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Wind Tunnels: Models, Aerodynamics and Applications

Edited by **Russell Mikel**

Clanrye International

New Jersey

Published by Clanrye International,
55 Van Reypen Street,
Jersey City, NJ 07306, USA
www.clanryeinternational.com

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International Standard Book Number: 978-1-63240-523-4 (Hardback)

Printed in China.

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Preface

The models, aerodynamics and applications of wind tunnels are discussed in this profound book. It will be a valuable tool for students and professionals. It provides an insight into various designs of wind tunnelling and their tremendous research potential. It compiles researches conducted by experts on subsonic and supersonic wind tunnel designs, applicable for a broad range of disciplines. The book discusses various aspects of stationary and portable subsonic wind tunnel designs. It also elucidates topics related to supersonic wind tunnel and discusses a method to address fluctuating effects of fan blade rotation. This book also covers an analysis of wind tunnel applications across a multitude of engineering fields including civil, mechanical, chemical and environmental engineering.

This book is a comprehensive compilation of works of different researchers from varied parts of the world. It includes valuable experiences of the researchers with the sole objective of providing the readers (learners) with a proper knowledge of the concerned field. This book will be beneficial in evoking inspiration and enhancing the knowledge of the interested readers.

In the end, I would like to extend my heartiest thanks to the authors who worked with great determination on their chapters. I also appreciate the publisher's support in the course of the book. I would also like to deeply acknowledge my family who stood by me as a source of inspiration during the project.

Editor

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Wind Tunnel Design

Chapter 1

Design Methodology for a Quick and Low-Cost Wind Tunnel

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Additional information is available at the end of the chapter

1. Introduction

Wind tunnels are devices that enable researchers to study the flow over objects of interest, the forces acting on them and their interaction with the flow, which is nowadays playing an increasingly important role due to noise pollution. Since the very first day, wind tunnels have been used to verify aerodynamic theories and facilitate the design of aircrafts and, for a very long time, this has remained their main application. Nowadays, the aerodynamic research has expanded into other fields such as automotive industry, architecture, environment, education, etc., making low speed wind tunnel tests more important. Although the usefulness of CFD methods has improved over time, thousands of hours of wind tunnel tests (WTT) are still essential for the development of a new aircraft, wind turbine or any other design that involves complex interactions with the flow. Consequently, due to the growing interest of other branches of industry and science in low speed aerodynamics, and due to the persistent incapability of achieving accurate solutions with numerical codes, low speed wind tunnels (LSWT) are essential and irreplaceable during research and design.

A crucial characteristic of wind tunnels is the flow quality inside the test chamber and the overall performances. Three main criteria that are commonly used to define them are: maximum achievable speed, flow uniformity and turbulence level. Therefore, the design aim of a wind tunnel, in general, is to get a controlled flow in the test chamber, achieving the necessary flow performance and quality parameters.

In case of the aeronautical LSWTs, the requirements of those parameters are extremely strict, often substantially increasing the cost of facilities. But low turbulence and high uniformity in the flow are only necessary when, for example, laminar boundary layers have to be investigated. Another example of their use is aircraft engines combustion testing; this in turns requires a costly system that would purify the air in the tunnel to maintain the same air quality. Another increasingly important part of aircraft design is their noise footprint and usually the only way to test this phenomenon is in a wind tunnel.

In the automotive applications, it is obvious that the aerodynamic drag of the car is of paramount importance. Nevertheless, with the currently high level of control of this parameter and also due to imposed speed limitations, most of the efforts are directed to reduce the aerodynamic noise. The ground effect simulation is also very important, resulting in very sophisticated facilities to allow testing of both the ground effect simulation and noise production in the test section.

In architecture, due to the fact that buildings are placed on the ground and are usually of relatively low height, they are well within the atmospheric boundary layer. Therefore, the simulation of the equivalent boundary layer, in terms of average speed and turbulence level, becomes a challenging problem.

The design of the wind tunnels depends mainly on their final purpose. Apart from vertical wind tunnels and others used for specific tests (e.g. pressurised or cryogenic wind tunnels), most of the LSWTs can be categorised into two basic groups: open and closed circuit. They can be further divided into open and closed test section type.

For most applications, mainly for medium and large size wind tunnels, the typical configuration is the closed circuit and closed test chamber. Although, due to the conservation of kinetic energy of the airflow, these wind tunnels achieve the highest economic operation efficiency, they prove more difficult to design resulting from their general complexity. Hence, we will pay more attention to them in this chapter.

Apart from some early built wind tunnels for educational purposes at the UPM, since 1995 a number of LSWTs have been designed following the methodology which will be presented here. It focuses on the reduction of construction and operation costs, for a given performance and quality requirements.

The design procedure was first used for a theoretical design of a LSWT for the Spanish Consejo Superior de Deportes, which was to have a test section of 3,0 x 2,5 x 10,0 m^3 with a maximum operating speed of 40 m/s. Based on this design, a 1:8 scale model was built at UPM. This scaled wind tunnel has been used for research and educational purposes.

The second time it was during the design of a LSWT for the Instituto Tecnológico y de Energías Renovables de Tenerife (ITER). That wind tunnel is in use since February 2001, operating in two configurations: medium flow quality at maximum operating speed of 57 m/s, and high flow quality at maximum operating speed of 48 m/s. For more information visit www.iter.es.

Another example of this design procedure is a LSWT for the Universidad Tecnológica de Perú, which is now routinely used for teaching purposes. This wind tunnel is now in operation for about one and a half year.

At the moment the same procedure is being utilised to design a LSWT for the Beijing Institute of Technology (BIT). This wind tunnel will be used for educational and research purposes. It will have a high quality flow, up to 50 m/s, in a test section of 1,4 x 1,0 x 2,0 m^3. It will be used for typical aerodynamic tests and airfoil cascade tests (utilising the first corner of the wind tunnel circuit).

The design method to be presented in this chapter is based upon classical internal ducts design and analysis method, e.g. *Memento des pertes de charge: Coefficients de pertes de charge singulières et de pertes de charge par frottement,* I.E. Idel'cik [Eyrolles, 1986]. It also includes design assisting software such as a macro-aided Excel spreadsheet with all the complete formulation and dimensioning schemes for automatic recalculation. At the moment the best example of use of the method is the BIT-LSWT, mentioned above, as it has been defined using the latest and most reliable generation of wind tunnel design methodology.

2. Main design criteria

The general layout of the proposed wind tunnel is shown in Figure 1. The airflow circulates in the direction indicated in the test chamber (counter clockwise in the figure). Upstream of the test chamber we find the other two main components of the wind tunnel: the contraction zone and the settling chamber. The other crucial component is of course the power plant. The remainder of the components just serve the purpose of closing the circuit while minimising the pressure loss. Nevertheless, diffuser 1 and corner 1 also have an important influence on the flow quality and they are responsible for more than 50% of the total pressure loss.

The design criteria are strongly linked with the specifications and requirements and those must be in accordance with the wind tunnel applications. The building and operation costs of a wind tunnel are highly related to the specifications and these are just a consequence of the expected applications.

In the case of the so called Industrial Aerodynamics or educational applications, the requirements related to flow quality may be relaxed, but for research and aeronautical applications the flow quality becomes very important, resulting in more expensive construction and higher operational costs.

The main specifications for a wind tunnel are the dimensions of the test section and the desired maximum operating speed. Together with this the flow quality, in terms of turbulence level and flow uniformity, must be specified in accordance with the applications. At this point it should also be defined whether all the components of the wind tunnel are going to be placed on the floor in a horizontal arrangement or in a vertical one, with only half of the circuit on the floor and the other half on top of it.

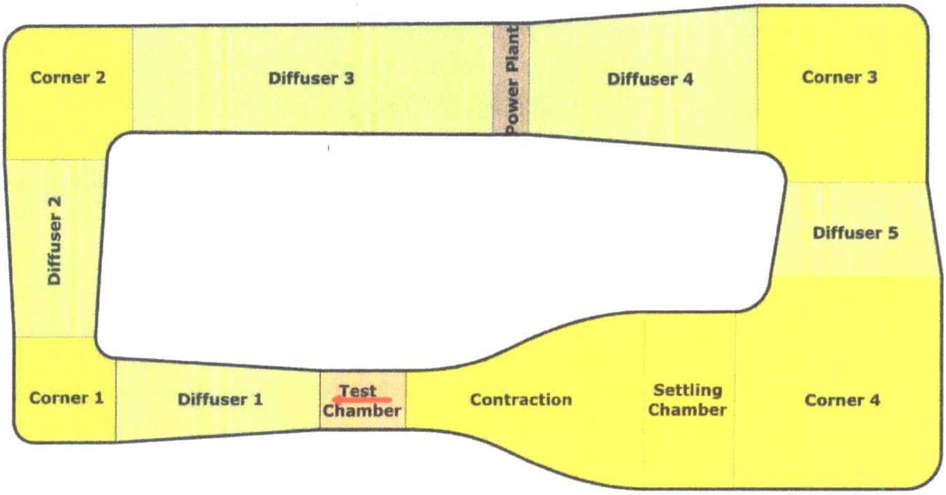

Figure 1. General layout of a closed circuit low speed wind tunnel. Figure labels indicate the part name, according to standards.

Flow quality, which is one of the main characteristics, is a result of the whole final design, and can only be verified during calibration tests. However, according to previous empirical knowledge, some rules can be followed to select adequate values of the variables that affect the associated quality parameters. The recommended values will be discussed in the sections corresponding to the Contraction, Settling Chamber, Diffusor 1 and Corner 1, which are the wind tunnel parts that have the greatest impact on the flow quality.

Once these specifications are given, it is very important to obtain on one side the overall wind tunnel dimensions to check their compatibility with the available room, and on the other side a preliminary estimation of the overall cost. The cost is mainly associated to the external shape of the wind tunnel and the power plant requirements.

For the benefit of new wind tunnel designers, a tool has been devised and implemented in an Excel spreadsheet (visit web page http://www.aero.upm.es/LSLCWT). Using this tool the designer will immediately get information about each part of the wind tunnel, the overall dimensions, the global and individual pressure loss coefficients, and the required power. This will be done according to the recommended input parameters and specification based on the intended use of the wind tunnel.

3. Wind tunnel components definition

In the following sections the design of each part will be thoroughly discussed and analysed in detail to get the best design addressing the general and particular requirements. Before dealing with each component, some general comments are given for the most important parts. In the case of the contraction zone, its design is crucial for achieving the required flow quality in the test section. In this sense, its contraction ratio, length and contour definition determine the level of uniformity in the velocity profile, as well as the necessary turbulence attenuation. It is crucial to avoid flow separation close to the walls of the contraction zone. At the stage of design, the most adequate method to verify that design meets those criteria is computational fluid dynamics (CFD).

Other important parts of the wind tunnel design worth mentioning here are the corners which incorporate turning vanes. Their aim is to reduce pressure loss and, in the case of the corner 1, possibly improve flow quality in the test section. The parameters to be considered in their design are the spacing between vanes (whether the space ought to be constant or not) and the possibility of expanding the flow (increasing the cross-section).

To complete the design process, the measurement equipment needs to be defined together with the complimentary calibration tests. Special attention needs to be devoted to the specification and selection of the balance for forces measurement, a device that is used to measure aerodynamic forces and moments on the model subjected to airflow in the test section. Since the drag force on test subjects can be very small and significant noise may be coming from the vibration of the tunnel components, such as the model stand, the true drag value may become obscured. The choice of an appropriate force balance is therefore crucial in obtaining reliable and accurate measurements.

The selection depends mainly on the nature of the tests. Wind tunnel balances can be categorized into internal and external ones. The former offers mobility since it is usually only temporarily mounted to the test section and may be used in different test sections. However, the latter has more potential in terms of data accuracy and reliability since it is tailored to a specific wind tunnel and its test section. Due to this reason, external force balances should be studied in greater depth.

3.1. Test chamber

The test chamber size must be defined according to the wind tunnel main specifications, which also include the operating speed and desired flow quality. Test chamber size and operating speed determine the maximum size of the models and the maximum achievable Reynolds number.

The cross-section shape depends on the applications. In the case of civil or industrial applications, in most of the cases, a square cross-section is recommended. In this case, the test specimens are usually bluff bodies and their equivalent frontal area should not be higher than 10% of the test chamber cross-sectional area in order to avoid the need of making non-linear blockage corrections. Accurate methods for blockage corrections are presented in Maskell (1963).

Nevertheless, a rectangular shape is also recommended for aeronautical applications. In the case of three-dimensional tests, a typical width to height ratio is 4:3; however, for two-dimensional tests a 2:5 ratio is advised in order for the boundary layer thickness in the test section to be much smaller than the model span.

Taking into account that it is sometimes necessary to place additional equipment, e.g. measuring instruments, supports, etc., inside the test chamber, it is convenient to maintain the operation pressure inside it equal to the local environment pressure. To fulfil this condition, it is recommended to have a small opening, approximately 1,0% of the total length of the test chamber, at the entrance of the diffuser 1.

From the point of view of the pressure loss calculation, the test chamber will be considered as a constant section duct with standard finishing surfaces. Nevertheless, in some cases, the test chamber may have slightly divergent walls, in order to compensate for the boundary layer growth. This modification may avoid the need for tail flotation correction for aircraft model tests, although it would be strictly valid only for the design Reynolds number.

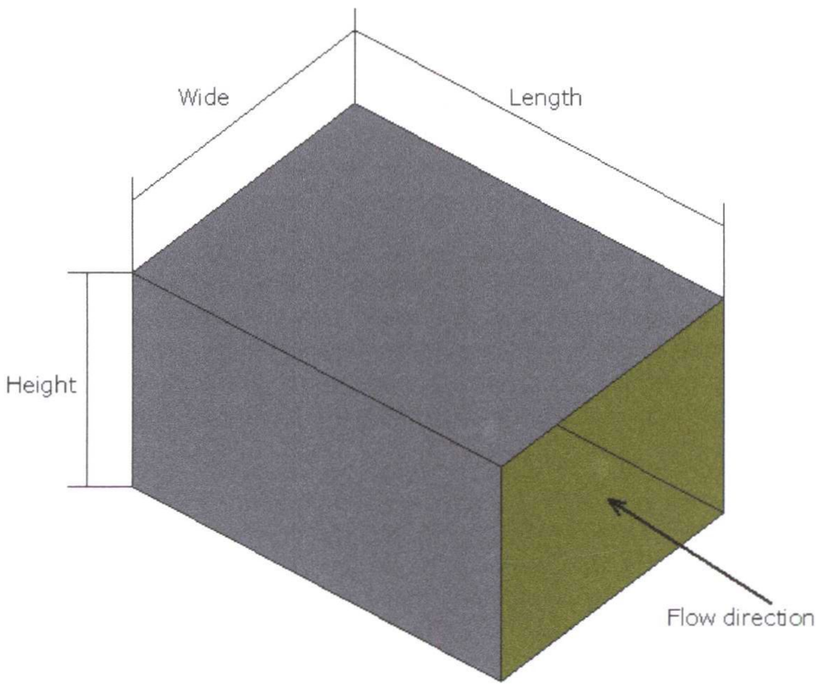

Figure 2. Layout of a constant section wind tunnel test chamber.

Figure 2 shows a design of a typical constant section test chamber. With the typical dimensions and velocities inside a wind tunnel, the flow in the test section, including the boundary layer, will be turbulent, because it is continuous along the whole wind tunnel. According to Idel'Cik (1969), the pressure loss coefficient, related to the dynamic pressure in the test section, which is considered as the reference dynamic pressure for all the calculations, is given by the expression:

$$\zeta = \lambda \cdot L \, / D_H,$$

where L is the length of the test chamber, D_H the hydraulic diameter and λ a coefficient given by the expression:

$$\lambda = 1/(1{,}8 \cdot \log Re - 1{,}64)^2,$$

where Re is the Reynolds number based on the hydraulic diameter.

3.2. Contraction

The contraction or "nozzle" is the most critical part in the design of a wind tunnel; it has the highest impact on the test chamber flow quality. Its aim is to accelerate the flow from the settling chamber to the test chamber, further reducing flow turbulence and non-uniformities in the test chamber. The flow acceleration and non-uniformity attenuations mainly depend on the so-called contraction ratio, N, between the entrance and exit section areas. Figure 3 shows a typical wind tunnel contraction.

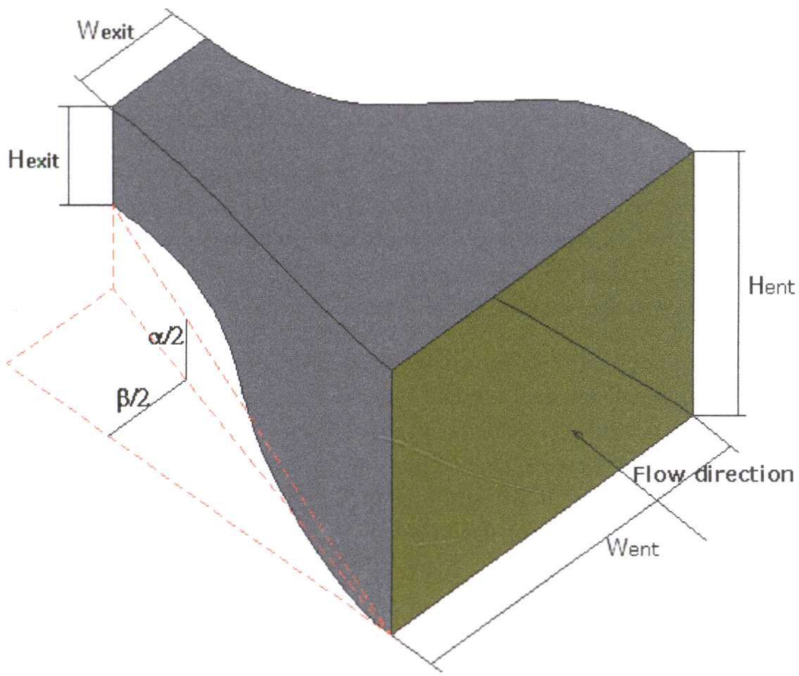

Figure 3. General layout of a three-dimensional wind tunnel contraction.

Although, due to the flow quality improvement, the contraction ratio, N, should be as large as possible, this parameter strongly influences the overall wind tunnel dimensions. Therefore, depending on the expected applications, a compromise for this parameter should be reached.

Quoting P. Bradshaw and R. Metha (1979), "The effect of a contraction on unsteady velocity variations and turbulence is more complicated: the reduction of x-component (axial) fluctuations is greater than that of transverse fluctuations. A simple analysis due to Prandtl predicts that the ratio of root-mean-square (rms) axial velocity fluctuation to mean velocity will be reduced by a factor $1/N^2$, as for mean-velocity variations, while the ratio of lateral rms fluctuations to mean velocity is reduced only by a factor of N: that is, the lateral fluctuations (in m/s, say) increase through the contraction, because of the stretching and spin-up of elementary longitudinal vortex lines. Batchelor, *The Theory of Homogeneous Turbulence*, Cambridge (1953), gives a more refined analysis, but Prandtl's results are good enough for tunnel design. The implication is that tunnel free-stream turbulence is far from isotropic. The axial-component fluctuation is easiest to measure, e.g. with a hot-wire anemometer, and is the "free-stream turbulence" value usually quoted. However, it is smaller than the others, even if it does contain a contribution from low-frequency unsteadiness of the tunnel flow as well as true turbulence."

In the case of wind tunnels for civil or industrial applications, a contractions ratio between 4,0 and 6,0 may be sufficient. With a good design of the shape, the flow turbulence and non-uniformities levels can reach the order of 2,0%, which is acceptable for many applications. Nevertheless, with one screen placed in the settling chamber those levels can be reduced up to 0,5%, which is a very reasonable value even for some aeronautical purposes.

For more demanding aeronautical, when the flow quality must be better than 0,1% in non-uniformities of the average speed and longitudinal turbulence level, and better than 0,3% in vertical and lateral turbulence level, a contraction ratio between 8,0 and 9,0 is more desirable. This ratio also allows installing 2 or 3 screens in the settling chamber to ensure the target flow quality without high pressure losses through them.

The shape of the contraction is the second characteristic to be defined. Taking into account that the contraction is rather smooth, one may think that a one-dimensional approach to the flow analysis would be adequate to determine the pressure gradient along it. Although this is right for the average values, the pressure distribution on the contraction walls has some regions with adverse pressure gradient, which may produce local boundary layer separation. When it happens, the turbulence level increases drastically, resulting in poor flow quality in the test chamber.

According to P. Bradshaw and R. Metha (1979), "The old-style contraction shape with a small radius of curvature at the wide end and a large radius at the narrow end to provide a gentle entry to the test section is not the optimum. There is a danger of boundary-layer separation at the wide end, or perturbation of the flow through the last screen. Good practice is to make the ratio of the radius of curvature to the flow width about the same at each end. However, a too large radius of curvature at the upstream end leads to slow acceleration and therefore increased rate of growth of boundary-layer thickness, so the boundary layer - if laminar as it should be in a small tunnel - may suffer from Taylor-Goertler "centrifugal" instability when the radius of curvature decreases".