Designing an Open Circuit Wind Tunnel for Atmospheric Boundary Layers

Thaer Obaid Roomi

Department of Atmospheric Sciences, College of sciences, University of Al-Mustansiriyah

Received 19 September 2015 ; Accepted 10 November 2015

Abstract

A standard, inexpensive open circuit wind tunnel was built to understand and study some applications that related with atmospheric boundary layers, pollution and generate electricity by wind. Its operation, efficiency, and features were tested. Air speed measurements were taken for both sides: inside and outside the tunnel and the air temperatures were measured, as well. Obstacles were put inside the tunnel to observe the air flow patterns. The relationship between the input voltage of fan and the speed of air inside the tunnel was established to calibrate different types of anemometers. Mach number was calculated for the tunnel which was about 0.02. Bernoulli principle was used to find air speed at the end of diffuser section. It was 1.38 m/s, that means this value was close to the observation value (1.5 m/s).

key words: Wind tunnel, Atmospheric boundary layers, Air flow

تصميم نفق رياح ذو دائرة مفتوحة للطبقات الجوية المحاددة

ثائر عبيد رومي

قسم علوم الجو، كلية العلوم، الجامعة المستنصرية

الخلاصة

تم بناء نفق رياح قياسي منخفض الكلفة ذو الدائرة المفتوحة لفهم ودراسة بعض التطبيقات المتعلقة بالطبقات المحاددة الجوية والتلوث وتوليد الطاقة الكهربائية بالرياح. تم فحص تشغيله وكفائته وخواصه. فقد تم اخذ قياسات سرع الهواء لكلا الجانبين: داخل وخارج النفق بالاضافة الى قياس درجات حرارة الهواء. كما تم ايضاً وضع عوائق داخل النفق لرصد انماط جريان الهواء. اسست علاقة بين الفولتية الداخلة الى المروحة مع سرعة الهواء داخل النفق لمعايرة مختلف اجهزة قياس السرعة. تم

احتساب قيمة عدد ماخ للنفق وكانت بحدود 0.02. استخدمت قاعدة برنولي لإيجاد سرعة الهواء عند نهاية مقطع المشتت وكانت بحدود 1.38m/s، وهذا يعني بأن القيمة المقاسة كانت قريبة الى القيمة المرصودة (1.5m/s).

الكلمات المفتاحية: نفق الريح، الطبقة المحاددة الجوية، جريان الهواء.

Introduction

A wind tunnel is a specially designed and protected space into which air is drawn, or blown, by mechanical means in order to achieve a specified speed and predetermined flow pattern at a given instant. An object, such as an obstacle, any small model, or some full-scale engineering structure, such as a vehicle, or part of it, can be immersed into the established flow, thereby disturbing it. The objectives of the immersion include being able to simulate, visualize, observe, and/or measure how the flow around the immersed object affects the immersed object [1, 2].

An advantage of using wind-tunnels is to work under well controlled flow circumstances compared to the open environment. To achieve the same Reynolds number as for the real application, the kinematic viscosity or flow velocity normally has to be changed. In most wind-tunnels air at atmospheric pressure is used, and the only option left is to increase the flow velocity. Often it is not possible to increase the velocity enough, so the results from wind-tunnel experiments fall in between those achievable in most well resolved simulations and the real application on a Reynolds number scale [3].Wind tunnels are extensively used for wide variety of applications such as tunnels with moving ground planes for automotive testing, icing tunnels for studying the effects of ice formation on aircraft wings, climate tunnels for simulating various environmental conditions, simulating of atmospheric boundary layer tunnels, etc. [4, 5].There are two basic layouts: closed- circuit and open-circuit wind tunnels. The closed-circuit is very large and expensive type of wind tunnel. It gives the engineers and scientists the great control over the flow of air, and produces the most efficient and precise results when models are tested. The open type has the advantage of saving the space and cost [6]. It also suffers less from temperature changes. Though it is not accurate as the closed type, it is possible with care to achieve a high performance with the open type [7]. Depending on the speed of air flow in the tunnel, there are many types of wind tunnel: (1) subsonic or low-speed wind tunnels, (2) transonic wind-tunnels, (3) supersonic wind-tunnels, (4) hypersonic wind-tunnels [3]. The classification above based on using a ratio called the Mach number which gives ranges of M<1 to subsonic and M>5 to Hypersonic. It is just the ratio of two speeds [1, 8],

$$\boldsymbol{Mach\ number\ (M)} = \frac{\boldsymbol{Air\ speed}}{\boldsymbol{Sound\ speed\ of\ the\ meduim}} \qquad (1)$$

If Mach number is less than 0.3 (M<0.3), the air is considered incompressible [9].

Compressible gaseous flow is primarily characterized by its Mach and Reynolds numbers. These parameters are critical, as one of the key, though often unrealizable, goals of wind-tunnel testing is dynamic similarity, where all relevant dimensionless parameters match between model and full scale. The key dimensionless parameter of interest in low-speed wind-tunnel tests is usually the Reynolds number, which is the ratio of inertial to viscous forces. For models exhibiting dynamic similarity, the forces and moments on full-scale models can be obtained by scaling the force and moment data. However, achieving Reynolds number similarity is a difficult task, even in incompressible flows [4]. The mathematic relationship of Reynolds number (Re) may be written as [10],

$$\boldsymbol{R_e} = \frac{\boldsymbol{L\,V\,\rho}}{\boldsymbol{\mu}} \qquad (2)$$

Where L is the characteristic length or the contraction length, V is air speed, μ is air viscosity. Assuming an air medium near standard conditions, the only way to match Re is to increase the tunnel velocity. In some cases, either a limit on maximum tunnel speed or the introduction of compressibility effects precludes Re matching. Thus, one is forced to accept the largest Re that can be achieved in the test section.

The General Framework of Wind Tunnels

The principal characteristics of wind tunnels are the same despite the great variety of types, dimensions, and designs. The differences are due only to the specific requirements which a given wind tunnel must fulfil [11]. The main parts are: (1) drive system which is either a compressor or an axial fan (sometimes a blower) that pushes or draws the fluid in or out of the wind tunnel, and (2) duct circuit which can be designed in two forms: open and closed. The open-circuit tunnel takes the air from one end of the tunnel and passes the air through the tunnel, and then releases current air flow to surroundings. The closed-circuit tunnel keeps and circulates the same fluid.

The Components Design Outlines

Wind tunnels designs vary according to their purposes (e.g. testing models, studying environmental conditions, assessment of high temperature exhaust from turbine and rocket engines) and features (e.g. geometry, flow speed, fluid type). However, it is best to refer here to the design that was achieved by Will Stark [12] to ease the explanation of the different components of wind tunnel. There are three main sections, contraction, test, and diffusion as in figure (1).

Figure (1) Open-circuit wind tunnel [12]

The contraction section accelerates and directs the flow in the test section. Its shape and size imposes the final turbulence strength levels in test section. The length of contraction section must be small enough to lessen the boundary layer growth and cost, but in the same time long enough to prevent the large harmful pressure gradients along the wall, generated by the streamlines curvature which may lead to flow separation [4].The common tunnels have a honeycomb which has many forms such as circular, square, and hexagon. A typical form of honeycomb is shown in figure (2). The honeycomb directs the flow with the axis of wind tunnel and breaks up the flow large eddies, for this reason it is used to straighten the flow with minimal losses and reduce the free-stream turbulence level to about 0.35% of the free-stream velocity [5, 10]. For good benefit the cell length should be about 6-8 times its diameter [7].

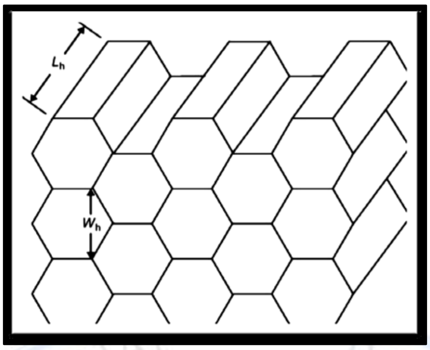


Figure (2) Honeycomb [4]

Test section should be easily accessed in order to put test models and instruments. In most cases this section is transparent to watching, observation, and filming.

The diffuser area should gradually increase along its axis, and hence it will prevent flow separation. For the conical diffuser, the semi-divergent angle of the diffuser walls equal or less than 3.5^{o} for a good design [7].

Fabrication And Running of The Wind Tunnel

Wind Tunnel Fabrication

A wind tunnel was built in an attempt to be as much as possible suitable for a wide range of applications and studies concerning of atmospheric sciences such as boundary layers, turbulence, and instruments calibration. This design adopted three main principles: matching standards, low cost, and ease of modification. This tunnel is based mostly on the design proposed by Will Stark [12]. It consists of three key parts: contraction section, test section, and diffusion section. The contraction and diffusion sections were made of plywood whereas the test section made mostly of glass. A schematic view of contraction section is shown in figure (3).

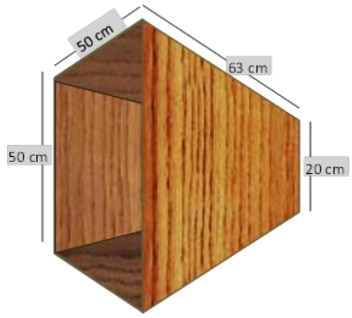


Figure (3) The contraction section

The test section was made of glass except the upper side which was made of a transparent plastic sheet in order to be easily opened and handled. The test section has size of 50 cm, 20 cm, and 20 cm for length, width, and height, respectively.

The diffusion section has size of 87 cm for length. The small lateral side is 20 cm * 20 cm and the large lateral side is 50 cm * 50 cm. The final sketch of the wind tunnel is shown in figure (4).

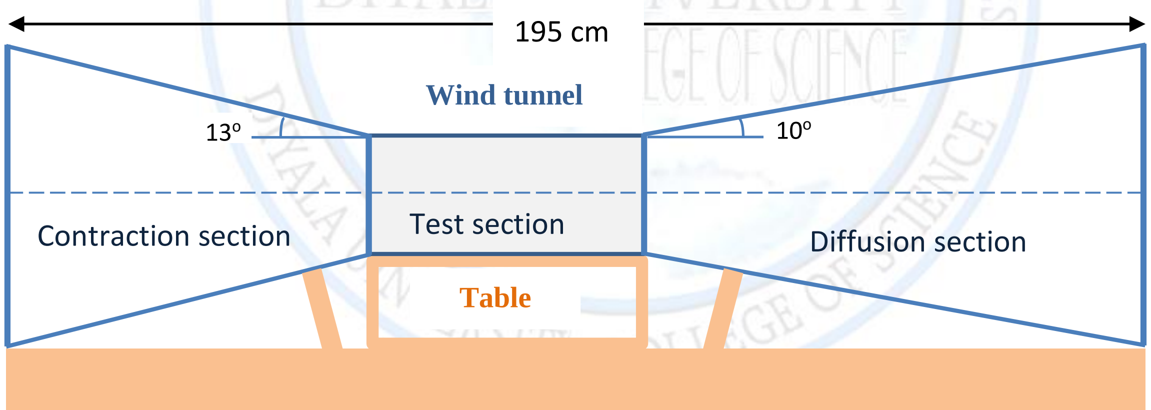


Figure (4) Wind tunnel setting layout

An axial, four blades, 45 cm diameter fan was used to give a suitable air sucking. Among the useful specifications of any fan are the power, number of rotations, and flow rate, which were 230 watt, 1400 cycle per minute, 82 cubic meters per minute, respectively. The appropriate high flow rate enables us to get an air speed reaches up 12 meter per second, which give good representativeness of the real atmospheric wind speed. Juice straws were used as honeycombs and are situated in the inlet of the test section. These have a length of 7 cm and diameter of 0.5 cm and they are properly pasted by glue as a package of 20 cm by 20 cm.

Wind Tunnel Components Assembling

The test section was put at a height of 18 cm and connected from both sides to the contraction section and the diffusion section. Polyurethane foam was used to tightly fasten the joints and voids. A 1.5 cm diameter hole was punched in the upper plastic sheet of test section to insert the probe of hot wire anemometer at 5 cm distance from the diffusion section. The fan was put at the end of the tunnel (diffusion section side) to pull the air out to avoid eddies that are arising from fan blades (Figure 5).

Figure (5) The fabricated design of wind tunnel

Running the Wind Tunnel

The fan was turned on in a highest speed and the hot wire anemometer was used to measure the air speed vertically and horizontally by inserting its probe gradually with steps of 1 cm from the top of the test section. Air temperature records were also made by a certain sensor contained in the same hot wire anemometer. It was found that there is no temperature change due to the movement of air inside the wind tunnel. Many cases of air speed were taken with and without the honeycomb. Figure (6) visualizes the air speed profiles inside the test section for some run attempts. The first attempt was run with the existence of air flow coming directly to the inlet of the wind tunnel from a one meter distant external fan. This was made to find out whether the tunnel is influenced by the air surrounding the wind tunnel. The second and third attempts were run with opened room's door and windows. The fourth attempt was made with closed door and windows. In general, it was found that the air speed profiles in the test section show a gradually decreasing from the bottom to the top of the test section. The decreasing of air speed may due to the unequal fun sucking of air because of its axis. However the air speed still irregularly decreasing up to the upper surface and this may belong to the outflow of air from the hole of the anemometer probe. The non-perfect contact between contraction section and test section is another possible reason. Although the researcher tried his best to correct this drawback, the situation remains as it is.

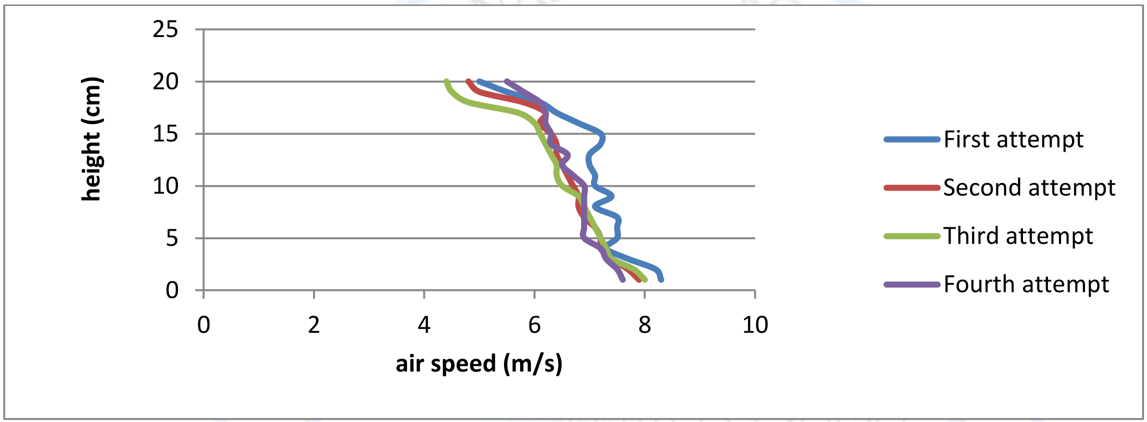


Figure (6) Air speed profiles inside the test section

It is clear that the average air speed is about 7 m/s for all attempts. The four profiles show fairly coincidence suggesting that the tunnel is offering a good isolation of the air flow from the ambient air outside. Another run was made by removing the honeycomb. It was found that the air speeds are higher (average=9.8 m/s) than the previous cases with honeycomb because of the resistance that is caused by the straws (honeycomb) in the air stream. However, the measurements without honeycomb suffer of fluctuations; hence they were not very accurate. The fluctuation is the reason of eddies that are passing in the case of removal of the honeycomb. Air speed in both directions, vertically and horizontally, at certain locations in the test section showed that there are no significant differences in the measurements horizontally as in the measurements in the vertical dimension which decreases upward (figure 7).

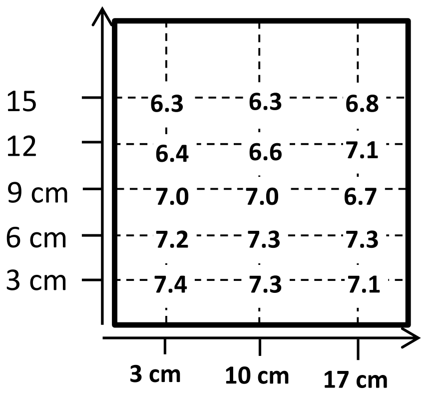


Figure (7) Horizontal and vertical measurements of air speed (m/s) in test section

Two Other Cases

- Measurements of air speed were taken outside the tunnel at distances 10 cm and 50 cm from the center of inlet and outlet to find out the effect of air stream inside the tunnel on the ambient air. In front of the contraction section the air speed was about 0.5 m/s at 10 cm whereas at 50 cm the air speed was zero. In front of the diffusion section, the air speed at 10 cm was about 1.5 m/s and at 50 cm was about 0.5 m/s. These low values of the air speeds confirm that the tunnel air is almost isolated from the ambient air.
- To study the effect of removing the conic shape of the contraction section, an opened distant sides' parallelogram, made of cardboard was put instead of the contraction section. The same vertical measurements of air speed inside the test section were carried with contraction section and then with the parallelogram. The results may properly be shown in figure (8) which clearly indicates that the contraction section is contributing in increasing the air speed.

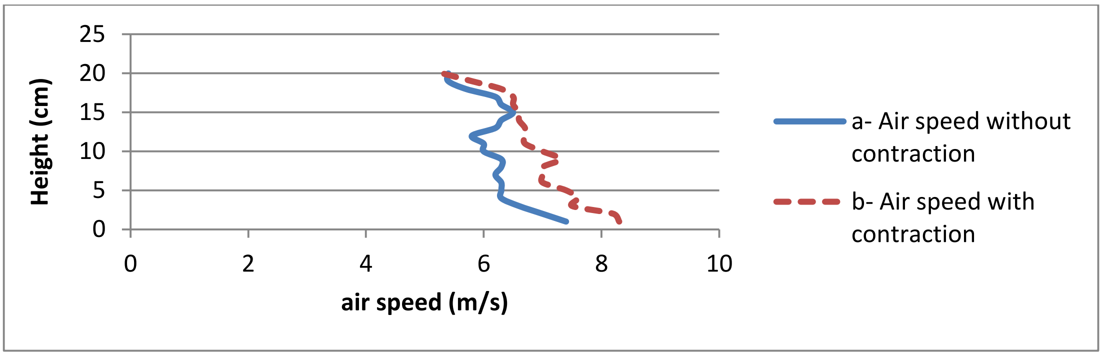
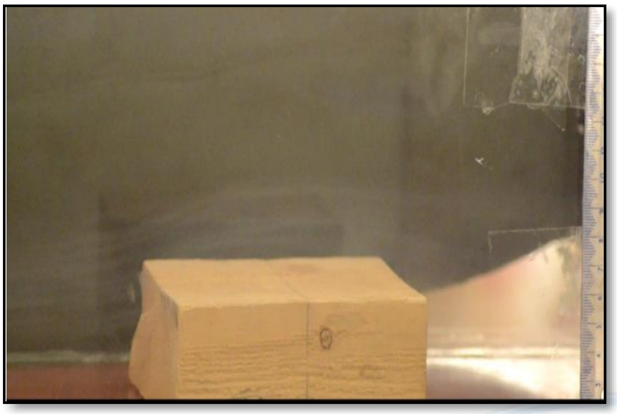


Figure (8) The effect of removing the contraction

Measurements and Visualization of Flow Using Obstacles

To observe the effect of putting an obstacle in the air stream inside the test section, a wooden parallelogram was put on the ground, at the middle of, the test section. The size of the wooden piece is (13 × 10 × 4.5) cm in a situation that the smaller side is facing the air flow direction as in figure (9). A lot of incense sticks were used to make smoke to give the air flow a visual effect. The graph which describes the relationship between the air speed and height at the presence of the obstacle is shown in figure (10). Making the x-axis represents the air speed and the y-axis represents the height enable us to mimic the real situation of the air flow in the test section. It is obvious that the speed is increased rapidly in the vicinity of the obstacle. Then because of the eddies that causes mixing of the air just above the obstacle, the air speed remains almost constant then to decrease after that due to the friction with the upper surface.



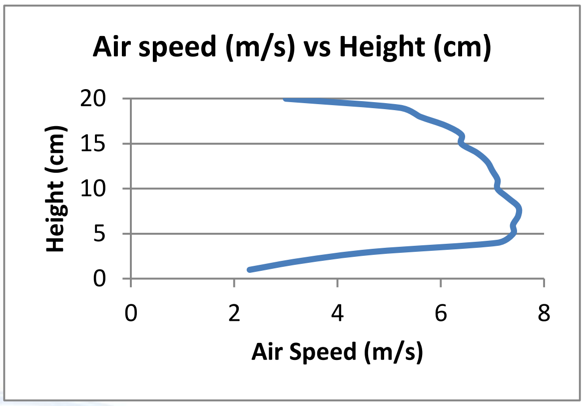
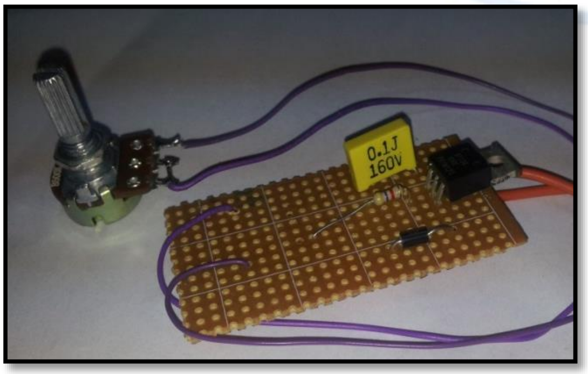


Figure (9) Air flow around an obstacle **Figure (10) Air speed profile**

Measurements of Air Speed by Changing the Input Voltage

An electronic circuit was made to offer the capability to change the input voltage of the fan and thus the air speed. This circuit bears a current reaches up to 12 amperes (figure 12). The air speeds relating to changing voltages were recorded as in table (1). Figure (13) shows the relationship between the input voltage and air speed. It clearly shows that the air speed is proportional to air speed which is very expected. The usefulness for this relationship is being in the possibility to use it as a reference profile for instruments calibration. By using this calibration, it is easy to use the wind tunnel to calibrate or check the instruments without using any anemometer since the air speed is becoming known and related to input voltage. The tunnel, furthermost, offers the facility of the calculation of the volume flow rate which is the air speed multiplied by cross section area of the test section.



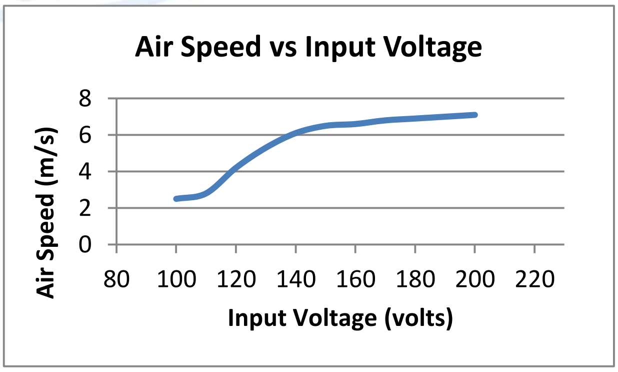


Figure (12) Electric circuit **Figure (13) Air speed vs input voltage**

Table (1) Input voltages versus the corresponding air speed and volume flow rate

Input voltages (volts)	100	110	120	130	140	150	160	170	180	190	200
Air speed (m/s) at 10 cm	2.5	2.8	4.2	5.3	6.1	6.5	6.6	6.8	6.9	7	7.1
Flow rate volume (m^3/s)	0.1	0.11	0.16	0.21	0.24	0.26	0.26	0.27	0.27	0.28	0.28

Calculation of Air Speed by Using Bernoulli's Principle

Bernoulli's principle can be used to calculate air speed at the of diffusion exhaust. This principle cannot be used without the assumption of the incompressible air. To assure that the air is incompressible one can estimate Mach number (should be less than 0.3), from equation (1):

$$M = \frac{Air\ speed}{Sound\ speed} = \frac{7\frac{m}{s}}{343.59\frac{m}{s}} = 0.02$$

This value is clearly less than 0.3, thus the air inside the tunnel is incompressible. As such, Bernoulli's principle was suitable for calculation of air speed. For air speed value inside the test section equal to 7 m/s, the air speed at the exhaust of diffusion section may be used by the following equation:

$$A_{Diffuser}\,V_{Diffuser} = A_{Test\ section}\,V_{Test\ section} \quad (3)$$

$$0.45\ m \times 0.45\ m \times V_{Diffuser} = 0.2\ m \times 0.2\ m \times 7\frac{m}{s}$$

$$V_{Diffuser} = 1.38\ \frac{m}{s}\ ,$$

this calculated value is close to the measured value.

Conclusion

The fabricated wind tunnel is made from inexpensive materials but it follows the scientific design structure and is suitable to carry out scientific experiments in the laboratory of atmospheric boundary layer. It gives air flow speeds similar to the average atmospheric wind velocity (up to 12 m/s) and hence one can use it to stimulate real phenomena. Four attempts with different conditions were used to study the air speed profiles inside the test section. In these cases, the air speeds in the tunnel decrease upward slightly and do not take the same trend because of the effects of the unequal air coming out the fun and because of air leakage. However, the air stream in the tunnel is still flowing in reliable manner. No significant differences were found among the last four cases suggesting that the tunnel is properly insulated from the ambient air. The research has proven that the straws (honeycomb) were essential to make the air stream more laminar and steady. However, the honeycomb makes the air speed slower because of the friction effect. There are no differences in the air speeds inside the test section in the horizontal dimension. The wind tunnel was not significantly affected by the ambient air and hence is highly isolated from the surroundings. This wind tunnel is suitable to visualize the air stream around obstacles in the test section by using smoke, so one can use it to observe and study the effect of the air on models, structures, topography, and wind plants. This work proved the importance of using contraction section which enhances the air speed inside the tunnel. By changing the input voltage of the fun, it was easy to calibrate the air speed inside the test section with the input voltage. This founding is useful to calibrate any anemometer. Calculation of Mach number gives a value of 0.02 which confirms that the air inside the tunnel is incompressible.

References

1. Libii, j. N., 2011: Wind tunnels and experimental fluid dynamics research. InTech, Croatia, pp260.

2. Lohan, J. D, 2002: Low speed wind tunnel design. June issue of “Z-Uutiset”, Trade Magazine published by ZIEHL-ebm Oy, Finland.

3. Lindgren, B. and A. V. Johansson, 2002: Design and evaluation of a low-speed wind- tunnel with expanding corners. *October 2002 Technical Reports from Royal Institute of Technology, SE-100 44*, Stockholm, Sweden.

4. Cattafesta, L., C. Bahr, and J. Mathew, 2010: Fundamentals of Wind-Tunnel Design. Encyclopedia of Aerospace Engineering, John Wiley and Sons.

5. Rona, A., 2010: Boundary layer trips for low Reynolds number wind tunnel tests. 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition 4-7 January 2010, Orlando, Florida.

6. Barlow, J. B., W. H.Rae, A. Pope, 1999: Low-speed wind tunnel testing. John Wiley & Sons, INC. 3rd ed., Canada, pp277.

7. Mehta, R. D. and P. Bradshaw, 1979: Design rules for small low speed tunnels. Technical Notes. The Aeronautical J. Royal. Aero. Soc., 443-449.

8. Pereira, J. D., 2011: Wind tunnels: Aerodynamics, Models and experiments. Nova Science Publishers, Inc. New York, pp277.

9. Fox, R. W., A. T. McDonald and P. J. Pritchard, 2004: Introduction to fluid mechanics. John Wiley and Sons, INC., 6th ed., pp 787.

10. Boudreau, H. S., 2009: Design, construction, and testing of an open atmospheric boundary layer wind tunnel. Summa Cum Laude Thesis, University of Florida.

11. Gorlin, S. M. and I. I. Slezinger, 1964: Wind tunnels and their instrumentation. NASA, pp592.

12. Stark, W., 2011: Building and testing tunnel. J. Student Res. Writing from Menlo School, 8, 79-92.