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REDUCTION OF WIND TUNNEL TURBULENCE INTENSITY BY INSTALLATION OF A HONEYCOMB STRAIGHTENER - CFD SIMULATION VS EXPERIMENT

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Abstract

Although CFD solvers can alone be used for complex 3D flow field analysis, their integration with an experiment is necessary for results validation. This approach allows to combine the robustness and possibilities of CFD with an accuracy of wind tunnel tests. Having a newly upgraded wind tunnel in the Institute of Turbomachinery (IMP) at the Technical University of Łódź (TUL), a series of CFD simulations has been performed in order to indicate the areas of possible flow quality improvement. One of the objectives was to minimize the turbulence intensity with the lowest possible pressure loss. The main reason of diminishing the flow velocity disturbances is the need for ensuring a good flow quality, well representing real life conditions modeled in the wind tunnel experiment. It is also required in order to perform the PIV experiment (PIV wind tunnel stand is under development at TUL).

There are two main methods of turbulence damping: reduction grids and honeycombs. Due to the fact that the tunnel was already equipped with flow stabilization section containing two mesh-wired screens (reducing mainly axial velocity fluctuations) it was decided to introduce the honeycomb section in order to diminish the lateral turbulence intensity. It is believed that application of the honeycomb structure (having optimum length to diameter ratio l/d of the cell) with a combination of existing screens should decrease the level of turbulence significantly. Additionally, CFD simulations were performed in order to gain information about the level of turbulence reduction and the associated pressure loss. The paper presents results from both: the measurements of turbulence intensity and pressure loss before and after the installation of the honeycomb in the IMP wind tunnel, as well as the associated simulation results conducted for a WT model (virtual WT) in ANSYS CFX 13.0/14.0.

Key words: Computational Fluid Dynamics (CFD), Wind Tunnel, Honeycomb

NOMENCLATURE

Parameters

β	Cross-section area ratio available for flow
γ	Relative turbulence reduction ratio
μ	Viscosity
ρ	Density
f	Turbulence reduction ratio

k Turbulent kinetic energy

K Pressure loss coefficient

K_{loss}^{S} Streamwise loss coefficient, [kg/m^4]

K_{loss}^{T} Transverse loss (streamwise loss coefficient multiplier)

K_{perm}^{S} Permeability in streamwise direction

K_{perm}^{T} Permeability in transverse direction

p Pressure

Q Volume flow rate

Re Reynolds number

S_M Momentum loss

t Time

Tu Turbulence intensity

U Freestream velocity

x,y,z Cartesian coordinates

Abbreviations

CFD Computational Fluid Dynamics

IMP Institute of Turbomachinery

PIV Particle Image Velocimetry

TUL Technical University of Lodz

WT Wind Tunnel

INTRODUCTION

Analysis of fluid motion is a vital aspect of numerous engineering applications. However, theories on phenomena like turbulent flow or boundary layer are still incomplete or not fully understood. Some assumptions can be made regarding certain fluid properties but the result will not show an exact representation of a real flow.

In aerodynamics, there is a necessity of supplementing the theory with an experiment - particularly to study a flow in a wind tunnel (WT). It offers a rapid, economical and reliable mean of flow study. Its main advantage over theoretical study is that during an experiment, although recreated artificially, the real flow is being investigated. To ensure the good flow representation one should have in mind how the accuracy of the results is influenced by the level of turbulence intensity in the subsonic wind tunnel. In order to decrease the turbulence levels, installation of flow manipulators such as screens and/or honeycombs is proposed (Scheiman et al., 1981).

During the last two decades, the computational fluid dynamics models have emerged as a reliable and powerful tool to model and examine different kinds of liquid and gas flows (Kulak, et al., 2011). Beside that fact, CFD is a perfect way to validate field measurements or wind tunnel tests. The results of simulations can be either used to support the WT data or even to be directly used to understand the specific case studies not easy to measure (Huber, 2004). The accuracy of these tools still must be proved, especially when the complex turbulent fluid flows appear.

The following paper consists of short presentation of the newly upgraded wind tunnel in the Institute of Turbomachinery (IMP) at the Technical University of Lodz (TUL) and the results from the measurements of turbulence intensity before and after the installation of the honeycomb. Also the associated simulation results conducted for a WT model (virtual WT) in ANSYS CFX 13.0/14.0 are presented.

FACILITY

Wind tunnel at the Institute of Turbomachinery (Instytut Maszyn Przepływowych - IMP) was designed to operate in low speed range (Ma < 0.3). Its original application was investigation of turbine blades cascade (Porochnicki et al., 1977), where boundary layer flows and laminar-turbulent transition were a primary focus. The last documented use of the wind tunnel, basing on available documentation, dates to the early 1990s. The tunnel can be described as an open-return, blow-down type wind tunnel. Both original and current designs posses a closed section located at the tunnel outlet. Air leaving the tunnel enters laboratory room in which a flow loop is being closed drawing the air back at the inlet channel. Access to the wind tunnel is possible from two building floors. Figure 1 presents a schematic view of the installation.

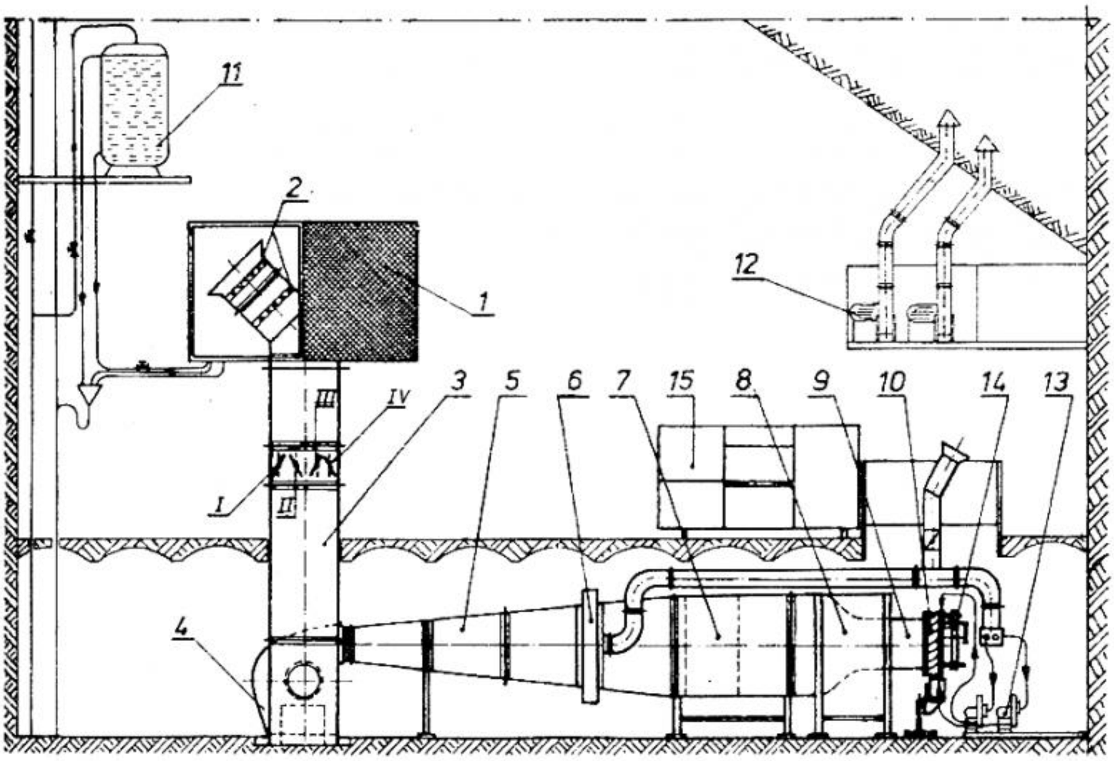

Figure 1 Scheme of the wind tunnel at Institute of Turbomachinery (original layout)

The wind tunnel is supplied by a centrifugal fan of nominal flow rate $Q=6.25m^3/s$ and total pressure of $p_c=6.55kPa$ powered with 55kW asynchronous motor.

Initial measurements of turbulence intensity at the WT outlet showed that in the test section there exist a quite considerable amount of turbulent kinetic energy. Figure 2 presents a record of one of the measurement sessions, where turbulent velocity fluctuations reach a level of more than 2% of the average value.

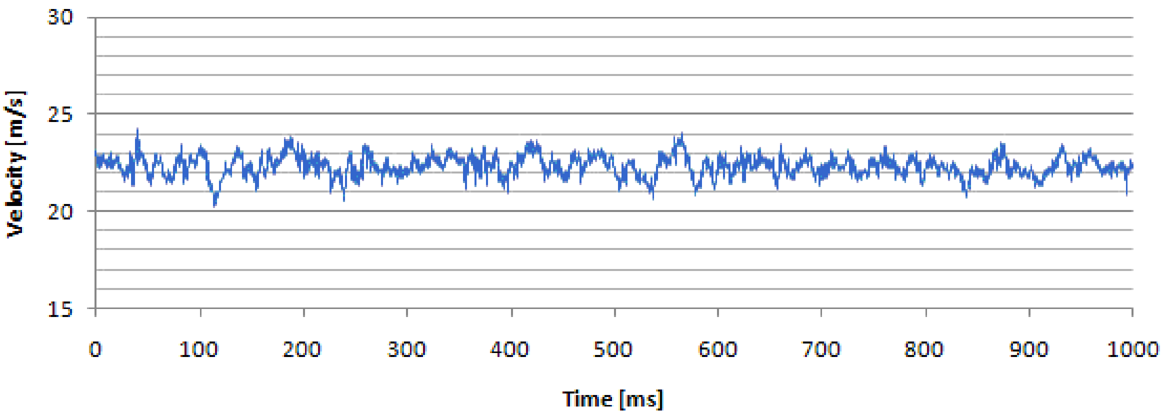

Figure 2 Velocity fluctuations measured with the hot wire probe by means of Constant Temperature Anemometry (CTA) - example of measurement taken at the point downstream the wind tunnel test section

In order to provide a good flow quality in the test section, turbulence should be kept at reasonably low level (values depending on the application). Not always extremely low turbulence levels are required, however, there is a call for controlling this factor and obtaining as high a turbulence reduction as possible. Reduction of turbulence intensity can be obtained by a combination of honeycomb, coarse mesh screens and contraction. Usage of all these methods results in a much diminished turbulence level.

Grids

Wind Tunnel at Institute of Turbomachinery is equipped with flow stabilisation section. Two turbulence reduction grids are located inside. Screens are uniform over their whole area. Mesh wire diameter is equal to 0.4 mm. Cell spacing is about 6 cells/cm in vertical direction and 7 cells/cm in horizontal direction. Basing on these data, theoretical value of turbulence reduction factor can be estimated. It is suggested to use two different turbulence reduction theories (Scheiman et al., 1981). Both are based on pressure-loss coefficient K that for lower Reynolds numbers can be expressed using equations (1) & (2).

$$K = K_0 + \frac{55,2}{Re} \tag{1}$$

$$K_0 = \left(\frac{1 - 0,95\beta}{0,95\beta}\right)^2 \tag{2}$$

Screens reduce axial and lateral turbulence at various rates. They are more effective at axial turbulence reduction. Suggested relation for axial turbulence prediction is expressed by equation (3) and equation (4) for lateral one (Kulkarni et al., 2011).

$$f = \frac{1}{1 + K} \tag{3}$$

$$f = \frac{1}{\sqrt{1 + K}} \tag{4}$$

Values of turbulence reduction factors calculated for manipulators mounted in the section of IMP WT are f_{axial}=0.52 and $f_{lateral}$=0.72 (Re calculated for 50% of maximum achievable airspeed). These are individual factors, i.e. each screen reduces turbulence incoming to it by a given value. Total reduction factor for a series of screens is equal to the product of individual reduction factors. Taking the above into account, total turbulence reduction factor of IMP WT grid arrangement is equal approximately to 0.27 and 0.52 for axial and lateral turbulence respectively.

TURBULENCE INTENSITY MEASUREMENT BEFORE HONEYCOMB INSTALLATION

Measurements inside the IMP WT were performed by means of a hot-wire anemometry (CTA - constant temperature anemometry). Acquired data will be used for comparison validating effectiveness of the honeycomb structure.

Experimental setup consisted of the following components:

- TSI 1299-20 triple wire probe,
- TSI Intelligent Flow Analyzer model IFA 100,
- IOtech DaqBook/2000 High-performance Multifunction 16-bit Data Acquisition System,
- PC with DaqBook/2000 Data Acquisition Software installed.

Figure 3 presents the locations, inside the test section, where turbulence intensity was measured. Results from the measurements are presented in Figure 4, x and y axis show values distance and turbulence intensity respectively according to the locations indicated.

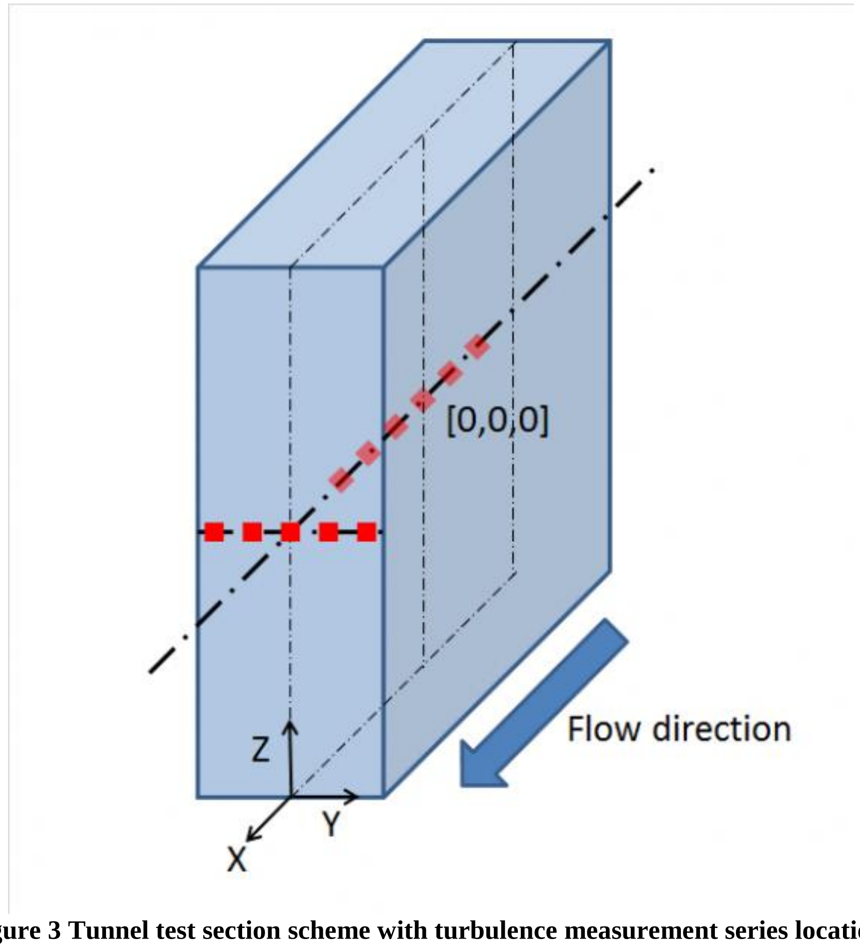

Figure 3 Tunnel test section scheme with turbulence measurement series locations

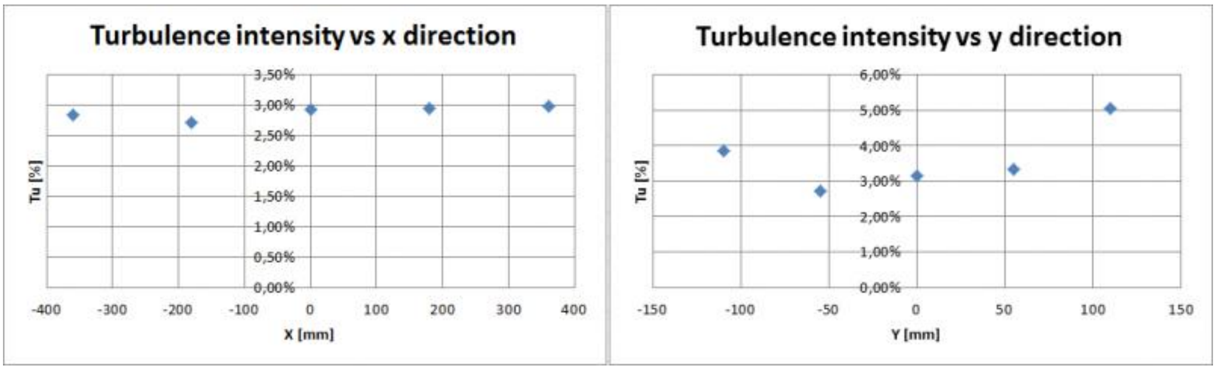

Figure 4 Turbulence intensity before honeycomb installation

The probe was used to measure the point-wise velocity. For each location three separate measurements were taken (3-wire probe) and the measurement was repeated twice after that. The minimum, maximum and standard deviations were computed for each measured data set. This information was used to obtain the specific turbulence intensity levels Tu. In total, this resulted in 9 separate values of Tu for each location. The values were then averaged. The further downstream, the level of turbulence was higher - the values varied from 2.7% to 3.0%. When taking into consideration turbulence intensity in y direction, the closer to the side walls of test section, the higher were the Tu values (3.0% in the tunnel axis to even 5% in the vicinity of walls).

Although triple wire probe was used, results presented in this paper are based on the independent voltage readings for each wire. Velocity was calculated for each sensor separately obtaining only amplitude of the velocity vector. Such a form of results presentation was enough for comparison with CFD simulation results.

TURBULENCE REDUCTION - HONEYCOMB INSTALLATION

Above chamber construction with two grids in series provided quite satisfactory reduction of axial turbulence. In order to improve flow quality by reducing lateral turbulence more efficiently, it was decided to introduce a new flow manipulator into the stabilisation section. Additional decrease in turbulence could be achieved by installing a honeycomb structure. It is a simple flow manipulator composed of cells of constant length-to-diameter ratio distributed across the whole channel. Unlike screens alone, honeycomb reduces lateral turbulence more than axial one. It is easy to imagine that any lateral velocity fluctuation larger than its cell size is effectively absorbed. What is more, any smaller turbulence would decay rapidly due to viscosity.

Design of a honeycomb limits to cell shape, cell size and length-to-diameter ratio specification. Most of design aspects of the honeycomb manipulator for IMP WT were based on the results of CFD simulations (Kulkarni et al., 2011). Suggested optimum length-to-diameter ratio is between 8 and 10. Such a range introduces the best relation between pressure losses and turbulence reduction. On the other hand, honeycomb depth recommendation given by (Loehrke et al., 1972) vary between 6 and 8 cell size. Moreover, taking into account the fact that turbulence intensity decay is high up to around the distance of eight times the cell size factor of 8 seems to be the best choice for designed structure. There are various types of honeycomb structures considering cell shape. Exemplary solutions are shown in Figure 5.

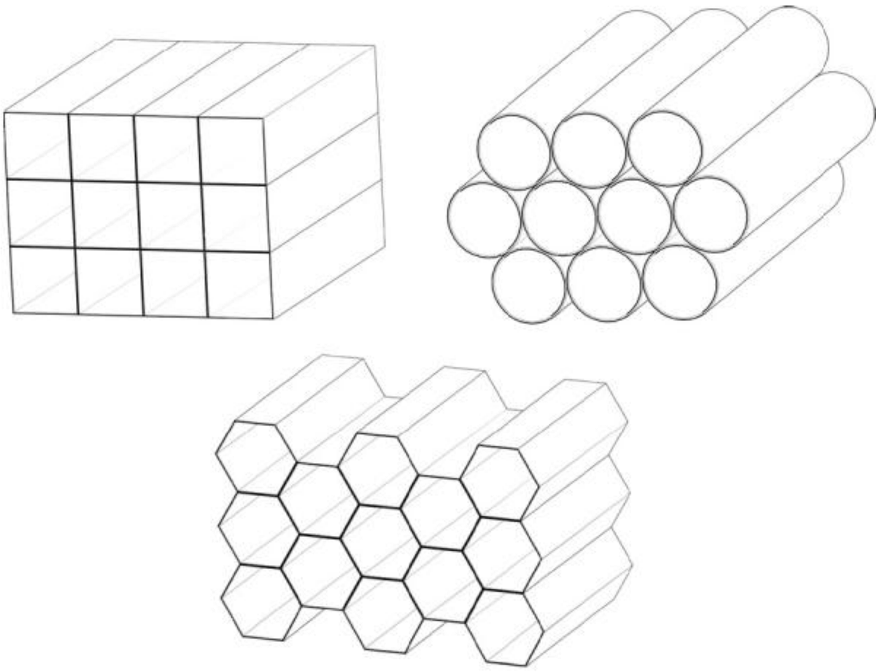

Figure 5 Schemes of various honeycomb structures (Kulkarni et al., 2011)

It has been shown that for specified length-to-diameter ratio, manipulator effectiveness is independent of the cell shape. That is why the simplest solution was chosen for IMP WT. The flow straightener was constructed using pipes arranged in a honeycomb-like structure. One of the design requirements was a choice of wall thickness t as small as possible in order to maximise porosity thus minimising pressure losses. Material chosen for considered design is PCV pipe due to economical reasons and desired material properties (smooth walls).

Combining screen's axial reduction effectiveness and lateral reduction provided by the honeycomb should allow to improve flow quality in IMP WT significantly. As it was indicated, best turbulence reduction is being obtained when the honeycomb is installed upstream the screens (Loehrke et al, 1972). Therefore, the honeycomb was mounted upstream the first grid.

TURBULENCE INTENSITY MEASUREMENT AFTER HONEYCOMB INSTALLATION

Turbulence was measured once again after the honeycomb was installed. Figure 6 presents the results of the measurement session.

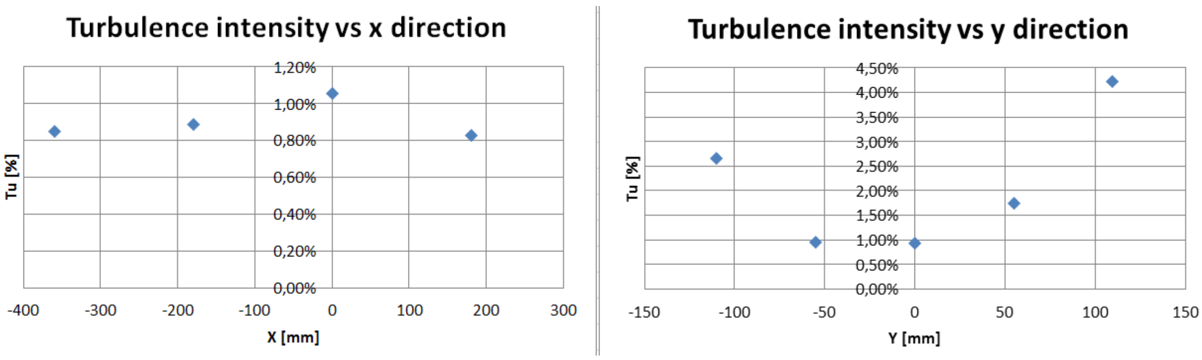

Figure 6 Turbulence intensity after honeycomb installation

After the installation of honeycomb, the levels of turbulence dropped significantly. In x direction maximum measured value of Tu was above 1.0%, while in the y direction the maximum value near the walls was 4.0%. In the most important area, the axis of a wind tunnel, the value of turbulence intensity dropped below 1.0%. Figure 7 compares the plots for turbulence intensity measurement for campaigns before and after installation of the honeycomb. Not all measurements were performed in the session after honeycomb installation hence more measurements from campaign before installation are visible.

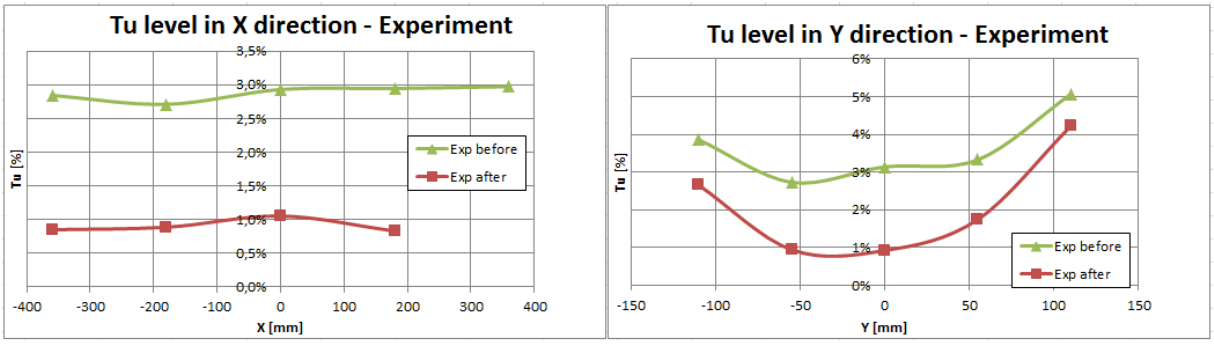

Figure 7 Turbulence intensity reduction - wind tunnel

In both series of measurements, one can notice how the honeycomb presence influenced the turbulence intensity - the improvement is well visible. Tu levels dropped from around 3% to a value of 1%. This confirmed the importance and the necessity of installing the flow straightener inside the IMP wind tunnel.

VIRTUAL WIND TUNNEL

Alongside measurements of turbulence intensity, a series of initial CFD computations was performed. The WT was modeled from the cross-section right after the fan engine up to the test section outlet. Figure 8 presents the numerical model and mesh used for this study. It was a first step in order to create a reliable, numerical representation of a physical object in the Institute of Turbomachinery. The computations were performed for the WT without honeycomb and with a model of honeycomb. This enabled a valuable comparison between the experiment and numerical analysis and delivered some information about details of flow in the test section.

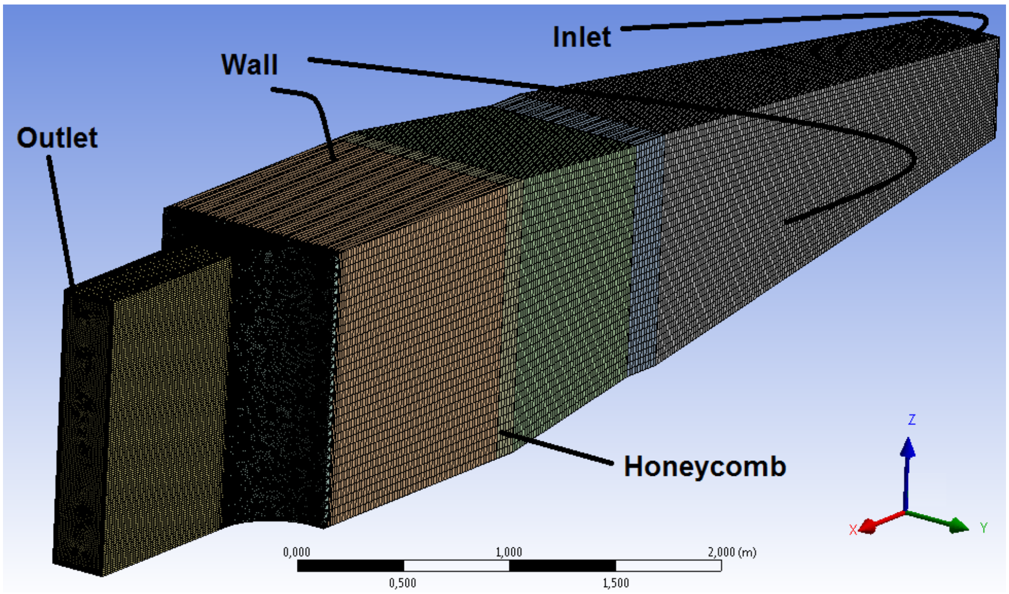

Figure 8 Numerical wind tunnel model mesh

Task Preparation and Pre-processing

The three-dimensional model of a wind tunnel consisting of diffuser, stabilization section, confusor and the test section was created in a CAD software. The dimensions were based on a measurement confirmed by the documentation.

The model for simulations with honeycomb straightener was a bit more complex than for simulations without it. A separate source domain (name Honeycomb in Figure 8) was inserted where flow equations were modified to account for directional loss resulting from porosity of the honeycomb. The mesh consisted of hexahedral elements in all regions except the confusor - due to its geometry tetrahedral elements needed to be used. The interface was modeled with 1:1 ratio. In order to provide better solution of boundary layer the inflation layers on all walls were also created. Figure 9 shows a zoom onto a mesh cross-section in the vicinity of actual WT test section, while Figure 10 presents an overall cross-sectional view of the virtual WT.

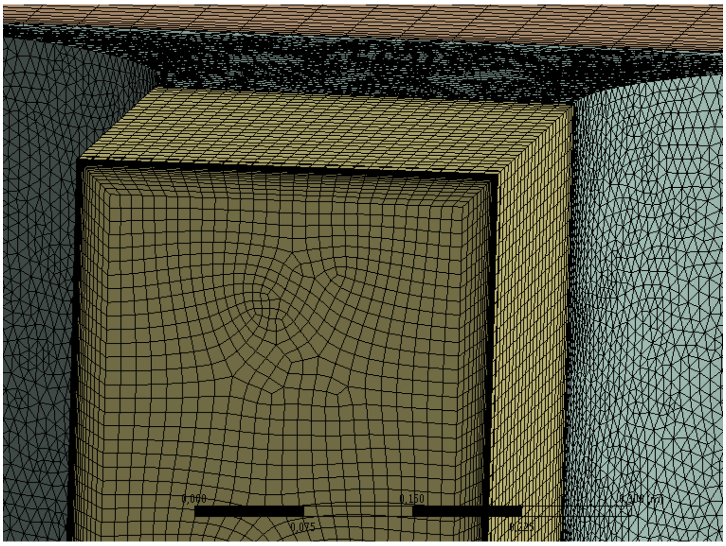

Figure 9 Wind tunnel model mesh - zoom on test section

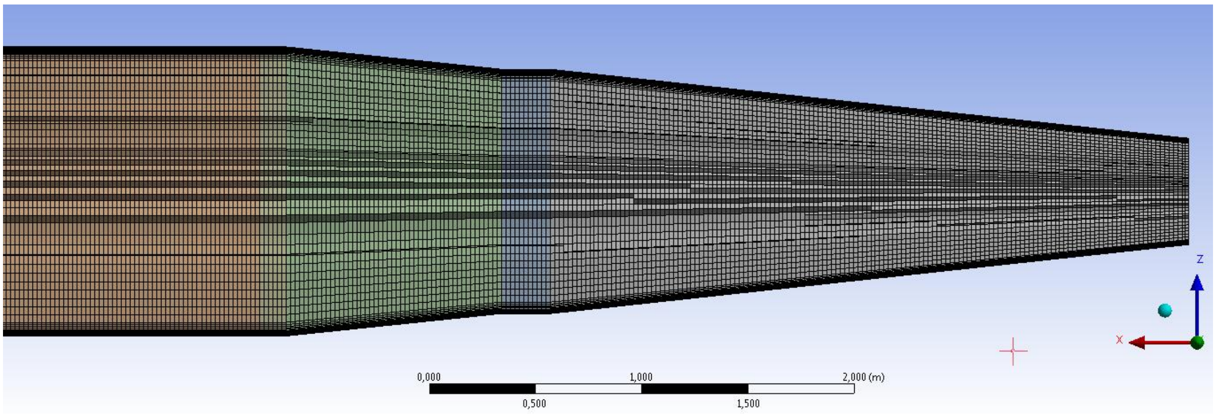

Figure 10 Wind tunnel model mehs - top view on diffuser section

The mesh consisted of about 4.1 mln elements.

As for the pre-processing, following boundary conditions were applied:

- inlet - mass flow rate equal to 5.15 kg/s,
- outlet - static pressure equal to ambient conditions (101325 Pa),
- walls - no slip, smooth wall.

In all simulations flow was treated as isothermal at T=298.15 K and having density ρ=1.185 kg/m^3. For the case after tunnel modification, the region representing honeycomb was simulated as a porous domain (volume porosity set to 0.81).

The simulations were treated as steady-state with a pseudo timestepping in place (ANSYS feature). For turbulence closure it was decided to use the SST turbulence model with an automatic wall function. Such choice was a direct result of a vast experience gathered by IMP in simulations of internal and external air flows. Turbulence intensity at the inlet was set to medium (5%), however its influence on simulation results should be also an aim of further investigations (Olasek et al., 2011).

The honeycomb was simulated as a porous body with momentum loss given by equations (5) - (7).

$$S_{M,x'} = -\frac{\mu}{K_{perm}^{S}} U_{x'} - K_{loss}^{S} \frac{\rho}{2} |U| U_{x'} \tag{5}$$

$$S_{M,y'} = -\frac{\mu}{K_{perm}^{T}} U_{y'} - K_{loss}^{T} \frac{\rho}{2} |U| U_{y'} \tag{6}$$

$$S_{M,z'} = -\frac{\mu}{K_{perm}^{T}} U_{z'} - K_{loss}^{T} \frac{\rho}{2} |U| U_{z'} \tag{7}$$

where x',y',z' are streamwise-oriented local coordinates. The x' coincides with a main flow direction, while y' and z' can be considered as pointing perpendicularly so in transverse plane. Such definitions requires definition of permeability and directional loss coefficients. Due to the nature of flow quadratic loss coefficients were defined for streamwise and transverse directions. Because no separated measurements were possible for the WT sections immediately before and after the honeycomb, various combinations of loss coefficients were tested to best approximate the actual pressure drop across the honeycomb and the pressure drop between Inlet and Outlet planes. Initially, a simple 2D relation to obtain a pressure drop across a model pipe with size identical to those installed in IMP WT, was used. The computed pressure drop was equal to 3 Pa. Next, a separate 3D CFD study for a pipe flow was considered, where it was determined that pressure drop across the honeycomb is 6 Pa. Based on the results from this, another set of coefficients was tested. Table 1 summarizes the combinations of quadratic streamwise and transverse loss coefficients used.

Table 1 Influence of parameter changes on the numerical simulations of flow in WT

Simulation	K_{loss}^{T}	K_{loss}^{S}	Factor for pseudo Δt [-]	Average Δp honeycomb [Pa]	Average Δp WT Inlet/Outlet [Pa]
001	10	2,28	1	2,94	-117,07
002	100	2,28	1	4,96	-117,21
003	256	2,28	1	5,49	-115,96
004	100	4,42	1	9,20	-111,15
005	100	4,42	5	11,38	-106,06
006	10	4,42	1	7,06	-112,84

Set up for simulation run 006 was seemed as best approximating the actual pressure drops. In future, a separate experiment on an arrangement of 7 pipes tested on a small scale wind tunnel, is planned to determine the pressure drop exactly. At the moment similar tests in the WT facility are not possible.

Solution

Numerical solution, at this initial stage, provided acceptable levels of convergence (residuals in range about 10^{-4}). The domain imbalances for simulations were below 0.1%. Also the following parameters were monitored: pressure drop on the honeycomb, difference between pressure at inlet and outlet, force exerted on confusor section. Fluctuations of these parameters were present due to the non-stationary character of the flow. Transient analyses, requiring significant amounts of resources, were not performed at this stage, but are planned in the months to come.

Results

After performing a series of simulations one indicated in table as 006 was chosen as a best representation of a real conditions invoked by honeycomb installation. The results of turbulence kinetic energy levels comparison are presented in figures below. The values were obtained from a converged steady-state simulation and extracted from locations corresponding to locations where turbulence intensity levels were measured. Unfortunately, steady-state simulation does not provide information about exact instantaneous flow parameters, hence computing a similar quantity such as turbulent intensity, is not possible in case of the presented CFD calculations. Instead, it was decided to observe turbulent kinetic energy. Figure 11 shows the results from CFD computations.

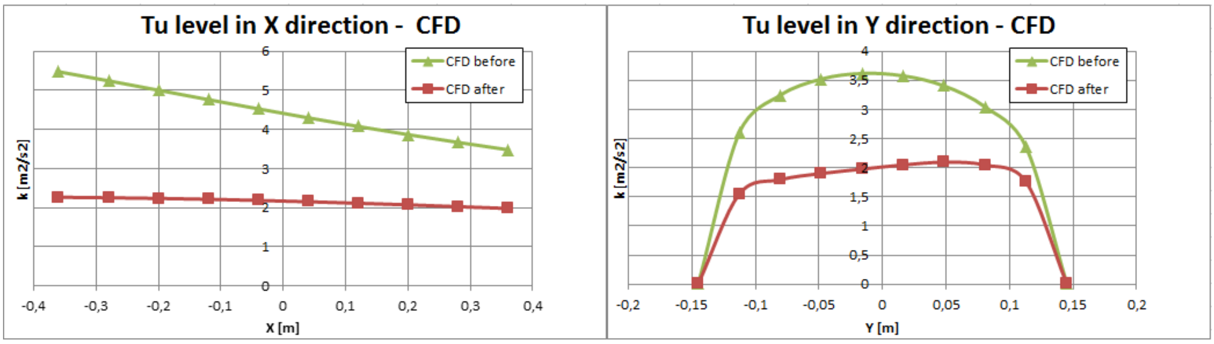

Figure 11 Turbulence kinetic energy level reduction - CFD simulation results

For both directions the level of turbulence was significantly dimished. For X direction one can notice that characteristics has been flattened: before honeycomb installation the level of turbulence kinetic energy was rapidly decreasing downstream. After honeycomb addition, the turbulence level along the x axis stabilized around the value of 2 m^2/s^2. This might suggest that numerical model for the WT state before honeycomb installation must be tuned. In Y direction, the introduction of honeycomb in virtual model decreased the level of turbulence kinetic energy and corresponds to velocity profile from before the installation. In order to compare the CFD results to WT measurements a non-dimensional parameter γ was introduced. For the WT data it represents the relative reduction of turbulent intensity by dividing the difference in Tu from before and after the honeycomb installation by the referential value (before the installation). Same operation is performed for CFD results this time taking the turbulent kinetic energy k into account. Figure 12 presents the comparison.

When comparing the results of turbulence reduction both from experimental measurements and from virtual model simulated by CFD, one can determine the relative gain obtained by honeycomb installation. In probe measurements the turbulence intensity level dropped by 60%-70%. In CFD simulation results the improvement is in the range of 40%-50%. More importantly though, the characteristics are quite similar and at this early stage of virtual tunnel creation provide valuable information that the simplifications introduced into CFD model are correct. The model must be fine tuned. This does not mean that additional appropriate flow control procedures for the WT facility, such as boundary layer suction, are unnecessary.

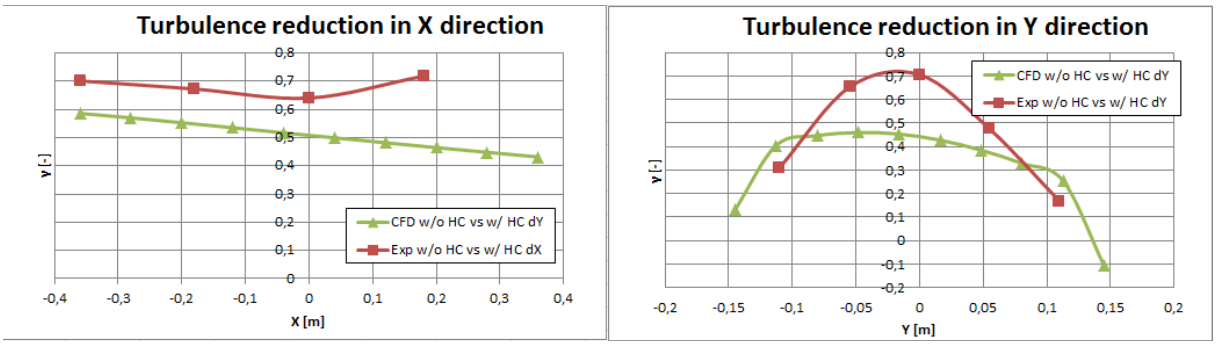

Figure 12 Comparison of relative turbulence level reduction - WT and CFD results

CONCLUSIONS

The objective of the honeycomb installation stated as minimalisation of turbulence intensity was fulfilled. Proper combination of flow straighteners - screens and honeycomb provided decrease of the Tu to the ranges around 1% for the half of the maximum IMP wind tunnel speed. This corresponds well to many academic quality tunnels found around the world. Additionally, the initial virtual model of facility was created in order to have a valuable means of flow details inside the WT facility at this early stage. Although it still needs more thorough verification, it indicated the expected tendencies of a turbulence intensity drop.

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