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MEASUREMENT OF TURBULENCE LEVEL IN THE TEST SECTION OF ITU TRISONIC WIND TUNNEL AT SUPERSONIC SPEEDS

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ABSTRACT

The turbulence level in wind tunnels is an important parameter for the experiments to be conducted. The purpose of this research is to obtain a measure of the turbulence intensity in 15×15 cm Trisonic Wind Tunnel at Istanbul Technical University (ITU) by means of fluctuating pressure measurements with a pitot probe. The measurement instrument was created by designing a pitot probe for supersonic speeds and by mounting a miniature dynamic pressure transducer to that pitot probe. In the first phase of the study, the pitot probe was mounted on the test section floor at the center location of cross-stream direction in order to measure the fluctuating total pressure along a vertical line between the floor and the ceiling of the test section. In the second phase, the pitot probe was mounted to side walls of the test section in order to observe the turbulent intensity variation on a plane which is perpendicular to the flow direction. In both cases, measurements were conducted at three nominal Mach numbers of 1.6, 1.8, and 2.1. Results indicated that the measured freestream turbulence levels of the wind tunnel calculated by averaging along the vertical center line and over the cross-stream plane were 0.93%, 0.76% and 0.71% for Mach 1.6, 1.8 and 2.1, respectively. Near the wall, pressure fluctuatios were affected by the interaction of incoming turbulent boundary and the strong bow shock wave that formed in front of the probe tip. The reason for the effect of this interaction is so great is that the probe is not designed to measure within the boundary layer. As a conclusion, turbulence level, an important parameter of the wind tunnel flow, was determined for ITU Trisonic Wind Tunnel in this study.

INTRODUCTION

Turbulence is still the most challenging problem for fluid dynamics [Cloutman L.D., 1999]. Both for the internal and external flow, it is important to understand the nature of it. Many experimental and computational studies have been performed to better understand the nature of turbulence [Roshko A. 1976]. There are great uncertainties in the theoretical ratios of heat transfer, turbulent mixing and other phenomena of practical interest. In incompressible flow, turbulent fluctuations influence velocity field and pressure, but in compressible flow they also have an effect on density and temperature. Turbulence level of a wind tunnel is an important information for the determination of the flow quality in the test section. Many studies have been conducted to measure and assess the turbulence characteristics in wind tunnels. For a proper comparison of wind tunnel experiments, turbulence level of the tunnels must be known so that experimental models can be utilized for real cases [Shaw R., Lewkowicz A.K., Gostelow J.P. 1966]. In a fully-developed channel and pipe flow, compressibility effects on turbulence structures have been investigated by direct numerical simulation and large-eddy simulation tools [Friedrich R. 2007]. Hot-wire measurements were obtained in various supersonic flows to obtain fluctuation diagrams [Kovasznay L. S. G., 1953]. To be able to measure the

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turbulence intensity of the tunnel, there are a couple of experimental techniques such as hot-wire and probe pressure measurement. In order to examine the test section turbulence level, measurements need to be made in specific locations in both freestream region and turbulence boundary layer near the tunnel wall [Gilder N., Santos C., Jabardo P. J. S., Cardoso M., Taira N. M., Pereira T. M., 2006]. A work was done to qualify a supersonic wind tunnel by using a various measurement techniques and all the measurement techniques implemented in that study were introduced [Bottini H., Paniagua G., Schreivogel P., Sonda A. and Heras S., 2014]. In another study, characterization of the low turbulence wind tunnel of Anemometry Laboratory of IPT was presented and turbulence intensity was obtained less than 0.4% [Nader G., Santos C., Jabardo P. J. S., Cardoso M., Taira N. M., and Pereira M. T., 2006]. In addition, Elliott and Samimy proved that the turbulence level fluctuations decrease with the increasing Mach number [Elliott G.S and Samimy M.,1990]. At supersonic speed, turbulence intensity of a good quality wind tunnel must be below 1% [Bottini, H., Paniagua,G., Schreivogel, P., Sonda and Heras S., 2014]. For high quality flow and accurate data, up to 0.5% turbulence level is needed in the test section. The intensity of the pressure fluctuations is commonly characterized by the rms (root mean square) of the unsteady signal. For high-speed experiments, normalization to Mach number is commonly used because of its convenience of measurement in comparison to shear stress and its practicality in engineering applications [Beresh S. J., Henfling J. F., Spillers R. W. and Pruett B. O. M., 2011]. Standard deviation alone, cannot give consistent information because it is in pressure unit and it varies significantly with position and Mach number. Hence, standard deviation of the calculated Mach number from the measured pressure can be normalized with mean Mach number [Trunkle J., Taifour, A., Weiss J., 2015].

In the present study, data acquired from the measurements were processed using a MATLAB script prepared in house to calculate the Mach number and speed by means of pressure and temperature data. In the analysis it is assumed that the rms of the instantaneous speed values calculated from the instantenous total and static pressure and temperature values is a measure of turbulence intensity. Before each run, data with no flow were acquired to avoid the deviation of the calibration curves of transducers from the origin. In order to calculate Mach numbers, standard supersonic flow theory applied to a pitot tube has been implemented. A bow shock forms in front of the pitot tube when the flow is supersonic. Pitot probe measures the total pressure behind the shock wave and the tunnel static pressure is also measured on the side wall of the test section during experiments. From the relation between probe total pressure and freestream static pressure, Mach number in supersonic regime, at the probe location can be calculated correctly by using the *Rayleigh-Pitot* equation given below:

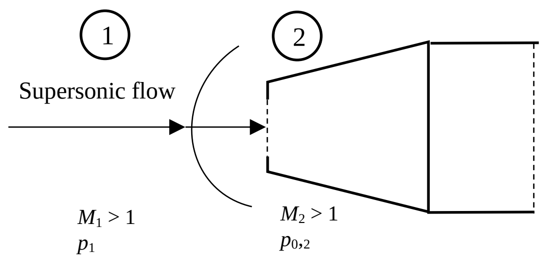


Figure 1: Pitot tube and shock wave [Anderson, J. D., 2001].

$$\frac{p_{0,2}}{p_1} = \left(\frac{(\gamma+1)^2 M_1^2}{4\gamma M_1^2 - 2(\gamma-1)}\right)^{\frac{\gamma}{\gamma-1}} \left(\frac{1-\gamma+2\gamma M_1^2}{\gamma+1}\right) \quad [1]$$

When the Mach number in the test section reaches the expected Mach number the pressure data from the probe were collected for approximately 2.5 seconds. Total temperature data are also collected during the experiments. Assuming an isentropic process, static temperature can be determined from the equation given below:

$$\frac{p_{0,1}}{p_1} = \left(\frac{T_0}{T_S}\right)^{\frac{\gamma}{\gamma-1}} \qquad [2]$$

Using the static temperature, the speed of sound, a, is calculated using $\sqrt{\gamma R T_s}$ where γ is the ratio of specific heats and R is the specific gas constant. The flow speed is in turn obtained from the Mach number and the speed of sound for each experiment by simply $u = M/a$. [Goebel S. G., Dutton J. C., 1991]. Turbulence Intensity (T.I) is a measure characterizing turbulence expressed as a percent [Shaw R., Lewkowicz A.K., Gostelow J.P. 1966].

$$\text{T.I} = \frac{u'}{\bar{U}} \times 100 \qquad [3]$$

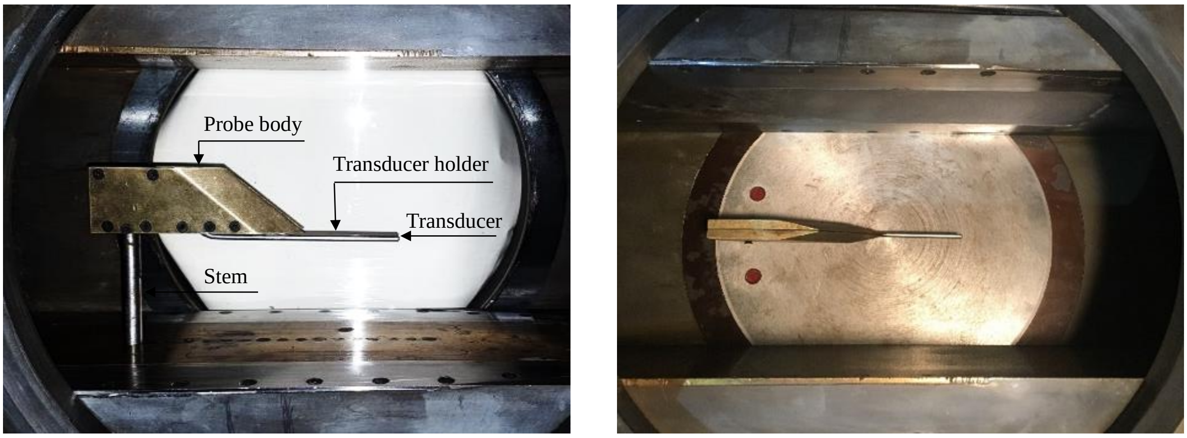
where u' is the root-mean-square (rms), or standard deviation, of the turbulent velocity fluctuations at a particular location over a specified period of time and $\bar{U}$ is the average of the velocity at the same location over same time period. In this study, velocity values at the probe location were obtained from the measured instantaneous pitot pressure values. Even though the static pressure and the total temperature both which are used to calculate velocity, are measured simultaneously, these are not local values at the probe location. Therefore the velocity obtained thus far does not truly give the actual local instantaneous value, but with its fluctuating character coming from the probe instantaneous total pressure, provides a good indication of local turbulence intensity. Therefore, turbulence intensity (T.I) values reported in this study are obtained in this fashion and should not be taken as standard turbulence intensity which is obtained from standard velocity measurements such as hot wire anemometry.

EXPERIMENTAL SETUP

Experiments were carried out in the trisonic blowdown wind tunnel at the Istanbul Technical University. The wind tunnel air is supplied by tanks with a volume of 90 m^3 at a pressure of about 2.7 MPa. Tests were conducted at temperature of approximately T_0 = 296 K and freestream pressure of p_∞ = 0.49 atm p_∞ = 0.45 atm and p_∞ = 0.29 atm for Mach numbers 1.6, 1.8 and 2.1. The nominal values of the freestream Mach number and velocity were 1.6, 1.8 and 2.1 and 448 m/s, 487 m/s and 556 m/s, respectively.

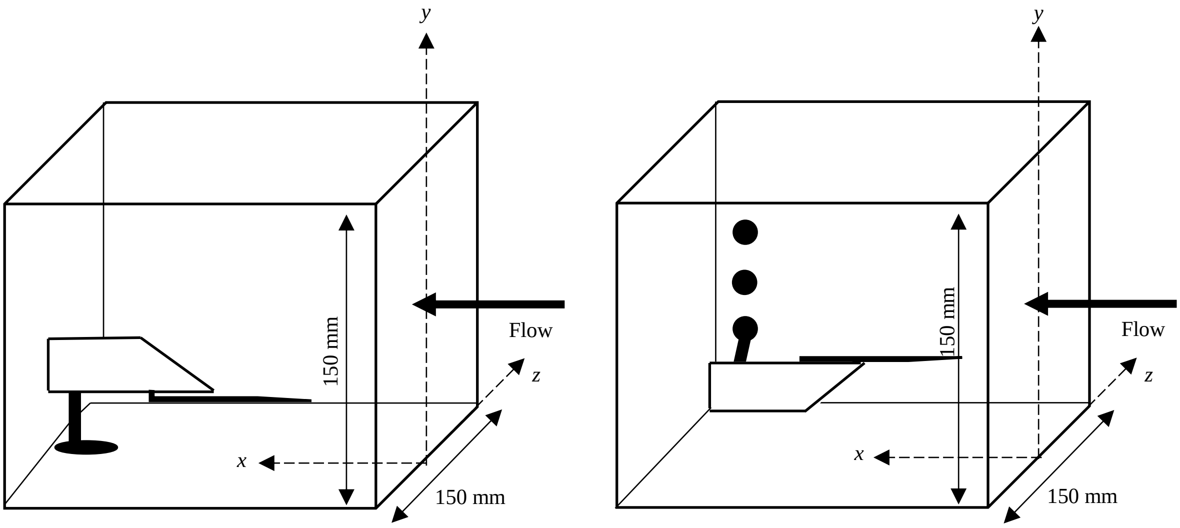
As shown in Figs. 2a and 2b, pitot probe was designed and manufactured to operate at speeds of Mach 1.6, 1.8 and 2.1. Pitot probe is an assembly of four parts, namely probe body, stem, transducer holder and the transducer. Probe body is a bolted assembly of two pieces of plates. When these plates mounted to each other, forms a small cavity inside to store the wires, connectors and temperature compensation module. The leading edge of the probe body has a 40-degree sweep-back angle and 14-degree sharp-edged side ramps. Stem is a simple pipe with a diameter of 10 mm and its purpose is to carry the probe as well as to adjust the location of probe. Transducer holder is also a simple tube with a diameter of 3.4 mm and it has a small cavity at its tip to insert the transducer into it. This design and geometric dimensions were chosen so that no distortions occur in the flow around the transducer an thus pressure was measured directly and correctly.

The fluctuating total pressure was measured using a fast-response pressure transducer placed at the tip of the pitot probe. Pressure transducers also known as pressure transmitters, are devices that transform values of pressure into equivalent analog electrical signals. Two Kulite brand miniature pressure transducers were used in this study. The XCQ-080-100A model transducer was used for the first three sets of experiments and the XCEL-072-50A model was used for the rest measurements. XCEL-072-50A and XCQ-080-100A transducers have a pressure range of 0-3.4 bars and 0-6.8 bars, respectively. The transducers both operate at absolute pressure mode. Fluctuating pressure data were acquired at a rate of 200 kHz with a National Instruments PCI-6110E A/D data acquisition card (DAQ). The DAQ card was controlled by a in-house LabVIEW code.



(a) (b)

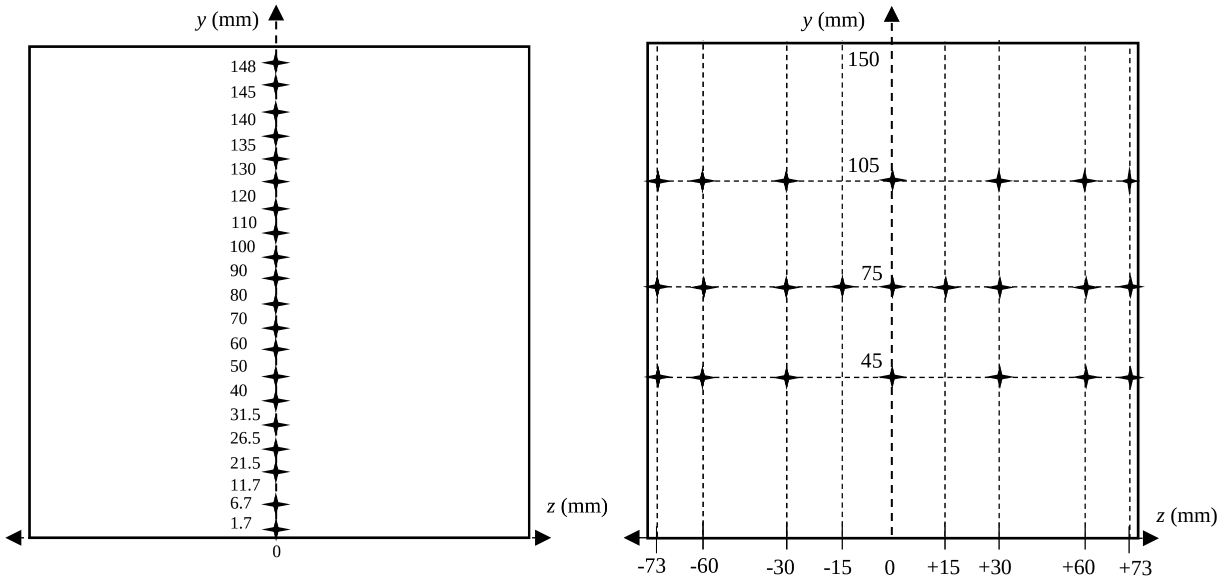
Figure 2: a) Pitot probe model mounted to the test section floor, b) Pitot probe model mounted to the test section side wall.



(a) (b)

Figure 3: a) Sketch of the floor mounted pitot probe, b) Sketch of the side wall mounted pitot probe

In the first phase of the study, the pitot probe was mounted on the test section floor at the center location of cross-stream direction as given schematically in Fig.3a. From the starting point (x = 0, y = 1.7 and z = 0 mm) which is slightly above the tunnel floor pitot probe was elevated with 5 mm intervals until it was reached to final point (x = 0, y = 148 and z = 0 mm). In Fig. 4a, the vertical positions of the probe along the y-axis is shown by the distance values from the floor for the first phase experiments. In the second phase, the pitot probe was mounted to side walls of the test section as shown schematically in Fig. 3b. Measuremets were conducted for seven different z locations at y = 45 mm and y = 105 mm, and for nine different z locations at y = 75 mm on the z direction. In total, fluctuating pressure was measured at 23 different points on a plane which is perpendicular to the flow direction. At each point, shown in Fig. 4b, total pressure fluctuations were measured for three different freestream Mach numbers.



(a) (b)

Figure 4: a) Measurement points along the vertical line. b) Measurement points over the test section.

RESULTS

It is aimed to get tangible information regarding the flow quality (turbulence levels) of the ITU trisonic wind tunnel. In the first phase of the study, instantaneous pitot pressures were measured along the vertical (*y*-axis) direction on the symmetry plane of the test section. However, as the probe was raised to higher *y* values the stem of the model has covered a larger area within the test section and thus generated a high blockage which prevented making succesfull measurements. At M = 1.6, a detached shock wave occurred in front of the probe above certain probe vertial positions, and as a result measurements could not be conducted accurately in the region between y = 130 mm and 150 mm. From the instantaneous pitot pressure data (and from overall static pressure and total temperature values) local Mach numbers and velocities were calculated at the measurement points for three different nominal tunnel Mach numbers of 1.6, 1.8 and 2.1. Turbulence intensity variation (as defined and described above for this study) along the *y*-axis at the middle of the tunnel test section are given for all three Mach numbers in Fig 5. The average freestream turbulence levels at Mach numbers 1.6, 1.8 and 2.1 are 0.72%, 0.61% and 0.55%, respectively. Inside the boundary layer regionon the floor of the test section the turbulence level increases up to 20%. This can be due to th fact that the bow shock wave formed in front of the probe tip interacts with boundary layer on the floor and generate these high fluctuations. Neverthelles, considering the low values of turbulence within the freestream outside the boundary layers these results indicate that the tunnel can be approved to have a good quality flow for a supersonic wind tunnel. In this study, the tunnel was operated separately at each measurement location and for all three speed values. At each run, tunnel throat area is settled at a slightly different position giving a slightly different Mach number due to the uncertainties and tolerances in the throat adjustment mechanism. For this reason, it is not possible to obtain exactly the same Mach number value in different experiments and there is always a small difference in the values. In order to compansate for this run-to-run variation Mach numbers measured by the probe in each run are normalized using the actual tunnel Mach number obtained for a given run. Vertical distribution of the normalized local Mach number for tunnel nominal Mach numbers 1.6, 1.8 and 2.1 are given in Figs. 6a, 6b and 6c, respectively. These profiles give a good idea about the boundary layer thickness and the freestream region can be determined clearly.

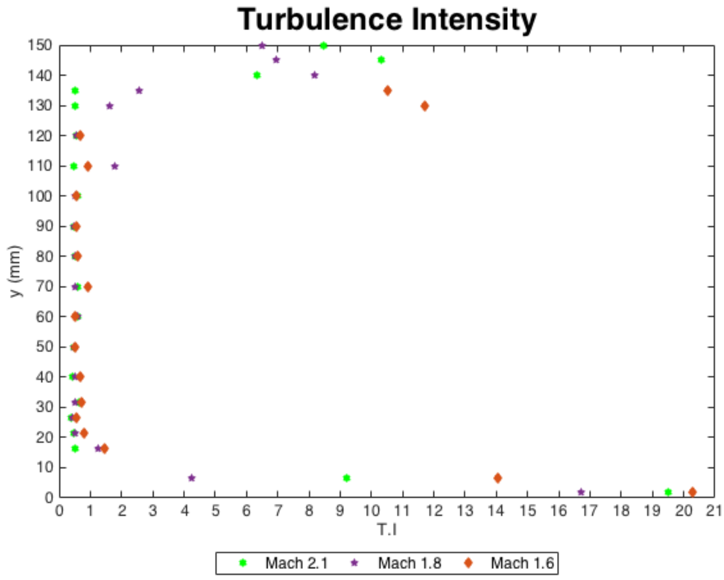


Figure 5: Turbulence intensity distribution along the y-axis for Mach 1.6, 1.8 and 2.1.

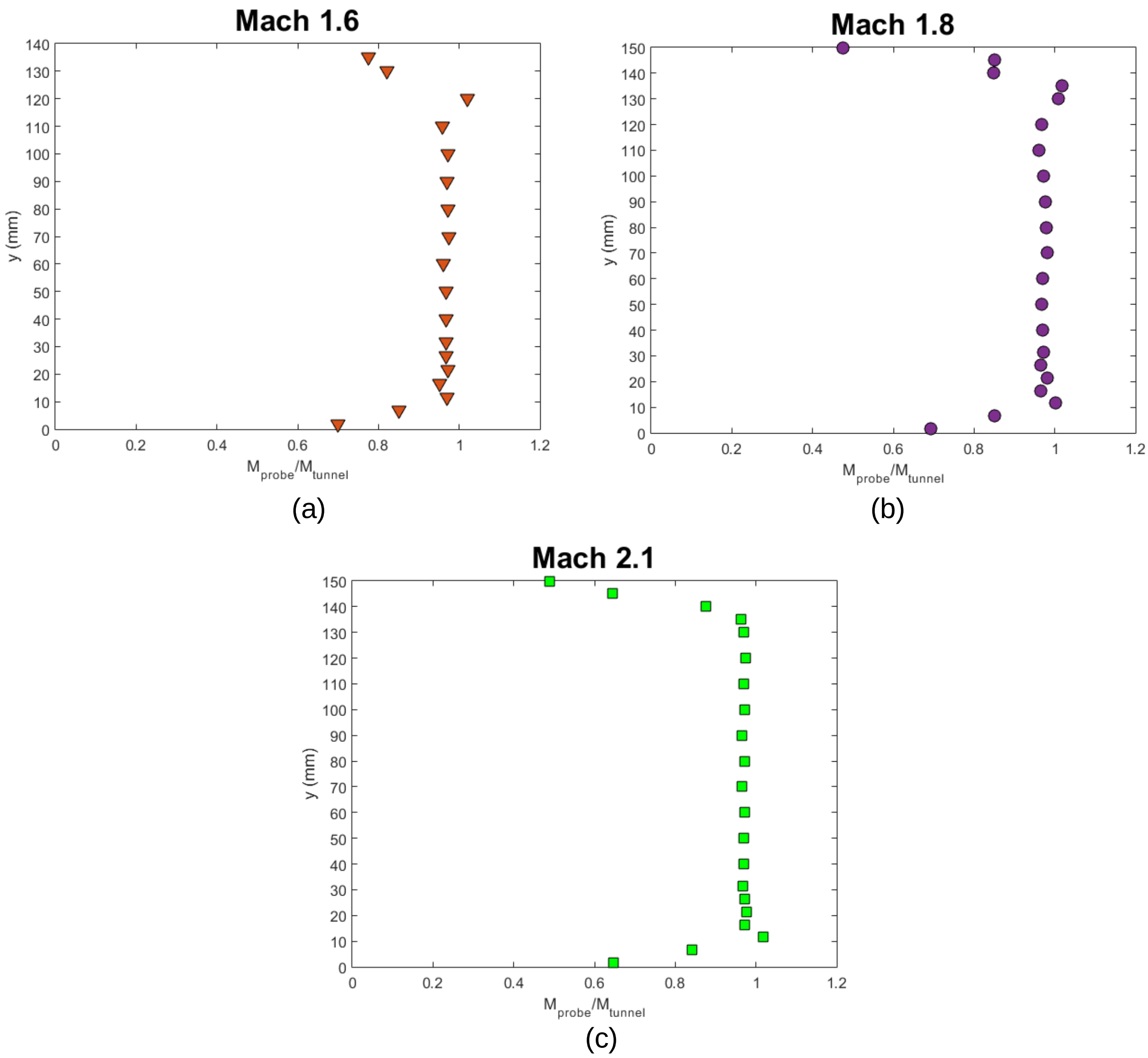


Figure 6: Normalized Mach number profiles along the y-axis for Mach numbers (a) 1.6, (b) 1.8 and (c) 2.1.

In the second phase, the pitot probe was mounted to side walls of the test section and pressure measurements were carried out at 23 locations on the perpendicular plane to the flow direction. On both sides of test section, at three positions along the *y*-axis measurements were performed at the closest location (y = 73 mm and y = -73 mm) to the side walls and we observed similar results with the previous experiments that were conducted in the first phase. The average freestream turbulence levels on the plane for Mach numbers 1.6, 1.8 and 2.1 are 1.15%, 0.92% and 0.88%, respectively. The difference in turbulence level values between two phases can be due to both two dimensionality effect, randomness and unpredictable nature of the turbulence. Turbulence intensity distributions over the chosen plane for Mach numbers 1.6, 1.8 and 2.1 are given in Figs. 7, 8 and 9, respectively. Fairly uniform distribution in the freestream region and due to the reasons explained earlier, high values were observed in the regions near the walls. As it is expected, the flow for the speed of Mach 1.6 is more turbulent and has a thicker wall boundary layer than for Mach 2.1 [Beresh S. J., Henfling J. F., Spillers R. W. and Pruett B. O. M., 2011].

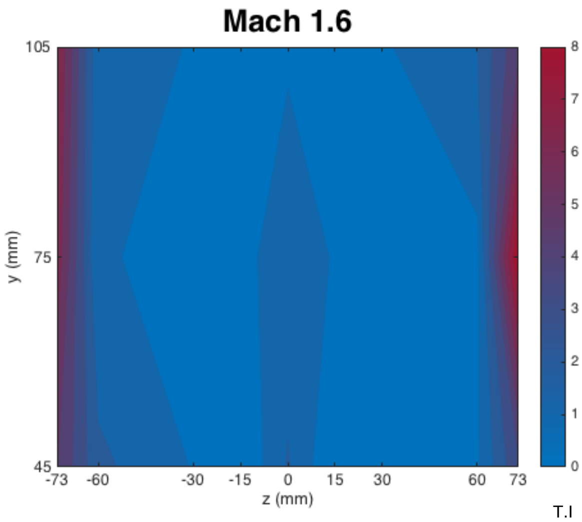


Figure 7: Turbulence intensity distribution over the test section at Mach 1.6.

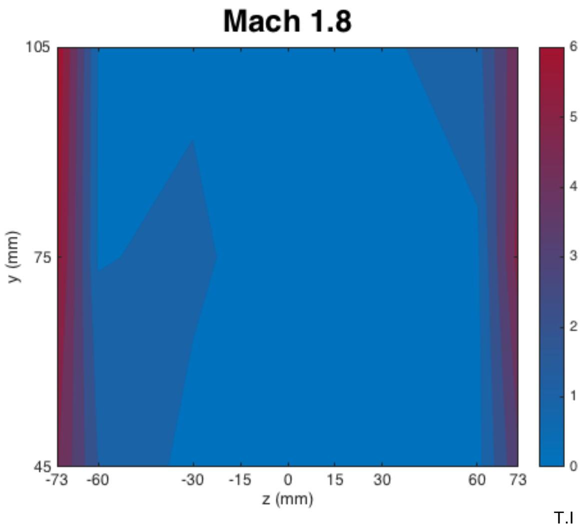


Figure 8: Turbulence intensity distribution over the test section at Mach 1.8.

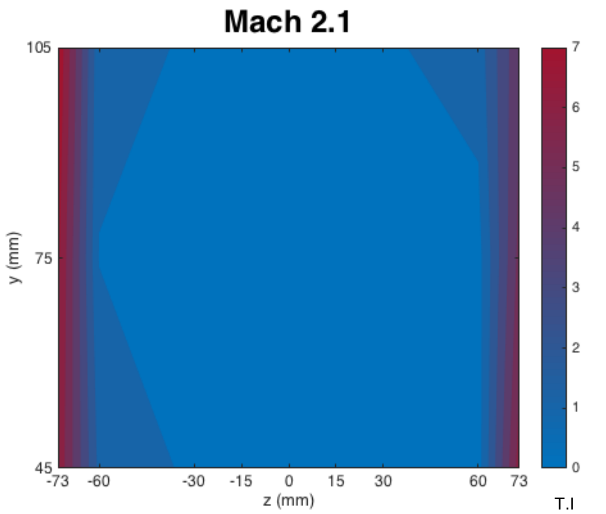


Figure 9: Turbulence intensity distribution over the test section at Mach 2.1.

Normalized Mach distributions over the chosen plane at Mach numbers 1.6, 1.8 and 2.1 are given in Figs. 10, 11 and 12, respectively. For each speed, Mach number distributes quite uniformly outside the side walls' boundary layer.

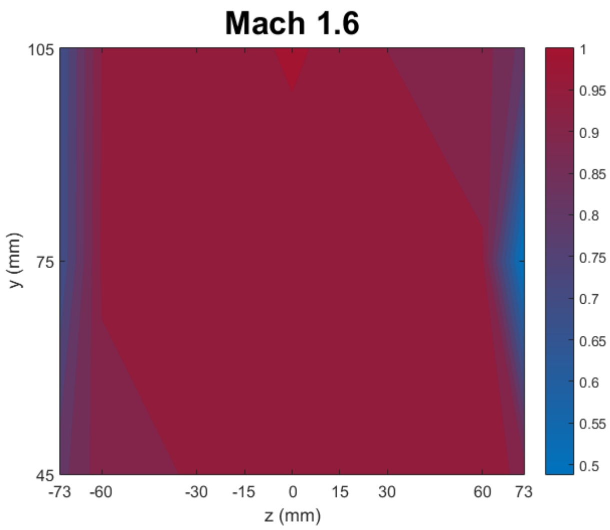


Figure 10: Normalized Mach number distribution over the test section for Mach 1.6.

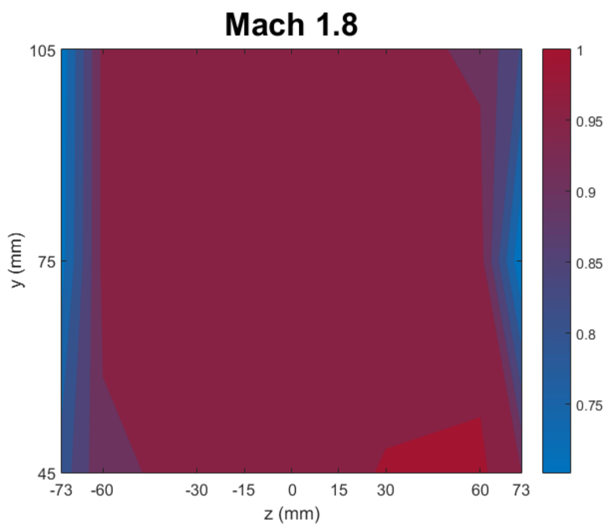


Figure 11: Normalized Mach number distribution over the test section for Mach 1.8.

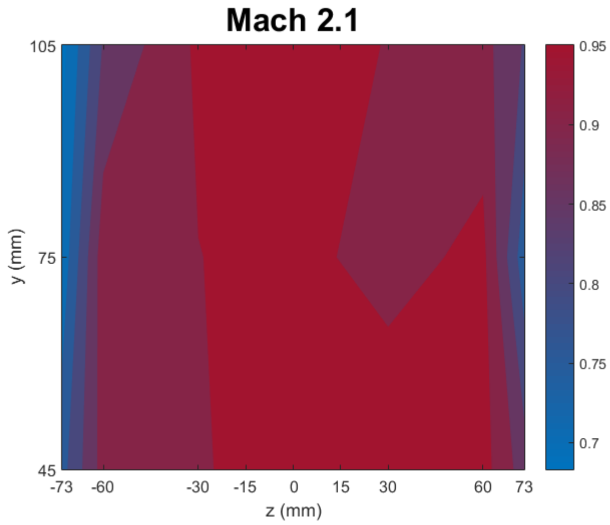


Figure 12: Normalized Mach number distribution over the test section for Mach 2.1.

CONCLUSION

Fluctuating total pressure measurements were conducted to observe both the mean turbulence level values and the distribution of turbulence level for Mach numbers 1.6, 1.8 and 2.1 in 15×15 cm Trisonic Wind Tunnel at Istanbul Technical University. The results obtained from this study provide an important information, a measure of turbulence intensity obtained from instantaneous local pitot pressures, as an indication of flow quality of the wind tunnel. Experiments were carried out by implementation of an in-house-designed and manufactured pitot probe, that can perform dynamic measurements at certain different locations in the test section of the tunnel. The average freestream turbulence levels along a vertical line in the center plane of the test section for Mach numbers 1.6, 1.8 and 2.1 are 0.72%, 0.61% and 0.55%, respectively. Over a cross-flow plane in the test section the average freestream turbulence levels on the plane for Mach numbers 1.6, 1.8 and 2.1 are 1.15%, 0.92% and 0.88%, respectively.The mean value of turbulence intensity in the freestream from the two measurement campaigns were obtained as 0.93%, 0.76% and 0.71% for Mach numbers 1.6, 1.8 and 2.1, respectively. The turbulence intensity results near the walls of the test section appeared too high which is probably due to the interaction between the bow shock in front of the probe tip and the boundary layer on the walls. The thickness of the boundary layer on the the test section walls was observed as approximately 10%, 8% and 6% of the test section total height for Mach numbers 1.6, 1.8 and 2.1, respectively. It can ben concluded that at supersonic speeds the flow in the tunnel test section is in the ‘quality’ class.

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