of about 40°. The honeycomb should be installed some way downstream of the wide-angle diffuser exit, so that the flow static pressures and angles have had a chance to become more uniform. Since screens with small β (less than about 0·57) tend to produce instabilities, presumably in the form of longitudinal vortices, at least one screen with a larger β ($> 0{\cdot}57$) should be used (in the most downstream position) if a truly two-dimensional boundary layer is required in the working section. Another alternative is to place the honeycomb downstream of the screens but this at best results in a rise in the turbulence level and is not recommended in general.

7.2. Spacing between screens

There are two important properties to consider:

(*i*) For the pressure drops through the screens to be completely independent, the spacing should be such that the static pressure has fully recovered from the perturbation before reaching the next screen (i.e. $\mathrm{d}p/\mathrm{d}y = 0$).

(*ii*) For full benefits from the turbulence-reduction point of view, the minimum spacing should be of the order of the large energy containing eddies.

It has been found that a screen combination with a spacing equivalent to about 0·2 settling chamber diameters performs successfully. The optimum distance between the last screen and the contraction entry has also been found to be about 0·2 cross-section diameters. If this distance is much shorter significant distortion of the flow through the last screen may be expected. On the other hand, if this distance, or for that matter the overall length of the settling chamber, is too long then unnecessary boundary layer growth occurs.

Installation of components

ns are normally tacked onto wooden frames. More is necessary when tacking on plastic screens since , being more flexible, tend to wrinkle along the lines nsion. The honeycomb is usually just push-fitted into wn frame. A useful arrangement for small tunnels is st the wide-angle diffuser, screen frames and con- on on a table and clamp them by drawbolts, so that es can be withdrawn easily. On larger tunnels, it is able to equip the settling chamber (and wide-angle ser) components with castors for ease of removal. in tunnels made of metal or concrete, the screens normally installed in separate frames which can be rawn from the tunnel for cleaning or replacement.

ONTRACTIONS

ntraction:

ncreases the mean velocity which allows the honey- comb and screens to be placed in a low speed region, hus reducing pressure losses.

Reduces both mean and fluctuating velocity variations o a smaller fraction of the average velocity.

he most important single parameter in determining effects is c, the contraction ratio. The factors of tion, as derived by Batchelor (1970) for $c \gg 1$,

-component mean velocity: $1/c$
or W-component mean velocity: $\sqrt{c}$
component rms intensity: $1/2c\,\{3\,(1n4c^3-1)\}^{1/2}$
or w component rms intensity: $(3c)^{1/2}/2$.

factor of reduction of percentage velocity variation en by multiplying the above expressions by $100/c$).

he design of a contraction centres on the production uniform and steady stream at its outlet, and requires voidance of flow separation. Two more desirable ia include minimum exit boundary layer thickness ninimum contraction length. A design satisfying all ia will be such that separation is just avoided and xit non-uniformity is equal to the maximum tolerable for a given application (typically $\pm\frac{1}{2}\%$ velocity ion outside the boundary layers).

Contraction lengths

lways possible to avoid separation in the contraction aking it very long, but this results in an increase of l length, cost and exit boundary layer thickness.

Contraction ratio

the power factor contribution of screens in the g chamber varies as $1/c^2$, large contraction ratios dvantageous. But large contraction ratios mean r construction and running costs besides possible ems of noise and separation near the ends. Therefore, action ratios between about 6 and 9 are normally at least for the smaller tunnels.

Cross-sectional shape

y contraction with a non-circular cross-section, the near the walls tends to migrate laterally, especially corners of a polygonal section. In any case the dary layers near the corners will be more liable to ate. However, recent investigations (Mehta, 1978) that this does not cause a problem in a well-designed *e* contraction; the effect of boundary layer migration ontraction whose cross-sectional aspect ratio changes its length can be reduced by adding small 45° corner fillets, but rapid termination of these in the working section must be avoided.

Two-dimensional contractions are sometimes preferred on tunnels used for boundary layer studies, where the working section is wide but shallow. However, if the boundary layers are thick, the plane walls tend to develop strong secondary flows. Also, 2-D contractions require about 25% more length to attain the same uniformity of pressure distribution as axisymmetric ones.

8.4. Wall shape

8.4.1. Theoretical design

The solution of the Laplace equation or the Stokes-Beltrami equation is relatively easy for simple geometries and many analytical solutions have been derived. With the onset of computers many numerical schemes have also been proposed. For a review *see* Mehta (1978).

There is no wholly satisfactory method of theoretical wall shape design, as distinct from analysis. The application of all these methods requires the establishment of some criteria and then the application of trial-and-error techniques for which limited guidance is given.

8.4.2. Design by eye

Designers have often used the rather unscientific method of design by eye. Note that the actual form of a contraction contour is not very important except near the ends, and that smoothness in contour shape is much more important than exact dimensions. In general the wall radii of curvature should be less at the narrow end and each end must join the parallel sections so smoothly that at least the first and second derivatives of the curve are zero (or very small) at the ends.

9. WORKING SECTIONS

Working section design is totally dependent on the requirements of the individual experimenter. Blower tunnels are more flexible in accepting a variety of working sections (with and without exit diffusers).

The flow out of a contraction often takes a distance equivalent to about 0·5 diameters before the non-uniformities are reduced below an acceptable level. Also, if a turbulence grid is installed, it may take up to 10–15 mesh lengths before a homogeneous flow is obtained. These requirements often fix the minimum length of the working section. The streamwise pressure gradient is best controlled by installing tapered fillets.

It is advisable to mount removable side panels on pinned hinges on large working sections which makes their 'single-handed' removal easier and safer.

Drag forces, being proportional to (velocity)^2, change by twice as large a fraction as the mean velocity; lift forces change because of the change in mean velocity and because of the influence of tunnel walls on the effective angle of incidence. Lift interference on a complete aircraft model in a rectangular-section tunnel is minimised if the ratio of working section breadth to height is $\sqrt{2}$ (with model span less than three-quarters of the breadth) so most general purpose aerospace tunnels are made with approximately this aspect ratio. However tunnels for measurements in boundary layers, growing on the tunnel floor say, have an optimum breadth-to-height ratio of about five since all that is necessary is that a reasonable thickness of irrotational flow shall remain between the roof and floor boundary layers at the end of the test section (a diffuser with such a non-uniform entry flow would not be very efficient). Tunnels for testing building complexes or natural terrain at model scale can also have a large breadth/height ratio; conversely, tunnels for testing isolated tower buildings or smokestacks can have a adth-to-height ratio *less* than unity, although the ratio model breadth to tunnel breadth must still be kept ll to minimise interference.

ESTIMATION OF TUNNEL POWER FACTOR

ving decided the size and configuration of a wind nel, the next design step is to estimate the tunnel ver factor, λ (equal to $H/\frac{1}{2}\rho_o U_o^3 A_o$, where H is the ft input power and subscript o refers to working sec- conditions) so that the fan and drive unit can be cted. It is difficult, but in fact not essential, to estimate power factor very accurately; adequate extra power st be installed to cope with a variety of model or king section configurations, not known in advance.

The pressure losses in a wind tunnel are due to diffuser es, resistive components such as screens, and friction the tunnel walls. The total pressure loss due to each ponent can be estimated separately, and then summed divided by the blower efficiency η, typically 0·8, to the tunnel power factor. Typical values for a tunnel lar to that shown in Fig. 1(*b*) are given below.

Losses due to skin friction.

$$\eta\Delta\lambda_1 = \frac{\Delta P}{\frac{1}{2}\rho_o U_o^2} = \left(\frac{A_o}{A}\right)^2 \int C_f \frac{S}{A} \mathrm{d}x,$$

where S is the duct local perimeter and remembering that the area ratio is the reciprocal of the velocity ratio. It is normally only necessary to estimate skin friction losses in the working section ($A/A_o = 1$). Those in the diffusers are normally accounted for in the efficiency and the other components do not contribute significantly.

Therefore, $\eta\Delta\lambda_1 \simeq C_f SL/A$, where L is the working section length. Typical value: $\eta\Delta\lambda_1 \sim 0{\cdot}07$, assuming $C_f \sim 0{\cdot}003$.

Losses due to screens, honeycomb and corner-vanes.

$$\eta\Delta\lambda_2 = K\left[\frac{A_o}{A}\right]^2.$$

So for a tunnel with four screens (two in the wide-angle diffuser with $A/A_o = 4$ and 6 respectively) each with $K = 1{\cdot}5$ (for $U = 5$–10 m/s), and a honeycomb with $K = 0{\cdot}5$ we have, taking $c = 9$, typical value: $\eta\Delta\lambda_2 = 0{\cdot}18$ (the screen at $A/A_o = 4$ contributes 0·094).

Loss of total head in the exit diffuser.

$$\eta\Delta\lambda_3 = (1 - \eta_D)\left[1 - \left(\frac{A_o}{A_{\mathrm{out}}}\right)\right],$$

where η_D is the diffuser efficiency. This is a loss due to the inefficiency of the diffuser in transforming kinetic energy into 'pressure energy' and is caused by boundary layer growth and non-uniformity of the flow. The efficiency of a wide-angle diffuser with screens is generally negative but Δp is small.

For a conical diffuser with $A \sim 2{\cdot}5$ and $2\theta \sim 5°$, Cockrell and Markland (1974) suggest $\eta_D = 0{\cdot}8$, but this may be lower for diffusers with rectangular cross-sections, typical value: $\eta\Delta\lambda_3 = 0{\cdot}25$ for $\eta_D = 0{\cdot}7$ and $A = 2{\cdot}5$.

(*iv*) Loss of total head at the exit of an open-circuit tunnel.

In an open-circuit tunnel, the amount of kinetic energy lost at the exit and dissipated into heat adds to the total losses.

$$\eta\Delta\lambda_4 = \left(\frac{A_o}{A_{\mathrm{out}}}\right)^2$$

[= 1 for blower tunnels with no exit diffuser],
typical value: $\eta\Delta\lambda_4 = 0{\cdot}16$ for $A = 2{\cdot}5$.
Therefore the estimated overall tunnel power factor,
$\lambda \equiv \sum_{n=1}^{4} \Delta\lambda_n/\eta \simeq 0{\cdot}825$ for the tunnel considered (with an exit diffuser), taking $\eta = 0{\cdot}8$.

Once the tunnel power factor has been estimated and the required fan static pressure rise determined, one can set about the selection of the optimum fan size. The *dynamic* pressure rise through a blower is usually ignored and can be thought of as a safety factor in the calculations.

The fan outlet flow will be least turbulent when the fan is operating near maximum efficiency. Fan efficiency is a function of the dimensionless flow rate; the pressure rise coefficient is a (weak) function of the dimensionless flow rate also, so that requiring maximum efficiency specifies both dimensionless flow rate and pressure rise coefficient. So for a given required flow rate and pressure rise, two equations are obtained which can be solved to give the fan size and optimum operating rpm. In practice the manufacturer's performance charts should be searched for a fan size (and rpm) giving near maximum efficiency for the required flow rate and pressure rise.

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