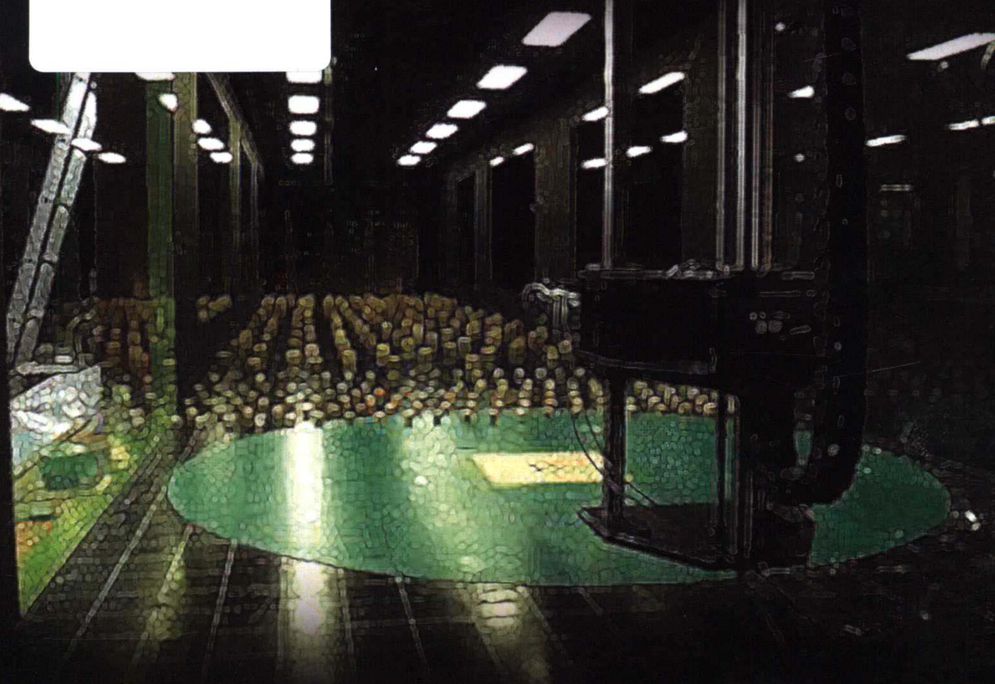
SUSAN B. CHAPLIN
EDITOR



Wind Tunnels

Design/Construction, Types and Usage Limitations

Mechanical Engineering Theory and Applications

Novinka

MECHANICAL ENGINEERING THEORY AND APPLICATIONS

WIND TUNNELS

DESIGN/CONSTRUCTION, TYPES AND USAGE LIMITATIONS

SUSAN B. CHAPLIN
EDITOR

NOVINKA
New York

Copyright © 2013 by Nova Science Publishers, Inc.

All rights reserved. No part of this book may be reproduced, stored in a retrieval system or transmitted in any form or by any means: electronic, electrostatic, magnetic, tape, mechanical photocopying, recording or otherwise without the written permission of the Publisher.

For permission to use material from this book please contact us:
Telephone 631-231-7269; Fax 631-231-8175
Web Site: http://www.novapublishers.com

NOTICE TO THE READER

The Publisher has taken reasonable care in the preparation of this book, but makes no expressed or implied warranty of any kind and assumes no responsibility for any errors or omissions. No liability is assumed for incidental or consequential damages in connection with or arising out of information contained in this book. The Publisher shall not be liable for any special, consequential, or exemplary damages resulting, in whole or in part, from the readers' use of, or reliance upon, this material. Any parts of this book based on government reports are so indicated and copyright is claimed for those parts to the extent applicable to compilations of such works.

Independent verification should be sought for any data, advice or recommendations contained in this book. In addition, no responsibility is assumed by the publisher for any injury and/or damage to persons or property arising from any methods, products, instructions, ideas or otherwise contained in this publication.

This publication is designed to provide accurate and authoritative information with regard to the subject matter covered herein. It is sold with the clear understanding that the Publisher is not engaged in rendering legal or any other professional services. If legal or any other expert assistance is required, the services of a competent person should be sought. FROM A DECLARATION OF PARTICIPANTS JOINTLY ADOPTED BY A COMMITTEE OF THE AMERICAN BAR ASSOCIATION AND A COMMITTEE OF PUBLISHERS.

Additional color graphics may be available in the e-book version of this book.

Library of Congress Cataloging-in-Publication Data

ISBN: 978-1-62618-396-4

Published by Nova Science Publishers, Inc. † New York

MECHANICAL ENGINEERING THEORY AND APPLICATIONS

WIND TUNNELS

DESIGN/CONSTRUCTION, TYPES AND USAGE LIMITATIONS

MECHANICAL ENGINEERING THEORY AND APPLICATIONS

Additional books in this series can be found on Nova's website
under the Series tab.

Additional e-books in this series can be found on Nova's website
under the e-book tab.

PREFACE

In this book, the authors discuss the design and construction, types and usage limitations of wind tunnels. Topics include the use of wind tunnels to analyze wind loading on scaffold structures; the characteristics of the Architecture and Building Research Institute wind tunnel project; analysis of the wind environment and air quality in densely populated areas using wind tunnel experiments; wind tunnel investigation into the drag characteristics of catamaran form; and environmental wind tunnels designed and constructed to investigate a wide range of aerodynamic tasks.

Chapter 1 - In 2001, the ABRI (Architecture and Building Research Institute, Ministry of the Interior, Taiwan) initiated a project to establish an environmental wind tunnel in the Kui-Ren campus of National Cheng Kung University. This project was completed in 2004. The wind tunnel is of a closed-return type, featuring two test sections in series. The primary test section is 3 m by 2.6 m in cross section and 36.5 m in length; the secondary test section is 6 m by 2.6 m in cross section and 21 m in length. The wind tunnel uses a 500 KW axial fan. Immediately after the completion of the wind tunnel, the wind tunnel was calibrated. The results of the calibration indicate that the maximum speed at the inlet of the primary test section is 36 m/s and that the turbulence intensity and non-uniformity of the flow measured at the inlet of the main test section are less than 0.3% and 0.4%, respectively. At a flow of speed more than 30 m/s, the energy ratio calculated from the fan test data, is about 0.94, which almost coincides with that predicted by the design data. The flow quality of the wind tunnel was further examined using an experiment with two circular cylinders at Reynolds numbers in the critical regime. The base pressure coefficients measured were found to be in good agreement with those reported in the literature. The oil-film flow visualization performed in this experiment further provides information regarding the flow patterns corresponding to different flow states in the critical regime.

Chapter 2 - This chapter presents an experimental investigation of wind flow characteristics and air quality along a street canyon located within a dense urban area. Four typical models of a highly populated urban area are studied and wind tunnel experiments are carried out over an extended range of the applied wind directions. The building patterns are represented by 1:100 scale models, where wind velocity, wind pressure and tracer gas concentrations are measured along the two sides of the street.

A serious problem associated with wind tunnel tests on the flow around buildings is that of blockage. To overcome such problem, an experiment for determining the building blocking effect was carried out and a correction factor was estimated and considered in the measured pressures. Details of such experiment are given at the end of this chapter.

The study results provide evidence that building configurations and wind directions are very important factors in determining both wind flow and pollutant dispersion characteristics within urban domains. Also, the results demonstrate that gaps between buildings are a very important factor to be considered by urban planners and designers, because, for a given building height, larger gaps induce more wind in urban canyons, thus improving the ventilation process.

Chapter 3 - The breakdown into the resistance or drag components of catamarans has been widely discussed worldwide in the last 30 years. The resistance interference (both wave and viscous parts) has been the major part among the components. Wave resistance interference can be rather easily estimated using tank test, whilst the viscous component is rather complicated to determine. Tank test can be used to estimate the skin friction, but correction should be made attributed to interference of wave resistance on skin friction or viscous resistance. In order to isolate the viscous resistance, hence free from wave component, wind tunnel test was carried out. A series of tests of catamaran forms were carried out using low speed wind tunnel. Various configurations of slender catamaran were made in order to identify the viscous resistance (hence the form factor) and viscous resistance interference.

The Chapter discusses the construction and experimental procedure of the wind tunnel test. Verifications were made with tank test and CFD (computational fluid dynamics) data in order to examine the accuracy of using wind tunnel. Overall results demonstrate the effectiveness of using wind tunnel test to estimate viscous resistance and its interference component.

Chapter 4 - A considerable variety of wind tunnels have been designed and constructed to investigate a wide range of aerodynamic tasks. Nowadays, environmental wind tunnels designed to simulate Atmospheric Boundary Layer are very attractive.

They are used to determine air pollution, wind loads on buildings and constructions, snowdrift, accident with the discharge of harmful substances, pedestrian wind comfort, etc. Several requirements for experiments in meteorological or environmental tasks have to be fulfilled in order to transfer results from small scale wind tunnel experiments to full scale: 1) proper scaling: matching the scale of the model and the boundary layer scale; 2) matching dimensionless similarity numbers, especially the Reynolds numbers; 3) proper simulation of air flow, including distribution of velocity and turbulence characteristics within the boundary layer; 4) acquiring the zero pressure gradient for equilibrium boundary layer. The similarity requirements are the starting point for the environmental wind tunnel design. Some types of these wind tunnels are introduced in this chapter, and their construction is briefly described. Integral part of environmental wind tunnel laboratories is their experimental equipment.

Special devices are described, including systems for flow visualization, for turbulent characteristics and concentrations measurements. Some examples of the tasks solved in the environmental wind tunnels are mentioned at the end.

Chapter 5 - This chapter describes the use of wind-tunnels to investigate the wind pressures applied to sheeted scaffold structures. A brief description of the problems of simulating wind in a tunnel is outlined. The tests required to calibrate a wind-tunnel are described with sample results presented. Wind-tunnel tests on a model of a clad cubical building and on a model of the Silsoe Experimental Building are presented together with pressure results showing the application of the procedures. The chapter shows that providing the procedures described are carried out that good agreement between wind-tunnel simulations and full-scale tests can be achieved. Finally, the method of deriving coefficients required for computational fluid dynamics calculations for permeable netting from experimental pressure-velocity measurements obtained in a small wind-tunnel is given.

CONTENTS

Preface **vii**

Chapter 1 The Characteristics of the ABRI Wind Tunnel **1**
J. J. Miau, Z. L. Chen and C. C. Hu

Chapter 2 Analysis of Wind Environment and Air Quality in Densely Populated Areas using Wind Tunnel Experiments **35**
Mahmoud Bady

Chapter 3 Wind Tunnel Investigation into the Drag Characteristics of Catamaran Form **73**
I. K. A. P. Utama and A. Jamaluddin

Chapter 4 Environmental Wind Tunnels **105**
Z. Janour and K. Jurcakova

Chapter 5 Use of Wind-tunnels to Analyse Wind Loading on Scaffold Structures **125**
H. Irtaza and R. G. Beale

Index **149**

In: Wind Tunnels
Editor: Susan B. Chaplin

ISBN: 978-1-62618-396-4

Chapter 1

THE CHARACTERISTICS OF THE ABRI WIND TUNNEL

***J. J. Miau*[1,*], *Z. L. Chen*[1] *and C. C. Hu*[2]**
[1]National Cheng Kung University, Tainan, Taiwan, ROC
[2]Kao Yuan University, Kaohsiung,, Taiwan, ROC

ABSTRACT

In 2001, the ABRI (Architecture and Building Research Institute, Ministry of the Interior, Taiwan) initiated a project to establish an environmental wind tunnel in the Kui-Ren campus of National Cheng Kung University. This project was completed in 2004. The wind tunnel is of a closed-return type, featuring two test sections in series. The primary test section is 3 m by 2.6 m in cross section and 36.5 m in length; the secondary test section is 6 m by 2.6 m in cross section and 21 m in length. The wind tunnel uses a 500 KW axial fan. Immediately after the completion of the wind tunnel, the wind tunnel was calibrated. The results of the calibration indicate that the maximum speed at the inlet of the primary test section is 36 m/s and that the turbulence intensity and non-uniformity of the flow measured at the inlet of the main test section are less than 0.3% and 0.4%, respectively. At a flow of speed more than 30 m/s, the energy ratio calculated from the fan test data, is about 0.94, which almost coincides with that predicted by the design data. The flow quality of the wind tunnel was further examined using an experiment with

---

[*] Corresponding author Email address: jjmiau@mail.ncku.edu.tw.

two circular cylinders at Reynolds numbers in the critical regime. The base pressure coefficients measured were found to be in good agreement with those reported in the literature. The oil-film flow visualization performed in this experiment further provides information regarding the flow patterns corresponding to different flow states in the critical regime.

Keywords: Environmental wind tunnel, closed-return loop, circular cylinder, critical regime

1. INTRODUCTION

The effect of wind on buildings, civil structures and bridges is a great concern for public safety and the economy. From the viewpoint of fluid dynamics, the flow over a structure or multiple structures induces pressure forces upon the surfaces and produces complex phenomena in the surroundings. Strong wind may cause damage to buildings and structural elements and can induce motion in tall buildings and bridges (Cermak et al., 1966; Cermak, 1975; Cermak 1976; Houghton and Carruther, 1976). However, the effects of light wind are predominant considerations in studies of air pollution.

The ABRI, a governmental agency, must evaluate the building codes of the country and propose modifications, if necessary. In 2000, ABRI made a general agreement with National Cheng Kung University to establish several large-scale facilities in the Kuei-Ren campus of the university, in Tainan, in order to fulfill this mission. One of the facilities was the environmental wind tunnel, addressed in this study.

In order to establish the wind tunnel facility, in 2001, ABRI formed a committee with members from several universities in Taiwan, namely, Professors C. M. Cheng and K. C. Woo from Tamkang University, Professor C. R. Chu from National Central University, Professor S. K. Ren from Cheng-Shiung University and Professors J. H. Chou and J. J. Miau from National Cheng-Kung University. This committee was chaired by Professor J. J. Miau. The committee was tasked to provide the technical assistance for the project, including the design of the wind tunnel, the monitoring the integration process for the wind tunnel, and calibration measurements to validate the design of the wind tunnel.

This facility was completed at the end of 2004. It is of a closed-return circuit and can be switched to an open loop to allow flow visualization and particle dispersion experiments. The wind tunnel features two rectangular test sections in series. The primary test section is 4 m by 3 m in cross section and is used mainly for testing building models; the secondary test section is 6m by 2.6m in cross section and is used mainly for testing bridge models.

This study provides a summary of the experience gleaned in the past ten years in the design and validation of the wind tunnel. In the following, the design aspects of the wind tunnel are given firstly. The construction and integration of the wind tunnel are then described, followed by the calibration results for the wind tunnel. Finally, the results of an experiment using two circular cylinders at critical Reynolds numbers are given and compared with those reported in literature.

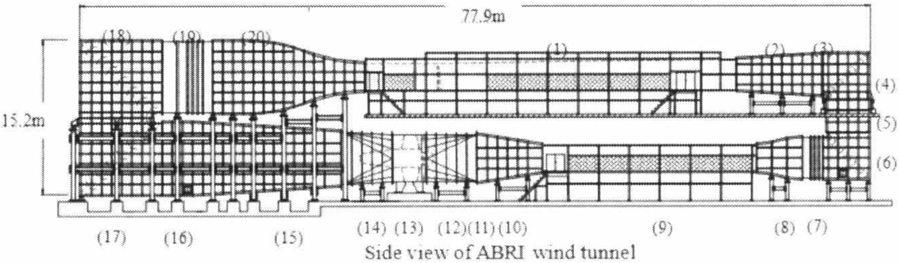
2. DESIGN ASPECTS OF THE ABRI WIND TUNNEL

The ABRI environmental wind tunnel was designed mainly for the testing of building and bridge models. However, in the initial phase of the design (Miau et al., 2004), it was realized that the requirements for building and bridge testing are in conflict, in regard to the cross-sectional shapes required for the test sections. A test section for the testing of building models normally has a low aspect ratio in cross section, whereas a test section for the testing of bridge models is preferred to be of a high aspect ratio. Unless the test section could be large enough to accommodate both requirements, multiple test sections were the only option.

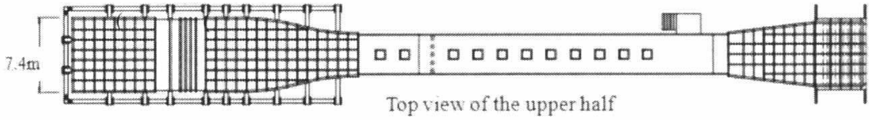
This wind tunnel uses two test sections in series, in a closed loop. One of the two test sections is 4 m by 2.6 m in cross section, in which the flow speed ranges from 1 and 30 m/s, and the other is 6 m by 2.6 m in cross section, for which the maximum speed is 20 m/s. The former test section, called the primary test section, was designed mainly for the testing of building models, whereas the latter, called the secondary test section, was for the testing of bridge models. The wind tunnel was also designed to be operated in an open-circuit mode, in order to conduct experiments for flow visualization and particle dispersion in the primary test section.

Gross Features of the Wind Tunnel

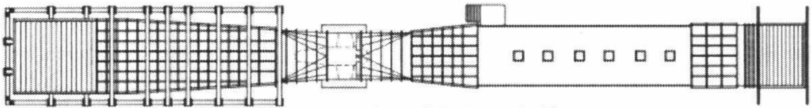
Figure 1 shows a schematic drawing of the wind tunnel, i.e., a closed single-return circuit with two test sections.



Side view of ABRI wind tunnel



Top view of the upper half



Top view of the lower half

Figure 1. A schematic drawing of ABRI wind tunnel. (Miau et al., 2003).

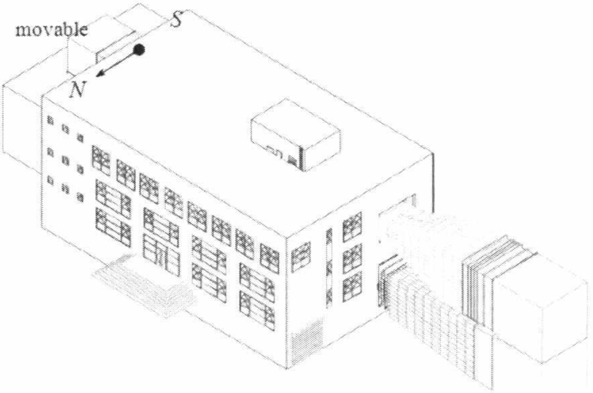


Figure 2. A perspective view of the wind tunnel and the building. (Miau et al., 2003).

The primary test section is 4 m by 2.6 m in cross section and 36.5 m in length. The test section is long enough for the natural development of a thick turbulent boundary near the downstream end, in order to simulate an atmospheric boundary layer. Artificial roughness elements with spires can also be installed at the inlet of the test section to produce an even thicker boundary layer, to simulate the atmospheric boundary layers under different specified environmental conditions. On the lower level of the circuit, the secondary test section is 6 m by 2.6 m in cross section and 21 m in length. As shown in Figure 1, the total length of the wind tunnel body is 77.9 m and its maximum width and height are 7.4 m and 15.2 m, respectively. For the convenience of later description, each of the wind tunnel components is assigned a number indicated in the figure. The primary test section is denoted as component (1). Following the flow direction, the remainder of the components are numbered accordingly. For instance, the diffuser immediately downstream of the primary test section is denoted as component (2).

Figure 2 shows that the wind tunnel and the laboratory building are integrated. The wind tunnel circuit consists of two floor levels. The primary test section is situated on the upper level and the secondary test section is situated on the lower level. There are two control rooms near the two test sections. A 90° corner in component (4) is actually situated on a rail, so that the corner could be moved aside during open-circuit operation.

The wind tunnel is driven by an axial fan of 500 kW, noted as component (13) in Figure 1. It is 4.75 m in diameter, with a center body 1.9 m in diameter. Figure 3 shows a photo of the fan. The fan is situated on an isolated foundation on the lower level floor. Two flexible joints are connected to the inlet and outlet of the fan section, to prevent fan vibration propagating to other components. Since the pitch angle of the fan blades is fixed, the speed of the airflow is solely controlled by the rotational speed of the fan. At the maximum flow rate, the total pressure produced by the fan was required to be at least 1000 Pa and the flow velocity in the primary test section to be no less than 30 m/s. However, the fan was also required to deliver a stable volume flow rate at 1 m/s in the primary test section, which defines the lowest flow rate to be delivered by the fan. In addition, a 1.5 hp blower is installed outside the fan, to cool the fan motor.

A closed-loop wind tunnel generally requires cooling devices to continuously extract heat from the air in the tunnel circuit. At the initial stage of the design, a trade-off study led to a decision to install a water-sprinkling system around two 90° corners outside the building; components (17) and (18) in Figure 1, respectively. This design is capable of cooling the wind tunnel body effectively and produces no additional pressure loss in the tunnel circuit. During operation, the cooling water is collected and recycled, for continuous use. Two adjustable breather slots are located immediately downstream of the primary test section and immediately upstream of the fan section. By adjusting the openings of these breather slots, the amount of air exchanged between the interior and exterior of the tunnel can be controlled.

Primary Test Section

The primary test section has dimensions of 4m by 2.6m in cross section and 36.5m in length, which is specifically designed for testing building models at flow speeds up to 30 m/s. Because of the thickening of boundary layers on the walls and the presence of test models, an undesirable streamwise pressure gradient was possible in the test section. In order to compensate for the pressure gradient, the ceiling of the primary test section was designed to be flexible, such that its vertical position could be varied in a range of ±300 mm. In order to allow viewing of the model in the test section and taking photographs during an experiment, some sections of the sidewalls have transparent glass windows in the lower halves, as shown in Figure 4.

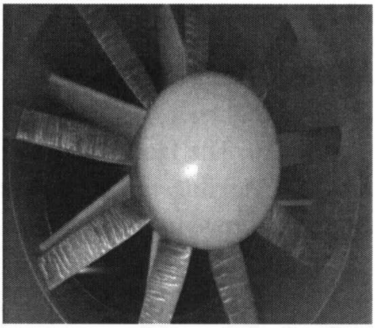


Figure 3. A frontal view of the fan.

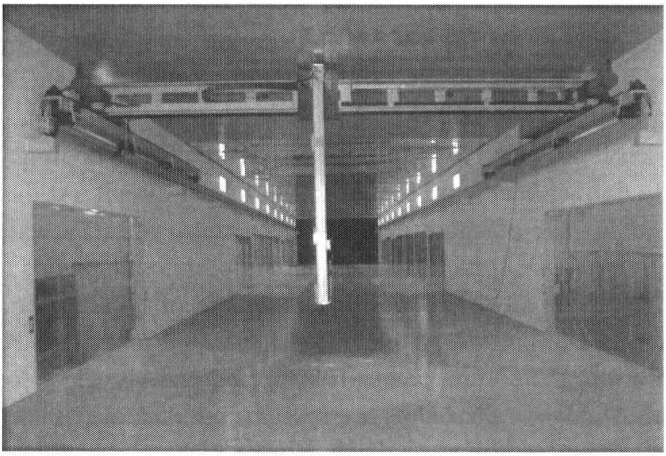


Figure 4. The primary test section with a 3-D traversing mechanism. (Kao, 2005).

These windows can be opened easily, using weight-balancing mechanisms. The test model can be placed on one of three turntables, located at 2.8 m, 25.5 m and 31.5 m downstream of the inlet of the test section. The farthest upstream is used for the experiments that require a uniform incoming flow.

The other two turntables are mainly for model testing in a thickened boundary layer. A three-dimensional traversing mechanism is provided in the test section for the convenience of a flow field survey, as seen in Figure 4. The traversing mechanism can be moved manually in the streamwise direction, for a distance of 8 to 34 m downstream of the inlet. The traversing mechanism is controlled to within an accuracy of 1mm by servo motors in a three-dimensional region of 4m, 3.8m and 2.6m in the streamwise, spanwise and vertical directions, respectively.

A turbulence generation device can be installed at the inlet of the primary test section to produce variable turbulence intensities in the free stream. These screens can be inserted or removed using a slide mechanism.

Secondary Test Section

The secondary test section has dimensions of 6m by 2.6m in cross section and 21m in length and flow speeds up to 20m/s are possible. It is designed mainly for experiments with bridge models. Similarly to the primary test section, the lower halves of the sidewalls have transparent glass windows, which can be opened easily, using weight-balancing mechanisms.

However, unlike the primary test section, the upper ceiling is not adjustable. Only one turntable is provided in this test section. It was anticipated that the flow quality in this test section would be inferior to that in the primary test section, because of the limited streamwise extent of flow management upstream.

Diffusers

As seen in Figure 1, three diffusers are provided in the wind tunnel circuit, labeled as components (2), (10) and (15), also named diffuser #1, diffuser #2 and diffuser #3, respectively, below.

The equivalent diverging angles of the three diffusers are 4.6°, 4.2°, and 4.6°, respectively. These angles are larger than the value of 3.0°, which is generally recommended to avoid the flow separation that occurs in a diffuser (Gorlin and Slezing, 1966; Rae and Pope, 1984).

As seen in Figure 1, the two sidewalls of diffuser #2 diverge widely, whereas the top and bottom walls appear to converge. This is due to the geometrical constraints at the inlet and exit of this diffuser. Therefore, two split plates are inserted vertically in diffuser #1, to divide the passage into three partitions; in diffuser #2, two split plates, perpendicular to each other, are inserted to equally divide the passage into four partitions. In diffuser #3, which is 16.5 m long, no split plates are installed, because the pronounced frictional loss might be caused by split plates. Since this diffuser is located immediately downstream of the fan section, the flow at the inlet of the diffuser contains fluctuations at high level, in addition to rotation, which actually hinders flow separation.

Flow Management Sections

Flow management sections upstream of the two contraction sections function to ensure that the flow at the inlets of the two test sections is uniform and steady. In the section labeled (19) in Figure 1, a honeycomb made of circular cells 19 mm in diameter and 200 mm in length, i.e., a length-to-diameter ratio of about 10, is installed at the inlet to straighten the flow in the streamwise direction. Downstream of the honeycomb, four screens of different mesh-sizes are installed with sufficient spacing to reduce the intensity of the turbulence of the flow. The screens have mesh sizes of 2, 5, 10, and 16, respectively.

In the flow management section, labeled (7) in Figure 1, three turbulence screens are arranged. These are mesh sizes 5, 10, and 16, respectively.

Contractions

The components immediately downstream of the flow management sections mentioned are the contraction sections, respectively labeled (20) and (8) in Figure 1, and also named as contraction sections #1 and #2 below. Note that the contraction ratios of these two contraction sections are 4.71 and 1.54, respectively, which are considerably smaller than the typical value of 6 to10 (Rae and Pope, 1984), because of the limits of the dimensions of the circuit. Only the top and bottom walls of contraction section #2 converge, so non-