WIND TUNNEL BLOCKAGE CORRECTIONS: AN APPLICATION TO VERTICAL-AXIS WIND TURBINES

Thesis
Submitted to
The School of Engineering of the
UNIVERSITY OF DAYTON

In Partial Fulfillment of the Requirements for
The Degree of
Master of Science in Aerospace Engineering

By
Ian J. Ross
Dayton, Ohio
May, 2010
WIND TUNNEL BLOCKAGE CORRECTIONS:
AN APPLICATION TO VERTICAL-AXIS
WIND TURBINES

APPROVED BY:

__________________________________  ______________________________
Aaron Altman, Ph.D.     Jewel Barlow, Ph.D.
Advisory Committee Chairman   Committee Member
Associate Professor, Department of
Mechanical & Aerospace
Engineering      Director, Glenn L. Martin
________________________________
Eric Lang, Ph.D.
Committee Member
Adjunct Professor,
University of Dayton Research Institute
________________________________
Malcolm W. Daniels, Ph.D.    Tony E. Saliba, Ph.D.
Associate Dean     Dean
School of Engineering     School of Engineering
ABSTRACT

WIND TUNNEL BLOCKAGE CORRECTIONS: AN APPLICATION TO VERTICAL-AXIS WIND TURBINES

Name: Ross, Ian J.
University of Dayton
Advisor: Dr. Aaron Altman

An investigation into wake and solid blockage effects of Vertical-Axis Wind Turbines (VAWTs) in closed test-section wind tunnel testing is described. Static wall pressures have been used to derive velocity increments along a wind tunnel test-section which in-turn are applied to provide evidence of wake interference characteristics of rotating bodies interacting within this spatially restricted domain. Vertical-axis wind turbines present a unique aerodynamic obstruction in wind tunnel testing whose blockage effects have not been extensively investigated.

The flow-field surrounding these wind turbines is asymmetric, periodic, unsteady, separated and highly turbulent. Static pressure measurements are taken along a test-section sidewall to provide a pressure signature of the test models under varying rotor tip-speed ratios (freestream conditions and model RPM’s). To provide some guidance on the scaling of the combined effects of wake and solid blockage, wake characteristics and VAWT performance produced by the same vertical-axis wind turbine concept have been tested at different physical scales in two different wind tunnels. This investigation provides evidence of the effects of large wall interactions and wake propagation caused by these models at well below generally accepted standard blockage figures.
ACKNOWLEDGMENTS

Firstly, I would like to thank my advisor Dr. Aaron Altman for his support, advice and above all, providing an unwavering mentorship throughout my time in Graduate School. His enthusiasm and passion for research instils a great appreciation and love for experimenting. His continual support and guidance has made it possible to complete the writing of this thesis. I gratefully acknowledge the research funding provided by the Department of Mechanical & Aerospace Engineering at the University of Dayton, specifically the Department Chair, Dr. Kevin Hallinan. Many thanks goes to the University of Dayton Research Institute, namely Tom Mooney and Dan Bowman for creating an excellent VAWT test facility at the University of Dayton Low-Speed Wind Tunnel, without their efforts this entire research would not have been possible. I would like to show my appreciation for the developmental funding provided by Twenty First Century Energy (TFCE), particularly the efforts of Doug Bogart for providing numerous wind tunnel models and the positive vision of Don Knoth CEO of TFCEnergy for his ongoing support of harvesting new ideas for wind energy systems. I would also like to thank Dr. Jim Crafton at Innovative Scientific Solutions, Incorporated, for his kind offer of equipment to help with our testing.

Finally, I realize this has not been an easy journey and I could not have made it this far without the overwhelming support from my Family, Friends and especially my girlfriend Stephanie for being there every step of the way.

Thank you
# TABLE OF CONTENTS

**ABSTRACT** .......................................................................................................................... iii

**ACKNOWLEDGEMENTS** ........................................................................................................ iv

**TABLE OF CONTENTS** ........................................................................................................ v

**LIST OF FIGURES** ............................................................................................................... ix

**LIST OF TABLES** ................................................................................................................ xv

**NOMENCLATURE** ............................................................................................................. xvi

**CHAPTER 1 - INTRODUCTION** .......................................................................................... 1

1.1 – Solid Blockage Effect ................................................................................................... 4

1.2 – Wake Blockage Effect ............................................................................................... 5

1.3 – Total Blockage Effect ............................................................................................... 6

1.4 – Bluff-Body Aerodynamics ....................................................................................... 6

**CHAPTER 2 – LITERATURE REVIEW OF VAWT STUDIES** ........................................... 8

2.1 – Aerodynamic Analysis of Savonius Rotors ............................................................... 8

2.1.1 – Aerodynamic Performance of Savonius Rotors ................................................... 8

2.1.2 – Unsteady Flow past a Savonius Rotor ................................................................. 10

2.2 – Wind Tunnel Testing of Savonius Rotors ................................................................ 12

2.2.1 – Design Configurations for a Savonius Rotor ....................................................... 12

2.2.2 – Performance Data for 2 & 3 Bucket Savonius Rotors ......................................... 13

2.2.3 – Experiments Investigating Savonius Geometry Influence ................................... 14

2.2.4 – Effect of Wind Tunnel Blockage on Performance ............................................... 17
2.3 – Flow-Field Visualization .................................................................18
2.3.1 – Flow Visualization in and around a Savonius Rotor ......................18
2.3.2 – Particle Tracking Velocimetry to estimate Pressure Field ...............20
2.4 – Turbine Wake Modeling ....................................................................22
2.4.1 – 3D Effects & Bluff-Body Vortex Shedding .................................22
2.4.2 – Mean Wind & Turbulence – Induction Effects ...............................23
2.4.3 – A Model for Unsteady Rotor Aerodynamics .................................24

CHAPTER 3 – WIND TUNNEL BLOCKAGE CORRECTION METHODS ....26
3.1 – Pope & Harper Blockage Correction ..................................................27
3.2 – Maskell Method .................................................................................27
3.3 – Extensions to Maskell’s Method for Bluff Bodies ...............................30
3.4 – Wake Corrections for Models subjected to Separated Flow ...................32
3.5 – Glauert Correction ............................................................................34
3.6 – Hackett, Lilley & Wilsden Method .....................................................35
3.7 – Wake Blockage Corrections via Wall Static Pressures .........................36
3.8 – Corrections for 2D Wind Tunnel Tests using WPM .............................39
3.9 – Hensel’s Velocity-Ratio Model ............................................................41
3.10 – Bluff-Body Blockage Studies ............................................................42

CHAPTER 4 – EXPERIMENTAL METHOD .................................................46
4.1 – Data Reduction ...................................................................................46
4.2 – Reynolds Number Scaling ..................................................................48
4.3 – Low-Speed Wind Tunnel – VAWT Testing Facilities .........................50
4.3.1 – Hysteresis Brake System .................................................................52
4.3.2 – Rotary Torque Transducer ...............................................................54
4.3.3 – Air Bearing ....................................................................................54
4.4 – Static Pressure-Taps..........................................................................................55
4.4.1 – Pressure Transducer Array System...............................................................56
4.5 – Pressure Coefficient from Euler’s Equations..................................................57
4.6 – Wind Tunnel Models ....................................................................................58
4.7 – Nd:YAG Laser System .................................................................................58
4.8 – (CCD) High-Shutter-Speed Camera .............................................................59

CHAPTER 5 – RESULTS & DISCUSSION.....................................................................60
5.1 – Dynamic & Static Loading ...........................................................................60
5.2 – Power & Torque Coefficient........................................................................62
5.3 – Blockage Effects ...........................................................................................64
5.4 – Wall Pressure Signature .............................................................................68
5.5 – Pressure Coefficient as a function of Location .............................................69
5.6 – Pressure Signature as a function of Sidewall Height ....................................72
5.7 – Pressure Coefficient vs. Location as a function of RPM .........................72
5.8 – Pressure Coefficient vs. TSR as a function of Longitudinal Location .......75
5.9 – Linear Regression Model ...........................................................................76
5.10 – (C_{pr} - TSR) Slopes as a function of Wind Speed .....................................77
5.11 – Flow-Field Visualization ...........................................................................78
5.11.1 – Influence of RPM ...................................................................................81
5.11.2 – Upstream Flow .......................................................................................84
5.12 – Application of Blockage Corrections..........................................................87
5.12.1 – Velocity Corrections ...............................................................................88
5.12.2 – Correcting Performance Curves...............................................................89

CHAPTER 6 – CONCLUSIONS & FURTHER WORK...............................................97

REFERENCES............................................................................................................101
LIST OF FIGURES

Figure 1.1 – Savonius Vertical-Axis Wind Turbine concepts from TFCEnergy [2] (Left) 3-Blade, (Right) 2-Blade Conventional Savonius ................................................................. 1

Figure 1.2 – Savonius Rotor configuration and geometrical parameters [17] ....................... 3

Figure 1.3 – Propeller-type and Darrieus-Curved Blade-type Turbines [Source: AWEA] ........ 3

Figure 1.4 – VAWT influence upon streamlines – Solid Blockage ........................................ 5

Figure 1.5 – Solid Body Blockage Effect – Variations with Velocity and Pressure [4] ............ 5

Figure 1.6 – VAWT influence upon streamlines – Wake Blockage ....................................... 5

Figure 1.7 – Wake Blockage Effect – Variation with Velocity and Pressure outside the wake [4] ........................................................................................................................................... 6

Figure 1.8 – Total Blockage Effect – Variation with Velocity and Pressure outside the wake [4] ........................................................................................................................................... 6

Figure 1.9 – Comparison of Streamlined and Bluff-Body Flow Interaction [5] ...................... 7

Figure 1.10 – Flow Confinement Effects on Bluff-Body & Streamlined Bodies [4] ............. 7

Figure 2.1 – Flow Field around a Savonius by smoke-wire method [6] ................................. 9

Figure 2.2 – Pressure Coefficient Distribution, $C_p$, for a Static Rotor (Left) and Rotating (Right) [6] .................................................................................................................... 9

Figure 2.3 – Flow patterns relating Blade Angle-to-Freestream with Time-steps, 60° (top) and 90° (bottom) for stationary rotor [7, 8, 9] ................................................................. 11

Figure 2.4 – Flow patterns relating blade angle-to-freestream with Time-steps, rotating turbine [7, 8, 9] ................................................................................................................... 12

Figure 2.5 – Power & Torque Coefficients vs. TSR, (top) 2 blade and (lower) 3 blade system [12] ......................................................................................................................... 14

Figure 2.6 – Correlation curve for single stage modified Savonius rotor (Reynolds numbers from 77,600 to 150,000) [15] ..................................................................................... 16

Figure 2.7 – Comparison of CP for experimental and correlation results (Single stage modified Savonius rotor at Reynolds numbers of 120,000 and 150,000) [15] ...................... 17
Figure 4.3 – UD Low Speed Wind Tunnel (Left): Contraction Section, (Right): Downstream View............................................................................................................ 51

Figure 4.4 – TFCEnergy Low-Speed Wind Tunnel....................................................................................................................... 51

Figure 4.5 – Turbine Torque and RPM wind tunnel testing facility.................................................................................................. 52

Figure 4.6 – Hysteresis Brake [48] .............................................................................................................................................. 53

Figure 4.7 – Stator Tooth Structure (Left) and Torque/Current Curve (Right) [48]................................................................. 53

Figure 4.8 – T11-2-A2A Bearingless Rotary Torque Transducer [49].............................................................................................. 54

Figure 4.9 – Spindle Application drawing using Thrust Bushings [50]............................................................................................. 54

Figure 4.10 – Static Pressure Wall Tap Locations.......................................................................................................................... 55

Figure 4.11 – Aerolab Test-Section & Pressure Traverse System [52]......................................................................................... 56

Figure 4.12 – Test-Section GUI PC Control Station [52].................................................................................................................. 57

Figure 4.13 – Nd:YAG Laser and Cylindrical Concave Optic [54].................................................................................................... 58

Figure 4.14 – Orientation of the Laser Sheet through the 2% Model ............................................................................................. 59

Figure 4.15 – PCO 1600 CCD Camera and Control Box [56]........................................................................................................ 59

Figure 5.1 – Wind Tunnel Data for the 10% Model, Turbine Torque and RPM vs. Time (Dynamically loading rotor models over a set time period creating max torque & RPM physical limits)......................................................................................................................... 61

Figure 5.2 – Power Curves of 1/40th and 1/30th Scale Models (Comparing Static to Dynamic Loading methods, computing Rotor Efficiency, both produce similar results).......................... 61

Figure 5.3 – Comparison of Two Wind Tunnel results for 1/40th Scale Model (Details Power Coefficients increasing as function of Blockage ratio increase 2 to 5.5%) ............................... 63

Figure 5.4 – Variation of Torque and Free-spin with Turbine RPM (Details Torque trends at varying wind speeds and resonance regions) ...................................................................................... 63

Figure 5.5 – Comparison of Power Coefficient vs. Tip-Speed-Ratio (Increasing power curves at 80 mph freestream with varying Blockage ratios)........................................................................ 64

Figure 5.6 – Comparison of Power Coefficient vs. Tip-Speed-Ratio (Shows the effect of blockage ratio on output of Savonius rotor) [57]..................................................................................... 65

Figure 5.7 – Power Curves from two Wind Tunnels [29, 30] (A comparison of results in Cranfield and Loughborough Wind Tunnels for Savonius Rotor with AR = 4.8).......................... 66

Figure 5.8 – Power Coefficient plotted with Tip-Speed-Ratio [58] (Showing the effect of blockage on power output of the Savonius rotor)..................................................................................... 67
Figure 5.9 – Maximum Power Coefficient plotted with Blockage Percentage [58] (Showing the effect of blockage on peak power coefficient for two different blade geometries) ..................................................................................................................................... 67

Figure 5.10 – Tip-Speed-Ratio plotted with Blockage Percentage [58] (Showing the effect of blockage on the tip-speed-ratio at peak power coefficient for two blade geometries) ..................................................................................................................................... 68

Figure 5.11 – Comparison of Wall Static Pressures (Shows reduced pressures relating higher velocities produced by the 10%, 2-Bladed Savonius Model at 40mph freestream with the shaded region displaying upstream segment of test-section) ........................................... 70

Figure 5.12 – Comparison of Wall Static Pressures (Shows possible contributions to reduced pressures from Solid/Bubble and by Wake Blockage for a 10%, 2-Bladed Savonius Model at 70mph freestream) .......................................................................................... 70

Figure 5.13 – Comparison of Velocity Increment as a function of Wind Tunnel Location [4] (Shows possible contributions to reduced pressures from Solid/Bubble and by Wake Blockage) ........................................................................................................... 70

Figure 5.14 – Comparison of Wall Pressure Coefficients at 60mph Freestream Velocity, 1000RPM (Cpr as a function of Area-Ratio) ......................................................................................................................................... 71

Figure 5.15 – 10% Blockage Model, Cpr vs. x-location (Comparison of Cpr distribution as a function of sidewall height & normalized longitudinal x-location) ......................................................................................... 73

Figure 5.16 – 8% Blockage Model, Cpr vs. x-Location (Comparison of Cpr distribution position as a function of longitudinal x-location, Top: 400 & 600RPM, Middle: 800 & 1000RPM, Bottom: 1200RPM) ......................................................................................................................................... 74

Figure 5.17 – 10% Blockage Model, TSR vs. Cpr (Selection of wind tunnel locations which displays the overall trend, across x-locations at 50 mph, described the reduction in blockage effect with increase in TSR) ........................................................................................................... 75

Figure 5.18 – TSR vs. Cpr (Compares the upper, lower and mid-range data for the 3 bladed models at 3.5% and 8% across x-location along wind tunnel at freestream 70 mph) .......... 76

Figure 5.19 – Correlated TSR vs. Cpr compared at x-location along wind tunnel at 60, 70 & 80 mph (Compares upper, lower and mid-range data for 8% model across x-location along wind tunnel, showing increasing TSR and Cpr decreasing and as wind speed increases, slope angle decreases) ........................................................................................................... 76

Figure 5.20 – Plots of Cpr vs. TSR Slopes (Comparison of Cpr vs. TSR slopes across freestream at 10, 8, 3.5 and 2%) ......................................................................................................................................... 77

Figure 5.21 – CCD Camera images across laser sheet (a – d, Compare high RPM’s to low RPM loaded rotor, e) Compares sidewall interaction, left and right test-section sidewall interactions, white strips marking 1 and 2 inches from sidewall surface) ....................................................... 79

Figure 5.22 – Flow patterns from the y-axial view [59] (Comparing rotor azimuth angle to freestream direction, all cases show a high degree of asymmetric wake) ......................................................................................... 80
Figure 5.23 – 10% Model at 20 mph with yellow dotted line denoting boundaries of the wake (Influence of RPM, Left: free-spinning model at 800RPM, Middle: 500RPM and Right: 100RPM) .................................................................................................................................. 81

Figure 5.24 – 10% Model at 50 mph (Attention to Streamline bending around the adverse side of the 2 Bladed Rotor) ................................................................................................................................... 81

Figure 5.25 – 10% Model at 60 mph (Influence of RPM, Left: free-spinning model at 2200RPM, Top: 2000 & 1500RPM & Bottom: 1000 & 600RPM) ................................................................................ 82

Figure 5.26 – 8% Model at 50 mph (Influence of RPM, Clockwise from Top: 880, 500, 250 and 100 RPM) ........................................................................................................................................ 83

Figure 5.27 – 3.5% Model at 60 mph (Influence of RPM, Top: 1400, 1000 and 500 RPM, Bottom: 250 and 100 RPM) ..................................................................................................................................... 83

Figure 5.28 – 2% Model at 80 mph (Influence of RPM, Top: 2150, 1500 and 1000 RPM, Bottom: 500 and 100 RPM) ..................................................................................................................................... 84

Figure 5.29 – 10% Model at 40 mph (Upstream Flow Influence of RPM: Left Column 1600 RPM, Middle Column: 1000 RPM, Right Column: 500 RPM. Top row: rotor at zero azimuth position and the bottom row with the rotor 90° to the freestream) ........................................ 85

Figure 5.30 – 10% Model at 60 mph (Upstream Flow Influence of RPM, Top: 2300RPM, Bottom: 1000 RPM. Left Column shows the rotor at 90° to the freestream and right column at approximately zero azimuth position) ......................................................................... 85

Figure 5.31 – 8% Model at 60 mph (Upstream Flow Influence of RPM, Top: 1000 RPM, Middle: 500 RPM and Bottom: 250 RPM) .................................................................................................................................. 86

Figure 5.32 – Flat Plates and Savonius Rotors term m vs. Blockage Ratio (S/A) ........................................ 88

Figure 5.33 – Comparison of Savonius Rotor Velocity Corrections – (Left) Comparison of Correction Methods, (Right) Relevant comparable plot zone from [29].............................................. 89

Figure 5.34 – Correcting 10% Rotor Power Curves – Shows variation of curves across wind speeds 30 to 60 mph and the curves coalescing as a function of each technique ......................... 91

Figure 5.35 – Correcting 8% Rotor Power Curves – Shows variation of curves across wind speeds 50 to 80 mph and a small change of coalescing as a function of technique................. 92

Figure 5.36 – Comparison of Correction Methods for 10% Rotor operating at 70 mph freestream – (at peak TSR, Pope, Delta WPM and Absolute WPM show little correction, however the Maskell Method reduced the power curve peak position by 59%) ................................................................. 93

Figure 5.37 – Comparison of Correction Methods - 8% Rotor operating at 70 mph freestream – (Maskell Method reduced power curves by 42% and the Absolute WPM shows results shifting towards this region) ....................................................................................... 93
Figure 5.38 – Comparison of Correction Methods – 3.5% Rotor operating at 70 mph freestream - (Uncorrected and Delta WPM Power Curves produced very similar values that superimposed in the figure, Pope method showing little correction, Maskell and Absolute WPM show a clear reduction) ........................................................................................................ 94

Figure 5.39 – Comparison of Correction Methods – 2% Rotor operating at 90 mph freestream - (Uncorrected, Delta WPM and Pope corrected Power Curves produced very similar values that superimposed in the figure, Maskell and Absolute WPM show a clear reduction with a possible over correction using the Absolute WPM) ........................................ 94

Figure 5.40 – Power Curves for 3-Blade Savonius Rotors at 60 mph Freestream (Left) Uncorrected data, (Middle) Pope Correction and (Right) Maskell Method Correction ............... 96
LIST OF TABLES

Table 4.1 – Geometric scaling of full-scale turbine to wind tunnel model ................................... 49

Table 4.2 – Reynolds Number scaled wind speeds ....................................................................... 49

Table 4.3 – Geometry of Wind Tunnel Models (C1 & C2 indicate tests in different wind tunnels) .......................................................................................................................................... 58

Table 5.1 – Results of corrections of Savonius Rotors operating in a restricted flow closed test-section wind tunnel .................................................................................................................................................................................. 95
NOMENCLATURE

A or C : Wind Tunnel Test-Section cross-section area
AR : Aspect Ratio
B : Wind Tunnel Width
c : Rotor Blade Chord
C_D : Drag Coefficient
C_D0 : Zero-Lift Drag Coefficient
C_L : Lift Coefficient
C_P : Power Coefficient
C_Pr : Pressure Coefficient
C_Q or C_t : Torque Coefficient
C_th : Thrust Coefficient
C_st : Static-Torque Coefficient
D : Drag Force
D_r : Turbine (Rotor) Diameter
D_f, D_P : End Plate Diameter
H : Height of Turbine
L : Lift Force
P : Static Pressure
P_{\infty} : Stagnation/Freestream Pressure
q : Dynamic Pressure
r : Turbine Radius
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_e$</td>
<td>Reynolds Number</td>
</tr>
<tr>
<td>$S$ or $S_{\text{swpt}}$</td>
<td>Swept Area of a Turbine</td>
</tr>
<tr>
<td>$U_\infty$</td>
<td>Free-stream Velocity</td>
</tr>
<tr>
<td>$\Delta u$</td>
<td>Velocity Increment</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Corrected Velocity</td>
</tr>
<tr>
<td>$X$</td>
<td>Longitudinal Wind Tunnel Location</td>
</tr>
</tbody>
</table>

**Greek symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon$</td>
<td>Blockage Correction Factor</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Tip-Speed-Ratio</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Angular Velocity</td>
</tr>
<tr>
<td>$\Omega$</td>
<td>Rotation Velocity, RPM</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Kinematic Viscosity</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Wind Turbine Azimuth Angle to Freestream Direction</td>
</tr>
<tr>
<td>$\Psi$</td>
<td>Ratio of Confined Flow Force Coefficients to Unconfined Flow Force Coefficients, e.g. = $C_D/C_{Df}$</td>
</tr>
</tbody>
</table>

**Abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACD</td>
<td>Actuator Disc Method</td>
</tr>
<tr>
<td>AWEA</td>
<td>American Wind Energy Association</td>
</tr>
<tr>
<td>AIAA</td>
<td>American Institute of Aeronautics and Astronautics</td>
</tr>
<tr>
<td>BEM</td>
<td>Blade Element Momentum theory</td>
</tr>
<tr>
<td>DVM</td>
<td>Discrete Vortex Method</td>
</tr>
<tr>
<td>FEA</td>
<td>Finite Element Analysis</td>
</tr>
<tr>
<td>FOV</td>
<td>Field of View</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphical User Interface</td>
</tr>
<tr>
<td>HAWT</td>
<td>Horizontal-Axis Wind Turbine</td>
</tr>
<tr>
<td>ISSI</td>
<td>Innovative Scientific Solutions, Incorporated</td>
</tr>
<tr>
<td>LSWT</td>
<td>Low-Speed Wind Tunnel</td>
</tr>
<tr>
<td>NRC</td>
<td>National Research Council Canada</td>
</tr>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
<tr>
<td>NSE</td>
<td>Navier Stokes’ Equations</td>
</tr>
<tr>
<td>PIV</td>
<td>Particle Image Velocimetry</td>
</tr>
<tr>
<td>PTA</td>
<td>Pressure Transducer Array</td>
</tr>
<tr>
<td>PTV</td>
<td>Particle Tracking Velocimetry</td>
</tr>
<tr>
<td>RAE</td>
<td>Royal Aircraft Establishment</td>
</tr>
<tr>
<td>RPM</td>
<td>Angular Velocity (Rotations per minute)</td>
</tr>
<tr>
<td>SL</td>
<td>Sea-Level Conditions</td>
</tr>
<tr>
<td>TFCE</td>
<td>Twenty First Century Energy</td>
</tr>
<tr>
<td>TSR</td>
<td>Tip Speed Ratio</td>
</tr>
<tr>
<td>UD</td>
<td>University of Dayton</td>
</tr>
<tr>
<td>UDRI</td>
<td>University of Dayton Research Institute</td>
</tr>
<tr>
<td>VAWT</td>
<td>Vertical-Axis Wind Turbine</td>
</tr>
<tr>
<td>WPM</td>
<td>‘Wall Pressure Method’ or ‘Wall Pressure Signature Method’</td>
</tr>
</tbody>
</table>
Chapter 1 - Introduction

Aerodynamics is an active and influential science, contributing to major aspects of wind turbine design. For the aerodynamicist the art of manipulating and adapting a moving fluid to optimize energy extraction can be challenging to achieve. Wind turbines have been studied since the earliest known ancient humans attempted to harness wind energy through diversified means. One of the manners to achieve this goal was through Vertical-Axis Wind Turbines (VAWT).

Figure 1.1 displays two such VAWT models similar in concept to designs devised in 1922 by the Finnish Engineer, Sigurd J. Savonius [1].

![Figure 1.1 – Savonius Vertical-Axis Wind Turbine concepts TFCEnergy [2] (Left) 3-Blade, (Right) 2-Blade Conventional Savonius](image)

Recently, there has been a resurgence of interest regarding sources of renewable energy, with numerous universities, companies and research institutions carrying out extensive research activities. These activities have led to a plethora of designs of wind turbines based mostly on computational aerodynamic models. Still largely restricted to an experimental subject, vertical-
axis wind turbines are appearing more frequently in the civilian and military market as research into their cost-effectiveness and simplicity progresses.

At present, there are two primary categories of modern wind turbines, namely horizontal-axis (HAWTs) and vertical-axis (VAWTs). The main advantages of the VAWT are its single moving part (rotor) where no yaw mechanisms are required, its low-wind speed operation and the elimination of the need for extensive supporting tower structures, thus significantly simplifying the design and installation. Blades of straight-bladed VAWTs can be of uniform airfoil section and untwisted, making them relatively easy to fabricate or extrude, unlike the blades of HAWTs, which are commonly twisted and tapered airfoils for optimum performance.

The motivation for the current research stems from an investigation into the accuracy of how wind tunnel models of this type (Dynamic Bluff-Bodies, such as VAWTs) have been previously tested. The study strives to establish answers and guidelines for the wind tunnel blockage effects on performance of the relatively inefficient VAWT and aims to prevent future wind tunnel testing from stating artificially augmented performance.

In order to improve upon the conceptual approach, previous knowledge of bluff-body aerodynamics has been applied to a rotational frame-of-reference for VAWT concepts. Savonius stated in his 1931 paper published by the Journal of Mechanical Engineering “The S-Rotor and its Application” [1], the maximum efficiency possible was only 31%. Following Savonius, numerous others have investigated the effect of geometric parameters such as blade number, blade gap-size and overlap ratio upon flow behaviour. Due to the complex nature of the flow-field surrounding a Savonius turbine produced by its geometrical shape, Figure 1.2, theoretical work in modeling the aerodynamics is indeed quite scarce. However, there are several developed theories to analyze the Darrieus and propeller type turbines, Figure 1.3, where lift is the dominant force.
Figure 1.2 – Savonius Rotor configuration and geometrical parameters [17]

Figure 1.3 – Propeller-type and Darrieus-Curved Blade-type Turbines - [Source: AWEA]

The Blade Element Momentum theory (BEM) predicts the performance of a Darrieus turbine well, following the “Wind Energy Handbook” Burton [3]. In order to perform an aerodynamic analysis of the flow-field around VAWTs and their interaction with closed test-section wind tunnels, a sample batch of wind turbines/bluff-body geometrical shapes have been constructed in the present study for wind tunnel testing, incorporating:

1) A qualitative comparison of tip-speed-ratio as a function of Reynolds number using flow visualization of the wake and flow regions around VAWTs
2) A comparison of coefficients of power, torque and pressure with blockage factor corrections.
A solid blockage effect is commonly observed in wind tunnel testing that in-turn produces an increase in the local wind velocity in the working section. Appendix A details the types of blockages in greater explanation of the physics involved. This increase is ideally accounted for by a theoretical wind tunnel blockage factor or ratio, of which several developed techniques will be discussed later. Numerous accounts of questionable accuracy have been debated throughout the literature concerning low-speed wind tunnel testing of rotating bluff bodies, especially of VAWT types. The possibility of previously undocumented variable deleterious effects of wind tunnel blockage in VAWT testing is observed in tests performed for this paper and are subsequently presented and discussed. Severe effects will be documented when models occupy a percentage of the tunnel cross-sectional area significantly less than the presently accepted heuristics. The present research details evolutionary steps in improving the practicality in testing sub-scale VAWT’s as well as an investigation into the methodology behind correcting for the flow constraining effect. The goal is to advance existing solid/wake blockage correction methodologies in order to appropriately or knowledgeably apply them to rotating test models and VAWT concepts which exhibit unique viscous and unsteady turbulent flow conditions because a question has arisen in research:

“Are the wind tunnel wall surfaces interacting with the model flow to the extent of impacting the efficiency of the rotor therefore, calling into question accurate comparison to real-scale prototypes?”

1.1 Solid Blockage Effect

Solid Blockage is created from a reduction in test-section area for flow to pass compared to an undisturbed and unrestricted freestream. It is both a function of volume and shape of the body. By Continuity and Bernoulli’s equation, velocity increases in the vicinity of the model compared to velocities in unconfined flow, Figure 1.4.
Increases in velocity compared to the unconfined flow situation (empty test-section) vary across the wind tunnel test-section, Figure 1.5. Continuity of mass flow through the test-section requires increases in velocity near the body with the downstream conditions assumed to revert to undisturbed upstream conditions, ESDU [4].

1.2 Wake Blockage Effect

It is understood to be increasingly difficult to model wake blockage for a stationary body, however, when the test concerns a dynamic rotating bluff-body producing large wake disturbances, the modeling process becomes extremely complex and it becomes quite difficult to predict the degradable effect on the flow. The wake generated has a lower mean velocity than the freestream, Figure 1.6. By Continuity, velocity outside this wake has a higher speed then the flow inside the wake region for a constant mass flow, Figure 1.7, yields lower pressure assuming conditions that satisfy Bernoulli’s equation.
The wake is seen to be an expanding low velocity region of flow extending downstream from the body, Figure 1.7. As the velocity outside the wake increases as a result of wake blockage so does the effective increase in velocity past the body location, ESDU [4].

1.3 Total Blockage Effect

Most importantly for understanding the flow physics involved in the current study, an article by ESDU [4] provides elementary theory for understanding the pressure signature application. Assuming that solid and wake blockage effects can be superimposed they will produce velocity and static-pressure variations along the wind tunnel of the form seen in Figure 1.8.

1.4 Bluff Body Aerodynamics

It is assumed that the flow past a bluff-body separates at sharp-edges and shear layers are shed downstream from points of separation. Shear layers begin at the separation points with
unknown free vortex strength. Houghton [5] provides the basic comparison of drags for various geometrical shapes, Figure 1.9.

As a general overview of the effects of flow confinement on bluff-bodies compared to streamlined bodies, Fig 1.10 details lines $a$-$b$ representing the wind tunnel sidewalls, the flow pattern is forcibly modified in order to be contained within the wind tunnel walls when the object is a large bluff-body normal to the freestream, Figure 1.10 (Top). A transitional relationship will now be created here that relates flows within confined wind tunnel test-sections using bluff-body aerodynamics to flows confined within wind tunnel testing of a Savonius rotor, which in the context of this study has been provided to represent an aerodynamic tool for creating a rotating bluff-body within a wind tunnel test-section.

Figure 1.9 – Comparison of Streamlined and Bluff-Body Flow Interaction [5]

Figure 1.10 – Flow Confinement Effects on Bluff-Body and Streamlined Bodies [4]
Chapter 2 – Literature Review of VAWT Studies

Experiments with Vertical-Axis Wind Turbines

Wind Turbine research is primarily driven towards proposing performance optimizations of horizontal-axis wind turbines, however progress has also been curved towards vertical-axis wind turbine applications concerning aerodynamic efficiency and performance regarding flow separation and alleviating adverse effects on energy production by assessing these characteristics in sub-scale testing. There remains no extensive availability of literature concerning specific Savonius aerodynamic model applications, but rather there is literature concerning the general study of the concept of the Savonius rotor with very few authors analyzing in-depth the aerodynamic phenomena that these models create as observed with blockage effects. A representative selection therefore, relevant to supporting the wind tunnel testing and blockage effects involved in this paper are reviewed and summaries provided of how the literature is incorporated into this study.

2.1 Aerodynamic Analysis of Savonius Rotors

2.1.1 Aerodynamic Performance of Savonius Rotors

Fujisawa [6] gives a detailed account of blade surface pressure distributions and flow physics created from rotating and fixed turbines by studying the aerodynamic performance of a Savonius rotor by flow-field visualization, Figure 2.1 and by measuring Pressure Distributions on the blade surfaces at various rotor angles and tip-speed ratios, Figure 2.2. Fujisawa observed that pressure distributions on the rotating turbine differed remarkably from those on the fixed rotor, especially
the convex side of the advancing blade where a low pressure region is formed by the moving wall effect of the blade. Torque and Power performances were evaluated by integrating pressure and agreed closely to the measured torque. Fujisawa discussed the large decrease in pressure and reduction of the separation region observed on the convex side of the advancing blade, which may be due to the higher flow speeds over the moving blade, at higher tip-speed-ratios.

Figure 2.1 – Flow Field around a Savonius by smoke-wire method [6]

Figure 2.2 – Pressure Coefficient Distribution, $C_p$ for a Static Rotor (Left) and Rotating (Right) [6]
The detailed surface pressure results provide a strong foundation to base predictions in the current study about flow phenomena. Fujisawa found that on the advancing blade, a large stagnation pressure appears on the concave side at large rotor angles (45° to 135°) causing it to rotate in the positive direction. The pressure on the convex side is slightly negative in most of the region and the flow is separating. On the advancing blade the pressure on the concave side is smaller than the still rotor case, because of the reduced stagnation effect on the concave side and the circulation produced at the rotor axis. Positive Torque on the advancing blade grows strongly around the blade centre with an increasing tip-speed-ratio up to 0.4. Increases in local torque were explained by the increased flow effect and a decrease caused by the reduced stagnation effect in the outer part of the concave side. Torque coefficient increases significantly with the tip-speed ratio in the range of X (TSR) up to 0.4 and a distinct decrease appears beyond X = 0.9.

2.1.2 Unsteady Flow past a Savonius Rotor

To assist in characterizing the flow surrounding a Savonius rotor, a mathematical model was presented by Fernando [7, 8, 9] based on the discrete vortex method. Relevant to the current study, Fernando’s model was compared with wind tunnel tests and flow visualization data showing good correlation with the additional comment that the model was also used to account for wind tunnel blockage. Fernando develops the discrete vortex method from the incompressible, inviscid, irrotational two-dimensional governing flow equations, specifying boundary conditions at the blade surface and applies a flow model coupled with a vortex shedding model. Figure 2.3 represents blade-tip vortex formation as a function of time-steps for a stationary rotor. These theoretical vortex structures for a rotating turbine have been compared with flow visualizations in the current study. Noticeably in the flow patterns, is the evolution of vortex clusters and drift downstream.
From pressure distribution results, it was observed that separation occurs due to an adverse pressure gradient and remains at this value in the wake. In Figure 2.4, important characteristics of the flow are summarised as a clockwise vortex near the centre of the rotor. Vortices shed from the tip form shear layers close to the blade and separating shear layers produce vortex structures which are eventually shed downstream. Fernando’s conclusions correlate with other studies observing that the turbine is not a pure drag device “at small rotor angles to the free-stream the rotor acts like a slender body with lift contributing to the power”. Also, with direct relevance to
the present study, the effect of blockage was seen to increase the peak power coefficient and the corresponding TSR.

![Flow patterns relating blade angle-to-Freestream with Time-Steps, rotating turbine](image)

**Figure 2.4 – Flow patterns relating blade angle-to-Freestream with Time-Steps, rotating turbine [7, 8, 9]**

### 2.2 Wind Tunnel Testing of Savonius Rotors

In order to assist in improving the accuracy and efficacy of wind tunnel testing to be conducted in this current study, a representative selection of wind tunnel testing reports has been gathered with the aim to assess blockage correction approaches.

#### 2.2.1 Design Configurations for a Savonius rotor

Covering the main results, Saha [10] experiments in number of stages having provided evidence that increasing from one to two increases $C_P$ considerably, and additional stages decreases $C_P$ due to increase in inertia, however this phenomena could intrinsically also be postulated as a blockage effect.
2.2.2 Performance Data for Two- and Three-Bucket Savonius Rotors

Providing the standard methods for wind tunnel testing of VAWTs, a Sandia Laboratory report produced by Blackwell [12] undertaking a US Energy Research and Development Contract, carried out an in depth investigation of Low-Speed Wind Tunnel testing of Savonius type rotors of two and three stages as well as two and three blades and at different Reynolds numbers. Blackwell measured test variables such as torque, RPM and tunnel conditions, whereby Wind Tunnel Blockage Correction Factors have been calculated. In Figure 2.5 the conclusions can be observed that increasing Re and/or Aspect Ratio improves performance. These relationships became apparently clear in the current study. The model was rotated by a pneumatic motor at very low constant rotational speeds to obtain the tare-torque of the system caused by the friction in the bearings, these methods were specifically noted when construction of the current test facility was being envisioned. Blackwell defines *Runaway* as the high-speed condition where the output torque is equal to the friction torque of the system and no power is produced. A similar situation arose during the current study as with Blackwell’s study that at the time of the Sandia Laboratory testing there was no universally accepted length scale with which to calculate a Reynolds number for a Savonius Rotor, this remains a questionable issue whether diameter of the rotor is classed as the reference length or chord length consisting of one blade diameter, which in a 2-bladed Savonius would be the rotor radius. The majority of literature describes the reference length as swept rotor diameter. Blackwell proposed that increasing the test Reynolds number from $4.32 \times 10^5$ to $8.67 \times 10^5$ generally improved aerodynamic performance.
2.2.3 Experiments Investigating Savonius Geometry Influence

Kamoji [13, 14, 15] provides a recent review of Wind Tunnel tests with Savonius rotors undertaken at the Indian Institute of Technology. Experiments were carried out in an open-jet type wind tunnel facility with conventional and modified Savonius rotors, varying aspect ratios, rotor stages and blade edge conditions in order to assess improvements in efficiency from scale-model testing.

The study emphasized an apparent power deterioration caused by the blockage effect in the wind tunnel exit. Comparisons of $U \cdot R_e$ and blockage ratios were compared to TSR, $C_p$, and $C_Q$, and $C_{st}$ at 15° rotor angles fixed by a load. Kamoji concluded that $C_p$, $C_Q$, TSR and RPM increase with increased $R_e \cdot U$ and $C_{st}$ was independent of $R_e \cdot U$. Blockage effects were negligible on $C_p$, $C_Q$, $C_{st}$, at $R_e$ between 100,000 and 120,000, however, extrapolating these relationships and
assumptions to the current study could be speculative due to the much higher operating Reynolds Numbers in the current study (400,000 to 500,000).

To support the aerodynamic assessment in the current study, it has been noted that numerous authors have proposed that the aerodynamic forces driving a Savonius rotor are not purely that by drag alone, Kamoji confidently states that at low angles of attack, the lift force also contributes to the torque production in a Savonius design, hence the rotor is a compound machine with the ability to go beyond the limitation of $C_p$ of a primarily drag type turbine ($C_{p_{\text{max}}}=0.08$ for Flat Plate type turbines). The current research aims to model Power Coefficient of Savonius Rotors and a wider application to Blockage Corrections of rotating wind tunnel models, a similar approach was suggested by Kamoji, whereby Power Coefficient was hypothesized as being a function of the shape of the rotor and Reynolds number, providing the following dimensionless expression:

$$C_p = f\left(\frac{m}{D}, \frac{H}{D}, \varphi, \frac{p}{q}, \frac{D_0}{D}, Re\right)$$  \hspace{1cm} (2.1)

Where:
- $m/D = \text{Overlap Ratio}$
- $H/D = \text{Aspect Ratio}$
- $\varphi = \text{Blade Arc Angle}$
- $p/q = \text{Blade Shape Factor}$
- $D_0/D = \text{Endplate Parameter}$
- $Re = \text{Reynolds number}$

To provide further assistance on what is to be expected with wind tunnel testing of Savonius rotors, Kamoji shows the influence of Reynolds number on the performance parameters of the rotors ranging from values of 80,000 (5.57 m/s) to 150,000 (10.44 m/s), these are much lower operating Reynolds numbers, however additional studies state these operating trends are indeed scalable. Kamoji [15] found that coefficient of power increased by 19% as Reynolds number increased from 80,000 to 150,000, this apparent relationship with increasing freestream effects could be postulated as a built-in effect with the current study when increasing blockage-ratio causing an increase in freestream value. Kamoji’s results support the 1978 Sandia Laboratory findings [12], stating that for a conventional Savonius rotor (at a given rotor diameter) the
delayed separation around the blades at higher wind velocities may be responsible for the increase in the maximum coefficient of power with the increase in Reynolds number.

The current study aims to correlate Power Coefficient with influences of angular moment and blockage corrections, proposing a similar correlation technique, Kamoji [15] implemented a regression analysis on variation of coefficient of torque at different Reynolds numbers, shown in Figure 2.6. These curves progressively collapse to a single line for $C_t/Re^{0.3}$. The correlation equation here is linear, and has been fitted for a TSR of 0.6. The parameter $C_t/Re^{0.3}$ computed using the correlation compared very well with the experimental results for TSR below 1.0, providing the correlation equation:

$$\frac{C_t}{Re^{0.3}} = -0.0107(TSR) + 0.0149, \quad 77600 \geq Re \leq 155,000, \quad TSR \geq 0.6$$  \hspace{1cm} (2.2)

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure2.6.png}
\caption{Correlation curve for single stage modified Savonius rotor \hspace{1cm} (Reynolds numbers from 77,600 to 150,000) [15]}
\end{figure}

Figure 2.7 shows the final comparison of the computed coefficient of power from the correlation to that of the open-jet wind tunnel experimental values for Reynolds numbers of 120,000 and 150,000, where it has been shown that they both compare extremely well. Although this technique has been assessed for feasibility in predicting Power Coefficient in the current overall study, it must be noted here, that because of the low operating Reynolds Numbers and the
Open-Jet wind tunnel facility used in Kamoji’s study it is speculative how effective or accurate corrections could transfer between studies.

![Figure 2.7 – Comparison of $C_p$ for experimental and correlation results](Single stage modified Savonius rotor at Reynolds numbers of 120,000 and 150,000) [15]

### 2.2.4 Effect of Wind Tunnel Blockage on Performance

Biswa [16] undertook an in-depth review of wind tunnel testing on three bladed Savonius designs. Relevance to the overall study, Biswa calculated Power Coefficients with and without Wind Tunnel Blockage Correction Factors for tunnel interference, adopting the Pope correction discussed in Chapter 3. It has been stated that tunnel blockage effect is an important parameter for wind tunnel performance analysis of VAWT’s, whose effect is much more severe in low speed wind tunnel applications. Biswa results support the current research by stating that the rotor blockage effect increases the local free stream velocity in the test section, of which the effect has been quantified using a velocity increment (Pope Correction). This study provided results on the performance of the rotor evaluated from variation of Power Coefficient $C_p$ with TSR. Allowing for the Blockage correction, the maximum $C_p$ on average reduced 5%, a significant reduction when dealing with a $C_p$ of 28%, this reduction is used as a source of comparison to later application of the Pope Correction to the current wind tunnel results.
2.3 Flow-Field Visualization

2.3.1 Flow Visualization in and around a Savonius rotor

In order to support the flow visualization results captured in the current research, a comparison is made to similar flow behavior studies by Fujisawa [17], whereby the flow in and around a Savonius rotor was observed using smoke and a smoke-wire visualization technique. The rotation effect is discussed in comparison with the measured pressure distributions on the blade surfaces. The lifting force created by a Savonius rotor was once again observed by Fujisawa, providing the statement that a Coandă-like flow pattern was found on the advancing blade, suggesting a lift force contribution to the power mechanism of the rotor. Special attention was given to the separation characteristics of the external flow at various TSR, since it was expected to have a strong influence on the power producing mechanism. The assumption of a direct relationship of Power with flow separation effects caused by variations in magnitude of angular moment of the rotor was applied later in this current research in assessing tip-speed-ratio effects.

**Visualization of External Flow:** To assist with validating a technique to visualize the flow around a Savonius rotor, the following method suggested by Fujisawa was closely followed. Figure 2.8 (left) details the experimental arrangement for visualizing the external flow around the rotor. The wake was observed simultaneously by injecting smoke through a nozzle located upstream, the observations were made at the mid-span of the rotor using a laser sheet from a 3W Argon-Ion Laser and a CCD camera with a shutter speed of 0.002s whilst testing at a tunnel flow velocity of 1.5 m/s.

**Visualization of Internal Flow:** Figure 2.8 (right) details the arrangement for visualizing the internal flow using a smoke-wire set in the mid-plane of the rotor, observed using a CCD camera and the illumination by three 300W lamps, testing at a tunnel velocity of 0.7 m/s.
The static and rotating observations were concentrated on smoke patterns inside the rotor, measured pressure coefficients on blade surfaces and points of separation and stagnation, Figure 2.9. The flow through the overlap induces a pressure recovery effect on the concave side of the returning blade; promoting a drag decrease on the returning blade.

Figure 2.8 – (Left) Experimental arrangement for visualizing the external flow, (Right) Visualizing the Internal Flow [17]

Figure 2.9 – Freestream Flow, Internal Flow, Flow Model, Surface Pressure Distribution, (Left) Static Rotor, (Right) Rotating [17]
**Flow in and around a Static Rotor:** External flow separates around both sides of the rotor, therefore the width of the wake agrees closely with the rotor swept/projected area. On the front side of the rotor, a stagnation point appears with Fujisawa’s results Figure 2.9, which has also been found in the current study.

**Flow in and around a Rotating Rotor:** Figure 2.9 (right) shows flow patterns for a dynamic rotor at a TSR of 0.9. Important vortex characteristics have been observed, whereby the injected flow grows into a vortex circulating in the rotating direction of the rotor, which increases in size downstream. The flow stagnation point is found to shift towards the center of the blade due to rotation effect.

### 2.3.2 Particle Tracking Velocimetry to estimate Pressure Field

An additional study to support the current flow visualization of Savonius is supplied by Murai [18]. The method is applied to a rotating turbine with TSR of 0.5 to find the relationship between torque behaviour and flow structure in a phase-averaged sense.

*Figure 2.10 – Pressure distribution for various rotor angles estimated by Navier–Stokes equations [18]*
Through-flow induced between the two cylindrical blades has been observed to produce a large vortex behind the turbine. Comparing to a static turbine, a large vortex is shed behind the returning blade because of a large velocity difference between the blade and the surrounding fluid, the large vortex shed from the returning blade is a flow phenomena observed with similar flow patterns in the results of the current research.

*Figure 2.11 – Streamlines obtained by the spatio-temporal interpolation, (top) Static, (bottom) TSR = 0.5 [18]*
2.4 Turbine Wake Modeling

Attempts have been made to correlate existing knowledge and treatments of horizontal-axis wind turbine wake especially applicable to wind tunnel testing conditions to effectively compare to applications of non-uniform VAWT wake.

2.4.1 3D Effects and Bluff Body Vortex Shedding

Medici [19] performed analysis of the velocity field in the wake of a 2-bladed HAWT model, studied under different conditions using a 2-component hot wire system. Results for Drag and Power are represented in Figure 2.12.

![Figure 2.12 – Drag & Power Coefficients as a function of TSR; turbulent & steady upstream [19]](image)

Hot wire anemometry has been applied to show velocity distribution for all velocity components downstream, giving evidence that a rotating turbine causes flow blockage similar to a stationary disc. Medici observes the flow approaching the turbine treats the object as a drag force, much the same way as a bluff body or disc does. A characteristic of bluff body flows is vortex shedding, known as the Von Karman vortex street for 2-D cylinders, which has subsequently been observed in the current research with the aid of flow visualization images shown in the results Chapter. Vortex shedding also appears behind 3-D bluff bodies such as circular discs.
2.4.2 Mean Wind & Turbulence - Induction Effects

A wind turbine wake study undertaken within a closed test-section wind tunnel, Neff [20] investigated the flow-field characteristics in the vicinity of a spinning HAWT rotor for a variety of flow conditions from steady to turbulent experiments. Four different approach flow conditions were studied, mean wind speeds of 6 and 7.6 m/s, and turbulent conditions (0.1% and 1.5 % intensity). The overall effect of wind condition upstream of a wind turbine was evaluated, the three-dimensional flow-field was measured (Axial, Radial, Angular Velocities) as a function of Rotor diameter, between 3d upstream to ½d downstream, Figure 2.13.

![Figure 2.13 – Mean Angular Velocity change versus Axial Distance from turbine][20]

Figure 2.13 shows wind turbine induction effects (velocity variations) and stream-line divergence caused by rotor hub and tower significantly distorting the free-stream flow-field values, these concepts have been qualitatively applied to assessing the upstream flow region of the Savonius rotor. Neff provides improved physical insight into the induction effects of the air as it approaches a wind turbine, which is a transferable factor between turbine types. Flow visualization displayed curving of streamlines radially outward around the spinning rotor blades.
and was a good demonstration of the existence of axial induction effects. Flow outside of the rotor was seen to accelerate, as was expected from Continuity.

2.4.3 A Model for Unsteady Rotor Aerodynamics

Sørensen [21] presents an Aerodynamic model for the simulation of Unsteady Flow past Wind Turbine Rotors. The model consists of an actuator disc model based on solving unsteady, axi-symmetric Euler or Navier Stokes’ equations. Sorensen employed an actuator disc in a generalized way by defining it as a surface, normal to the flow direction, on which a uniform distribution of blade forces acts upon the incoming flow, it can be inferred that a similar concept of an actuator conservation of momentum can be assumed to model Savonius wake/body acting in a similar fashion in slowing the freestream velocity across a generalized region. At the same time as it is exposed to surface forces it is assumed that the flow can pass through the disc. It was stated that decreasing the wind velocity, the blockage effect of the rotor becomes more pronounced. This causes the complexity of the flow-field to increase and may result in separation and unsteady 3D behaviour, which has been an inherent flow condition observed with VAWT wind tunnel testing.

Figure 2.14 displays instantaneous streamlines and iso-vorticity lines about the model turbine under conditions of 6.5 and 10 m/s. For U = 6.5 m/s, separation occurs downstream of rotor. Since the flow is unsteady at this velocity the streamlines can only be depicted as a snapshot giving instantaneous values at a specific time. For U = 10 m/s flow is steady and the streamlines pass smoothly through the rotor, wake expansion is observed occurring a small distance downstream from the rotor, this wake expansion behavior behind wind turbine bodies or revolution can be assumed to occur with the Savonius models in this study, however due to constrained flow visualization FOV downstream, this has not been verified.
Figure 2.14 – Instantaneous Streamlines & Iso-vorticity lines, (left) $U=10\text{m/s}$, (right) $U=6.5\text{m/s}$ [21]
Chapter 3 – Wind Tunnel Blockage Correction Methods

It is defined that the total blockage correction factor is the sum of the velocity increment caused by wake blockage and solid blockage however these are incredibly difficult factors to assess for unusual geometry/flows such as the Savonius rotor. It has long been a standard for low-speed wind tunnel testing to operate within an area-ratio (tunnel cross-section to model swept-area) between 1 → 10 %, as proposed by Pope & Harper [22] in their 1966 text “Low-Speed Wind Tunnel Testing” and earlier by Pankhurst & Holder [23] in their 1952 text “Wind-Tunnel Technique: An Account of Experimental Methods in Low- and High-Speed Wind Tunnels”, both provide various solid and wake-blockage correction techniques.

Sandia Laboratories can be credited with initiating the resurgence of Vertical-Axis Wind Turbines in the United States [12]. As a result, they set the standard for wind tunnel blockage corrections of VAWTs, this being a correction factor previously stated by Pope & Harper, based on a generalized correction for the testing of any unusual shapes. A review of recent developments in the calculation of closed test-section low-speed wind tunnel interference studies was conducted by Hackett [24], in which an extensive interpretation of wall pressures provided by Ashill [25] is covered where corrections have been proposed, assuming $x$ the distance in the streamwise direction and $y$ the distance along the sidewall in the direction normal to $x$. Hackett assumes pressure, $p$ is at the wall using Prandtl’s classical assumption for boundary layers and $u$ and $v$ are velocities in the $x$ and $y$ directions.
The current chapter discusses the original blockage methods, with focus on the Hackett & Wilsden *Wall Pressure Method* [40] modified in this study with the aim to provide a more detailed assessment of partitioning solid and wake blockage when the flow behavior increasingly becomes more three-dimensional, highly separated, unsteady and turbulent.

### 3.1 Pope & Harper Blockage Correction

Correcting velocity measurements [22] and subsequent data modifications to allow for these changes are shown, summarizing 2D corrections by: (subscript *u* values are uncorrected)

- **Velocity correction:**
  \[ V = V_u (1 + \varepsilon_t) \]  
  \[ (3.1) \]

- **Dynamic Pressure correction:**
  \[ q = q_u (1 + 2\varepsilon_t) \]  
  \[ (3.2) \]

- **Reynolds Number correction:**
  \[ R = R_u (1 + \varepsilon_t) \]  
  \[ (3.3) \]

- **Drag Coefficient correction:** (From dynamic pressure effect plus the wake gradient term):
  \[ C_{D0} = C_{D0u} (1 - 3\varepsilon_{sb} - 2\varepsilon_{wb}) \]  
  \[ (3.4) \]

  \[ \varepsilon_t = \text{Solid Blockage} + \text{Wake Blockage} = \varepsilon_{sb} + \varepsilon_{wb} \]  
  \[ (3.5) \]

  Pope explains: “*for finding the blockage corrections for some unusual shape that needs to be tested in a tunnel the following is suggested*”

  \[ \varepsilon_t = \frac{1}{4} \frac{\text{Model frontal area}}{\text{Test section area}} \]  
  \[ (3.6) \]

  Barlow, Rae & Pope [26] suggest for general wind tunnel testing a maximum ratio of model frontal-area to test-section cross-sectional area of 7.5% should probably be used unless errors of several percent can be accepted and that blockage in open test-sections is of opposite sign and smaller than for a closed tunnel.

### 3.2 Maskell Method

Maskell’s [27] approach was the first to address the problems with non-streamline flow bodies, such as bluff-body testing (flat plates normal to freestream) in closed wind tunnel sections
and that of partially stalled shapes (such as wings). Maskell found that when the high-lift characteristics of particular delta wing aircraft models of small aspect ratio were tested in different wind tunnels at the Royal Aircraft Establishment (RAE), marked differences were observed at the onset of stall beginning at the wing tips and spreading inboard with increasing incidence. The different results could only be reconciled through a wall interference factor, that equivalent to an increase in velocity of the undisturbed stream on a much larger scale than previous standard estimations. Maskell’s research goal was to establish a more convincing existence of this interference factor and the need for corrections, by relating effective increase in the dynamic pressure $q$ of the stream due to a solid blockage constraint. Maskell’s theory holds true for nearly all two-dimensional bluff-body flows and for situations of closely axi-symmetric wake downstream for 3-D flows. Maskell derived a blockage correction based on applied theory when testing thin flat plates normal to the freestream, finding their static pressure over the wake boundary is constant up to the position of maximum separation bubble, Figure 3.1, Maskell states that for 2-D and small AR flat plates the base pressure was also constant and equal to the separation and wake surface pressure.

![Figure 3.1 - Control Surface representing the Conservation of Momentum and bluff body wake](image)

*(Solid walls of the wind tunnel, solid body and the constant-pressure surface bounding an effective wake, two surfaces shown lying normal to the undisturbed velocity vector, Surface 1 lying upstream of the body and Surface 2 where the wake cross-section is greatest)* [4]
The derivation of Maskell’s Method [27] and the overview covered in ESDU [4] relate to Figure 3.1, where a Surface 1 represents a plane normal to the freestream direction (upstream of the influence of the flat plate) and a Surface 2 which is bounded by the rear surface of the plate, the wake boundary and a plane normal to the freestream direction (which is at the position of maximum separation –bubble area). The complete process to derive the blockage correction is provided in Appendix B. As part of Maskell’s method, a semi-empirical term \( m \) is applied in the blockage correction which is based on experimental data taken from four square flat plates up to 4.5% Blockage Ratio, based on coefficient of drag and base pressure:

\[
m = \frac{C_D(S/A) - C_{p_{ps}} - \sqrt{(C_D(S/A) - C_{p_{ps}})^2 - 4C_D(1-C_{p_{ps}})(S/A)}}{2(1-C_{p_{ps}})(S/A)} \tag{3.7}
\]

Maskell’s Correction:

\[
\varphi = \frac{C_D}{C_{Df}} = \frac{1}{1 - m(S/A)} \tag{3.8}
\]

Cowdrey [28] re-derived Maskell’s Method without the wake distortion effect for 3-D bodies that lie in their own wakes (leading-edge separation). Cowdrey shows that the constant-base-pressure assumption is not required and produced an updated Equation 3.8, which extends the derivation to incorporate correcting dynamic pressure which does not depend on the measured drag, although still requiring the semi-empirical constant \( m \) that is a function of body geometry:

\[
\varphi = \left( \frac{C_D u}{C_{D\infty}} \right) = \left( \frac{q_c}{q_u} \right) = \frac{1}{1 - m(S/A)} \tag{3.9}
\]

Alexander [29, 30] has extended the above derivation by applying it to correcting Savonius Rotors. Firstly, by simplifying the correction to represent velocity, by equating terms in dynamic pressure:

\[
\begin{align*}
\frac{q_c}{q_u} &= \frac{1}{2} \rho_{air} \frac{V_c^2}{V_u^2} = \left( \frac{V_c^2}{V_u^2} \right) = \left( \frac{V_c}{V_u} \right)^2 \tag{3.10}
\end{align*}
\]
Alexander has experimentally determined the semi-empirical term $m$ for Savonius Rotors by measuring drag forces from a Savonius Rotor in closed test-section wind tunnels and comparing drag values to that produced by an equivalent area of a flat plate normal to the freestream. Figure 3.2 is provided for extrapolating the $m$ term and insertion into the following blockage correction for velocity:

$$\varphi = \left( \frac{C_{D_u}}{C_{D\infty}} \right) = \left( \frac{q_c}{q_u} \right) = \left( \frac{V_u^2}{V_c^2} \right) = \frac{1}{1-m(S/A)} \quad (3.11)$$

Where:
- $V_c$ is the corrected wind velocity
- $V_u$ is the undisturbed wind velocity
- $S$ is the flat plate or Savonius maximum frontal area
- $A$ is the wind tunnel working section cross sectional area
- $V$ is the undisturbed wind velocity
- $m = (B/S)$ extrapolated value from Fig. 3
- $B$ is the wake area normal to wind

For small values of blockage ratio, $(S/C \leq 0.045)$ Maskell gives $m = 3.15$ (constant value). Alexander suggests that due to restriction on the wake by the tunnel walls at high S/C values, the value of $m$ falls, reaching a value close to 2.0 for $S/C = 0.3$ (30% Blockage).

3.3 Extensions to Maskell’s Method for Bluff Bodies

Hackett [31] presents a review of the efforts to improve and extend the Maskell theory by applying a technique to a family of flat-plate wing models in a small, low-speed wind tunnel at the NRC, Canada. Wing models were tested at angles of attack $-10^\circ$ to $+110^\circ$ with a maximum
blockage of 16%. The purpose of this study was to compare corrections to lift and drag data between models of different sizes and at different offsets from the tunnel centerline. Comparisons were made with corrections using the pressure-signature and the two-variable methods emphasizing post-stall conditions.

In summary: Maskell developed theory for the blockage of bluff bodies in a closed test-section wind tunnel that recognizes the fact that the shape of a separation bubble is changed by the presence of the tunnel walls. However, Hackett comments that this was treated entirely as a dynamic pressure effect, which obscures the fact that two distinct phenomena are involved: a drag increment due to wake distortion and a change in dynamic pressure. The wake distortion occurs at in-tunnel dynamic pressure so the drag increment should be removed before applying the dynamic pressure correction. Because of this oversight, it was found that the original Maskell method over-corrects bluff-body drag data. Hackett developed a two-step process, based on Maskell’s intermediate results, that separates the two corrections.

Detailing the two-step process for correcting for wind tunnel interference, in which step one is the assessment stage, determining tunnel-induced changes to the model flow environment and the second step as the correction stage, calculating and applying force and moment increments, followed by dynamic pressure and angle of attack corrections at the model. Four flat-plate, reflection-plane wing models were mounted, in turn, on a six-component balance at the NRC Aerodynamics Laboratory, with blockage ranging 4% to 16%. 240 pressure taps were distributed across the tunnel walls for use with both methods.

It was also noted that wall pressures opposite to the model revealed incomplete pressure recovery and possible flow separation from the wall for the largest two models when close to the sidewall. Finally, through the use of plotting $C_L$ corrections as a function of model size and separately $C_L$ corrections as a function of wall distance, results from 1) Uncorrected, 2) Maskell III, 3) Pressure-signature and 4) Two-variable method, it was shown that if each method worked
perfectly, and if no uncorrectable interferences due to wall proximity existed, then the corrected lift curves would collapse to coincident horizontal lines.

### 3.4 Wake Corrections for Models subjected to Separated Flow

Relevant to assessing the effects of incrementally increasing to larger blockage ratios in the current study, an advancement of the Maskell wake blockage correction method is presented by Gould [32], applying to rectangular flat plates normal to the flow, mounted on the tunnel wall and axis, in order to correct for large blockages arising in the testing of bluff models, particularly those mounted on the floor.

Applying Maskell’s relationship for the correction of force and pressure coefficients measured in closed test-section wind tunnels on bluff models subject to separated flow:

\[
\frac{C_D}{C_{Dc}} = \frac{q_s}{q} = \frac{1 - C_{pr}}{1 - C_{pr_c}} = 1 + nC_D \frac{S}{C}
\]  

(3.12)

Rewriting the blockage term \( nC_D \frac{S}{C} \) as \( \frac{nD}{qC} \) for a given approach dynamic head, \( q \), the blockage effect varies directly with the drag per unit area of the tunnel section. Figure 3.3 shows the values of measured drag coefficients plotted against blockage parameter \( C_D \frac{S}{C} \), points were represented by the quadratic curve expressions:

**Centrally-mounted plates**

\[
C_D = 1.163[1 + 2.81C_D \frac{S}{C} - 0.96 \left(C_D \frac{S}{C}\right)^2]
\]  

(3.13)

**Wall-mounted plates**

\[
C_D = 1.132[1 + 2.79C_D \frac{S}{C} - 1.12 \left(C_D \frac{S}{C}\right)^2]
\]  

(3.14)

Interesting conclusions at this stage, Gould observes that position of the model in the tunnel has no significant effect on the wake blockage correction for flat plates and that measurements made to determine blockage corrections with large models subject to separated flow can be used by linear interpolation to deduce blockage corrections on smaller geometry similar models. When plotting blockage factor over a range of distances upstream and downstream, a similarity exists
between different plates for distances upstream but widely different between downstream values, giving rise to evidence that upstream results are independent of the flat plate size.

Gould concludes:

- Maskell’s wake blockage corrections for a model subject to separated flow apply regardless of the position of the model relative to the tunnel axis.
- The presence of a large model in a wind tunnel will produce genuine wake-blockage effects. In addition it may affect the static pressure in the region of wall-pressure taps used to measure wind speed, this is an important point to emphasize in the current study. Thus, unless steps are taken to eliminate errors in the measurement of tunnel speed, genuine wake blockage cannot be studied separately.

Figure 3.3 – Drag Coefficient vs. Blockage Parameter [32]
3.5 Glauert Correction

In 1947 Glauert [33, 34] presented the derivation of a blockage correction especially applicable to propeller testing as subsequently applied by Fitzgerald [35]. Glauert’s correction can be summed-up as an expression for an equivalent free stream velocity, \( V' \) by the relationship:

\[
\frac{V}{V'} = \left[ 1 - \left( \frac{T_4 \alpha_1}{2 \times (1 + 2 \times T_4 \alpha_1)^2} \right) \right]^{-1}
\]

\[
T_4 = T / (\rho AV^2)
\]

\[
\alpha_1 = A / C
\]

Where:
- \( V' \) is the equivalent freestream airspeed,
- \( V \) is the wind tunnel datum velocity
- \( T \) is the thrust (lbs)
- \( \rho \) is the air density (lbs/ft\(^3\))
- \( A \) is the cross-sectional area of propeller (ft\(^2\))
- \( C \) is the wind tunnel cross-sectional area (ft\(^2\))

Utilizing the theory of continuity and of an actuator disc, the same volume of air must pass fore and aft an object and the slipstream must accelerate greater than the wind tunnel datum velocity. The flow outside the slipstream/wake has a lower velocity, and hence a higher static pressure. Glauert applies Bernoulli’s relationship to state that the static pressure of the air inside the wake is identical to that outside the wake/slipstream. The resulting higher static pressure actually observed must therefore act back upon the object/propeller and thus generates a greater thrust than it would in a non-constrained environment. It is sufficient enough to assume that the equivalent airspeed value is less than the wind tunnel datum airspeed.

Glauert also proposed a theory, based in part upon the Helmholtz model of the flow past a bluff body, according to which the drag \( D_c \), in an unlimited stream is related to the drag \( D \), in the wind tunnel by:

\[
D_c = D (1 - \eta t / h)^2
\]

Where:
- \( t \) is the thickness of the bluff base
- \( h \) is the tunnel height
- \( \eta \) is an empirical factor
The disadvantage of this method is the empirically determined term which is dependent upon interpolation between known experimental results. Unfortunately Glauert’s wake blockage relationship is only applicable to streamline flow models not bluff body problems.

Ferreira [36] provides results which disagree with Glauert’s derived corrections, in a test of 2D techniques to investigate aerodynamic behavior of a straight bladed H-rotor type VAWT operating in a wind tunnel, with a focus on the development of the dynamic stall at different TSR’s using a model with 32% blockage, Ferreira states that for a VAWT, most induction is concentrated at the rotor axis height; Navier-Stokes simulations performed by Ferreira of the experiment show that the blockage effect could be neglected for the present analysis. Ferreira approaches the problem of wind tunnel blockage by suggesting that in the case of a VAWT, the load and induction is not uniform over the rotor area, which usually presents a sinusoidal distribution, with a peak around y = 0 mm and the effect is much smaller than what is calculated with the constant induction assumption postulated by Glauert in 1935.

3.6 Hackett, Lilley & Wilsden Method

Lockheed scientists; Hackett, Lilley & Wilsden [37] produced an updated blockage correction methodology to Hensel’s [38], by adopting sources and sinks to represent an equivalent body surface in a stream, advancing the original method of distribution of wind tunnel images as proposed by Herriot [39]. Static pressures measured at the sidewalls are used to construct a relatively simple singularity set to represent the test article and then calculate the wall effects based on that singularity set. They show tunnel wall static pressures can be used to infer wake geometry and hence wake blockage using a row of pressures along the center of the tunnel sidewall giving the axial distributions of both solid and wake blockages with a velocity peak just aft the model. Through a wind tunnel testing campaign, involving models of varying sizes and blockages up to 10%, wall pressure signatures were used to determine source, sink and strengths.
with wind tunnel span and locations. Essentially the concept resolves pressure signatures into their solid and wake counterparts, signifying the symmetric and anti-symmetric regions with the parameters formulated from these parts a velocity increment expression is obtained.

### 3.7 Wake Blockage Corrections via Wall Static Pressures

Hackett & Wilsden [40] provide a theoretical method in determining wind tunnel solid/bubble and viscous blockage from wall and roof pressure measurements involving lifting and non-lifting, powered and non-powered models, Figure 3.4. The method has also been successfully applied to corrections for a series of flat plates normal to the freestream. In order to calculate corrected pressure coefficients:

\[
C_{prc}(x) = \left[ \frac{C_{pru}(x) - 1}{1 + \left( \frac{\Delta u}{U_{\infty}} \right)^2} \right] + 1 \quad (3.19a)
\]

Rearranged to represent a velocity increment:

\[
\frac{\Delta u}{U_{\infty}} = \sqrt{1 - \left( C_{pr,empty} - C_{pr,model} \right) - 1} \quad (3.19b)
\]

![Figure 3.4 – Effects at a Wind Tunnel wall of solid/bubble and viscous wake blockage [40]](image-url)
Sources of tunnel blockage fall into three general groups:

I. **Solid-Body Blockage** (involves increment of flow acceleration around body, but no far downstream total or static pressure changes)

II. **Viscous Drag** (reduces both total and static pressure far downstream of the model)

III. **Separated Flows** involves both of the above. (A separation bubble expands downstream of a bluff model and can behave as a solid body, so far as tunnel wall pressures are concerned, and possesses a viscous wake which permanently reduces static and total pressures downstream)

IV. **Induced Drag** (Potential Flow phenomenon producing no wake or equivalent solid blockage)

A series of pressures along the test section length is used to characterize the tunnel flow. Analysis of this “signature” yields not only individual estimates of solid/bubble and wake blockage but also corresponding axial velocity interference increments anywhere in the test section. The feasibility of this approach was established by Hackett & Wilsden with normal flat plates of various sizes in the Lockheed $16 \frac{1}{4} \text{ ft} \times 23 \frac{1}{4} \text{ ft}$ wind tunnel.

Figure 3.4, measured Wall pressure distributions ($C_p$) with wall location, detailing the evidence of an adequate upstream test section but inadequate length downstream for the asymptotic condition when testing larger flat plates. The largest model tested provided 16.9% blockage was stated to require an improved curve-matching method to be able to apply the same method to models larger than 10%. In general, it has been suggested that if static pressures fail to stabilize downstream of the test section length, in order to utilize this method best, it is advised to use a more sophisticated curve-matching method to establish a proper downstream pressure reference.
Hackett [41] comments:

“...test sections of about 1.5 times tunnel width is desirable to obtain adequate asymptotes to the pressure signatures. Orifice spacing should be smallest opposite the model and its’ immediate wake and may increase towards the test section ends where pressure gradients are less.”

Hackett [24] makes an important remark for accuracy in obtaining good asymptote definitions, whereby it is frequently observed that test-sections are too short especially for large models, furthermore pressures at the piezometer ring upstream of the test-section can also be compromised, causing a vertical shift in the Pressure Signature, asymptote estimation is therefore an important feature of the Pressure Signature method with well-defined asymptotes needed at each end of a pressure signature in order to define wake blockage successfully well.

Figure 3.5 represents the close comparison of fitting the signature to experimental data, however, because of asymptote difficulties the original fit lies below the measured data and not well-defined at the centerline tunnel cases. Hackett rectified this by stretching the orifice array by a factor of 1.5 giving an improved asymptote definition, eliminating the signature shifting effect.

![Figure 3.5 - Comparisons between “measured” & fitted Pressure Signatures (16% model) [24]](image)
Overall, predictions from the Pressure Signature method are generally high, particularly for smaller models. Conclusions from Hackett’s Pressure Signature studies are that they provide good blockage results for center tunnel and off-center tunnel model positions. A suggestion is made upon whether a single signature comprising 20 points is sufficient to define a reliable flow model even when combined with lift and moment balance measurements, however he later provides evidence to answer this question, with the fact that the flow models produce very good results nonetheless when compared to experimental data.

3.8 Corrections for 2-D Wind Tunnel Tests using WPM

Allmaras [42] provides a report outlining a 2-D version of the wall-pressure signature method, giving a comparison between blockage corrections obtained using this method and those by Hackett’s original method which has been simplified in the context of the current research. The original method was devised for 3-D tunnel setups and has been revised in this study for 2-D tests of the XV-15 wings, Figure 3.6.

Allmaras derives an improved wall-pressure signature method and concludes in comparing data to Hackett’s original method. An interesting comparison to the current study, Allmaras describes the improved Wall-Pressure Signature Method as pertaining to 2-D tests of bluff bodies. Figure 3.7, details a typical experimental setup for a 2-D wind tunnel.
The resulting incremental velocity distribution is assumed to consist of the superposition of the velocities for two flow fields, one symmetric and the other anti-symmetric, Figure 3.8.

\[
q_c = q_m (1 + \varepsilon_{\text{max}})^2
\]  

(3.20)
Correcting Drag in a similar fashion:

$$C_{Dc} = (C_{Dm} + \Delta C_{DB}) \left( \frac{q_m}{q_c} \right)$$ (3.21)

The reason for the present study came about from an uncertainty in the conventional corrections used by Hackett for the unusually large blockage effects found. Hence those corrections are compared with Allmaras’ method who adopted a 2-D triangle test model, and approximating/optimizing the anti-symmetric signature modeling (wake) by using a hyperbolic tangent function giving a conflicting wake source strength equation to that of Hackett’s, and also curve fitting the resulting symmetric signature to a parabola trend, whereby from this curve fit, the peak velocity and position are determined and subsequently the following revised blockage correction formulas are obtained:

$$q_c = q_m (1 + \varepsilon b), \quad C_{Dc} = C_{Dm} (1 - \varepsilon b C_{Dm})$$ (3.22)

Where $b$ is the ratio of the model width to tunnel width, and $\varepsilon$ was estimated to be $0.65 \pm 0.05$. For the triangle test model in this study, $b = 0.10$ and the, measured drag coefficient was $C_{Dm} = 1.582$. The two methods surprisingly compared very well, giving indication that the corrections used by Hackett were, in fact, valid despite the magnitude of the blockage effects.

### 3.9 Hensel’s Velocity-Ratio Method

Hensel [38] provides a derivation of equations representing velocity increments caused by solid blockage in a closed test-section wind tunnel. The study investigated the velocity increments caused by a variety of test bodies:

- 2D airfoils
- Small bodies of revolution
- Straight, un-tapered, finite-span wings of varying span
- Swept, un-tapered, finite-span wings of varying span
Hensel later applies the velocity increments to a method first adopted by Thom [43]. Thom simplifies the solid-blockage correction for 2-D tunnels, giving:

$$\varepsilon_{sb} = \frac{K_1 (\text{model volume})}{C^2}$$  \hspace{1cm} (3.23)

- $K_1$ equals 0.74 for a wing spanning the tunnel breadth
- $K_1$ equals 0.52 for a wing spanning the tunnel height
- $C$ is the tunnel test-section area

An incremental velocity is produced at the model by the walls that should be added to the tunnel results to allow for wake blockage:

$$\varepsilon_{wb} = \frac{\Delta V}{V_u} = \tau c du$$ \hspace{1cm} (3.24)

Where:

$$\tau = \frac{c}{h}$$ \hspace{1cm} (3.25)

Thom’s equation [43] for solid blockage for a 3D body:

$$\frac{\Delta V_{sb}}{V_u} = \varepsilon_{sb} = \frac{K (\text{model volume})}{C^2}$$ \hspace{1cm} (3.26)

- $K$ equals 0.9 for a 3D wing
- $K$ equals 0.96 for a Body of Revolution

Hensel applies an adapted expression for small corrections given by Thom, as $q/q_u$ the ratio of dynamic pressure corrected for solid blockage to the uncorrected, or calibration dynamic pressure:

$$\frac{q}{q_u} = 1 + \left( \frac{u}{U_A} \right) (2 - M_{iu}^2)$$ \hspace{1cm} (3.29)

### 3.10 Bluff-Body Blockage Studies

Broughton [44] presents results of experimental testing of the interference effects of large area and volume bluff bodies in a longitudinally slotted and solid test-section wind tunnel, with the aim to indicate if certain body shapes are more susceptible to wall effects. Broughton notes that,
slotted wall test-sections with an OAR of approximately 30% produce excellent pressure distributions for automotive models with area blockages up to 0.21. Figure 3.9 displays axial positions normalized by $\sqrt{S}$ so that all the pressure distributions would be identical if the flow were dynamically similar for all sizes of the blocks. A good flow similarity (absence of interference) upstream of the models is observed. It is postulated that a shorter separation bubble is observed if referring to the plot, implying a longer region of attached flow and increased skin friction drag for the larger blocks. Interference effects seem to be mainly caused by wall constraint and effects of the downstream boundary conditions.

![Figure 3.9 - Pressure distribution along ground plane centerline for sharp blocks](image)

Broughton suggests three sources of interference remain in wind tunnels, providing that the test-section length upstream the model and ground plane boundary layer effects are minimal:

1. Wall effects
2. Incorrect static pressure at test-section exit due to wake blockage at the collector
3. Insufficient distance between downstream face of the model and the test-section exit.
Patil [45] states that the nature of wall confinement affects the behavior of vortex shedding behind an obstacle. Patil’s study provides a report on dependence of the critical Reynolds number for onset of planar vortex shedding on blockage ratio and the effect of wall confinement on characteristic features of the wake, such as wake bubble size and shear layer. The characteristic relationship between Strouhal number and flow Reynolds number was presented for different values of blockage ratios.

It is observed that the length of the wake bubble decreases with increase in blockage ratio, except for BR = 0.6. Figure 3.10 displays plots of the ratio of maximum width of shear layer to the tunnel width for a range of blockage ratios. It has been noted that the curve shows an increasing nature with increase in the value of blockage ratio indicating that the maximum fractional width of the shear layer grows with increasing blockage. This has been stated to be the effect that the onset of vortex shedding becomes increasingly delayed or postponed in terms of the critical Reynolds number due to increase in blockage ratio.

Figure 3.10 – (a) Location of maximum width of the shear layer for Re = 100 and BR = 0.25 and (b) Variation of maximum width of shear layer against blockage ratio for Re = 1000 [45]
Similar investigations of bluff-body blockages were carried out by Okajima [46], where the flow around a stationary and oscillating square cylinder was numerically simulated at various blockage ratios in order to study the effects of wall confinement on the aerodynamic characteristics of the cylinder. Simulating conditions of different blockage ratios in order to verify experimental dynamic characteristics and flow patterns around the cylinders from tow tank testing. Simulations were run at blockage ratios of $H/L = 0.04$ to 0.4. Initial simulation results revealed that drag and lift forces and Strouhal numbers all increased with the increase of blockage ratios. When the blockage ratio increases to a certain degree, the streamlines show a much more regular swing of the wake both in the near and far wakes and the vortices are forced to form in a narrow space very densely. Furthermore, it is noted that in these cases, there is not enough space in the lateral direction for the vortices to shed further downstream.
Chapter 4 – Experimental Method

4.1 Data Reduction

The following is a summation of formulae adopted by numerous authors in their wind tunnel experimental campaigns of VAWTs, which appears to be the de-facto standard in wind turbine data reduction.

Freestream Dynamic Pressure

\[ q_\infty = \frac{1}{2} \rho_{\text{air}} U_\infty^2 \]  

Where: \( \rho_{\text{air}} = \text{Air Density (slug/ft}^3) \)  
\( U_\infty = \text{Wind Speed (ft/s)} \)

Tip-Speed Ratio

\[ \lambda = \frac{\Omega}{\left( \frac{60 \pi D_R}{U_\infty} \right)} \]  

Where: \( \Omega = \text{Angular Velocity (RPM)} \)  
\( D_R = \text{Rotor Diameter (ft)} \)

Power Extracted

\[ P_{\text{extracted}} = \frac{\Omega}{60(2\pi)} (T) \]  

Where: \( T = \text{Turbine Torque (lb/ft)} \)

Power Available

\[ P_{\text{available}} = q_\infty U_\infty A_{\text{swept}} \]  

\( A_{\text{swept}} \)
Power Coefficient (Measure of Efficiency)

Applying theory from references [3, 47], Appendix C details the derivation of Power Coefficient from fundamental laws of physics, providing the following equation for efficiency

$$C_P \ (\text{Efficiency}) = \frac{p_{\text{extracted}}}{p_{\text{available}}} = \left( \frac{n}{60(2\pi)} \right) \left( \frac{T}{q_n U_n A_{\text{swept}}} \right) = \lambda C_Q \quad (4.5)$$

Where:
$$A_{\text{swept}} = D_R H_R$$
$$H_R = \text{Rotor Height (ft)}$$

Torque Coefficient

$$C_Q = \frac{4T}{\rho_{\text{air}} U_\infty^2 D_R^2 H_R} = \left( \frac{C_P}{\lambda} \right) \quad (4.6)$$

Air Density, (kg/m³)

Formula used in the calculation of Low-Speed Wind Tunnel Velocity Measurements [26]

$$\rho_{\text{air}} = \left( \frac{0.0034647}{T} \right) \left( P - 0.003796 R_h e_s \right) \quad (4.7)$$

Where:
$$T = \text{Atmospheric Temperature (K)}$$
$$P = \text{Atmospheric Pressure (Pa)}$$
$$R_h = \text{Relative Humidity (％)}$$
$$e_s = \text{Saturation Vapor Pressure at Test Day Temperature (Pa)}$$

Air Density, (lb/ft³)

Simplified calculation:

$$\rho_{\text{air}} = \left( \frac{P}{T} \right) 1.325 \quad (4.8)$$

Where:
$$T = \text{Atmospheric Temperature (^°F)}$$
$$P = \text{Barometer Atmospheric Pressure (Inches Hg)}$$

Wind Tunnel Velocity, (ft/s)

$$U_\infty = \sqrt{\frac{2 \rho_{\text{water}} g \Delta H}{\rho_{\text{air}}}} \quad (4.9)$$

Where:
$$\rho_{\text{water}} = H_2O \text{ Density (slug/ft}^3\text{)}$$
$$\rho_{\text{air}} = \text{Air Density (slug/ft}^3\text{)}$$
$$g = \text{Gravity (ft/s}^2\text{)}$$
$$\Delta H = \text{U-Tube Manometer Reading (ftH}_2\text{O)}$$
4.2 Reynolds Number Scaling

It is common practice in aerodynamic testing of scaled models in wind tunnels to apply the Reynolds number scaling principle. In order to theoretically obtain the same atmospheric wind conditions it is common to require the use of a higher wind speed for smaller scale models. For the primary testing phase in this investigation, a full scale Savonius Turbine was envisioned having an A_{swept} of 1m², that is, having a chord length (single blade diameter when 2 blades complete the rotor diameter) of 0.5 m.

Figure 4.1 – Wind Power & Speeds for United States - (NREL 2008)

Figure 4.1 provides the annual averaged wind power & wind speed for the US. From this it can be concluded that a wind turbine will not be expected to operate above 11 m/s on average in the US. With these benchmark ranges it is possible to take the chords of model and full-scale rotors Table 4.1, and relate them through R_e.
Table 4.1 – Geometric scaling of full-scale turbine to wind tunnel model

<table>
<thead>
<tr>
<th>Full-scale Rotor Geometry</th>
<th>Model Rotor Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>Diameter</td>
</tr>
<tr>
<td>1m (3.28ft)</td>
<td>0.24m (0.78ft)</td>
</tr>
<tr>
<td>Height</td>
<td>Height</td>
</tr>
<tr>
<td>1m (3.28ft)</td>
<td>0.26m (0.85ft)</td>
</tr>
<tr>
<td>Chord</td>
<td>Chord</td>
</tr>
<tr>
<td>0.5m (1.64ft)</td>
<td>0.12m (0.39ft)</td>
</tr>
</tbody>
</table>

Geometric Scale Ratio’s

<table>
<thead>
<tr>
<th>Diameter</th>
<th>Height</th>
<th>Chord</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.20</td>
<td>3.84</td>
<td>4.23</td>
</tr>
</tbody>
</table>

ISA Constants

| Air Density @SL          | 0.00227723 slugs/ft³ |
| Air Viscosity @SL        | 3.742E-07 slugs/(ft/s) |

Applying an atmospheric wind speed of 30 ft/s (approx 20.5 mph) produces:

\[
R_e = \frac{\rho U_c}{\mu} = \frac{0.002277 \times 30 \times 1.64}{3.742 \times 10^{-7}} = 299,411
\]  \hspace{1cm} (4.10)

Using this Reynolds number and model chord length to obtain a required wind tunnel speed:

\[
U_{\text{wind tunnel}} = \left( \frac{299,411 \times (3.742 \times 10^{-7})}{0.002277 \times 0.3875} \right) = 126.98 \text{ ft/s} = 86.57 \text{ mph}
\]

Table 4.2 – Reynolds Number scaled wind speeds

<table>
<thead>
<tr>
<th>Full Scale Wind Speed</th>
<th>Full Scale R_e</th>
<th>Wind Tunnel Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>mph</td>
<td>ft/s</td>
<td>m/s</td>
</tr>
<tr>
<td>5</td>
<td>7.33</td>
<td>2</td>
</tr>
<tr>
<td>10</td>
<td>14.66</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>21.99</td>
<td>7</td>
</tr>
<tr>
<td>20</td>
<td>29.32</td>
<td>9</td>
</tr>
<tr>
<td>25</td>
<td>36.65</td>
<td>11</td>
</tr>
</tbody>
</table>
4.3 Low-Speed Wind Tunnel – VAWT Testing Facilities

A high precision VAWT test bed facility has been installed at the University of Dayton Low-Speed Wind Tunnel Laboratory, housing an Eiffel-type tunnel with a contraction ratio of 16:1 and a working section $30'' \times 30'' \times 96''$ length, Figures 4.2 & 4.3. The test section inlet freestream turbulence intensity is less than 0.1% and tunnel maximum velocity is 40 m/s. Four VAWT models have been considered in this study, with the aim to obtain a data base of pressure signatures at varying fixed and dynamic RPM operating conditions. Chapter 1 presented rapid-prototype models created by TFCE representing scaled versions of a subsequently decommissioned VAWT project. Three similar concept models of varying geometry, 1/20th, 1/30th and 1/40th were created and scaled to a full size prototype; (blade height 10ft $\times$ rotor diameter 20ft) providing swept areas; (6” $\times$ 12”), (4” $\times$ 8”) and (3” $\times$ 6”), producing solid blockage values in the University of Dayton wind tunnel ranging from 2%, 3.5% and 8%. The 1/40th scale model (3” $\times$ 6”) was concurrently tested in a smaller tunnel at the TFCE wind tunnel facility, Figure 4.4; an open circuit, closed-test section wind tunnel having a working section 18” height $\times$ 18” width and tunnel maximum velocity of 45 m/s, producing a blockage of 5.5%. The larger 2-blade Savonius model has been compared for extreme blockage testing conditions, occupying 10% of the wind tunnel cross-sectional area.

The test system is shown in Figure 4.5, situated below the wind tunnel test-section, a spindle driven by the turbine passes through an air bearing producing a theoretically non-friction system, continues into a bearing-less rotary torque transducer and finally, a hysteresis braking system. Load is electronically applied on the hysteresis brake by the use of a function generator, applying negative torque on the turbine accurate to 0.01V increments. Rotors are tested at constant RPM conditions with varying freestream velocities and are tested under dynamic loading and unloading conditions using a Dataq acquisition system interfaced with a PC for real-time analysis of the system.
Figure 4.2 – 10% 2-Bladed Mode secured in the test-section for testing

Figure 4.3 – UD Low Speed Wind Tunnel (Left: Contraction Section, Right: Downstream View)

Figure 4.4 – TFCEnergy Low-Speed Wind Tunnel
4.3.1 Hysteresis Brake System

A Magtrol high precision Hysteresis Brake [48] has been used in the testing phase to provide a smooth, infinitely controllable torque loading device independent of speed. Primarily, the braking system composes the pole structure and the rotor, which interact magnetically to produce a braking or clutching force, Figure 4.6. As current is applied to the coil, a magnetic field proportional to current is established within the air gap. The rotor, located within the air gap, becomes magnetized. Due to its specific hysteresis properties the rotor resists movement, creating a braking torque (or clutch linkage) between the pole structure and rotor.
The Magtrol HB-450-2 is a DC powered device with a diameter of 1.25 inches and has a loading capability of 450 oz-in with a 2.75 inch thrust face, the amount of braking torque transmitted by the brake is proportional to the amount of current flowing, however the current is different when the control current is increasing than when decreasing due to the hysteresis in the rotor material, Fig. 4.7 (right). It is important to note that during wind tunnel testing there was a frequent problem of having an accidental salient pole condition set-up on the brake rotor which results in “Cogging Torque” (sometimes referred to as torque ripple), Figure 4.7 (left). Cogging torque is an inherent characteristic of a hysteresis brake which following simple steps provided by Magtrol, can be avoided and/or controlled as not to bias the torque readings.
4.3.2 Rotary Torque Transducer

The Interface T11-2-A2A Bearingless Rotary Torque Transducer [49], Figure 4.8, has a 2Nm torque capacity with a 30,000 RPM maximum performance. The system has a springrate of 5.0 x 10^5 Nm/rad, a drive side Moment of Inertia 9.1 x 10^7, a test side Moment of Inertia 8.3 x 10^-8, a maximum thrust loading 50N, a sample rate of 10 kHz and performs with a combined accuracy error ± 0.1%.

![Figure 4.8 – T11-2-A2A Bearingless Rotary Torque Transducer [49]](image)

4.3.3 Air Bearing

Figure 4.9 details the application of the air bearing incorporating a New Way Thrust Bushing [50], with a 1.25 inch bushing capable of withstanding a thrust load of 145 lb. The system uses a spindle with a thrust flange in the center of a bushing housing which has been custom made for the VAWT testing facility.

![Figure 4.9 – Spindle Application drawing using Thrust Bushings [50]](image)
4.4 Static Pressure-Taps

Eighteen pressure taps run along the center of the test-section sidewall, with increased frequency in close proximity to the model, Figure 4.10. Pressure differential readings are digitally displayed in steady-state recordings accurate to 0.1 N/m² by a separate pressure-traverse system from an existing AEROLAB test-section, Figure 4.11, were compared to an installed Pitot-Static tube output display on a U-tube manometer reading of the undisturbed freestream conditions forward of the model. The traditional definitions of pressure differential and pressure coefficient were used following Anderson [51], for the wall pressure measurement analysis:

**Pressure Differential**

\[ \Delta P = P - P_\infty \]  

(4.11)

**Pressure Coefficient**

\[ C_{pr} = \frac{P - P_\infty}{\frac{1}{2} \rho_{air} U_\infty^2} = \frac{\Delta P}{\rho_{\infty} U_\infty^2} \]  

(4.12)

*Figure 4.10 – Static Pressure Wall Tap Locations*
4.4.1 Pressure Transducer Array System

Eighteen Static Pressure taps used in the determination of pressure signatures for this study have been recorded using an AEROLAB [52] Pressure Transducer Array (PTA) system employing eighteen individual Low Total Error Band Pressure Transmitters. The RS-485 Transducers used in this study are rated at 3bar with an accuracy of ± 0.05%. For temporal response, it must be noted that the existing AEROLAB PTA system was not designed as a real-time system, the transducers communicate on a serial bus where readings are requested and received in sequence. Each transducer reports on average two readings (averaging and A/D conversion occurs on-board) and applies an on-board temperature compensation. The customized GUI used with the PTA system is shown in Figure 4.12.
4.5 Pressure Coefficient from Euler’s Equations

Ashill and Keating [53] provide a derivation of pressure coefficient from the basis of flow physics, the current study has tailored the derivation to extract and calculate tunnel wall interference from static pressure measurements. Appendix D details this process with the following end-results for a velocity ratio:

\[(1 + \varepsilon)^2 = 1 - C_{pr} \quad \text{or} \quad (1 + u/U_\infty)^2 = 1 - C_{pr}\] (4.13)

This can be re-written in velocity increment form for application to the current study, a method adopted by Fitzgerald [35]

\[\frac{\Delta u}{U} = (1 - \Delta C_{pr})^{1/2} - 1\] (4.14)
4.6 Wind Tunnel Models

Chapter 1 detailed two main rotors used in this investigation in the form of CAD models. A process of rapid-prototyping, created wind tunnel models with the following geometry, Table 4.3.

<table>
<thead>
<tr>
<th>Rotor Type:</th>
<th>2-Blade</th>
<th>3-Blade-A</th>
<th>3-Blade-B</th>
<th>3-Blade-C1</th>
<th>3-Blade-C2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Diameter, $D_R$</td>
<td>9.38</td>
<td>12</td>
<td>8</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Rotor Height, $H_R$</td>
<td>10.25</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Blade Radius, Chord, $c_B$</td>
<td>2.53</td>
<td>6</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Blade Thickness, $t_B$</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>End Plate Diameter, $D_P$</td>
<td>9.38</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Overlap Distance, $a$</td>
<td>0.24</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Overlap Ratio, OR</td>
<td>0.05</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rotor Aspect Ratio, AR</td>
<td>1.09</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Blockage Area-Ratio, B</td>
<td>0.10</td>
<td>0.08</td>
<td>0.035</td>
<td>0.02</td>
<td>0.055</td>
</tr>
</tbody>
</table>

4.7 Nd:YAG Laser System

To investigate instantaneous flow patterns surrounding the models operating at high RPM, a laser sheet was produced using a New Wave [54] Solo-PIV Nd:YAG laser with an energy output 15 – 200mJ supplied by ISSI [55], the sheet was created using a single cylindrical concave optic Figure 4.13. The orientation of the laser sheet is detailed in Figure 4.14.
4.8 (CCD) High-Shutter-Speed Camera

The laser sheet was pulsed at 10 Hz using a DG535 Four Channel Digital Delay/Pulse Generator coupled with a 1600 PCO Charge-Coupled Device (CCD) Camera, Figure 4.15, fitted with a 25 mm wide-angle lens at a distance of approximately 55 inches vertically from the test-section floor, this height allowed maximum Field of View (FOV). The PCO 1600 from the CooKe Corporation [56] has a 1600 X 1200 pixel monochrome Charge-Coupled Device (CCD) array, it has been used to capture images comparing rotor RPM at fixed freestream conditions and at fixed rotor RPM with freestream being the variable.
Chapter 5 – Results & Discussion

Wind Tunnel Measurements & Data Reduction

The formulae presented in this thesis have been applied to measured torque and RPM data from testing of four models, in order to assess VAWT efficiencies and power production capability, power curves are plotted for comparison. Testing of a 1/40th scale model in both TFCE and the UD LSWT has provided marked differences in efficiency characteristics and torque readings. This is the first instance of a possible influence of blockage on the efficiency of a VAWT rotor. The set of wind tunnel models (2, 3.5, 8, 5.5 and 10% Blockage Models) have been used to determine the influence of blockage ratio on the power curves.

5.1 Dynamic & Static Loading

The turbine testing facility installed at UD has the capability for loading rotor models by two different methods, through the use of the hysteresis braking system, the rotors can be dynamically loaded, whereby a transient loading and unloading cycle can be applied under a constraining time period. The results of such a loading method are presented in Figure 5.1, showing the direct relationship between increasing torque (brake) and turbine angular velocity (RPM) for a test of the 10% model, with special attention directed to the red shaded region in the figure, detailing possible effects of a resonance frequency/excitation of structural modes occurring between the wind tunnel fan and the turbine models.
As the experimental phase of the project matured, so did the appreciation and understanding of inertial effects of the turbines. To explain this point further, Figure 5.2 shows a comparison of the two loading methods, dynamic and static, whereby static loading is the technique of obtaining constant RPM at a constant load. Both methods produce almost exact power curves proving that fewer data points are required in the static loading method, which is much more efficient in terms of data processing and time management for wind tunnel testing of turbine models.

Figure 5.1 – Wind Tunnel Data for the 10% Model, Turbine Torque and RPM vs. Time
(Dynamically loading rotor models over a set time period creating max torque & RPM physical limits)

Figure 5.2 – Power Curves of 1/40th and 1/30th Scale Models
(Comparing Static to Dynamic Loading methods, computing Rotor Efficiency, both produce similar results)
5.2 Power & Torque Coefficient

Figure 5.3 displays coefficient of power and velocity ratio (TSR); these normalized curves give an indication of the ‘efficiency’ of each rotor at specific operating conditions. As expected with normalizing data, the curves coalesce neatly for the 2% blockage test giving a peak performance value at 4.5% efficient at extracting energy from the freestream, curves for 50 to 90 mph freestream lie closely together with fixed RPM testing.

It is pertinent at this point to reiterate the main purpose of this study; it is an investigation of the relatively rarely documented and assessed blockage effect phenomena of rotating bluff-bodies and the assessment of how effectively corrections applied to static testing can be applied to unique, rotating and dynamic flow situations (utilizing the Savonius VAWT in this study as an aerodynamic tool to study the angular velocity effect) and more importantly it shall be highlighted that the purpose of this study has not been to improve upon the performance of these wind turbine concepts.

Running tests on the same model in a smaller wind tunnel with a reduction by almost half in tunnel cross-sectional area, operating at 5.5% blockage area-ratio produces marked differences both in trend and absolute values. It can be argued that this is beyond the critical blockage size for experiments with rotating bluff-bodies in closed-test section wind tunnels such as these in question.

The curves exhibit shifts in their efficiency peaks as wind speed increases and displays curves collapsing only at the lower tip-speed-ratio region. It can be clearly observed that there is an artificial rise in turbine efficiency when increasing the blockage ratio. Applying the formula for Power Coefficient, as previously described, if there is a flow condition occurring where the true velocity experienced in the model region is below what is expected or programmed by the wind tunnel operator into corresponding $C_P$ calculations, this leads to artificially higher $C_P$ values.
Figure 5.3 – Comparison of Two Wind Tunnel results for 1/40th Scale Model
(Details Power Coefficients increasing as function of Blockage ratio increase 2 to 5.5%)

Figure 5.4 displays raw torque loading data as a function of turbine RPM. As expected, reducing the rotational speeds of the turbines through increased loading, translates this to a torque loading capability indicating the peak positive torque region increases as a function of increasing freestream speeds. Resonance frequencies exist between the wind tunnel fan and the turbine models (red shaded region in the figure).

Figure 5.4 – Variation of Torque and Free-spin with Turbine RPM
(Details Torque trends at varying wind speeds and resonance regions)
5.3 Blockage Effects

Assessing solid and/or wake effect on induced velocity distributions Figure 5.5 displays power curves for the four models varying in absolute swept-area. This comparative plot provides evidence of a rightward shift in efficiency peaks when the blockage ratio is increased by increasing the swept-area of the rotor. That is, the freestream velocity increases due to higher levels of flow constriction because of a larger body placed in the flow. This is a positive step in comparing the influence of blockage on artificially increasing efficiency of VAWTs due to the wind tunnel velocity increments. Again, an actual flow speed higher than what is used in calculation of the power coefficient and tip speed ratio produces lower $C_p$ values. Likewise values of freestream predicted higher than actual, produce lower values of $C_p$.

![Figure 5.5 – Comparison of Power Coefficient vs. Tip-Speed Ratio](image)

The findings of this study compare well to those of Modi [57, 58]. As part of a project to design a wind turbine driven irrigation system for use in rural farming communities in Indonesia, Modi analyzed wall confinement effects on performance by testing a family of Savonius models of varying blockage ratios. The models were tested under several smooth-flow conditions using
two wind tunnels of different cross-sectional areas. Figure 5.6 shows clearly a dramatic increase in Power Coefficient which Modi explains is primarily due to an increase in local velocity with blockage and that wind-tunnel results presented by different investigators often do not correlate, because of different test conditions. One of the major parameters affecting such test data is blockage. Modi does not provide any details of correcting for blockage but positively states that an increase in wall confinement from 5 to 20% can raise power coefficient by around 70%, thus leading to a highly optimistic performance estimate if the blockage effect is not corrected.

Wind tunnel results of the current study has additionally been supported by results from an investigation of blockage effects on power coefficient for a Savonius rotor in low-speed wind tunnels by Alexander [29, 30], in which a similar technique was adopted to utilize two low-speed wind tunnel facilities with varying test-section cross-sectional areas to assess the influence of blockage.

Figure 5.6 – Comparison of Power Coefficient vs. Tip-Speed Ratio
(Shows the effect of blockage ratio on output of Savonius rotor) [57]
Tests were conducted at two low-speed facilities; the 4 ft x 2 ft tunnel at Loughborough University of Technology and the 8 ft x 4 ft at Cranfield Institute of Technology, giving blockage ratios (S/C) of 0.249 and 0.121 respectively. Figure 5.7 details the artificial increase in efficiency (power coefficient) curve with increasing blockage ratio.

![Figure 5.7 – Power Curves from two Wind Tunnels [29, 30]
(A comparison of results in Cranfield and Loughborough Wind Tunnels for Savonius Rotor with AR = 4.8)](image)

The method in which Alexander has corrected the data will be assessed in a later section in this study. Importantly, at this stage in the assessment of blockage effects, comparisons of the current results to the two selected papers can be made. There are two similar phenomena occurring when increasing blockage ratio: (the second is more clearly shown in Modi’s study)

1) **Power curves are increasing in absolute value and**

2) **the Power Coefficient peak experiences a rightward shift towards higher TSR,**

A later study by Modi [58] reinforces the above statements showing these exact effects occurring in Figures 5.8, 5.9 & 5.10.
Figure 5.8 – Power Coefficient plotted with Tip-Speed-Ratio [58]
Showing the effect of blockage on power output of the Savonius rotor

Figure 5.9 – Maximum Power Coefficient plotted with Blockage Percentage [58]
Showing the effect of blockage on peak power coefficient for two different blade geometries
5.4 Wall Pressure Signature

For an explanation of the artificial shift of VAWT efficiencies in wind tunnel testing, changes to the pressure signature created from different rotors has been assessed. The next stage in quantifying a realistically accurate blockage correction factor is to record wall-static pressures along the center-line of the closed test-section wind tunnel sidewall with the goal to representing coefficients of differential pressures whilst relating the origins of these pressure differentials to that caused by velocity increments across the flow inside the test-section, closely resembling the work of Hackett-Wilsden [40], noting that due to the gross asymmetry of the flow created, both sidewalls were studied and accounted for in the pressure distribution analysis.

Comparing static pressure readings upstream of the model, reveals that for some experiments the values are lower than an empty test-section. This provides evidence of the possibility of wake propagation far upstream of the model reaching into the wind tunnel contraction, noting that the VAWT model was placed at the streamwise centerline position and that the test-section is three times longer than the test-section width. Static pressure readings reveal a large pressure decrease immediately aft of the models, Figure 5.11. This relates to an increased local freestream velocity,
which is a product of both flow constriction due to solid body interaction and the propagating wake from a rapidly spinning model.

5.5 Pressure Coefficient as a function of Location

Figures 5.11 & 5.12 show a sample analysis of the 10% [largest solid blockage] geometry model. The plots describe flow behavior as a function of wind tunnel velocity and model RPMs by non-dimensionalizing wind tunnel X-location by wind tunnel span, B. Trends compare well with theory, Figure 5.13. Comparing static pressure upstream of the model reveals values are lower than an empty test section, this could provide evidence of upstream wake propagation far forward of the model reaching the tunnel contraction. At slow speeds, 30-50 mph, normalized curves of $C_p$ do not coalesce neatly. This could be a factor of instrument range. With increasing freestream velocity, results show there is a functional relationship with a larger pressure decrease and increased RPM. Negative pressure coefficient is a factor of higher freestream velocities with a model present in the flow. This aerodynamic characteristic has been observed with all test objects. A pressure coefficient of zero indicates that the pressure along the tunnel sidewall is equivalent to that of the empty test-section, providing a conclusion that the model would have no aerodynamic influence at all on the freestream velocity. The plots reveal large pressure decreases immediately aft the models. Following incompressible flow assumptions, increased local freestream velocity is a product of both flow constriction due to solid-body interaction and wake propagation from an object with high angular velocity.
Figure 5.11 – Comparison of Wall Static Pressures
(Shows reduced pressures relating higher velocities produced by the 10%, 2-Bladed Savonius Model at 40mph freestream with the shaded region displaying upstream segment of test section)

Figure 5.12 – Comparison of Wall Static Pressures
(Shows possible contributions to reduced pressures from Solid/Bubble and by Wake Blockage for a 10% 2-Bladed Savonius Model at 70mph freestream)

Figure 5.13 – Comparison of Velocity Increment as a function of Wind Tunnel Location [4]
(Shows possible contributions to reduced pressures from Solid/Bubble and by Wake Blockage)
Figure 5.12 compares pressure differential when a model is freely spinning at maximum RPM in the test section with a 70 mph freestream. Analysis of this pressure distribution reveals that the 10% and 8% models have a profound influence on the freestream pressure, and that the smaller models 3.5% and 2% have minimal influence, as expected. Using this evidence and normalizing the values with a dynamic pressure formulates a pressure coefficient signature inside the tunnel for each model at a 60 mph freestream condition, Figure 5.14. This plot provides a high negative pressure coefficient displaying increased freestream velocity in the tunnel especially observed with the larger models. Only a few static-tap ports required elimination from the data sets in order to eradicate the probability of skewing the trend, hence a strong degree of confidence can be gained from the analyses and results. The few spurious static pressure readings were postulated as being affected by limited transient pressure transducer response capability compared to that demanded by the high RPM turbines. The results recorded for the 3.5% and 2% models show that the pressure readings are likely to be approaching sensor sensitivity; as such the absolute values are likewise somewhat questionable in these regions, however the overall trend should still be identifiable as considerably less than those for the larger swept-area models.

Figure 5.14 – Comparison of Wall Pressure Coefficients at 60mph Freestream Velocity, 1000 RPM
(Cpr as a function of Area-Ratio)
5.6 Pressure Signature as a function of Sidewall Height

Because of the gross asymmetry of the flow-field surrounding the turbine rotors in wind tunnel testing, it is not wholly-sufficient to rely upon the flow behavior and modeling from a single sidewall pressure distribution. Therefore, two additional static pressure-tap rows were installed in order to support the flow obstruction observations. The opposing sidewall was pressure tapped at the same height (mid height) of the sidewall and a second row of pressure readings were taken within the height of the largest 10% model, at approximately 7 inches above the test-section floor. To support the proposed flow behavior and wake pattern stated earlier, it is logical to assume that the lower pressure-tap row would produce marked differences in both absolute value and severity of the pressure differentials upstream and downstream because of its increased proximity to the rotor models. Figure 5.15 shows this trend clearly, with the blue line representing the lower pressure-tap row and the higher position both left and right sidewall provide an almost exact flow behavior. However, there is a clear coalescing trend as a function of increasing freestream. The pressure distribution from the lower pressure-row tends to decrease with increasing freestream from 30 to 70 mph, revealing a functional relationship with flow obstruction and freestream.

5.7 Pressure Coefficient vs. Location as a function of RPM

Reflecting upon the previous results; as the freestream velocity increases there is an associated decrease in wind tunnel blockage effect (represented by a drop in pressure coefficient), a cross-plot of pressure distribution is created with the aim to investigate whether the previous results are entirely a factor of freestream or a combination of factors also incorporating fluid dynamic angular velocity imparted by the rotors. Figure 5.16 displays results for the 8% model, as RPM is increased there is no associated increase in tendency of the curves to coalesce. Freestream conditions have a much larger impact on the results, showing at higher freestream velocities the distributions coalesce.
Figure 5.15 – 10% Blockage Model, $C_p$, vs. $x$-Location
(Comparison of $C_p$ distribution as a function of sidewall height & normalized longitudinal $x$-location)
Figure 5.16 – 8% Blockage Model, $C_p$ vs. $x$-Location

(Comparison of $C_p$ distribution position as a function of longitudinal $x$-location, Top: 400 & 600RPM, Middle: 800 & 1000RPM, Bottom: 1200RPM)
5.8 Pressure Coefficient vs. TSR as a function of Longitudinal Location

Plotting $C_{Pr}$ with TSR shows the influence of rate-of-rotation upon the flow conditions within the wind tunnel test-section. The decreasing $C_{Pr}$ distribution has been shown to be a factor of increasing TSR this has been compared along the longitudinal static-pressure port positions upstream and downstream of the model centerline. Figure 5.17 shows the relationship for a 10% area-blockage model at a freestream of 50 mph. It can be shown that as TSR increases over the range 0.3 to 1.1, the pressure coefficient reduces in absolute value therefore providing a conclusion that increasing angular velocity imparted by the rotors causes a reduced influence upon the freestream. The results present evidence that the wake propagation from the turbine is contained closer at higher RPMs. Results show smaller delta $C_{Pr}$ values obtained at higher TSR; this provides evidence for a higher freestream velocity present. The pressure signature from the opposing sidewall was obtained and provided additional evidence in support of this statement.

Figure 5.18 supports a negative slope theory with increasing TSR, with a plot of upper, lower and mid-range data from the 3.5% & 8% models with a freestream of 70 mph, all displaying negative slopes within the TSR range. A wide range of wind speeds has been studied and reveals strong homogeneity in the results irrespective of the freestream conditions. Influence of model rotation is consistent over a wide range of wind speeds.

![Figure 5.17 – 10% Blockage Model, TSR vs. $C_{Pr}$](image)

*(Selection of wind tunnel locations which display the overall trend, across x-locations at 50 mph, describes the reduction in blockage effect with increase in TSR)*
5.9 Linear Regression Model

As a step towards quantifying the effects of blockage-ratio upon the efficiency of VAWT models, rotor RPM has been studied for its effects on freestream pressure distributions. Using the results from the previous phase of data analysis, correlations were created from linear regressions across longitudinal locations. Slopes were created from the previous plots of $\Delta C_{pr}$ vs. TSR. Figure 5.19 shows upper, lower and mid-range data using the slope equations as a function of TSR for the 8% area-blockage model from 60 to 80 mph. The data provides similarity between the slope equations obtained by linear regression. The slope equations found for TSR range 0.2 to 0.6 have been extended up to 1.1 and these are shown in Figure 5.20 for all the models, displaying similar variations in slopes.
5.10 \((C_{pr} - TSR)\) Slopes as a Function of Wind Speed

Using the individual slope equations obtained at each longitudinal location and across wind speeds at the higher pressure-tap rows, their absolute values of \((C_{pr} - TSR)\) slopes have been analyzed as a function of wind speed for the 8\% area-blockage model. The functional relationship between pressure coefficient and tip-speed-ratio from the 8\% blockage model can be extrapolated to a relationship independent of wind tunnel wind speed conditions, indicated by horizontal lines from the higher pressure-tap rows. Similar results were obtained for the 3.5 and 10\% blockage models however reviewing Figure 5.20 describes flow improvements in the wind tunnel as a direct function of increasing RPM \textit{and} increasing freestream. The \(C_{pr} - TSR\) slopes produce negative trends supporting the previous statement. Increasing freestream shows the slope produces lower delta \(C_{pr}\) values, verifying that the flow \textit{improves} with increasing RPM and freestream.
5.11 Flow-Field Visualization

To approach the problem of blockage effects, a clear understanding of the flow-field is required, to appreciate the flow physics around a Savonius rotor in a low-speed wind tunnel, a flow visualization study was undertaken using a laser sheet with an energy output 15 – 200mJ and a single cylindrical concave optic. The laser sheet was pulsed at 10 Hz coupled with a (CCD) Camera fitted with a 25 mm wide angle lens. Smoke was seeded at 5 psi using an oil-based fluid Vi-Count Smoke Generator charged with a Nitrogen supply. Figure 5.21 provides a selection of images captured to compare varying rotor RPM at fixed freestream conditions and comparing varying freestream conditions at fixed rotor RPM. Observations were made about the flow region between the rotor and the wind tunnel sidewalls. The 2-bladed model, Figure 5.21 a) exhibited significant streamline bending around the reverse side of the blades. In most instances this flow is turned fully into the opposing freestream direction. This flow phenomenon at high rotor RPM produces an adverse pressure gradient which could lead to a thinning or narrowing of the wake which could explain a smaller wake influence when compared to the low RPM conditions. In Figure 5.21 a) (right), the rotor acts increasingly like a static bluff-body in the flow, producing a Von Kármán-type bluff body alternating vortex street downstream, similar to that stated by Medici [19] as characteristic of bluff-body flows particularly found with vortex shedding from 2-D cylinders. This scales well with smaller rotor models. The flow visualizations reveal similarities to Fujisawa’s [17] results, there is a common occurrence of strong asymmetry of the wake, however Fujisawa’s published images have a restricted FOV so it is unclear if the results supported a sidewall interaction. His results cannot provide a conclusive analysis of rotation as an influence on wake propagation. Results confirm the initial choice of wind tunnel sidewall used for pressure tapping was in error, Figure 5.21 e). Images show a much wider wake on the opposing (right) side indicating right sidewall pressures were required before reaching any conclusions.
Figure 5.21 – CCD Camera images across laser sheet
(a - d, Compare high RPM’s to low RPM loaded rotor, e) Compares sidewall interaction, left and right test-section sidewall interactions, white strips marking 1 and 2 inches from sidewall surface)
Figure 5.22 – Flow patterns from the y-axial view [59]
(Comparing rotor azimuth angle to freestream direction, all cases show a high degree of asymmetric wake)

The flow patterns observed in Figure 5.21 as a result of smoke seeding can be compared to flow visualization undertaken by Nakajima [59], using a water tunnel seeded with a pigment streak-line method, Figure 5.22. Of major importance from this comparison, is the supporting evidence that Nakajima can provide by displaying the highly asymmetric wake being produced with the two blade rotor.
5.11.1 Influence of RPM

A comparison has been made of constant freestream conditions with varying RPM to assess the influence of angular velocity on the flow physics. Figure 5.23 depicts the 10% model in a 20 mph freestream, with the RPM’s decreasing in the images from left to right. There is a clear trend represented by the streamlines around the rotor, as the angular velocity is decreased there is decreased tendency to bend the streamlines around the reverse of the blades. At 100 RPM the rotor is acting as a static bluff body/flat-plate in the flow with a much larger aft wake (this comparison becomes an important factor for later corrections at low RPM) with none of the vortex formation visible at higher RPM. Figure 5.24 details closely the streamline bending phenomenon, in specific cases the streamlines are turned completely into the oncoming freestream direction. A similar trend observed in Figure 5.23 has been found at higher freestream, Figure 5.25 with a freestream velocity of 60mph, the lower first image captured the instantaneous real-time image of the rotor in full-spin and the upper image captured the flow-field with the laser sheet. Similar flow characteristics are observed, weaker streamline bending, weaker aft adverse pressure gradient and a less distinct vortex pair separating from the blades as RPM decreases.

![Figure 5.23 – 10% Model at 20mph with yellow dotted line denoting boundaries of the wake (Influence of RPM, Left: free-spinning model at 800RPM, Middle: 500RPM and Right: 100RPM)](image)

![Figure 5.24 – 10% Model at 50mph (Note: Streamline bending around adverse side of the 2 Bladed rotor)](image)
Investigation of the influence of angular velocity on the flow-field has been captured for the three remaining rotor models and a selection of freestream speeds has been provided for comparison in Figures 5.26, 5.27 & 5.28 showing the influence of RPM upon the 8%, 3.5% and 2% rotors respectively. In the case of the 8% rotor, Figure 5.26 shows a similar trend to the 10% rotor, acting as a static bluff-body in the flow as RPM values are reduced (additional support for applying flat plate corrections), showing very little streamline bending and flow curving with the vortex propagating from the aft blade, shown in the upper region of the images, this is especially clear when comparing the 880 RPM case to that of the 100 RPM case. The improved flow characteristic with a functional relationship to TSR could be a factor of improved pressure recovery by a reduction in the wake velocity deficit caused by this increase in angular velocity of the rotor and corresponding reduced energy extraction from the flow. Although, with the 3.5% and 2% cases the smoke distribution covers a much wider flow-field encompassing almost the entirety of the surrounding flow region, the flow behavior scales well to the 8% rotor. Reduced
streamline bending and weaker vortex patterns are observed at low RPM’s. The wake appears more widely dispersed at low RPM conditions and more concentrated within the vortex wake shedding found at higher RPM conditions, although it would be pertinent to account for a major consideration that the freestream velocity in certain experiments could be too high for the periodic vortices to form downstream of the rotors.

Figure 5.26 – 8% Model at 50mph
(Influence of RPM, Clockwise from Top: 880, 500, 250 and 100 RPM)

Figure 5.27 – 3.5% Model at 60mph
(RPM Influence, Top: 1400, 1000, 500RPM, Bottom: 250, 100RPM)
5.11.2 Upstream Flow

To assess potential evidence of upstream wake propagation, analysis was performed of the upstream flow regions surrounding the rotors, Figures 5.29 & 5.30 show the flow visualization around the 10% & 8% rotors respectively. Shifting the laser sheet and the FOV towards the upstream region provided an ideal visual tool to assess the flow behavior as a function of RPM and freestream effects.

Figure 5.29 displays a pair of images at each RPM condition, the top image captures the flow with the turbine in a zero (stalled) azimuth position to the freestream direction and the lower images deal with the turbine at a 90 degree azimuth position to the oncoming freestream, both however show similar flow characteristics and influence upstream of the rotor. Figure 5.30 describes a similar flow behavior with an increased freestream. All images show a clear flow stagnation point at the rotor centre line, a feature Fujisawa [6] observed. Figure 5.31 displays the 8% rotor case, here the stagnation point is clearly identifiable.
Figure 5.29 – 10% Model at 40mph
(Upstream Flow Influence of RPM; Left Column: 1600 RPM, Middle Column: 1000 RPM, Right Column: 500 RPM. Top row: rotor at zero azimuth position and the bottom row with the rotor 90° to the freestream)

Figure 5.30 – 10% Model at 60mph
(Upstream Flow Influence of RPM, Top: 2300 RPM, Bottom: 1000 RPM. Left Column shows the rotor at 90° to the freestream and right column at approximately zero azimuth position)
Figure 5.31 - 8% Model at 60mph
(Upstream Flow Influence of RPM, Top: 1000 RPM, Middle: 500 RPM and Bottom: 250 RPM)
5.12 Application of Blockage Corrections

The underlying goal of this study has been to improve accuracy of dynamic wind tunnel testing. The following formulae outline the process of comparing performance data of wind turbines in full-scale, unrestricted flow domains to sub-scale wind tunnel testing.

*Full-scale Atmospheric Tests: (Two Driving Variables in Power Coefficient Equation)*

\[ C_p = f(\lambda, C_q) \]  

(5.1)

*Sub-Scale Wind Tunnel Tests: (Three Driving Variables in Power Coefficient Equation)*

\[ C_p = f(\lambda, C_q, \epsilon_{total}) \]  

(5.2)

1. **Solid Blockage:**

\[ \epsilon_{solid} = f(S/A) \]  

(5.3)

2. **Wake Blockage:**

\[ \epsilon_{wake} = f(S/A, \lambda) \]  

(5.4)

3. **Total Blockage:**

\[ \epsilon_{total} = \epsilon_{solid} + \epsilon_{wake} \]  

(5.5)

The results have given evidence that tip-speed-ratio has a profound influence on conditions inside a closed test-section wind tunnel as well as area-ratio influence. Therefore, total blockage corrections should be required to incorporate both factors. Three correction methods have been assessed in this study:

1. Pope & Harper Correction [22], widely used in VAWT testing. Based on area-ratio.

2. Hackett-Lilley-Wilsden Method [37], which has been simplified to base assessments on a measured wall-pressure-signature method, this method favored capability to allow for dynamic effects and static influences in the formula.

3. Maskell Method [27, 28, 29], a modified version used a semi-empirical term collected from previous pressure and drag measurements on a Savonius rotor. This method based on higher fidelity inputs using actual data was favored to show good end-results.
5.12.1 Velocity Corrections

Wind tunnel corrections used in this study aim to provide accurate velocity measurements, which are much closer to characterizing the real flow physics occurring inside the test-section. It is the difference in their approach by which each method takes to reach the end goal of a velocity ratio (corrected velocity to freestream velocity) which has been assessed here.

The method for obtaining the Pope and Hackett velocity increments has previously been detailed. However, in order to obtain the velocity increment for the Maskell method a semi-empirical term $m$ is calculated. This has been extrapolated from data provided by Alexander’s study. Figure 5.32 clarifies the rotor model (S/A) values in the current study and their corresponding $m$ terms estimated from the Savonius Rotor curve. Appendix E provides additional $m$ terms and blockage factors for general shapes in two and three-dimensional flows.

![Figure 5.32 – Flat Plates and Savonius Rotors term $m$ vs. Blockage Ratio (S/A)](image)

Figure 5.32 – Flat Plates and Savonius Rotors term $m$ vs. Blockage Ratio (S/A)
Figure 5.33 – Comparison of Savonius Rotor Velocity Corrections
(Left) Comparison of Correction Methods and (Right) Relevant comparable plot zone from [29]

Figure 5.33 presents a comparison of the correction methods used in this study. Comparison is made by plotting the effective severity of velocity change computed by each method represented by the ratio \( V_c/V_u \). It is observed that for a flat plate normal to the freestream, the velocity correction is a positive linear trend, which the Maskell method follows closely. Interestingly, the de-facto method popularly used for VAWT testing is the Pope correction however in comparison to Maskell’s approach it shows no close similarity in velocity correction, both in absolute value and functional dependency with blockage ratio. Applying the Wall-Pressure-Method (WPM) with delta \( C_{pr} \) values obtains a similar end-result to Pope, however at higher blockage percentage (8% and 10%) the WPM using absolute values produced a trend line correlating with Maskell, although this trend was not observed at lower percentages.

5.12.2 Correcting Performance Curves

To assess the effectiveness of the chosen correction methods, formulae for velocity corrections for each method have been applied to the wind tunnel test data. In order to fully incorporate the velocity increments into the data reduction process; TSR, \( C_\Omega \) and \( C_p \) have been modified to accept updated wind tunnel freestream conditions.
Figure 5.34 shows the application of the different correction techniques to the 10% rotor case. The series of plots show the Power Curve trends across wind speeds 30 to 60 mph. Uncorrected data show some discrepancy across wind speeds with $C_p$ peaks dropping as a function of increasing wind speed. Most methods show little improvement, however WPM using absolute $C_{pr}$ showed good coalescing of curves as did the Maskell method, all decreased performance of the 10% rotor considerably as a result.

Figure 5.35 shows a similar comparison assessed for the 8% rotor case, across wind speeds there was no apparent change with corrections in respect of coalescing tendency. The power curves increased with increasing wind speed and application of the Maskell Method reduced performance with a 28% drop in overall efficiency. The most dramatic influence of correcting the data is seen when comparing power curves across correction methods, Figures 5.36 to 5.39 detail the severity in which different methods change the end-result. Figure 5.36 shows comparison of methods for the 10% rotor case. Applying WPM using delta $C_{pr}$ showed very little reduction in the data from the uncorrected curve and this was observed with all rotor cases to the extent at small blockage ratio the delta WPM showed no change from the uncorrected data. A trend which logically follows the statements in this study, that for small blockage ratios the corrections are inherently small, however the WPM using delta $C_{pr}$ does not establish required severity at higher blockage ratios, as seen with Figure 5.36.

Figures 5.37 to 5.39 plot the correction made on the series of 3 bladed rotors. Interestingly, the Maskell method produces ideal characteristics for power curves that coalesce well across rotors of the same type, giving an approximate performance for the 3 bladed rotor at $C_p = 0.04$ to 0.05. Application of the Pope correction shows only small changes in the data and does not clearly show merit in improving results.

Application of the WPM using absolute $C_{pr}$ values showed a tendency to over-correct velocity at the smaller blockage ratios, Figure 5.39 clearly shows this tendency in the bottom curve.
Figure 5.34 – Correcting 10% Rotor Power Curves – Shows variation of curves across wind speeds 30 to 60 mph and the curves coalescing as a function of each technique.
Figure 5.35 – Correcting 8% Rotor Power Curves - Shows variation of curves across wind speeds 50 to 80 mph and a small change of coalescing as a function of technique.
Figure 5.36 – Comparison of Correction Methods for 10% Rotor operating at 70mph freestream
- (at peak TSR, Pope, Delta WPM and Absolute WPM show little correction, however the Maskell Method reduced the power curve peak position by 59%)

Figure 5.37 – Comparison of Correction Methods – 8% Rotor operating at 70mph freestream
- (Maskell Method reduced power curves by 42% and the Absolute WPM shows results shifting towards this region)
Figure 5.38 – Comparison of Correction Methods – 3.5% Rotor operating at 70mph freestream,
- (Uncorrected and Delta WPM Power Curves produced very similar values that superimposed in the
figure, Pope method showing little correction, Maskell and Absolute WPM show a clear reduction)

Figure 5.39 – Comparison of Correction Methods – 2% Rotor operating at 90mph freestream
- (Uncorrected, Delta WPM and Pope corrected Power Curves produced very similar values that
superimposed in the figure, Maskell and Absolute WPM show a clear reduction with a possible over
correction using the Absolute WPM)
Table 5.1 lists the percentage variation of the peak power coefficients between corrected vs. uncorrected data for each method across a range of wind speeds and blockage ratios. The table provides a simple but effective technique to verify trends of velocity corrections as a function of wind speed and/or blockage. Tabulating results for the Wall-Pressure-Method (WPM) show that the trend is obtained with increasing percentage variation is a function of both blockage ratio and interestingly, this method shows good results in supporting the claim that wind tunnel conditions are improved with increased freestream velocity, as is shown when corrections decrease with increasing wind speed.

Table 5.1 – Results of corrections of Savonius Rotors operating in a restricted flow closed test-section wind tunnel

<table>
<thead>
<tr>
<th>Blockage (S/A) %</th>
<th>Wind Speed ft/s (mph)</th>
<th>Initial Peak TSR</th>
<th>Power Coeff</th>
<th>( \Delta C_{pr} ) WPM</th>
<th>% ( \Delta \text{Power} )</th>
<th>WPM Abs. Power Coeff</th>
<th>Pope</th>
<th>Maskell</th>
<th>Maskell Updated</th>
</tr>
</thead>
<tbody>
<tr>
<td>10%</td>
<td>103.15 (70)</td>
<td>0.74</td>
<td>0.1316</td>
<td>-1.74%</td>
<td>-19.69%</td>
<td>-8.23%</td>
<td>-59.37%</td>
<td>0.0826</td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>89.33 (60)</td>
<td>0.56</td>
<td>0.1356</td>
<td>-1.84%</td>
<td>-20.43%</td>
<td>-8.23%</td>
<td>-59.37%</td>
<td>0.0851</td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>73.30 (50)</td>
<td>0.63</td>
<td>0.1521</td>
<td>-2.40%</td>
<td>-32.64%</td>
<td>-8.23%</td>
<td>-59.37%</td>
<td>0.0903</td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>59.26 (40)</td>
<td>0.67</td>
<td>0.1588</td>
<td>-3.60%</td>
<td>-49.55%</td>
<td>-8.23%</td>
<td>-59.37%</td>
<td>0.0943</td>
<td></td>
</tr>
<tr>
<td>10%</td>
<td>44.21 (30)</td>
<td>0.67</td>
<td>0.1657</td>
<td>-5.64%</td>
<td>-85.04%</td>
<td>-8.23%</td>
<td>-59.37%</td>
<td>0.0983</td>
<td></td>
</tr>
<tr>
<td>8%</td>
<td>117.30 (80)</td>
<td>0.263</td>
<td>0.0674</td>
<td>-0.98%</td>
<td>-15.58%</td>
<td>-6.12%</td>
<td>-41.88%</td>
<td>0.0475</td>
<td></td>
</tr>
<tr>
<td>8%</td>
<td>103.15 (70)</td>
<td>0.311</td>
<td>0.0726</td>
<td>-1.38%</td>
<td>-20.35%</td>
<td>-6.12%</td>
<td>-41.88%</td>
<td>0.0512</td>
<td></td>
</tr>
<tr>
<td>8%</td>
<td>89.33 (60)</td>
<td>0.251</td>
<td>0.0606</td>
<td>-2.02%</td>
<td>-24.83%</td>
<td>-6.12%</td>
<td>-41.88%</td>
<td>0.0427</td>
<td></td>
</tr>
<tr>
<td>8%</td>
<td>73.30 (50)</td>
<td>0.298</td>
<td>0.0624</td>
<td>-2.47%</td>
<td>-33.68%</td>
<td>-6.12%</td>
<td>-41.88%</td>
<td>0.0440</td>
<td></td>
</tr>
<tr>
<td>3.5%</td>
<td>132.00 (90)</td>
<td>0.313</td>
<td>0.0533</td>
<td>-0.10%</td>
<td>-12.34%</td>
<td>-2.69%</td>
<td>-19.50%</td>
<td>0.0446</td>
<td></td>
</tr>
<tr>
<td>3.5%</td>
<td>117.30 (80)</td>
<td>0.295</td>
<td>0.0524</td>
<td>-0.14%</td>
<td>-14.55%</td>
<td>-2.69%</td>
<td>-19.50%</td>
<td>0.0439</td>
<td></td>
</tr>
<tr>
<td>3.5%</td>
<td>103.15 (70)</td>
<td>0.269</td>
<td>0.0507</td>
<td>-0.01%</td>
<td>-19.00%</td>
<td>-2.69%</td>
<td>-19.50%</td>
<td>0.0424</td>
<td></td>
</tr>
<tr>
<td>3.5%</td>
<td>89.33 (60)</td>
<td>0.318</td>
<td>0.0532</td>
<td>0.06%</td>
<td>-23.02%</td>
<td>-2.69%</td>
<td>-19.50%</td>
<td>0.0445</td>
<td></td>
</tr>
<tr>
<td>2%</td>
<td>132.00 (90)</td>
<td>0.319</td>
<td>0.0448</td>
<td>&lt; 0.0%</td>
<td>-19.32%</td>
<td>-1.51%</td>
<td>-10.25%</td>
<td>0.0406</td>
<td></td>
</tr>
<tr>
<td>2%</td>
<td>117.30 (80)</td>
<td>0.273</td>
<td>0.0437</td>
<td>&lt; 0.0%</td>
<td>-21.56%</td>
<td>-1.51%</td>
<td>-10.25%</td>
<td>0.0396</td>
<td></td>
</tr>
<tr>
<td>2%</td>
<td>103.15 (70)</td>
<td>0.305</td>
<td>0.0449</td>
<td>&lt; 0.0%</td>
<td>-28.02%</td>
<td>-1.51%</td>
<td>-10.25%</td>
<td>0.0407</td>
<td></td>
</tr>
<tr>
<td>2%</td>
<td>89.33 (60)</td>
<td>0.301</td>
<td>0.0440</td>
<td>&lt; 0.0%</td>
<td>-33.93%</td>
<td>-1.51%</td>
<td>-10.25%</td>
<td>0.0399</td>
<td></td>
</tr>
<tr>
<td>2%</td>
<td>73.30 (50)</td>
<td>0.287</td>
<td>0.0431</td>
<td>&lt; 0.0%</td>
<td>-47.88%</td>
<td>-1.51%</td>
<td>-10.25%</td>
<td>0.0391</td>
<td></td>
</tr>
</tbody>
</table>

Applying absolute \( C_{pr} \) values with the WPM produce results which the author thought possible to occur, showing to over-correct vastly at small blockage (S/A) values and must now be clarified.
that the WPM is entirely built for delta $C_{pr}$ as predicted. Both Pope and Maskell corrections show good trends with increasing severity with blockage (S/A) value, but only allow for a constant correction with no variation or functional dependency upon tip-speed-ratio which is the goal for a correction of dynamic bluff-body wind tunnel testing. Selecting the Maskell approach as a viable correction for coalescing power curves of different (S/A) values, Table 5.1 provides the updated peak power coefficient values using this method, this is a clear indication for the 3 blade rotors showing much improved similarity in performance.

Figure 5.40 displays the effectiveness of two methods, Pope and Maskell, showing uncorrected power curves alongside their respective corrected power curves. Table 5.1 grouped the overall results covering correction methods and details their effectiveness at coalescing the maximum power coefficient regions across blockage ratio. The coalescing trend shown in Figure 5.40 (right) from applying the analogy between correcting for a flat plate normal to the freestream to that of an equivalent frontal area of a Savonius rotor normal to the freestream direction as provided by Maskell and adopted by Alexander, in the current research $m$ values have been extrapolated from Figure 5.32, this provides a very effective end-result, reducing the performance of the 8% rotor model successfully into the region of a much smaller sub-scale rotor model.

*Figure 5.40 – Power Curves for 3-Blade Savonius Rotors at 60mph Freestream*
*(Left) Uncorrected data, (Middle) Pope Correction and (Right) Maskell Method Correction*
Chapter 6 – Conclusions & Further Work

A good foundation to base further testing and implementation of modified and improved existing blockage methodologies for static testing has been provided for application to dynamic wind tunnel models with a possible further application to dynamic flapping wing and rotating bluff-bodies being tested in restricted flow domains. The goal remains in quantifying a blockage correction to apply to rotating bluff-body models in closed test-section, low-speed wind tunnel testing.

Firstly, the performance characteristics of the sample VAWT concepts were obtained through a campaign of dynamic and static loading of the rotors under varying wind tunnel freestream conditions. The next phase involved static wall pressure measurements taken along the test-section sidewalls to provide a comprehensive pressure signature database of test models under varying freestream conditions and RPM’s in an attempt to provide a blockage correction with the ability to incorporate dynamic effects (TSR). Wake characteristics produced by the same Vertical-Axis Wind Turbine concept have been investigated at different physical scales in an attempt to provide some guidance on the scaling of the combined effects on blockage with supporting flow visualizations. The results suggest that the precise critical point at which blockage causes a departure from the expected results has not been absolutely identified. Operating models of 2 and 3.5% solid blockage there are no evident issues due strictly to blockage. Results suggest at 8 and 10% the area-ratio would cause some difference in results due to large pressure drops and below a certain wind speed the curves no longer coalesce. There is evidence of an adequate upstream test-section but inadequate length downstream for the
asymptotic condition. However this has not yet been validated with flow visualization due to restricted FOV downstream. Correlations of pressure coefficient as a function of TSR have been provided and their susceptibility to wind speed and wind tunnel longitudinal location has been observed forward and aft the rotors. It is the ultimate aim of this study to quantify the shift in efficiency curves and define a trend behind shifting efficiencies upon a functional dependency of solid-body flow interaction, wind tunnel speed and wake constriction due to wind tunnel wall interference.

It was found that wake constriction for a bluff-body has a stronger influence from model rotation than from freestream conditions and the following conclusions have been considered:

- Assessment of the Pope Correction [22] concluded that derived formula for velocity increments do not effectively account for wake blockage, however the method reduces peak power coefficients effectively.

- Wall-Pressure-Method (WPM) adapted from Hackett-Lilley & Wilsden [37] provides a logical trend in severity of corrections. Correlated pressure coefficient techniques show a correction decrease with increasing wind speeds and increasing RPM. This supports earlier pressure signature results. However, the method originally applied by Hackett, assumes that the pressure signatures are more likely to be driven by drag forces and that an application to a domain not involving correcting drag forces could be problematic. It was also concluded that the test set-up applies steady-state pressure transducers for recording the pressure differentials; this was a limitation of the facility. The author recognizes the periodicity of the wake of the rotors and that it can be assumed the pressure signatures obtained in the testing phase have been based on averaged pressure signatures due to the steady-state and non-transient pressure transducers employed, these
are additional factors for the Wall-Pressure-Method being unsuccessful at correcting for
models creating periodic wake and dynamic blockage variations.

- Corrections have been assessed based on an adapted Maskell Method [27, 28, 29] for
correcting large bluff-body shapes. Special attention has been focused on the analogy
supplied by Alexander [29] of comparing the corrections used for a Flat-Plate normal to
the freestream have a strong similarity with corrections required for a Savonius Rotor
occupying an equivalent frontal area. The derivation of a corrected velocity based on this
method, produced data revealing strong coalescing trends, a result that strongly shows
characteristics of curves collapsing when plotting normalized coefficients. Further testing
would be ideally suited to verifying tip-speed-ratio influences in the semi-empirical $m$
term used in Maskell’s theory and an additional investigation into partitioning the
Maskell correction into its solid and wake counterparts by observing which elements of
the semi-empirical $m$ equation is driven by each type of blockage.

For future testing of VAWTs of this concept, it would be logical, following results of this
study that for closed test-section wind tunnels to be aware of a deleterious effect caused by wake
interaction and model rotation effects and that application of an adapted Maskell Method should
supersede using a Pope correction for VAWT testing. In order to precisely recommend a
maximum area-ratio to adopt with closed test-section experiments, further work is required to
assess if corrections can be achieved successfully and accurately with existing blockage
techniques proposed in this study to fully incorporate dynamic conditions.

Additional studies are highly suggested for investigating possible correlations between
blockage ratio and induction factor, providing supplemental driving forces for influences
affecting blockage testing for wind turbine devices which are intrinsically designed to slow down
the velocity of the approaching wind speed.

99
Thus, the relationship commonly assumed in the wind turbine literature between power coefficient and induction factor could provide interesting similarities between power coefficient and severity of velocity change (a by-product of induction factor) in the current study.

Additionally, further assessment of the Maskell Method measuring drag forces on the test models would provide a logical focus for further studies for experimentally calculating the empirical $m$ term commonly used and ultimately provide an update to incorporate dynamic tip-speed-ratio effects.
References


2 Twenty First Century Energy: http://www.tfcenergy.com


Ashill, P. R., Weeks, D. J., “A method of determining wall interference corrections in solid-wall tunnels from measurements of static pressure at the walls,” AGARD CP-335, (1982)


31 Hackett, J. E., Cooper, K., R., “Extensions to Maskell’s theory for blockage effects on bluff bodies in a closed wind tunnel”, The Aeronautical Journal, pp 409-418, August, (2001)


34 Glauert, H.: “Wind Tunnel Interference on Wings, Bodies, and Airscrews.” R&M no. 1566, British A.R.C., (1933)


48  Magtrol: http://www.magtrol.com
49  Interface: http://www.interfaceforce.com
50  New Way Air Bearings: http://www.newwayairbearings.com
52  Aerolab: http://www.aerolab.com
54  New Wave: http://www.new-wave.com
56  Cooke Corporation: http://www.cookecorp.com
Appendix A

Definitions of Horizontal Buoyancy & Blockage


**Horizontal Buoyancy:** “This refers to a variation of static pressure along the test section when no model is present. It is nonzero in many wind tunnels. It produces a drag force analogous to the hydrostatic force on objects in a stationary fluid in a uniform gravitational field. It may produce a significant effect in the thrust direction for some short-section free-jet configurations. This should not be confused with static pressure variation along the test section that is induced by the presence of a test article. There is a possible interaction of the two gradients in some cases of sufficiently large test articles. This effect may be considered as a non-uniformity of flow in the streamwise direction but is induced by the lateral boundaries.

**Solid Blockage:** “The ratio of the “frontal area” of an article to the stream cross-sectional area is effectively zero in most actual operations. In wind tunnel tests, this ratio reflects the relative size of the test article and the test section. It is usually chosen in the range of 0.01 – 0.10 with 0.05 being typical. An effect of this ratio being finite is that the surface stresses are larger than for the corresponding free-air condition in the case of a closed test section and smaller for an open jet. The effect is greater at a given value of the ratio for the closed test section than for the open jet. This effect is represented by considering the ‘blockage’ to produce an effective
change in oncoming flow speed or dynamic pressure. This representation to a first order assumes no change in the distribution of the surfaces stresses as a result of the finite area ratio. This assumption is obviously not valid for “large” values of the blockage.

**2D Solid Blockage:** “The presence of the tunnel walls confining the flow around a model in the test section reduces the area through which the air must flow as compared to free-air conditions and hence, by continuity and Bernoulli’s equation, increases the velocity of the air as it flow in the vicinity of the model. This increase of velocity, which is approximated as constant over the model for customary model sizes, is called solid blockage”.

**Wake Blockage:** “This effect is a result of the finite size of a body wake and is somewhat similar to solid blockage. It is more complicated because the size of the wake is itself a function of the body shape and the ratio of the wake area to the tunnel area. The magnitude of the correction for wake blockage increases with an increase of wake size, which corresponds to an increase in drag. In a closed test section wake blockage increases the measured drag. Wake blockage is frequently considered negligible with an open test section, since the airstream is then free to expand. Actually it is more free to expand than in an infinite stream.”

**2D Wake Blockage:** Any real body without suction-type boundary layer control will generate a wake that will have a mean velocity lower than the free stream. According to the law of continuity, the velocity outside the wake in a closed tunnel must be higher than the free stream in order that a constant volume of fluid may pass through each cross section. The higher the velocity in the main stream has, by Bernoulli’s principle, a lowered pressure, and this lowered pressure, arising as the boundary layer (which later becomes the wake) grows on the model, puts the model in a pressure gradient, and results in a velocity increment at the model.
Appendix B

Deriving Maskell’s Method for Flat Plates

Following Maskell’s derivation process [27] and the overview covered in ESDU [4], using Figure 3.1, a surface 1, represents a plane normal to the freestream direction, upstream of the influence of the flat plate and surface 2 is bounded by the rear surface of the plate, the wake boundary and a plane normal to the freestream directions at the position of maximum separation – bubble area, this provides the following relationship:

\[ D + p_z B = \int_A (p_1 + \rho u_1^2) \, dy \, dz - \int_{A-B} (p_2 + \rho u_2^2) \, dy \, dz \quad (B.1) \]

Applying Bernoulli’s equation and Conservation of Momentum:

\[ p_1 + \frac{1}{2} \rho u_1^2 = p_2 + \frac{1}{2} \rho u_2^2 \quad (B.2) \]

Substituting the Equation B.1 into B.2:

\[ D + p_z B = \int_B (p_1 + \frac{1}{2} \rho u_1^2) \, dy \, dz + \int_A \frac{1}{2} \rho u_2^2 \, dy \, dz - \int_{A-B} \frac{1}{2} \rho u_2^2 \, dy \, dz \quad (B.3) \]

Maskell assumes: Surface 1, \( p_1 \) and \( u_1 \) are equal to the undisturbed freestream \( p_\infty \) and \( V_\infty \). Representing the mean value of \( u_2 \) as \( U_2 \), at Surface 2, \( u_2 = U_2 + u'_2 \), thereby, the following terms are now neglected: \( \int_{A-B} u_2' \, dydz \) and \( \int_{A-B} \frac{1}{2} u_2'^2 \, dydz \) producing an updated Equation B.3 as:

\[ D = (p_\infty - p_s)B = \frac{1}{2} \rho V_\infty^2 (A + B) - \int_{A-B} \frac{1}{2} \rho u_2^2 \, dy \, dz \quad (B.4) \]

For Continuity of Mass Flow, \( AV_\infty = (A - B)U_2 \) giving:

\[ D = -(p_s - p_\infty)B + \frac{1}{2} \rho V_\infty^2 \left[ A + B - \frac{A^2}{A - B} \right] \quad (B.5) \]
Displaying in Coefficient Form:

\[ C_D = -C_{ps} \frac{B}{S} - \frac{B^2}{(A-B)S} \]  \hspace{1cm} (B.6)

As part of Maskell’s method, Equation B.6 is simplified using a semi-empirical term \( m \):

\[ C_D = -m \left[ C_{ps} + \left( \frac{m(S/A)}{1 - m(S/A)} \right) \right] \]  \hspace{1cm} (B.7)

Whereby \( m = B/S \), the term \( m \) is formulated by:

\[ m = \frac{C_D(S/A) - C_{ps} - \sqrt{(C_D(S/A) - C_{ps})^2 - 4C_D(1 - C_{ps})(S/A)}}{2(1 - C_{ps})(S/A)} \]  \hspace{1cm} (B.8)

Maskell provides values for the term \( m \) from experimental data taken from four square flat plates up to 4.5% Blockage Ratio’s. Subsequently Maskell confirmed the principle of Invariance of the wake geometry from these experiments giving, \( m_f = m \).

In the limit when the models have very small areas compared to the wind tunnel cross-sectional area:

\[ S \ll A, \quad S/A \rightarrow 0, \quad C_{D_f} = -m_f C_{psf} \]  \hspace{1cm} (B.9)

Combining Equations B.7 and B.9 and taking, \( m_f = m \):

\[ \frac{C_D}{C_{Df}} \frac{C_{ps} + \left( \frac{m(S/A)}{1 + m(S/A)} \right)}{C_{psf}} = \frac{C_{ps} - 1 + \left( \frac{1}{1 - m(S/A)} \right)}{C_{psf} - 1 + 1} \]  \hspace{1cm} (B.10)

Maskell assumes the flow pattern is invariant under constraint in order to produce term \( \varphi \), ratio of confined flow Force Coefficients to unconfined flow Force Coefficients, e.g. \( C_D/C_{Df} \)

\[ \frac{C_D}{C_{Df}} = \frac{C_{ps} - 1}{C_{psf} - 1} = \left( \frac{V_\infty + \Delta V_\infty}{V_\infty} \right)^2 = \varphi \]  \hspace{1cm} (B.11)

Equation B.10 reduces to:

\[ \varphi = \frac{C_D}{C_{Df}} = \frac{1}{1 - m(S/A)} \]  \hspace{1cm} (B.12)

Cowdrey [28] re-derived Maskell’s method without the wake distortion effect for 3-D bodies that lie in their own wakes (leading-edge separation). Cowdrey has shown that the constant-base-
pressure assumption was not required and produced an updates to Equation B.12, which extends the derivation to incorporate correcting Dynamic Pressure which does not depend on the measured drag, although still requiring the semi-empirical constant $m$ that is a function of body geometry:

$$\varphi = \left( \frac{C_{Du}}{C_{D\infty}} \right) = \frac{q_c}{q_u} = \frac{1}{1 - m(S/A)}$$

Alexander [29, 30] has extended the above derivation by applying it to correcting Savonius Rotors, firstly, by simplifying the Blockage Correction to incorporate velocity terms, by equating terms in the dynamic pressure’s:

$$\left( \frac{q_c}{q_u} \right) = \left( \frac{1}{2} \rho_{air} \frac{V_c^2}{V_u^2} \right) = \left( \frac{V_c^2}{V_u^2} \right)$$ \hspace{1cm} (B.14)

Alexander has experimentally determined the semi-empirical term $m$ for Savonius Rotors by measuring drag forces from a Savonius Rotor in closed test-section wind tunnels and comparing drag to an equivalent area of a flat plate normal to the freestream, provides, Figure B.1 for extrapolating the $m$ term and insertion into the following Blockage Correction for velocity:

$$\varphi = \left( \frac{C_{Du}}{C_{D\infty}} \right) = \frac{q_c}{q_u} = \left( \frac{V_c^2}{V_u^2} \right) = \frac{1}{1 - m(S/A)}$$ \hspace{1cm} (B.15)

Where:

- $V_c$ is the corrected wind velocity
- $V_u$ is the undisturbed wind velocity
- $S$ is the flat plate or Savonius maximum frontal area
- $A$ is the wind tunnel working section cross sectional area
- $V$ is the undisturbed wind velocity
- $m = \left( \frac{B}{S} \right)$ extrapolated value from Fig. 3
- $B$ is the wake area normal to wind
For small values of blockage ratio, \((S/C \leq 0.045)\) Maskell gives \(m = 3.15\) (constant value).

Alexander suggests that due to restriction on the wake by the tunnel walls at high S/C values, the value of \(m\) falls, reaching a value close to 2.0 for \(S/C = 0.3\) (30% Blockage).

*Figure B.1 – Flat plates and rotors relationship of \(m\) vs. \(S/C\) [29]*
Appendix C

Deriving Power Coefficient

Applying theory from references [3, 47], where it is stated that Bernoulli’s equation under steady conditions, the total energy in the flow, comprising kinetic energy, static pressure energy and gravitational potential energy, remains constant provided no work is done on or by the fluid, this it has been shown for a unit volume of air:

\[ \frac{1}{2} \rho U^2 + P + \rho g h = \text{constant} \quad (C.1) \]

Providing the upstream relationship as:

\[ \frac{1}{2} \rho_\infty U_\infty^2 + \rho_\infty g h_\infty = \frac{1}{2} \rho_{\text{downstream}} U_{\text{downstream}}^2 + P_{\text{downstream}} + \rho_{\text{downstream}} g h_{\text{downstream}} \]

Following these relationships the force or power extracted from the air can be given as

\[ \text{Power} = FU_{\text{downstream}} = 2 \rho A_{\text{downstream}} U_\infty^2 a(1 - a)^2 \quad (C.2) \]

Defining Power Coefficient:

\[ C_P = \frac{\text{Power extracted}}{\text{Power available}} = \frac{\text{Power extracted}}{\frac{1}{2} \rho U_\infty^2 A_{\text{downstream}}} \quad (C.3) \]

According to the Betz limit ‘the maximum achievable value of power coefficient’ named after Albert Betz the German aerodynamicist states that the maximum value of \( C_P \) occurs:

\[ \frac{dC_P}{da} = 4(1 - a)(1 - 3a) = 0 \quad (C.4) \]

Giving a value of Induction Factor, \( a = \frac{1}{3} \). To date of writing, there has been no wind turbine design capable of exceeding this power coefficient maximum:

\[ C_{P\text{max}} = 16/27 = 0.593 \quad (C.5) \]
Appendix D

Deriving Pressure Coefficient from Euler’s Equations

Ashill and Keating [53] provide a derivation of pressure coefficient from the basis of flow physics, within the following derivation process it has been tailored to extract and calculate tunnel wall interference from static pressure measurements.

Firstly, let \( x \) be distance in the streamwise direction and \( y \) the distance along the wall in the direction normal to \( x \). For a flat or planar wall Euler’s equations for the flow at the edge of the boundary layer may be written as

\[
(U + u) \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x} \quad (D.1a)
\]

\[
(U + u) \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y} \quad (D.1b)
\]

Here the pressure \( p \) is taken to be that at the wall using Prandtl’s classical assumption for boundary layers and \( u \) and \( v \) are velocities in the \( x \) and \( y \) directions. Noting that

\[
C_{pr} = \frac{p - p_\infty}{\frac{1}{2} \rho U^2} \quad (D.2)
\]

Where suffix \( \infty \) refers to conditions far upstream of the model, Equations E.1a & E.1b may be rewritten for incompressible flow as

\[
(1 + \varepsilon) \frac{\partial \varepsilon}{\partial x} + \delta \frac{\partial \varepsilon}{\partial y} = -\frac{1}{2} \frac{\partial C_p}{\partial x} \quad (D.3)
\]

\[
(1 + \varepsilon) \frac{\partial \delta}{\partial x} + \delta \frac{\partial \delta}{\partial y} = -\frac{1}{2} \frac{\partial C_p}{\partial y} \quad (D.4)
\]

Where: \( \varepsilon = u/U \) and \( \delta = v/U \)
It can be shown that Equations E.3 & E.4 are hyperbolic in nature, with the two characteristics: the lines, \( x = \text{constant} \) and the streamlines of the edge flow defined by

\[
y - \int_{\delta}^{0} \frac{\delta}{\varepsilon} \, dx = \text{constant.} \tag{D.5}
\]

Except in the most extreme cases, for example, when a model is close to the wall, the streamlines are closely aligned with the \( x \) direction, and so numerical integration of equations may safely be performed in the specified Cartesian coordinates. Otherwise, integration in the streamwise direction is best performed along the streamline characteristics, the shape of which has to be determined as the solution proceeds downstream. To solve the equations it is necessary to know the initial conditions at an \( x \) station far upstream of the model as well as the side-edge boundary conditions. The former may be taken as \( \varepsilon = 0, C_p = 0 \) and, for a rectangular working section, the latter is taken as \( \delta = 0 \). The equations reduce to a parabolic form along lines where: \( \delta = 0 \), such as at a line of symmetry, for example, at the centerline of the roof or floor of the working section when a symmetrical centered model has a vertical plane of symmetry. For this case it is only necessary to know the initial conditions. As a simple illustration of the latter case, Ashill considers an incompressible flow at a line of symmetry. Equation E.3 reduces to

\[
(1 + \varepsilon) \frac{d\varepsilon}{dx} = -\frac{1}{2} \frac{dC_{pr}}{dx} \tag{D.6}
\]

Integrating from far upstream with respect to \( x \), where the initial conditions are \( \varepsilon = 0 \) and \( C_{pr} = 0 \), Equation E.6 reduces to:

\[
(1 + \varepsilon)^2 = 1 - C_{pr} \quad \text{or} \quad (1 + u/U_\infty)^2 = 1 - C_{pr} \tag{D.7}
\]

This can be re-written in a velocity increment form for application to the current study, a method adopted by Fitzgerald [35]:

\[
\frac{\Delta u}{U} = \left(1 - \Delta C_{pr}\right)^{1/2} - 1 \tag{D.8}
\]
Which is recognized as Bernoulli’s equation for two-dimensional, incompressible flow. For incompressible flow (It should be noted that, strictly, the use of the Euler equations rather than the linearized Bernoulli equation to determine the streamwise component of velocity at the wall is only justified for flows at low Mach number. Therefore, the use of the incompressible flow approximation is consistent with this restriction).
## Appendix E

### Blockage Correction Factors [4]

(Left) $\varepsilon$ and $m$ for Two-Dimensional Flow  

<table>
<thead>
<tr>
<th>Body shape</th>
<th>$\varepsilon$, $m$, maximum $S/A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat plate</td>
<td>$\varepsilon = 0.96$; $m = 1.85$; for $S/A \leq 0.25$</td>
</tr>
<tr>
<td>Rectangular prism</td>
<td>$\varepsilon = 1.11 + 0.04a/b$ for $0.2 &lt; a/b &lt; 0.6$; $\varepsilon = 1.11 - 0.14a/b$ for $0.75 &lt; a/b &lt; 3$; for $S/A \leq 0.20$</td>
</tr>
<tr>
<td>Equilateral wedge</td>
<td>$\varepsilon = 0.98$; $m = 2.06$; for $S/A \leq 0.20$</td>
</tr>
<tr>
<td>Circular cylinder, sub-critical flow</td>
<td>$m = 1.38$; for $S/A \leq 0.20$</td>
</tr>
<tr>
<td>Lattice, open area ratio $= 0.5$</td>
<td>$m = 1.30$; for $S/A \leq 0.10$</td>
</tr>
</tbody>
</table>

(Right) $\varepsilon$ and $m$ for Three-Dimensional Flow  

- Flat plate, centre-mounted
  - $\varepsilon = 2.84 - 0.07H/b$ and $m = 3.20 - 0.05H/b$ for $H/b \leq 0.20$; for $S/A \leq 0.10$.
- Flat plate, surface-mounted
  - $\varepsilon = 2.37; m = 2.84$ for $H/b \leq 3$; for $S/A \leq 0.10$. For $H/b > 3$ use value for centre-mounted plate of $2H/b$ aspect ratio.
- Near-circular, triangular flat plates, $H/b < 1$
  - Use value for rectangular plate of same $H/b$; for $S/A \leq 0.15$.
- Rectangular block
  - Use value for flat plate of same $H/b$ provided flow restriction does not occur, $a/b \leq 2.5$; for $S/A \leq 0.10$. 
