iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 7 Issue: III Month of publication: March 2019

DOI: http://doi.org/10.22214/ijraset.2019.3136

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International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 7 Issue III, Mar 2019- Available at www.ijraset.com

Dimensioning and Pressure Drop in a Subsonic Wind Tunnel for Automotive Tests of Reduced Scale Models

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Abstract: This is a synthesis of some aspects of the project developed by Salvador, M. W.; Guimarães, N. C. F.; Saldanha, W.A.R. (2018). Detailed design of the definition of the geometric profile of each of the components is presented for the construction of a subsonic wind tunnel of the suction type, closed test chamber and open circuit, for the purpose of performing tests on small scale models. The project was developed considering as initial conditions the reproduction of the parameters of the flow generated in a medium sized car moving at a speed of 14.4 m/s. The scale determined for the model for the test is 3/8. The scale and velocity were defined taking into account the feasibility of the dimensions of the tunnel and its propeller element. Energy requirements were established and presented in detail by means of the pressure drops in each component of the circuit and the total pressure drop of the wind tunnel. The calculations made make it possible to define the appropriate propulsion element for the wind tunnel under consideration. The designed wind tunnel has a section of tests of 2.25 m² of cross section and 5 m of length, where any model that does not exceed 20% of block of that cross-sectional area can be tested. The maximum velocity reached in the test section should be 50 m/s, with the speed of 37.333 m/s being determined for the proposed test, so that the rules of similarity between model and prototype are respected.
Keywords: Subsonic Wind Tunnel; Dimensional analysis; Prototype and Model; Pressure drop.

I. INTRODUCTION

One of the major challenges of engineering is to obtain, with precision, a modeling that describes the behavior of physical systems White, F. M. (2011). Good modeling can lead to admissible solutions without the need for exhaustive experimental studies. The purely analytic approach is not as accurate and does not always generate sufficient information for decision-making in some projects. According to Çengel and Cimbala (2012), the analytical approach has the advantage of being fast and low cost, but the results obtained are conditioned to the precision of the hypotheses, approximations and idealizations made in the analysis.

It is observed that, despite all the advances in mathematical and computational methods, it is still necessary to perform tests of all types to obtain conclusive information on the design of complex equipment. Due to the difficulties of properly modeling complex equipment, sometimes a purely experimental solution is used. In fact, the purely experimental approach has the advantage of dealing with the physical system itself and the desired quantity is determined by measuring within the limits of the experimental error Çengel, Y. A.; Cimbala, J. M. (2012).

However, such an approach is expensive, time-consuming and often impractical.

The solution, when a purely experimental approach is impractical, is to reproduce the conditions of the real phenomenon in scale simulations, based on the theory of dimensional analysis. In this way it is possible to complement the analysis with experimental results. In this context, at the end of the 19th century wind tunnels, carefully designed equipment, began to be used in order to perform tests on objects subjected to the action of air flow generated by a propeller element.

The industry is living a constant search for sustainability. According to Hucho, W. H. (1993), the current automobile market demands rigor in compliance with legislation and standards, and one of the key points for the adequacy of its product is the emission rate of pollutants. Another crucial factor for the success of automakers is the consumption rate of the vehicle produced, as this is a criterion for the car's acceptance by the customer.

To meet these law and customer requirements, automakers are looking for a number of alternatives, such as: reducing vehicle weight, searching for clean energy sources with hybrid and electric motors, reducing friction between tire and ground through the evolution of materials, among others. Among these alternatives is the optimization of the vehicle's aerodynamics. This feature provides a reduction in aerodynamic drag and, consequently, reduction of fuel consumption and emission of pollutants caused by combustion.

Vehicle aerodynamics tests are of great relevance in the development of new, more efficient vehicle models. However, they are very expensive tests when applied in models in real scale, since they require expenses with many resources, such as: functional prototype, running time, fuel, pilot, component wear, etc. and are at risk of inefficiency, which would result in further modifications and would require more time. In turn, the computational resources do not yet present a great reliability in their results, which can also hinder the process of development of the vehicle.

Through the use of a wind tunnel developed for vehicular aerodynamic tests, it is possible to integrate these two universes, physical and computational, and to present reliable results, with less expenses and in the time allowed. The advantages of small-scale testing are that the models are easy to manipulate and can be quickly modified Hucho, W. H. (1993).

Wind tunnels are widely used equipment in various fields for research and development in the field of fluid mechanics. According to Barlow, J. B et. al (1999), wind tunnels are often the fastest, most economical and accurate means for conducting aerodynamic surveys and obtaining aerodynamic data to support design decisions.

Much of the physical phenomena in fluid mechanics depends on geometric and flow parameters, which are highly complex. Thus, solving these problems using only analytical equations are complex and do not give satisfactory results Anderson Jr., J. D. (2001).

The use of the equations in the dimensionless form, can then help in solving problems, understanding the fundamentals of physical phenomena and identifying the preponderant aspects. According to Fox, R. W.; Mcdonald, A. T.; Pritchard, P. J. (2010), in two geometrically similar flows, but at different scales (model and prototype), the dimensionless equations would only give the same mathematical results if the two flows had the same relative importance of gravity, viscosity and inertial forces. Flows are identical if they are geometrically and dynamically similar. Fortunately, dimensional analysis made it possible to solve this dilemma through the use of dimensionless quantities.

The wind tunnels began to be applied in automobiles after they were already consolidated in the aeronautical sector. Historically, automobile wind tunnel testing has started with small-scale models. Some European countries use 1: 4 or 1: 5 scales, and in the United States they use scales of 3: 8.

Hucho, W. H. (1993); Sacomano Filho, F. L. (2008) point out that a wind tunnel simulates the natural conditions of running in the test, and their reproduction is not exact. The inaccuracies, with respect to the real conditions will always be present, not being easy to quantify.

The results obtained in wind tunnels do not have to be equal to the real one, because, the equipment costs would be very high, leaving the tests unviable. However, it is important to have an acceptable precision for the incremental analysis to be performed successfully Katz, J. (1995).

According to Sacomano Filho, F. L. (2008), the standardization of some conditions for an automotive test to be validated in a tunnel requires that some flow parameters in the test section be satisfied, such as:

1) Plane velocity profile;
2) Local deviations of the average speed of up to 0,5%;
3) Maximum pitch and yaw angles up to 5º;
4) Turbulence levels up to 0,5%.

Another important factor to consider in wind tunnel trials is the cross-sectional area blocking rate of the test section, or blocking. It is recommended by current practices that this block is around 5%, so that the interaction of the flow with the model and the walls do not generate undesirable effects and hinder the data obtained in the test. However, correction techniques can be used to overcome any extrapolation of the recommended blocking limit, assuming blocking rates of up to 20% are allowed with the use of these techniques.

II. OBJECTIVES

Because it is an extremely complex equipment, the present work only addresses the constructive characteristics of the components of a wind tunnel.

The main objective is to present the design and profile of each component of the wind tunnel, calculate the pressure drop in each component and determine the total pressure drop so that the tests can be performed with considerable precision in a model subject to conditions pre-defined.

III.METHODOLOGY

A. Components And Parameters Of Wind Tunnel Construction

For each wind tunnel model, rules that define geometric characteristics according to their purpose are adopted Barlow, J. B et. al (1999). However, for the type of tunnel being addressed, one can generically divide the components into 5 main parts: the contraction nozzle; the testing section; the diffuser (or diffusers); the stabilization chamber and the propulsion system, Figure 01:

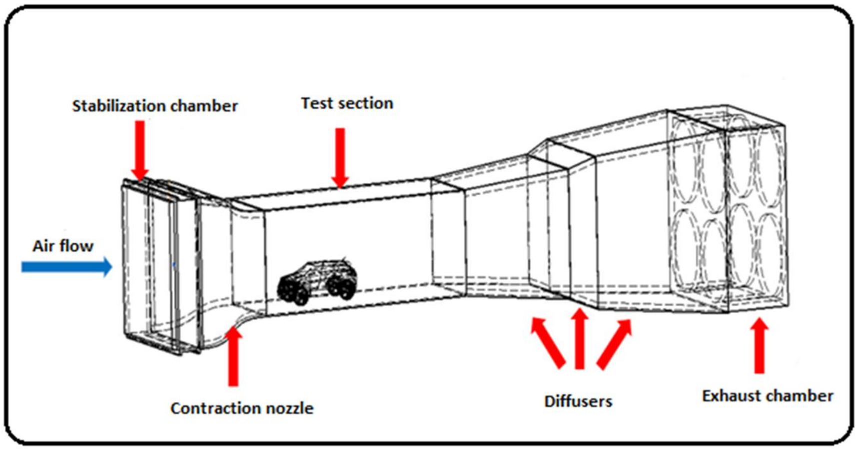

Figure 01: Illustration of the proposed wind tunnel and its components

In addition to the above-defined components, there is a variety of apparatuses which can be incremented to the wind tunnel according to the intended use. For example, there are tunnels equipped with air conditioning system, turbulence modelers, vortex generators, roughness simulators, platforms on sloping surfaces, flow brokers, etc.

According to Barlow, Rae and Pope (1999), each part of a wind tunnel has specific construction criteria, however the most particular element is the test chamber which must have the proper shape, suitable material, good visibility and space sufficient for a good allocation of the model, so that there is no interference in the flow.

In order to start the design of a wind tunnel it is necessary to identify and establish the main conditions and objectives of the test.

The test conditions are those that one wishes to reproduce from the real phenomenon to the simulation in the wind tunnel. In this case, the key point will be the speed of movement of the vehicle to be simulated. For reasons of viability, a velocity of 14 m/s (or 50,4 km/h) was used for the real phenomena. The dimensional information of the vehicle can be found in Figure 02 below:

Dimensions

Length	4370 mm	Width	1965 mm
Length between the axis	2660 mm	Height	1635 mm
Front gauge	1621 mm	Rear gauge	1628 mm
Trunk	575 litros	Fuel tank	54 litros
Weight	1844 kg	Useful load	556 kg
Trailer without brake	750 kg	Trailer with brake	2000 kg
Input angle	23,2 graus	Exit angle	33 graus
Central angle	22 graus	Water Crossing	500 mm
Free from soil	211 mm		
Aerodynamics			
Front area (A)	2,73 m²	Aerodynamic coefficient (Cx)	0,37
Corrected front area	1,010 m²		

Figure 02: Technical specifications and dimensions of the vehicle considered for analysis

Then, from the defined speed and the information made available through Figure 02, we can calculate the Reynolds number associated with the real phenomena. According to Pritchard, Fox and Mcdonald (2016), the characteristic length L is a descriptive parameter of the flow geometry. Thus, the characteristic length L is the height (h) of the vehicle shown in the data sheet of Figure 02.

The value of the Reynolds number for the real-scale object, which we shall call prototype by definition, Re_p, obtained for these conditions was:

$$Re_p = 1566494{,}41 \quad (01)$$

B. Similarity Between Model and Prototype

As the real-scale wind tunnel tests are complex and the construction of an equipment for this type of test has a high cost, the concept of a small-scale test was adopted for the design of this wind tunnel. Thus, according to the advantages of running tests in wind tunnels in small scale models, and also for feasibility reasons of construction, a scale factor was used $\frac{L_m}{L_p} = \frac{3}{8}$, being L_m the characteristic length of the model and L_p the characteristic length of the prototype. For the sake of criticality, a simplified cross-sectional area was used for the prototype and model, that is, instead of using the real front area of the vehicle, extrapolation was made considering them as objects of simple geometry. Using the height (h) and width (w) data obtained in the data sheet presented in Figure 02, it is possible to calculate the simplified area of the cross section of the model A_{modelo}:

$$A_{modelo} = (h.w).\frac{L_m}{L_p} \quad (02)$$

Therefore,

$$A_{modelo} = (1{,}635.1{,}965).\frac{3}{8} = 0{,}451\ m^2 \quad (03)$$

This configuration will be the basis for the sizing of the testing section. It is important to make it clear that this extrapolation is only allowed for design purposes and cannot be used for testing purposes.

One of the concerns when it comes to testing in small scale models is the precision of the results generated in the test. According to Pritchard; Fox and Mcdonald (2016), to obtain reliable data from an assay it is necessary that the prototype and the model are in a condition of dynamic similarity, that is, that the data of the prototype and the model are coherently correlated. In this way, there are some important requirements that must be taken into account.

The geometric similarity determines that the model and the prototype are of the same shape and that all the dimensions of the model are related to the dimensions of the prototype, and that the two flows are kinematically similar when the velocities at the defined points of the flow are the same, in terms of vector quantities. These similarities are differentiated only by a constant scale factor.

Kinematic similarity is an important requirement, but does not ensure the dynamic similarity. In order to determine the conditions necessary to obtain complete dynamic similarity, all forces (viscous, pressure, surface tension, etc.) involved in the flow must be taken into account. Thus, considering that the flow in the model and the prototype are geometrically similar, they will also be dynamically similar if the Reynolds number is identical for the model and the prototype. For the given scale factor, it is possible to calculate the flow velocity required in the test session using the dynamic resemblance condition:

$$Re_m = Re_p \quad (04)$$

that is,

$$\frac{\rho V_m L_m}{\mu} = \frac{\rho V_p L_p}{\mu} \quad (05)$$

Since the maximum flow velocity is less than Mach 0,3, incompressible flow can be considered. In this way the fluid in question will have the same density ρ and dynamic viscosity μ for model and prototype.

$$V_m = V_p.\frac{L_p}{L_m} \quad (06)$$

Therefore,

$$V_m = 14\,.\frac{8}{3} = \frac{37{,}33m}{s} \quad (07)$$

This means that the speed in the test section will be approximately 135 km/h so that it can meet the test conditions. Therefore, the propulsion system should be defined in a way that meets the pre-established design specifications.

C. Sizing of wind tunnel components

1) *Sizing of the Test Section:* According to Barlow, Rae and Pope (1999) for the section of tests directed to automobile models it is recommended a long section length. A length about 3 times the length of the model would meet this criterion. Thus, with the preset scale factor, it is possible to calculate the length of the section using the equation below:

Since l_p is the length of the prototype (data in the datasheet, Figure 02), the length of the test section is calculated by:

$$l_{seção} = \left(l_p.\frac{L_m}{L_p}\right).3 \quad (08)$$

Therefore,

$$l_{seção} = \left(4{,}370.\frac{3}{8}\right).3 = 5m \quad (09)$$

Another parameter of enormous importance for the reliability of the tests carried out on small scale models is the blocking relation of the test section. The ratio between the cross-sectional area of a model, A_{model}, and the cross-sectional area of the test chamber section, $S_{seção}$, is called the blocking rate B. Blocking rates of up to 20% are sometimes used in automobile tests Hucho; Sovran (1999).

$$B = \frac{A_{model}}{S_{seção}} \quad (10)$$

In order for the blocking conditions using a 20% rate to be met, with the dimensions of the selected model, the area of the test section, $S_{seção}$, should be:

$$S_{seção} = \frac{0{,}45}{0{,}2} = 2{,}25m^2 \quad (11)$$

For reasons of practicality a square section format was chosen for all the components, facilitating the dimensioning of the hydraulic diameters.

In Table 01, below, are the dimensions of the test section as calculated above:

TABLE 01
Dimensions of the test section

Width ($\boldsymbol{w_{seção}}$)	1,5 m
Height ($\boldsymbol{h_{seção}}$)	1,5 m
Length ($\boldsymbol{l_{seção}}$)	5 m
Area ($\boldsymbol{S_{seção}}$)	2,25 m²

2) *Sizing the Shrink Nozzle: Area ratio will be used, A_r=6, to determine the nozzle inlet area, A_{ebocal}, so the outlet area of the nozzle, As_{bocal}, will be the entrance area of the test section, $S_{seção}$.*

$$Ae_{bocal} = 6 \,.\, 2{,}25m^2 = 13{,}5m^2 \quad (12)$$

In this way the height of the nozzle inlet can be obtained, so h_2 will be:

$$h_2 = \frac{\sqrt{Ae_{bocal}}}{2} = 1{,}83712\,m \quad (13)$$

For the length, L_{bocal}, was adopted the value of 2 times the value of h_1, where h_1 is half the height of the test section, $h_{seção}$.

$$L_{bocal} = 2\,.\,h_1 = 1{,}5m \quad (14)$$

In possession of the values of h_1, h_2 e L_{bocal}, the curve of the nozzle can be generated according to the values in Table 02, below:

$$X_m = \frac{x_m}{L_{bocal}} \quad (15)$$

$$y = (h_1 - h_2)[1 - \frac{1}{{X_m}^2}\left(\frac{x}{L_{bocal}}\right)^3 + h_2\,; para\ x < X_m \quad (16)$$

$$y = \frac{(h_1 - h_2)}{(1 - {X_m}^2)}\left(\frac{x}{L_{bocal}}\right)^3 + h_2\,; para\ x > X_m \quad (17)$$

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 7 Issue III, Mar 2019- Available at www.ijraset.com

TABLE 02
Table of generation of the curve of the shrink nozzle

n°	L_{bocal}	x_m	h_2	h_1	X_m	x	y
1	1,5	0,75	1,837117	0,75	0,5	0,0000	1,8371
2	1,5	0,75	1,837117	0,75	0,5	0,1500	1,8328
3	1,5	0,75	1,837117	0,75	0,5	0,3000	1,8023
4	1,5	0,75	1,837117	0,75	0,5	0,4500	1,7197
5	1,5	0,75	1,837117	0,75	0,5	0,6000	1,5588
6	1,5	0,75	1,837117	0,75	0,5	0,7500	1,2936
7	1,5	0,75	1,837117	0,75	0,5	0,9000	1,0283
8	1,5	0,75	1,837117	0,75	0,5	1,0500	0,8674
9	1,5	0,75	1,837117	0,75	0,5	1,2000	0,7848
10	1,5	0,75	1,837117	0,75	0,5	1,3500	0,7543
11	1,5	0,75	1,837117	0,75	0,5	1,5000	0,7500

In the following Table 03, and Figure 03, are the dimensions of the contraction nozzle, according to the calculations that were developed above:

TABLE 03
Contraction nozzle dimensions

Length (L_{bocal})	1,5m
Area (Ae_{bocal})	13,5m^2
Area (As_{bocal})	2,25 m^2

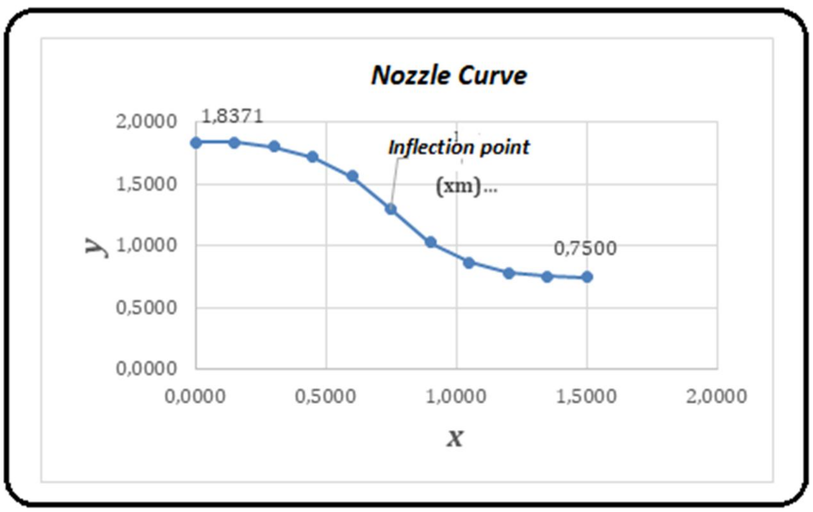

Figure 03: Curve of shrink nozzle for the wind tunnel

3) *Sizing the Diffuser 1: Using the concept presented by Barlow, Rae and Pope (1999), in order to avoid separation of the flow, it is necessary to use two halves of diffusers respecting an area ratio, A_r, of 2: 1, this ratio being half the ratio that would be used if the tunnel were only a long diffuser. This implies in the separation of the flow, causing an undesirable situation. Thus, for the dimensioning, the 2: 1 area ratio was used to find the R_2.*

$$A_r = \frac{As_{dif1}}{Ae_{dif1}} \tag{18}$$

Being, $Ae_{dif1} = S_{seção} = 2{,}25m^2$

$$D_2 = \sqrt{4{,}5} \tag{19}$$

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$$R_2 = \frac{\sqrt{4{,}5}}{2} \cong 1{,}061m \quad (20)$$

With R_2 already calculated and using an angle θ_r of 5º one can calculate the length of the diffuser 1:

$$L_{dif1} = \frac{R_2 - R_1}{\tan\theta_r} \quad (21)$$

$$L_{dif1} = \frac{1{,}061 - 0{,}75}{\tan 5°} \cong 3{,}55m \quad (22)$$

Table 4 below shows the dimensions of diffuser 1, according to the calculations developed above:

Table 04
Diffuser 1 dimensions

Length ($\mathbf{L_{dif1}}$)	3,55m
Height ($\mathbf{h_{edif1}}$)	1,5 m
Width ($\mathbf{w_{edif1}}$)	1,5 m
Height ($\mathbf{h_{sdif1}}$)	2,122 m
Width ($\mathbf{w_{sdif1}}$)	2,122 m
Area ($\mathbf{Ae_{dif1}}$)	2,25m²
Area ($\mathbf{As_{dif1}}$)	4,5 m²

4) *Dimensioning the Open Angle Diffuser:* Following the diffuser design parameters, it is necessary to use an open-angle diffuser to optimize the flow expansion and reduce the size of the tunnel, since using only a diffuser with a 5 ° angle would require a high length to satisfactorily reduce the flow velocity.

In the design, an area ratio $A_{rdifw} = 2$ and an angle of 22.5 °, as proposed by Barlow, Rae and Pope (1999). Then, the value of R_2 through an area relation is equal to:

$$A_{rdifw} = \frac{As_{difw}}{Ae_{difw}} \quad (23)$$

Sendo, $Ae_{difw} = Ae_{dif1} = 4{,}5\, m^2$.

$$R_2 = \frac{\sqrt{9}}{2} \cong 1{,}5m \quad (24)$$

Since R_1 is equal to R_2, one can determine the length of the open-angle diffuser:

$$L_{difw} = \frac{R_2 - R_1}{\tan\theta_r} \quad (25)$$

$$L_{difw} = \frac{1{,}5 - 1{,}06}{\tan 22{,}5°} \cong 1.062 \quad (26)$$

Table 05, below, shows the dimensions of the open angle diffuser according to the calculations that were developed above:

TABLE 05 Dimensions of the open angle diffuser

Length ($\mathbf{L_{difw}}$)	1,062m
Height ($\mathbf{h_{edifw}}$)	2,12 m
Width ($\mathbf{w_{edifw}}$)	2,12 m
Height ($\mathbf{h_{sdifw}}$)	3 m
Width ($\mathbf{w_{sdifw}}$)	3 m
Area ($\mathbf{Ae_{difw}}$)	4,5m²
Area ($\mathbf{As_{difw}}$)	9 m²

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5) *Dimensioning the Diffuser 2:* In the design of the diffuser 2, the same design parameters of the diffuser 1 are used, however, as established by Pereira, J. D. (2011), instead of using the 2: 1 area ratio, for construction feasibility reasons, is placed in a dimension where the area of the outlet of the diffuser 2 is equal to the inlet area of the contraction nozzle.

Being, $Ae_{dif2} = As_{difw} = 9m^2$ *e* $As_{dif2} = Ae_{bocal} = 13{,}5\,m^2$.

$$As_{dif2} = 13{,}5m^2 \quad (27)$$

$$R_2 = \frac{\sqrt{13{,}5}}{2} \cong 1{,}84m \quad (28)$$

Since R_1 is equal to R_2 of the open-angle diffuser, the length of the diffuser 2 has been determined:

$$L_{dif2} = \frac{1{,}84 - 1{,}5}{\tan 5°} \cong 3{,}9m \quad (29)$$

In Table 06 below are the dimensions of the diffuser 2 according to the calculations that were developed above:

TABLE 06

Diffuser 2 dimensions

Length ($\boldsymbol{L_{dif2}}$)	*3,9m*
Height ($\boldsymbol{h_{edif2}}$)	*3 m*
Width ($\boldsymbol{w_{edif2}}$)	*3m*
Height ($\boldsymbol{h_{sdif2}}$)	*3,68 m*
Width ($\boldsymbol{w_{sdif2}}$)	*3,68 m*
Area ($\boldsymbol{Ae_{dif2}}$)	$9m^2$
Area ($\boldsymbol{As_{dif2}}$)	*13,5m²*

6) *Sizing the Honeycomb:* Pereira, J. D. (2011) recommends that the porosity value β_h be greater than or equal to 0,8 and that the ratio between the hydraulic diameter d_h of the cell and the length of the walls l_h is between 6-8. These parameters are key factors in the honeycomb sizing. Thus, some data for sizing the honeycomb are specified below:

TABLE 07

Honeycomb manufacturer catalog data

PCGA-XR2 3003 - Aluminum Honeycomb	
Cell diameter ($\boldsymbol{d_{honey}}$)	*0,009525m*
Sheet thickness ($\boldsymbol{s_{honey}}$)	*0,0000762m*

With input data from Table 07 we can size the beehive using the specific equations for this format, which were established by Pereira, J. D. (2011). It is worth mentioning that there are several methods of sizing specific to each beehive model.

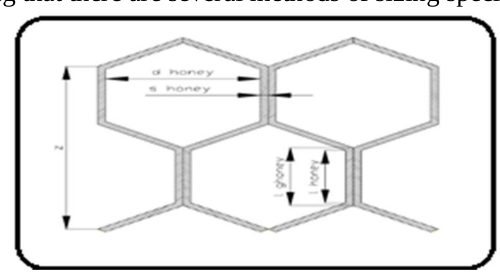

Figure 04: honeycomb structure and symbols Pereira, J. D. (2011)

One can calculate the internal lateral length of the l_{honey} cell, and the external lateral length l_{ghoney}:

$$l_{honey} = \frac{d_h}{2.\,sen60°} = 0{,}00412m \quad (30)$$

$$l_{ghoney} = l_{honey} + 2.\frac{s_{honey}}{tan60°} = 0{,}00421m \quad (31)$$

Thus, the length of the cells, z, is calculated using the equation below:

$$z = 2l_{honey} + l_{ghoney} = 0{,}01246m \tag{32}$$

Consequently, the number of cell divisions can be calculated, n_z, where L_1 is equal to the height of the nozzle inlet, being approximately equal to 3.67m:

$$n_z = \frac{L_1}{z} = 294{,}54 \tag{33}$$

In terms of width, one can find the number of divisions associated with the thickness of the beehive plate, n_{sheet}t, where L_2 is the width of the nozzle entrance, being approximately equal to 3.67m:

$$n_{sheet} = \frac{L_2}{\frac{d_{honey}}{2} + s_{honey}} = \frac{3{,}67}{\frac{0{,}009525}{2} + 0{,}0000762} = 758{,}48 \tag{34}$$

According to Pereira, J. D. (2011), the internal lateral length of the cell, l_{honey}, the external lateral length of the cell, l_{ghoney}, the length of cells, z, the number of cell divisions, n_z, and the number of leaf divisions (thickness), n_{sheet}, are essential parameters for calculating the sheet area, A_{sheet}. However, it is necessary to calculate the areas that define the profile of the honeycomb plate.

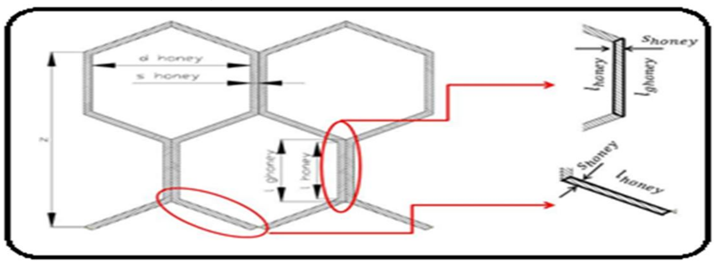

Figure 05: Profile for calculating the parallelogram and trapezoid area

$$A_{paralelogramo} = l_{honey} \cdot s_{honey} \tag{35}$$

$$A_{trapezio} = \frac{(l_{honey} + l_{ghoney}) \cdot s_{honey}}{2} \tag{36}$$

$$A_{sheet} = 2(A_{paralelogramo} \cdot A_{trapezio}) n_z \cdot n_{sheet} = 0{,}2829m \tag{37}$$

According to Pereira, J. D. (2011), the strength of the beehive, σ_h, is defined as the ratio between the cross-sectional area occupied by the plate, A_{sheet}, and the cross-sectional area of the entrance of the contraction nozzle, Ae_{bocal}l, which is the same area that will be used for the stabilization chamber. Using the equation below, one can calculate the strength of the beehive, σ_h, the total area being equal to the area of the nozzle, $A_{total} = Ae_{bocal} = 13{,}5m^2$.

$$\sigma_h = \frac{A_{sheet}}{A_{total}} = \frac{0{,}2829}{13{,}5} = 0{,}021 \tag{38}$$

The porosity equation, $\beta_h = \frac{A_{fluxo}}{A_{total}}$, and the solidity equation, $\sigma_h = \frac{A_{sheet}}{A_{total}}$, are complementary factors. Thus, the sum of them is an identity. Therefore, the porosity can be calculated with the equation below:

$$\beta_h = 1 - \sigma_h = 1 - 0{,}021 = 0{,}98 \tag{39}$$

The hydraulic diameter of the cell must be calculated, starting with the equation of the cell area, A_{cell}, which is the area of six equilateral triangles, as shown in the figure below:

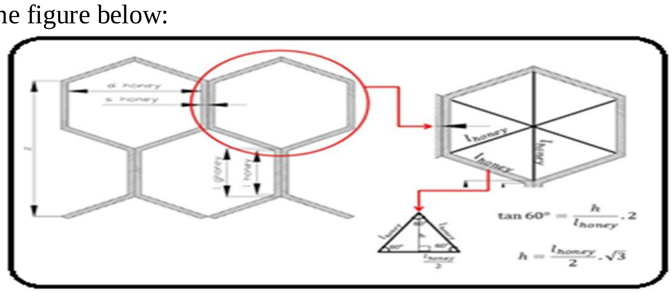

Figure 06: Honeycomb cell geometry for calculating your area

$$A_{cell} = \frac{3}{2} \cdot \frac{d_{honey}{}^2}{\sqrt{3}} \tag{40}$$

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 7 Issue III, Mar 2019- Available at www.ijraset.com

The hydraulic diameter can be calculated by establishing that the area of the cell is equal to the area of a circle, $\frac{\pi D_h{}^2}{4}$:

$$D_h = d_h.\sqrt{\frac{6}{\pi\sqrt{3}}} = 0{,}009525.\sqrt{\frac{6}{\pi\sqrt{3}}} = 0{,}010m \quad (41)$$

Thus, one can obtain the length of the beehive wall, L_h, following the parameters pre-established at the beginning of this section:

$$L_h = 6.D_H = 6.0{,}010 = 0{,}060m \quad (42)$$

According to the criteria imposed by Pereira, J. D. (2011), the sizing of the beehive meets the wind tunnel design. In Table 08, below, is a synthesis of the honeycomb sizing.

TABLE 08
Dimensions of the honeycomb

Colmeia hexagonal - Honeycomb	
External Side Length ($\mathbf{l_{honey}}$)	0,009525m
Internal Side Length ($\mathbf{l_{ghoney}}$)	0,0000762m
Length of cells ($\mathbf{z}$)	0,01246m
Number of cell divisions ($\mathbf{n_z}$)	294,54
Number of sheet divisions ($\mathbf{n_{sheet}}$)	758,48
Strength of the honeycomb ($\boldsymbol{\sigma_h}$)	0,021
Porosity of the honeycomb ($\boldsymbol{\beta_h}$)	0,98
Hydraulic diameter of the honeycomb ($\mathbf{D_h}$)	0,010m
Wall length of the beehive ($\mathbf{L_h}$)	0,060m

7) Dimensioning of Screen

TABLE 09
Data for screen sizing

Stainless teel Screen - 16x30 DWG	
Wire Diameter ($\mathbf{d_w}$)	0,0003m
Length of mesh ($\mathbf{w_m}$)	0,00129m

In Table 09 are some data that were used for the sizing of the screen.
The range of values for the porosity of the screen, β_s, which guarantees a more homogeneous flow, is defined by:

$$0{,}58 \leq \beta_s \leq 0{,}8 \quad (43)$$

where,

$$\beta_s = \left(1 - \frac{d_w}{w_m}\right)^2 = \left(1 - \frac{0{,}0003}{0{,}00129}\right)^2 = 0{,}59 \quad (44)$$

The solidity of the screen, σ_s, is a function of porosity:

$$\sigma_s = 1 - \beta_s = 1 - 0{,}59 = 0{,}41 \quad (45)$$

TABLE 10
Screen dimensions

Tela 16x30 DWG	
Height ($\mathbf{h_s}$)	3,67m
Width ($\mathbf{w_s}$)	3,67m
Screen Area ($\mathbf{A_s}$)	13,5m²
Wire Diameter ($\mathbf{d_w}$)	0,0003m
Length of mesh ($\mathbf{w_m}$)	0,00129m
Porosity ($\boldsymbol{\beta_s}$)	0,59
Solidity ($\boldsymbol{\sigma_s}$)	0,41

8) *Dimensioning of the Stabilization Chamber:* The cross-sectional area of the stabilization chamber depends on the dimensions of the entrance of the contraction nozzle, the dimensions of the beehive and the screen. The length of the chamber is usually adjusted according to the occupation of the components that compose it. According to Barlow, Rae and Pope (1993), this length is based on the sum of the length of the beehive,L_h, and the distances between the screens (if there is more than one) and more than 0,2 times the hydraulic diameter of the nozzle inlet, D_{hbocal}.

Another important parameter is the distance between the beehive and the screen. This distance must be at least once the hydraulic diameter of the honeycomb, D_h, being also necessary to be added to the length of the stabilization chamber, $L_{câmara}$.
Thus, one can find the length through the equation below:

$$L_{câmara} = L_h + d_w + 2.D_h + 0{,}2.D_{hbocal} = 0{,}060 + 0{,}0003 + (2.0{,}010) + (0{,}2.3{,}67) = 0{,}81m \quad (46)$$

The hydraulic diameter of the stabilization chamber, $D_{hcamara}$, is defined by:

$$D_h = \frac{4A_{câmara}}{\sigma_{camara}} = \frac{4.13{,}5}{14{,}68} = 3{,}678m \quad (47)$$

TABLE 11
Dimensions of the Stabilization Chamber

Câmara de Estabilização	
Height ($\mathbf{h_{câmara}}$)	3,67m
Width ($\mathbf{w_{câmara}}$)	3,67m
Area ($\mathbf{A_{câmara}}$)	13,5m²
Length ($\mathbf{L_{câmara}}$)	0,81m
Hydraulic Diameter ($\mathbf{D_{hcamara}}$)	3,678m

Where σ_{camara} is the wetted perimeter of the section, as the cross section of the stabilization chamber is square, we have $L_{câmara}$ = $h_{câmara}$= $w_{câmara}$.

D. Calculation of pressure drops on components

After having scaled all the components it becomes necessary to calculate the loss of load of each of them. For the calculation of the loss of load of the components the general equation is used:

$$\Delta P_i = 0{,}5\rho_i C_i^2 K_i \quad (48)$$

By using the specific equations for each component, it is possible to determine the respective pressure drops.

1) *Pressure drop in the testing section:* In order to calculate the pressure-drop, in the test section, the coefficient of friction is first calculated. The hydraulic diameter in the test section is defined by:

$$D_H = \frac{4.A}{\sigma} \quad (49)$$

The wetted perimeter σ can be calculated using the width dimensions $w_{seção}$ and height $h_{seção}$ of the test section:

$$\sigma = (2.w_{seção}) + (2.h_{seção}) = 6m \quad (50)$$

Being, $A = S_{seção} = 2{,}25m^2$, thus, the value of the hydraulic diameter can be obtained:

$$D_H = 1{,}5m \quad (51)$$

The velocity stipulated at the entrance of the test section, C_{test}, was 37.33 m / s, being the same velocity of the output, thus, it was not necessary to determine a mean velocity, and the Reynolds number in the test section is equal to:

$$Re_{test} = \frac{\rho C_{test} D_H}{\mu} = \frac{1{,}225.37{,}33.1{,}5}{1{,}79.10^{-5}} = 3.832.060 \quad (52)$$

Using the bisection method, the friction factor can be determined, without considering the roughness of the surface:

$$\frac{1}{\sqrt{f_{seção}}} = 2\log\left(Re_{seção}\sqrt{f_{seção}}\right) - 0{,}8 \quad (53)$$

$$f_{seção} = 0{,}0093 \quad (53.1)$$

The pressure drop factor, $K_{seção}$, is a function of the length of section $l_{seção}$ = 5 m and the hydraulic diameter $D_{hseção} = 1{,}5\ m$:

$$K_{seção} = f_{seção}\frac{l_{seção}}{D_{Hseção}} = 0{,}03084 \quad (54)$$

Finally:

$$\Delta P_{seção} = 0{,}5\rho_i C_{seção}^2 K_{seção} = 0{,}5.1{,}225.37{,}33^2.0{,}03084 = \mathbf{26{,}32\ Pa} \quad (55)$$

2) Pressure drop in the contraction nozzle

For the loss in the contraction nozzle, ΔP_{bocal}, we have:

$$\Delta P_{bocal} = 0{,}5\rho\bar{C}^2{}_{bocal}K_{bocal} \quad (56)$$

Where the mean velocity in the nozzle, $\bar{C}_{bocal}$, is calculated using the hydraulic cross-sectional diameter of the nozzle, D_{ts}, i.e. using the hydraulic diameter of the point x_m. With the aid of Table 02 the average radius is identified, $\bar{y}$ de 1,2936m. The average area of the nozzle, $\bar{A}_{bocal}$, is then determined:

$$\bar{A}_{bocal} = (\bar{y}.2)^2 = (1{,}2936.2)^2 = 6{,}694m^2 \quad (57)$$

Using the mean area, $\bar{A}_{bocal}$, as reference, one can find the average velocity in the nozzle section, $\bar{C}_{bocal}$:

$$\bar{C}_{bocal} = \frac{C_{teste} \times S_{seção}}{\bar{A}_{bocal}} = \frac{37{,}33 \times 2{,}25}{6{,}6936} = 12{,}55\frac{m}{s} \quad (58)$$

Given the average velocity, one can find the Reynolds number relative to the nozzle, Re_{bocal}:

$$Re_{bocal} = \frac{\bar{C}_{bocal}.\rho.(2\bar{y})}{\mu} = \frac{12{,}549.1{,}225.(2.1{,}2936)}{0{,}0000179} = 2.221.888 \quad (59)$$

Therefore,

$$K_{bocal} = 0{,}32 f_{bocal}\frac{L_{bocal}}{D_{ts}} \quad (60)$$

The friction factor, f_{bocal}, is determined using the same approximation procedure already used in the test section:

$$\frac{1}{\sqrt{f_{bocal}}} = 2\log\left(Re_{bocal}\sqrt{f_{bocal}}\right) - 0{,}8 \quad (61)$$

$$f_{bocal} = 0{,}0101 \quad (61.1)$$

Thus, the pressure drop factor is determined:

$$K_{bocal} = 0{,}32.0{,}0101\frac{1{,}5}{2{,}5872} = 0{,}0032 \quad (62)$$

The pressure drop can now be calculated:

$$\Delta P_{bocal} = 0{,}5.1{,}225.12{,}549^2.0{,}0032 = 0{,}31\ \text{Pa} \quad (63)$$

3) Pressure Drop In The Stabilization Chamber: The pressure drop in the stabilization chamber is determined by the sum of the losses in the screen (or screens), honeycomb and the constant section that separates them.

a) Loss of charge in the Honeycomb

According to Equation 48, we have:

$$\Delta P_h = 0{,}5\rho C_h^2 K_h \quad (64)$$

Where ΔP_h is the loss of charge in the hive, C_h is the velocity of the flow relative to the honeycomb and K_h is the coefficient of loss of charge of the honeycomb:

$$K_h = \left(\lambda_h\frac{L_h}{D_h} + 3\right)\left(\frac{1}{\beta_h}\right)^2 + \left(\frac{1}{\beta_h} - 1\right)^2 \quad (65)$$

$$\lambda_{h=}\begin{cases} 0{,}375\left(\frac{\Delta}{D_h}\right)^{0{,}4} Re_\Delta{}^{-0{,}1} & Re_\Delta \le 275 \\ 0{,}214\left(\frac{\Delta}{D_h}\right)^{0{,}4} & Re_\Delta > 275 \end{cases} \quad (65.1)$$

In order to calculate the pressure-drop in the honeycomb it is necessary to analyze the data obtained in the sizing of the nozzle. Initially, it is essential to find the flow velocity relative to the honeycomb. In this case, it becomes necessary to determine the velocity of the flow at the inlet of the section of the contraction nozzle, C_{ebocal}:

$$C_{ebocal} = \frac{C_{teste} \times S_{seção}}{A_{ebocal}} = \frac{37{,}33 \times 2{,}25}{13{,}5} = 6{,}222\frac{m}{s} \quad (66)$$

When determining the flow velocity at the nozzle inlet, use the ratio below to obtain the flow velocity relative to the honeycomb, C_h. Since the entrance and exit area of the hive is the same as A_h, and that its value is the same as that of the entrance area of the nozzle, A_{ebocal}. With porosity, β_h, already calculated:

$$C_h = \frac{C_{ebocal} \cdot A_h}{A_h \cdot \beta_h} = \frac{6{,}2216.13{,}5}{13{,}5.0{,}98} = 6{,}35\frac{m}{s} \quad (67)$$

Therefore,

$$Re_\Delta = \frac{\rho C_h D_h}{\mu} = \frac{1{,}225.6{,}3485.0{,}010}{0{,}0000179} = 4.344{,}64 \quad (68)$$

As $Re_\Delta > 275$:

$$\lambda_{h=} 0{,}214\left(\frac{0{,}00005}{0{,}010}\right)^{0{,}4} = 0{,}026 \quad (69)$$

and,

$$K_h = 0{,}02570\left(\frac{0{,}060}{0{,}010} + 3\right)\left(\frac{1}{0{,}98}\right)^2 + \left(\frac{1}{0{,}98} - 1\right)^2 = 0{,}242 \quad (70)$$

With the data obtained in the above calculations one can calculate the pressure drop in the honeycomb:

$$\Delta P_h = 0{,}5.1{,}225.6{,}3485^2.0{,}242 = \mathbf{5{,}974\ Pa} \quad (71)$$

b) Pressure Drop On The Screen

According to Equation 48, we have:

$$\Delta P_s = 0{,}5\rho C_m^2 K_m \quad (72)$$

Where ΔP_s is the pressure drop on the screen, C_m is the velocity of the flow relative to the screen and K_m is the pressure drop factor:

$$K_m = K_{mesh}K_{Rn}\sigma_s + \frac{{\sigma_s}^2}{{\beta_s}^2} \quad (73)$$

$$K_{Rn} = \begin{cases} 0{,}785\left(1 - \frac{Re_w}{354}\right) + 1{,}01 & se\ \ 0 \le Re_w < 400 \\ 1.0 & se\ \ Re_w \ge 400 \end{cases} \quad (73.1)$$

Similar to the beehive, it is necessary to find the velocity of the flow relative to the screen, C_m, and determine the Reynolds relative to the wire Re_w.

$$C_m = \frac{A_s \cdot C_{ebocal}}{A_s \cdot \beta_s}\frac{13{,}5.6{,}2216}{13{,}5.0{,}59} = 10{,}54\frac{m}{s} \quad (74)$$

With the value of the wire diameter, d_w, one can find the Reynolds number Re_w:

$$Re_w = \frac{\rho C_m d_w}{\mu} = \frac{1{,}225.10{,}5450.0{,}0003}{0{,}0000179} = 216{,}50 \quad (75)$$

As Re_w <400, we have,

$$K_{Rn} = 0{,}785\left(1 - \frac{Re_w}{354}\right) + 1{,}01 = 0{,}785\left(1 - \frac{216{,}4965}{354}\right) + 1{,}01 = 1{,}32 \quad (76)$$

According to the parameters established by Chik, I. E (1966), a mesh factor K_{mesh}=1,3 was adopted:

$$K_m = 1{,}3.1{,}3149.0{,}41 + \frac{0{,}41^2}{0{,}59^2} = 1{,}184 \quad (77)$$

Pressure drop on the screen:

$$\Delta P_m = 0{,}5.1{,}225.10{,}5450^2.1{,}1837 = \mathbf{80{,}62\ Pa} \quad (78)$$

c) Pressure drop in the cross section of the test chamber

The constant length that separates the honeycomb and the screen has the pressure drop factor expressed by:

$$K_{camara} = f_{camara}\frac{L}{D_{hcamara}} \quad (79)$$

Where the friction factor, f_{camara}, can be obtained by the iterative method, as defined in the test section and the contraction nozzle, using the equation:

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 6.887
Volume 7 Issue III, Mar 2019- Available at www.ijraset.com

$$\frac{1}{\sqrt{f_{camara}}} = 2\log\left(Re_{camara}\sqrt{f_{camara}}\right) - 0{,}8 \qquad (80)$$

The Reynolds number relative to the cross section of the stabilization chamber is given by:

$$Re_{camara} = \frac{\rho C_{ebocal} D_{hcamara}}{\mu} = \frac{1{,}225.6{,}2216.3{,}678}{0{,}0000179} = 1.566.018{,}43 \qquad (81)$$

Therefore,

$$K_{camara} = 0{,}0104\frac{0{,}81}{3{,}678} = 0{,}0023 \qquad (82)$$

Pressure drop in the chamber:

$$\Delta P_{camara} = 0{,}5\rho C_{ebocal}^2 K_{camara} = 0{,}5.1{,}225.6{,}2216^2.0{,}00229 = \mathbf{0{,}0543\ Pa} \qquad (83)$$

4) *Pressure drop on diffusers:* The pressure drop in the diffusers depends on the values of specific coefficients. Therefore, the coefficients were determined using the specific dimensions of each diffuser.

In the diffusers it was necessary to find the mean hydraulic diameter, $\bar{D}_{Hdif}$, and the mean velocity, $\bar{C}_{dif}$, since the sections are not constant. The equations below have been developed specifically for diffusers. If D_{Hedif} is the hydraulic diameter of the diffuser inlet, D_{Hsdif} the hydraulic diameter of the diffuser outlet and $\bar{C}_{dif}$ the diffuser inlet speed, we have:

$$\bar{D}_{Hdif} = \frac{D_{Hedif} + D_{Hsdif}}{2} \qquad (84)$$

$$\bar{C}_{dif} = \frac{2.C_{edif}.Ae_{dif}}{Ae_{dif} + As_{dif}} \qquad (85)$$

It is important to calculate the output velocity of the diffusers C_{sdif}. Always the input velocity of a diffuser, C_{edif}, will be the output velocity of the posterior one.

a) *Pressure Drop on Diffuser* 1: In order to calculate the Reynolds number, the equations were used

$$\bar{D}_{Hdif1} = \frac{\frac{4Ae_{dif1}}{(2.h_{edif1}) + (2.w_{edif1})} + \frac{4As_{dif1}}{(2.h_{sdif1}) + (2.w_{sdif1})}}{2} = \left(\frac{2{,}25}{(1{,}5+1{,}5)} + \frac{4{,}5}{(2{,}122+2{,}122)}\right) = 1{,}81\,m \qquad (86)$$

Being $C_{edif1} = C_{test} = 37{,}33\,m/s$, the average speed is obtained:

$$\bar{C}_{dif1} = \frac{2.C_{edif1}.Ae_{dif1}}{Ae_{dif1} + As_{dif1}} = \frac{2.37{,}33.2{,}25}{2{,}25+4{,}5} = 24{,}89\frac{m}{s} \qquad (87)$$

As:

$$C_{edif1} \times Ae_{dif1} = C_{sdif1} \times As_{dif1} \rightarrow 37{,}33 \times 2{,}25 = C_{sdif1} \times 4{,}5 \rightarrow C_{sdif1} = 18{,}67\frac{m}{s} \qquad (88)$$

The Reynolds number for diffuser 1 is calculated using the mean velocity and hydraulic diameter values:

$$Re_{dif1} = \frac{\rho \bar{C}_{dif1}\bar{D}_{Hdif1}}{\mu} = \frac{1{,}225.24{,}89.1{,}8103}{0{,}0000179} = 3.083.603{,}33 \qquad (89)$$

The coefficient of friction can be calculated in the usual way:

$$\frac{1}{\sqrt{f_{dif1}}} = 2\log\left(Re_{dif1}\sqrt{f_{dif1}}\right) - 0{,}8 \qquad (90)$$

$$f_{dif1} = 0{,}009918 \qquad (90.1)$$

The pressure drop factor K_f:

$$K_f = \left(1 - \frac{1}{A_{rel\,Dif1^2}}\right)\frac{f_{dif1}}{8\,sen\theta} = \left(1 - \frac{1}{\left(\frac{4{,}5}{2{,}25}\right)^2}\right)\frac{0{,}009918}{8\,sen5°} = 0{,}011 \qquad (91)$$

To calculate the expansion coefficient, K_{exp}, it is necessary to calculate the coefficient $k_e(\vartheta_e)$, defined by the geometry of the section. Since the cross-section of the diffuser is square, $1{,}5 \le \vartheta_e \le 5°$, the following function is used for its determination:

$$k_e(\vartheta_e) = A_2 - B_2\vartheta_e + C_2{\vartheta_e}^2 - D_2{\vartheta_e}^3 + E_2{\vartheta_e}^4 - F_2{\vartheta_e}^5 - G_2{\vartheta_e}^6 \qquad (92)$$

where,

$$k_e(\vartheta_e) = 0{,}1222 - 0{,}0459\vartheta_e + 0{,}02203\vartheta_e{}^2 - 0{,}003269\vartheta_e{}^3 - 0{,}0006145\vartheta_e{}^4 + 0{,}000028\vartheta_e{}^5 - 0{,}00002337\vartheta_e{}^6 = 0{,}0765 \quad (92.1)$$

Calculating the coefficient of expansion, we have:

$$K_{exp} = k_e(\vartheta_e)\left(\frac{A_{rel\,Dif1} - 1}{A_{rel\,Dif1}}\right)^2 = 0{,}0765\left(\frac{\frac{4{,}5}{2{,}25} - 1}{\frac{4{,}5}{2{,}25}}\right)^2 = 0{,}0191 \quad (93)$$

The pressure drops factor of diffuser 1 K_{dif1} is:

$$K_{dif1} = K_f + K_{exp} = 0{,}0107 + 0{,}0191 = 0{,}030 \quad (94)$$

Diffuser 1 pressure drop:

$$\Delta P_{dif1} = 0{,}5\rho\bar{C}^2_{dif1}K_{dif1} = 0{,}5.\,1{,}225.24{,}89^2.\,0{,}0298 = \mathbf{11{,}30\ Pa} \quad (95)$$

b) Pressure drop on the open angle diffuser

Initially one obtains o $\bar{D}_{Hdifw}$ e $\bar{C}_{difw}$:

$$\bar{D}_{Hdifw} = \frac{\frac{4Ae_{difw}}{(2.\,h_{edifw}) + (2.\,w_{edifw})} + \frac{4As_{difw}}{(2.\,h_{sdifw}) + (2.\,w_{sdifw})}}{2} = \left(\frac{4{,}5}{(2{,}122 + 2{,}122)} + \frac{9}{(3+3)}\right) = 2{,}56\,m \quad (96)$$

Being $C_{edifw} = C_{sdif1} = 18{,}67\ m/s$, the average speed is:

$$\bar{C}_{difw} = \frac{2.\,C_{edifw}.\,Ae_{difw}}{Ae_{difw} + As_{difw}} = \frac{2.18{,}67.4{,}5}{4{,}5 + 9} = 12{,}44\frac{m}{s} \quad (97)$$

Output speed C_{sdifw}:

$$C_{edifw} \times Ae_{difw} = C_{sdifw} \times As_{difw} \rightarrow 18{,}67 \times 4{,}5 = C_{sdifw} \times 9 \rightarrow C_{sdifw} = 9{,}335\frac{m}{s} \quad (98)$$

The Reynolds number for the open-angle diffuser was calculated using the mean velocity and hydraulic diameter values:

$$Re_{difw} = \frac{\rho\bar{C}_{difw}\bar{D}_{Hdifw}}{\mu} = \frac{1{,}225.12{,}44.2{,}56}{0{,}0000179} = 2.179.432{,}40 \quad (99)$$

The coefficient of friction:

$$\frac{1}{\sqrt{f_{difw}}} = 2\log\left(Re_{difw}\sqrt{f_{difw}}\right) - 0{,}8 \rightarrow f_{difw} = 0{,}010 \quad (100)$$

Pressure drop factor K_f:

$$K_f = \left(1 - \frac{1}{A^2{}_{rel\,Difw}}\right)\frac{f_{difw}}{8\,sen\theta} = \left(1 - \frac{1}{\left(\frac{9}{4{,}5}\right)^2}\right)\frac{0{,}009934}{8\,sen\,22{,}5°} = 0{,}00243 \quad (101)$$

Since the open-angle diffuser has the same geometry as the diffuser 1, and $\vartheta_e > 5°$, the following equation is used to calculate the coefficient of expansion:

$$k_e(\vartheta_e) = A_3 + B_3\vartheta_e = -0{,}01322 + 0{,}05866\vartheta_e = 0{,}0098 \quad (102)$$

Given the coefficient of expansion, we obtain:

$$K_{exp} = k_e(\vartheta_e)\left(\frac{A_{rel\,Difw} - 1}{A_{rel\,Difw}}\right)^2 = 0{,}0098\left(\frac{\frac{9}{4{,}5} - 1}{\frac{9}{4{,}5}}\right)^2 = 0{,}00245 \quad (103)$$

Pressure drop factor of the open-angle diffuser. K_{difw}:

$$K_{difw} = K_f + K_{exp} = 0{,}00243 + 0{,}00245 = 0{,}00488 \quad (104)$$

Pressure drop for the open-angle diffuser:

$$\Delta P_{difw} = 0{,}5\rho\bar{C}^2_{difw}K_{difw} = 0{,}5.\,1{,}225.12{,}44^2.\,0{,}00488 = \mathbf{0{,}46\ Pa} \quad (105)$$

c) Pressure drop on diffuser 2

Determination of $\bar{D}_{Hdif2}$ e $\bar{C}_{dif2}$:

$$\bar{D}_{Hdif2} = \frac{\frac{4Ae_{dif2}}{(2.h_{edif2}) + (2.w_{edif2})} + \frac{4As_{dif2}}{(2.h_{sdif2}) + (2.w_{sdif2})}}{2} = \left(\frac{9}{(3+3)} + \frac{13{,}5}{(3{,}68 + 3{,}68)}\right) = 3{,}33\,m \qquad (106)$$

Being $C_{edif2} = C_{sdifw} = 9{,}335\,m/s$, one can calculate the average velocity:

$$\bar{C}_{dif2} = \frac{2.C_{edif2}.Ae_{dif2}}{Ae_{dif2} + As_{dif2}} = \frac{2.9{,}335.9}{9 + 13{,}5} = 7{,}47\frac{m}{s} \qquad (107)$$

Output speed C_{sdif2}:

$$C_{edif2} \times Ae_{dif2} = C_{sdif2} \times As_{dif2} \rightarrow 9{,}335 \times 9 = C_{sdif2} \times 13{,}5 \rightarrow C_{sdif2} = 6{,}223\frac{m}{s} \qquad (108)$$

The Reynolds number for the diffuser 2 is calculated using the mean velocity and hydraulic diameter values:

$$Re_{dif2} = \frac{\rho \bar{C}_{dif2}\bar{D}_{Hdif2}}{\mu} = \frac{1{,}225.7{,}468.3{,}33}{0{,}0000179} = 1.701.890{,}45 \qquad (109)$$

The coefficient of friction:

$$\frac{1}{\sqrt{f_{dif2}}} = 2\log\left(Re_{dif2}\sqrt{f_{dif2}}\right) - 0{,}8 \rightarrow f_{dif2} = 0{,}0105 \qquad (110)$$

The pressure drop factor K_f:

$$K_f = \left(1 - \frac{1}{A^2{}_{rel\,Dif2}}\right)\frac{f_{dif2}}{8\,sen\theta} = \left(1 - \frac{1}{\left(\frac{13{,}5}{9}\right)^2}\right)\frac{0{,}010469}{8\,sen\,5°} = 0{,}00834 \qquad (111)$$

To calculate the coefficient of expansion it is necessary to calculate the coefficient $k_e(\vartheta_e)$, however, in this case the $k_e(\vartheta_e)$ of the diffuser 2 will be the same as the diffuser 1, since both have the same expansion angle ϑ_e.

$$k_e(\vartheta_e) = 0{,}0765 \qquad (112)$$

Coefficient of expansion K_{exp}:

$$K_{exp} = k_e(\vartheta_e)\left(\frac{A_{rel\,Dif2} - 1}{A_{rel\,Dif2}}\right)^2 = 0{,}0765\left(\frac{\frac{13{,}5}{9} - 1}{\frac{13{,}5}{9}}\right)^2 = 0{,}0085 \qquad (113)$$

The diffuser 2 pressure drop factor. K_{dif2} is:

$$K_{dif2} = K_f + K_{exp} = 0{,}00834 + 0{,}0085 = 0{,}01684 \qquad (114)$$

Thus, the pressure drops of the diffuser 2 can be calculated:

$$\Delta P_{dif2} = 0{,}5\rho\bar{C}^2_{dif2}K_{dif2} = 0{,}5.1{,}225.7{,}468^2.0{,}01684 = \mathbf{0{,}5752\ Pa} \qquad (115)$$

E. Total Pressure Drops

The total pressure drop ΔP_{total} can be calculated by summing the pressure drops of all components of the tunnel ΔP_{comp}, according to the equation below:

$$\Delta P_{total} = \sum \Delta P_{comp} \qquad (116)$$

Table 12 shows the total pressure drop and the percentage relative to the total loss of each of the components, and in Table 13 the actual pressure loss of the system.

TABLE 12 Total pressure drops

	(Pa)	%
Inlet nozzle	0,3115	0,25%
Test section	26,3231	20,84%
Diffuser 1	11,2984	8,95%
Open angle diffuser	0,4637	0,37%
Diffuser 2	0,5759	0,46%
Screens	81,2823	64,36%
Honeycomb	5,9807	4,74%
Stabilization chamber	0,0548	0,04%
Total pressure drop (ΔP_{total})	126,290	Pa

The total pressure loss of the system $\mathbf{\Delta P_{tot;sistema}}$ can be found by adding up the total pressure drop to the recovery pressure drop, $\mathbf{\Delta P_{rec}}$. The recovery pressure drops, $\mathbf{\Delta P_{rec}}$, is the loss occurring due to the pressure variation at the outlet of the diffuser 2 and can be represented as the dynamic pressure at the outlet of the diffuser 2, $\boldsymbol{Pd_{dif2}}$:

$$\Delta P_{rec} = \frac{1}{2}\rho C_{sdif2}{}^{2} = \frac{1}{2}.1{,}225.6{,}223^{2} = \mathbf{23{,}412\ Pa} \tag{117}$$

The results obtained are summarized in Table 13, below.

TABLE 13
Actual pressure loss

	Pa	mmH2O
Pressure drop of tunnel components (ΔP_{total})	126,2903	12,8780
Pressure Recovery (ΔP_{rec})	23,4117	2,3873
Real Pressure Loss ($\Delta P_{tot;sistema}$)	149,70	15,2654

The information obtained, Tables 12 and 13, are of great importance for the critical analysis of each of the components considered in the analysis. The actual pressure loss is associated to the stated conditions, whose fundamental parameters are the velocity of 37,33 m/s in the test section and the mass flow rate of air Q equal to 83,99 m³/s.

IV. DISCUSSION

The sizing was performed with the objective of presenting a viable solution for the demand of aerodynamic tests in medium-sized automotive models. Researches carried out present the great difficulties in meeting the parameters of real scale test in wind tunnels, due to the high cost that involves the construction and operation of such equipment, which led us to opt for the method of reproducing a test in model reduced in wind tunnel.

It was observed a great difficulty in reproducing flows of real proportions with moderate speed (above 60 km/h) in small scale tests, because there are physical limitations related to the similarity parameters that make these conditions unfeasible. The model reduction scale and the simulation speed were determined in an iterative way, aiming at balancing the test parameters so that the designed equipment assumed feasible dimensions and energy demands, generating useful data for later studies and the possible optimization of a model more refined.

For the effective sizing of all the components of the tunnel, an extensive bibliographical research was carried out in books and articles related to the subjects of aerodynamics, simulations and construction of wind tunnels. The most relevant aspects related to the research carried out are related to the equations and recommendations that govern the geometry of the components, most of which are derived from experimental studies and empirical analyzes.

Some particular factors of the project carried out were taken into account when applying theories and equations, aiming to always maintain the viability of construction. Thus, the designed wind tunnel assumes the following generic dimensions and functional characteristics, Table 14:

TABLE 14
Wind tunnel final characteristics

Total length	15,83 m
Overall width	3,7 m
Total height (without stand)	3,7 m
Test section area	2,25 m²
Recommended test speed	37,33 m/s
Maximum allowed test speed	50 m/s
Required Power	34,039 HP

V. CONCLUSION

A suction-type subsonic wind tunnel design with closed test section was presented to test small car models and generate important data for the study of their aerodynamics. The designed wind tunnel can be used for testing on any models that meet the prerequisite of occupying less than 20% of the cross-sectional area of the test section, equal to 2.25 m².

The designed wind tunnel reaches the maximum speed of approximately 50 m/s in the test section, but it is recommended, for reasons of energy efficiency, that the operating range does not exceed 40 m/s. The dimensioning was delimited to the geometric dimensioning of the components and in the determination of the energy requirements of the propulsion system in order that the design conditions were met.

It should be emphasized that the functionality and validation of the data obtained must be corroborated by the construction, installation and instrumentation of the dimensioned equipment.

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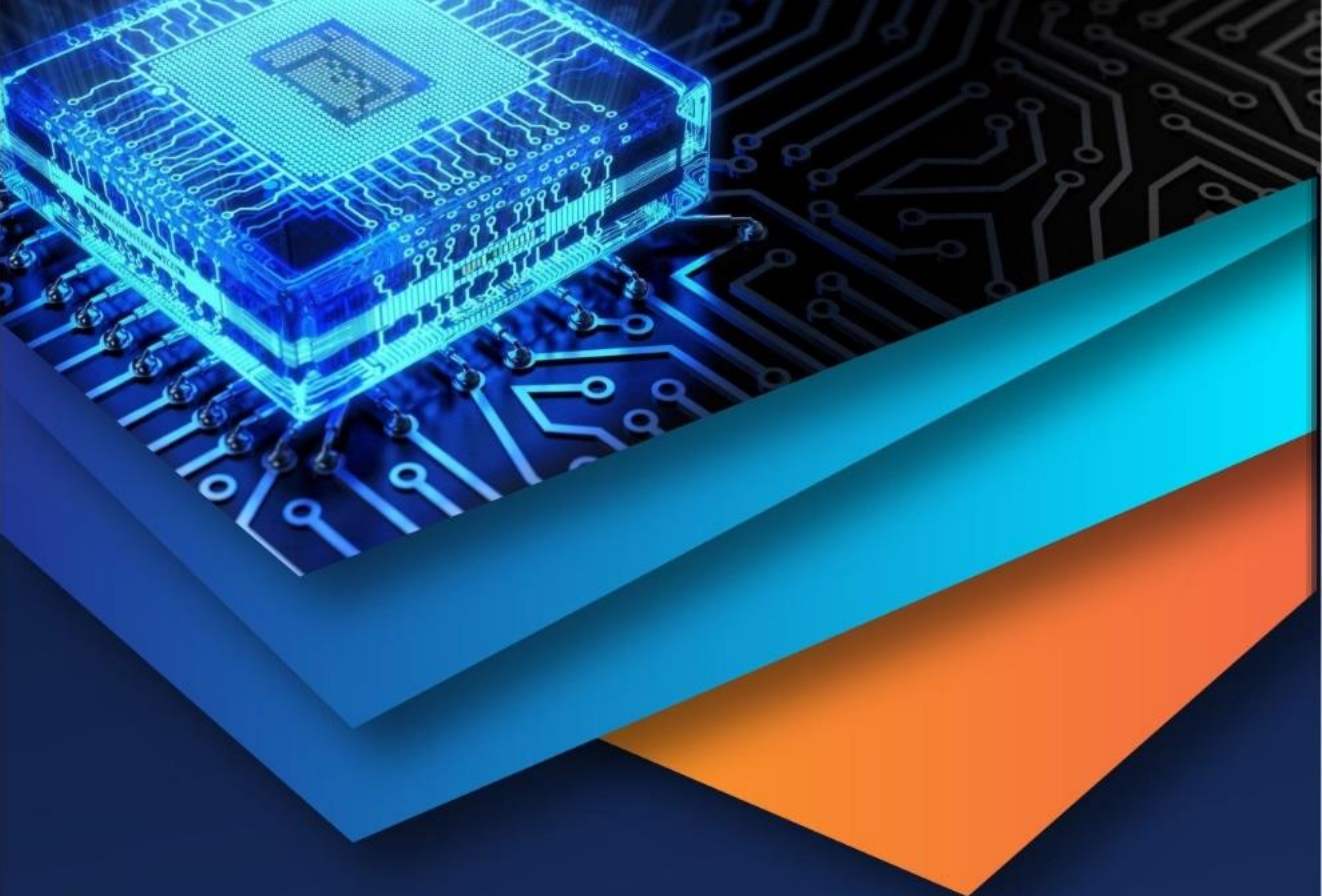

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