Modes for measuring aerodynamic resistances in the wind tunnel in the laboratory

O Nedelcu\textsuperscript{1}, I C Salisteau\textsuperscript{1}, O Magdun\textsuperscript{1}, V Dogaru\textsuperscript{2} and M Diaconu\textsuperscript{3}

\textsuperscript{1}Valahia University of Targoviste, Electronics, Telecommunication and Power Engineering Department, Aleea Sinaia str., no. 13, 130003 Targoviste, Romania
\textsuperscript{2}Valahia University of Targoviste, Doctoral School, Aleea Sinaia str., no. 13, 130003 Targoviste, Romania
\textsuperscript{3}Valahia University of Targoviste, Student in Industrial Energy, Aleea Sinaia str., no. 13, 130003 Targoviste, Romania

E-mail: otilia.nedelcu@valahia.ro

Abstract. The paper is focused on the architecture and design of a wind tunnel for measurement of aerodynamical resistances. The quantities which influence the flow of fluids and the applied laws in this case are described on short. Taking into account the main criteria for wind tunnels classification (architecture, test chamber type, test chamber fluid speed) type of the tunnel will be chosen followed by the design and construction. Test chamber measurements are carried on by an anemometer. The physical results are compared with the modelling results obtained for ideal conditions with the aid of SolidWorks software.

1. Introduction
Analysis and solving fluid flow problems in the fluids dynamics (CFD) can be done with the help of the appropriate software that uses numerical analysis and data structures, simulating the fluid flow and fluid interaction with certain defined boundary surfaces.

Better solutions to solve complex flow fluid problems in the wind tunnel can be achieved by using high speed computers. In this research, we used a computer and the SolidWorks software that helped the accuracy and speed of the scenario we proposed. The analytical and empirical analyzes made previously have been compared and thus, the wind tunnel model was executed.

If we use a scaled model, the aerodynamic properties of the reference object will not remain the same as the scaled model, but using certain rules of similarity, we can get as much approximation as possible between the aerodynamic properties of the reference object and those of the scaled model.

The main conditions that we must take into account to achieve this similarity are: when constructing the scaled model, the geometric ratio must be respected; Reynolds’s number; (the flow must be of the same type: laminar, transient or turbulent); Mach number (must be the same for the reference object and the scaled model).

2. The laws applicable to dynamics of fluids

2.1. Continuity law
Continuity Law is based on the law of conserving the mass, so in the constant flow of fluids, i.e. the flow in which the flow does not change, it remains constant over time we can say that the flow
entering through a section in a pipe multiplied with the surface of that section is equal with the flow going through a section of the same pipe multiplied by the surface of the output section. [1]

\[ v_{in} Q_{in} = v_{out} Q_{out} \]  

(1)

2.2. Bernoulli’s law

We have a fixed hydraulic system, chose on pipeline two transversal sections as which in each section the movement is parallel. The unidimensional model can be characterised so:

- in section 1 the model is characterised by \( v_1 \) and \( H_{p1} = \left( z + \frac{P}{\gamma} \right)_1 \)
- in section 2 the model is characterised by \( v_2 \) and \( H_{p2} = \left( z + \frac{P}{\gamma} \right)_2 \)

Due to the fact that the movement is permanent, the mechanical energy of fluid, which is between sections 1 and 2, into volume D, is constant in time, because the equation which described this doesn’t vary in time. This energy has as support the particles of fluid and it is carried of this, so that it will be stays to stable, must energy flow which enter (\( E_1 \)) into volume D will be equal with energy flow which exit.

2.3. Reynolds’s number

Reynolds’s number (\( R_e \)) is a dimensionless measure that determines fluid movement and account of the determinant parameters of the motion regime into pipeline: pipe speed (\( v \)); pipe diameter (\( D \)); the kinematic viscosity of the fluid (\( \nu \)). [1]

\[ R_e = \frac{vD}{\nu} \]  

(2)

According to the similarity theorem, the transition from the laminar regime to the turbulent motion regime is made at a certain criterion value:
- laminar - when \( Re < 2300 \)
- transient - when \( 2300 < Re < 4000 \)
- turbulent - when \( Re > 4000 \)

2.4. Loss of pressure

The loss of pipeline pressure depends on the flow rate, pipe length, pipe diameter, and a friction factor based on pipe roughness and whether our flow is turbulent, transient or laminar - the Reynolds number.

2.5. The Mach number

In general, wind tunnels can be divided into four broad categories by their speed ranges: subsonic with a maximum Mach number of up to 0.4; transonic with a maximum Mach number to 1.3; supersonic with a maximum Mach number up to 4.0 to 5.0; and hypersonic with a Mach number 5.0 or higher [2].
3. The design of the aerodynamic tunnel

3.1. Component parts description and geometric calculus

The purpose of the sedimentation chamber is to reduce turbulence in the airflow before entering the contraction cone. The cross-sectional diameter of the sedimentation chamber is equal to the inlet diameter of the contraction cone.

Air flow uniformity screen has the role of reducing the fluctuating variations of the airflow cross-sectional velocity, it has a reduced effect on the flow rate due to the fact that the decrease of the sieve pressure is small. The length of the sieve should be about 10 times the diameter of a cell.

Three factors are considered for the design: Length (Lₜₜₜ), Hydraulic Diameter (Dₜₜₜ) and Porosity (βₜₜₜ). Porosity is the ratio between the real cross-sectional area of the flow and the total area of the cross-section [3].

\[ \beta_h = \frac{A_{\text{flow}}}{A_{\text{total}}} \] (3)

For design, two criteria must be met:

\[ 6 \leq \frac{L_h}{D_h} \leq 8, \quad \beta_h \geq 0.8 \] (4)
**Contraction cone** - The contraction exit length is sensitive to the required length in the test section for a uniform velocity profile [4]. The ratio between the inlet and outlet sections of the contraction cone should be as large as possible to cause total pressure loss through the screens mounted between the sedimentation chamber and the contraction cone, this ratio should be between 6 and 10.

If the ratio between the inlet and outlet surfaces is greater than 10, the inlet dimensions will be excessive, and if less than 6 the result will be high pressure loss through the screens. A ratio equal to 6 was chosen.

**Diffuser 1** - The diffuser is between the output of the test chamber and the fan; it has the role of reducing velocity in the shortest possible distance to minimize losses. [5] The primary parameters for a loudspeaker are the equivalent conic expansion angle and the ratio of the surface. Consider a conical diffuser with a $R_1$ radius, at the input, a radius $R_2$ at the output, and a length $L$ as shown in the Figure 2.

The conic equivalent angle is defined as follows: either $R_1$ half of the input hydraulic diameter $D_1$ and $R_2$ half of the hydraulic output $D_2$ and $AR$ is equal to the ratio of the $A_2/A_1$ input and output surfaces.

![Figure 3. Geometry and diffuser notations](image)

The conic equivalent expansion angle is given by the relationship:

$$\Theta_e = \arctan \left( \frac{R_2 - R_1}{L} \right) = \arctan \left( \frac{1}{2} \sqrt{\frac{A_2}{A_1}} \right) \quad (5)$$

**Test chamber** - The first step in wind tunnel design is defining a priori the test chamber criteria which are dimensions, shape and desired air velocity. [4] A test section for the aerodynamic tunnel, sized for automobiles, is usually longer than a test section for aircraft, and the width-to-height ratio is approximated by the standard-width ratio of standard cars. Ideally, the lock, the ratio between the front surface of the model and the test section area, will be 5% or less. The length of the test chamber should be greater than 0.5 x hydraulic diameter and less than 3x hydraulic diameter.

$$0.5D < L < 3D \quad (6)$$

**Fan** - The important characteristics that determine the type of fan are flow, pressure, rotational speed, absorbed power, specific air weight, efficiency.

The fan used is axial, made of a treated stainless steel, which gives the blades a long-lasting resistance and is painted in the electrostatic field.
Table 1. Dimensions of wind tunnel

| Components                        | Dimension | Size | Measure unit |
|-----------------------------------|-----------|------|--------------|
| Sedimentation chamber             | Diameter ($D_{CS}$) | 490  | mm           |
|                                   | Length ($L_{CS}$)   | 368  | mm           |
|                                   | Porosity ($\beta_h$) | 0.8  |              |
|                                   | Total area ($A_{total}$) | 188478.5 | mm$^2$ |
| Cone admission diameter ($D_{adm_con}$) | 490 | mm |
| Flow area ($A_{flow}$)            | 150782.8  | mm$^2$ |
| The length of a hole ($L_h = 10 \times D_h$) | 100  | mm |
| The diameter of a hole ($D_h$)    | 10        | mm |
| Air flow uniformity screen       | Number of holes | 852  |              |
| Contraction cone                  | The inlet diameter ($D_{inlet}$) | 490  | mm |
|                                   | The out diameter ($D_{out}$) | 200  | mm |
|                                   | The length ($L_{con_con}$) | 245  | mm |
| Diffuser 1                        | Diameter ($D_{out_diff}$) | 310  | mm |
|                                   | Angle      | 50   |              |
|                                   | Length diffuser ($L_{diff}$) | 629.6 | mm |
| Diffuser 2                        | Diameter ($D_{out_diff}$) | 332  | mm |
|                                   | Length diffuser ($L_{diff}$) | 126  | mm |
| Test chamber                      | Diameter ($D$)     | 200  | mm           |
|                                   | Length ($L$)       | 400  | mm           |
|                                   | Maximum air flow   | 2550 | m$^3$/h      |
|                                   | Speed             | 2640 | rpm          |
|                                   | Weight            | 5.4  | kg           |
|                                   | Pressure          | 100  | Pa           |
|                                   | Capacity          | 4    | $\mu$F       |
|                                   | Maximum Power     | 0.85 | A            |
|                                   | Nominal input power | 186  | W            |
|                                   | Noise level       | 65   | dB           |
|                                   | Voltage           | 230  | V            |
|                                   | Frequency         | 50   | Hz           |
|                                   | Total length      | 2068.6 mm |

3.2. Determining the flow regime

We chose different possible air temperatures in the test chamber, temperatures determined exclusively by the ambient temperature, we determined the density and specific weight of the air in the test chamber, and with these sizes we determined the dynamic viscosity, kinematic viscosity.

Table 2. The flow regime depending on Reynolds’ number in the test chamber

| Air temperature ($^\circ$C) | Air Density (Kg/m$^3$) | Dynamic Viscosity (kg/ms) x10$^{-5}$ | Cinematic Viscosity (m$^2$/s) x10$^{-5}$ | Pressure (N/m$^2$) | Specific Mass | Reynolds’ number in the Test Chamber | Air velocity in the test chamber (m/s) |
|-----------------------------|------------------------|--------------------------------------|----------------------------------------|-------------------|--------------|--------------------------------------|--------------------------------------|
| 0                           | 1.293                  | 1.715                                | 1.328                                  | 105               | 12.68433     | 379518                               |                                      |
| 15                          | 1.225                  | 1.789                                | 1.461                                  | 105               | 12.01725     | 344969                               |                                      |
| 20                          | 1.205                  | 1.813                                | 1.506                                  | 105               | 11.82105     | 334661                               | 28                                    |
| 25                          | 1.184                  | 1.837                                | 1.552                                  | 105               | 11.61504     | 324742                               |                                      |

Max. 28
Depending on the air velocity in the test chamber, the Reynolds number was determined to find the flow regime. In our case the flow regime is a turbulent regime.

3.3. Pressure loss

According to the energy equation, the total energy in a fluid can be summed up as the sum of: energy of height, speed and pressure energy. The energy equation can be expressed as:

\[ p_1 + \frac{\rho v^2}{2} + \rho gh_1 = p_2 + \frac{\rho v^2}{2} + \rho gh_2 + p_r \]

where:
- \( p \) – fluid pressure [N/m\(^2\)]
- \( v \) – fluid velocity [m/s]
- \( h \) – height
- \( p_r \) – pressure loss [N/m\(^2\)]

Loss of pressure in pipelines depends on flow rate, pipe length, pipe diameter, and a friction factor based on pipe roughness and whether our flow is turbulent or laminar - the Reynolds number.

Loss of pressure in a pipe due to friction can be expressed as:

\[ p_r = \frac{\lambda}{2} \frac{\rho v^2}{d_h} \]

\( \lambda \) - friction coefficient
\( l \) – pipe length
\( d_h \) – hydraulic diameter (for cylindrical pipes, the hydraulic diameter is equal to the diameter of the pipe)

For turbulent flow, the friction coefficient depends on the Reynolds number and the roughness of the pipe or pipe wall. In functional form, it can be expressed as:

\[ \lambda = f\left(Re, \frac{k}{d_h}\right) \]

\( k/d_h = r \) – the relative roughness of the material. For PVC or plastic \( k = 0.0015 – 0.007 \) mm.

**Figure 4. Wind tunnel**
\[ r = 3.8 \times 10^{-5} \]
\[ \lambda = 0.0098 \text{ (in the test chamber)} \]
\[ p_r = 2.31 \text{ N/m}^2. \]

4. Flow simulation. The measurements in the wind tunnel

4.1. Flow simulation

In order to simulate the operating conditions and to measure the sizes that interest us inside the wind tunnel using the CFD-SOLIDWORKS simulation program, we have made the geometry of the wind tunnel keeping the proportion of 100% with the physical model achieved. The geometry was made for each component of the equipment, after they were assembled to perform the simulation.

In order to be able to simulate the CFD-SOLIDWORKS software we have sectioned the wind tunnel with a horizontal plan so that we can put the working conditions inside the equipment.

Boundary conditions are set by inserting the space through which the airflow enters and the space through which the airflow exits, as well as the areas wetted by the airflow. At the same time, the static pressure inside the wind tunnel was also represented.

![Figure 5. Inlet flow / outlet flow / static pressure from the wind tunnel](image)

The graph of the obtained measurements can be found in Figure 6, measurements shown after solving the simulation with 62 iterations.
4.2. The measurements with anemometer with Pitot tube

For measurements inside the testing room, we used an anemometer which is a measuring instrument that, usually, measures the wind speed and, also, the speed of a mobile relative to the air.

The anemometer used is a TA400 with a Pitot Trotec tube that can measure air velocities of up to 80 m/s, ambient temperatures and airflow, differential and static pressures.

In order to use it, the cross-sectional shapes of the air passages must be set.

The tube provides ideal conditions especially for fast and dusty airflows, being almost free of mechanical or dirt-sensitive sensors, optimal for use in very harsh environments.

The TA400 anemometer features internal memory, it can save measured data for pressure, flow and outlet, anytime during measurement.

We have made a set of measurements with the wind tunnel, without using the uniformity screen, in the centre of the test chamber and we have obtained the values from the following table.

The measurements have been performed at 1 second for 100 iterations, for pressure, velocity, flow and outlet, at a temperature of about 25 degrees Celsius.

Table 3. Pressure, speed, flow rate values - no uniformity screen

| Number of iterations | Pressure (Pa) | Velocity (m/s) | Temperature (°C) | Flow (m³/min) |
|---------------------|--------------|---------------|-----------------|--------------|
| 1                   | -7           | -3.58         | 24.8            | -1.6879      |
| 2                   | 0            | -0.2          | 24.8            | 0            |
| 3                   | 27           | 6.81          | 24.8            | 3.2102       |
| 10                  | 229          | 19.57         | 24.8            | 9.2224       |
| 20                  | 231          | 19.62         | 24.8            | 9.2473       |
| 30                  | 236          | 19.83         | 24.8            | 9.3470       |
| 50                  | 236          | 19.86         | 24.8            | 9.3620       |
| 70                  | 229          | 19.56         | 24.8            | 9.2191       |
| 80                  | 228          | 19.5          | 24.8            | 9.1916       |
| 98                  | 235          | 19.79         | 24.8            | 9.3271       |
| 99                  | 234          | 19.76         | 24.8            | 9.3134       |
| 100                 | 233          | 19.71         | 24.8            | 9.2900       |
| 101                 | 231          | 19.63         | 24.8            | 9.2545       |
After about 50 seconds the maximum value for the speed is obtained resulting 7.2144 km/h (20.04 m/s). Increasing speed and flow from a minimum value to a value that is kept approximately constant throughout the measurement is 8 seconds. The air flow rate ranged between 9.1 and 9.4 m$^3$/min.

We have repeated the measurements using the uniformity screen.

**Table 4.** Pressure, speed, flow rate values - with uniformity screen

| Number of iterations | Pressure (Pa) | Velocity (m/s) | Temperature (°C) | Flow (m$^3$/min) |
|----------------------|---------------|----------------|-----------------|------------------|
| 1                    | -9            | -3.88          | 23.6            | -1.8308          |
| 2                    | -9            | -3.89          | 23.6            | -1.8343          |
| 3                    | -8            | -3.87          | 23.6            | -1.8251          |
| 10                   | 50            | 9.14           | 23.6            | 4.3096           |
| 20                   | 116           | 13.92          | 23.6            | 6.5619           |
| 30                   | 114           | 13.81          | 23.6            | 6.5091           |
| 50                   | 115           | 13.85          | 23.6            | 6.5291           |
| 70                   | 116           | 13.93          | 23.6            | 6.5651           |
| 80                   | 115           | 13.87          | 23.6            | 6.5399           |
| 98                   | 115           | 13.89          | 23.6            | 6.5475           |
| 99                   | 115           | 13.89          | 23.6            | 6.5501           |
| 100                  | 115           | 13.88          | 23.6            | 6.5425           |
5. Conclusions

The construction of air tunnel complies with the main construction criteria: the open-air aerodynamic tunnel limited by solid walls with the maximum reference speed for the low subsonic aerodynamic tunnel and the depression chamber.

All components of the equipment complied with the geometrical dimensions of the construction.

We determined the flow regime with Reynolds number established following the application of Bernoulli’s law and continuity law and pressure loss.

The wind tunnel model can be used for testing cars models, sports equipment, golf balls, bicycle equipment, racing car helmets and more.

From the data obtained as a result of the measurements performed, we can see that there are differences between the two sets of measurements (with and without air uniformity screen) of pressure, velocity and flow.

![Figure 8. The graph of the obtained values - with uniformity screen](image)

The negative values obtained at the beginning of the measurements are explained by the creation of a low-pressure zone in the test chamber at the starting of the fan. However, they disappear after the first 3 seconds in the case of measurements without uniformity screen, respectively 8 seconds in the case of measurements with uniformity screen.

We also notice that experimentally obtained data are different from those resulted in the ideal simulation conditions in SolidWorks.

By using a pressure sensor attached to the sample body in the test chamber, we can determine the force of the aerodynamic push. We can use smoke to visualize fluid lines and turbulence created by

| Value   | Pressure (Pa) | Velocity (m/s) | Flow (m³/min) |
|---------|---------------|----------------|---------------|
|         | No screen     | With screen    | No screen     | With screen |
| Min     | -7            | -9             | -3,58         | -3,89       | -1,6879 | -1,8343 |
| Max     | 248           | 117            | 20,34         | 13,99       | 9,5856  | 6,5949  |
| Average | 223,11        | 103,31         | 19,02         | 12,38       | 7,9756  | 5,9104  |
the sample body, but the density of the smoke differs from the air and so we can only use it for visualization.

References
[1] Nedelcu O 2012 Bazele hidraulicii Ed. Bibliotheca
[2] Rae W H and Pope A 1984 Low Speed Wind Tunnel Testing Second edition
[3] Bradshaw P and Mehta R D 1979 Design rules for small low speed wind tunnels The Aeronautical Journal of the Royal Aeronautical Society, November
[4] Arifuzzaman Md and Mohammad Mashud 2012 Design Construction and Performance Test of a Low Cost Subsonic Wind Tunnel, IOSR Journal of Engineering (IOSRJEN) 2(10) 83-92
[5] Goldberg B and Carlone T 2008 Building a Wind Tunnel: It will blow your mind, A project report submitted to university of Florida