Effects of turbulence on the separating-reattaching flow above surface-mounted, three-dimensional bluff bodies

Abul Fahad Akon
The University of Western Ontario

Supervisor
Professor Gregory Alan Kopp
The University of Western Ontario

Graduate Program in Mechanical and Materials Engineering
A thesis submitted in partial fulfillment of the requirements for the degree in Doctor of Philosophy
© Abul Fahad Akon 2017
Abstract

Investigations of separated and reattaching flows over three-dimensional bluff bodies in turbulent boundary layers are important because of the large aerodynamic loads that these flows cause. For example, roofs of low-rise buildings are vulnerable to this kind of wind loading. Turbulence in the upstream flow affects the pressure distributions and the mean size of separation bubbles formed on bluff body surfaces. Whereas a number of studies have focussed on two-dimensional separation bubbles and surface pressures, a comprehensive understanding of the surface pressures and the separating-reattaching flows in relation to the turbulence in the incident boundary layers for surface-mounted, three-dimensional bluff bodies have not been developed. In this study, the effects of turbulence intensities and length scales in the approaching boundary layer flows on surface-mounted three-dimensional bluff bodies are investigated. Particle Image Velocimetry measurements of the roof separation bubble, along with surface pressure measurements, were taken for six different upstream conditions. The results were analyzed to understand the responses of the separating-reattaching flows, along with the mean and fluctuating pressure fields, to the turbulence properties in the approach flow.

The mean reattachment length is found to be unaffected by the turbulence length scales (over the range examined), whereas turbulence intensity affects reattachment lengths significantly. The normalized mean pressure distribution was found to be a function of both the mean reattachment length and the upstream turbulence intensity. A method of estimating the mean reattachment lengths of the roof separation bubble from measured surface pressures and roof height turbulence intensity is proposed. Separating-reattaching flows exhibit self-similarity of the mean flow field, whereas the fluctuating flow fields do not exhibit similarity. The distributions of surface pressure fluctuations respond to both turbulence intensity and length scales in the upstream flow. Surface pressures near the leading edge are observed to be highly correlated with the velocity field just outside the separated shear layer near the leading edge and with the area-averaged swirling strength under the whole separation bubble. For surface-mounted three-dimensional bluff bodies,
these findings provide some valuable insights on the fundamental features of the separated-reattaching flows and surface pressures.

Keywords

Bluff body aerodynamics; separated flows; reattaching flows; atmospheric boundary layers; turbulence; low-rise buildings; building aerodynamics.
Co-Authorship Statement

In this integrated article thesis, the articles are co-authored. I performed the experiments with valuable feedback from my supervisor, Professor Gregory A. Kopp. In the process of obtaining the experimental results, I was responsible for conducting the experiments and primarily responsible for analysing the experimental data with direction provided by Professor Kopp. While I prepared the first drafts for each of the manuscripts, Professor Kopp contributed to the final versions by providing important comments, helping to refine ideas, and by providing recommendations for editing of the text.
Acknowledgments

First of all, I would like to express my sincere gratitude to my supervisor, Professor Gregory Alan Kopp, who has been very supportive throughout the completion of the thesis with his patience, valuable knowledge, feedback and directions while allowing the room to work in my own way. This has helped me a lot to develop my learning skills. I am thankful to him for providing me the opportunities to present my work in different international conferences. Professor Kopp has always been available for constructive discussions on my research and different other topics. Almost every time I met him, whether for my research or not, I learnt something new. Despite intense rivalry between the soccer teams we support, I enjoyed every bit of the discussions we had about soccer. I truly am grateful for all the supports provided by him. I would also like to express my deepest appreciation and gratitude to my advisory committee members, Professor Kamran Siddiqui and Professor Eric Savory. They have helped the progression of the thesis by providing new ideas and constructive suggestions. Their curiosities in this research project made me think about different aspects of the research outcome.

I acknowledge the support of Mr. Robart Nicolas Pratt, who helped me a lot to get familiarized with the TR-PIV system. I am also grateful to Mr. Gerry Dafoe and Mr. Anthony Burggraaf for their technical supports during the experiments. I would like to thank Dr. Chowdhury Md. Jubayer and Mr. Chieh-Hsun Wu, who were always open for technical discussions related to this research.

The first year of my PhD program is memorable as Eshita and I got married. For successful completion of my thesis, she has made every compromise and sacrifice required throughout this long journey. She has always been by my side accepting me as I am, boosting my mental strength and helping me to keep focus on my work. I express my affectionate appreciation to my parents. From my childhood till now, they have been sacrificing their happiness to make me happy.
Table of Contents

Abstract ........................................................................................................................................... i
Co-Authorship Statement .................................................................................................................. iii
Acknowledgments ............................................................................................................................. iv
Table of Contents ............................................................................................................................. v
List of Tables ..................................................................................................................................... ix
List of Figures ..................................................................................................................................... x
List of Appendices .......................................................................................................................... xvi
Nomenclature ................................................................................................................................... xvii
Chapter 1 ......................................................................................................................................... 1
1 Introduction ..................................................................................................................................... 1
  1.1 Background ............................................................................................................................... 1
  1.2 Thesis Objectives ..................................................................................................................... 7
  1.3 Thesis Layout ........................................................................................................................... 7
References ......................................................................................................................................... 10
Chapter 2 ......................................................................................................................................... 12
2 Mean pressure distributions and reattachment lengths for roof-separation bubbles on low-rise buildings\(^1\) ........................................................................................................... 12
  2.1 Introduction ............................................................................................................................ 12
     2.1.1 Two-dimensional bluff bodies ....................................................................................... 12
     2.1.2 Surface-mounted, three-dimensional bluff bodies ......................................................... 15
  2.2 Experimental Set-Up .............................................................................................................. 16
     2.2.1 Building Models and Pressure Measurements ............................................................... 16
     2.2.2 Terrain simulation ............................................................................................................ 18
     2.2.3 Particle Image Velocimetry measurements ................................................................. 21
2.3 Mean reattachment lengths .................................................. 23
  2.3.1 Reattachment lengths from the PIV data ................................... 23
  2.3.2 Mean reattachment lengths from pressure data .......................... 25
  2.3.3 Effects of aspect ratio ...................................................... 30
  2.3.4 Discussion ...................................................................... 33
2.4 Mean pressure distribution ......................................................... 35
2.5 Discussion ............................................................................ 37
2.6 Conclusions ......................................................................... 39
References .................................................................................. 41

Chapter 3 ..................................................................................... 44

3 The effects of turbulence on the mean and fluctuating velocity fields within the
separated-reattaching flow of a surface-mounted prism ......................... 44

3.1 Introduction .......................................................................... 44
3.2 Normalization of the velocity field ............................................ 47
  3.2.1 Variable normalization ...................................................... 47
  3.2.2 Vertical axis normalization and thickness of the separation bubbles ...... 48
  3.2.3 Axial measurement locations ............................................. 49
3.3 Results and discussions .......................................................... 50
  3.3.1 Mean streamwise velocity ($U$) ............................................ 50
  3.3.2 Mean vertical velocity component ($V$) ................................. 53
  3.3.3 Mean velocity magnitude, $|V|$ ........................................... 59
  3.3.4 Streamwise Reynolds normal stresses ($u'u'$) ......................... 62
  3.3.5 Vertical velocity fluctuations, $v'v'$ .................................... 70
  3.3.6 Reynolds shear stress, $-u'v'$ ............................................. 75
  3.3.7 Fluctuations in velocity magnitude, $|V'|$ ................................. 81
  3.3.8 Turbulence energy budget ................................................ 85
3.3.9 Growth of the separated shear layer............................................................. 92
3.4 Discussions on the results .............................................................................. 95
3.5 Conclusions..................................................................................................... 97
References ........................................................................................................... 99

Chapter 4 ............................................................................................................. 101

4 Effects of boundary layer turbulence on roof-surface pressure fluctuations for a
three-dimensional prism ...................................................................................... 101

4.1 Introduction ..................................................................................................... 101
4.2 Surface pressure fluctuations under the separation bubble ......................... 106
4.3 Effects of flow parameters on surface pressure fluctuations ......................... 112
4.4 Examination of Separated-Shear-Layer Dynamics ......................................... 114

4.4.1 Identification of the instantaneous positions of the separated shear
layer....................................................................................................................... 114

4.4.2 Influence of shear layer movement on surface pressures ...................... 115
4.5 Influence of velocity gusts on surface pressure fluctuations ......................... 117
4.6 Influence of vortices on surface pressure fluctuations ................................ 122
4.7 Combined effects of both velocity gust and vortices on surface pressure
fluctuations.......................................................................................................... 127
4.8 Discussions on the findings .......................................................................... 132
4.9 Conclusions ................................................................................................... 136
References .......................................................................................................... 138

Chapter 5 ............................................................................................................. 140

5 Conclusions and Recommendations ................................................................. 140

5.1 Conclusions ................................................................................................... 140
5.2 Recommendations for future work ................................................................. 142
References .......................................................................................................... 144

Appendices ......................................................................................................... 145
Appendix A: Measurement Uncertainties .......................................................... 145
  A.1 Uncertainties in the measurements of $C_{p_{ref}}$ ........................................ 145
  A.2 Uncertainties in the measurements of velocity by Cobra probe .............. 146
  A.3 Uncertainties in the measurements of velocity ratio ($T_R$) and $C_p$ ......... 147
Appendix B: Velocity Profiles ............................................................................ 149
Appendix C: Correlation coefficients of velocities and $\lambda$ with surface pressures ..... 154
Appendix D: Statistical distributions of $|V|_{CA}/U_{r,LE}$ ....................................................... 164
Appendix E: Permissions for reuse of copyrighted material ............................. 165
Curriculum Vitae ................................................................................................ 170
List of Tables

Table 2.1: Model details. .................................................................17

Table 2.2: Characteristics of the atmospheric Boundary Layer Simulations........21

Table 2.3: Mean reattachment lengths, \(X_r\), obtained via PIV measurements for Building-1. .................................................................24

Table 2.4: Estimated reattachment lengths, \(X_r\), for Building-1 and Building-2 using the fit from Figure 2.8. .................................................................28

Table 2.5: Flow characteristics and estimated \(X_d/H\) for buildings from the NIST dataset (Ho et al., 2005). All dimensions are in full-scale; the roof slope is 1:12 unless otherwise stated. \(y_o\) for open and suburban terrains are 0.03m and 0.3m respectively. .................29

Table 2.6: Symbols used for NIST data in Figure 2.11. ..............................30

Table 3.1: Maximum thickness of the mean separation bubble......................49

Table 3.2: Axial locations considered for velocity profile investigations. .............49

Table 4.1: Axial locations of \(C_p\)’max.........................................................109

Table 4.2: Skewness in \(-C_p\) at pressure tap 2. ..........................................114

Table 4.3: Correlation coefficients of \(|V|_{CA}/U_{LE}\) with \(\lambda_{CA}\)..................129
List of Figures

Figure 2.1: Schematic diagram of a separating and reattaching flow over a sharp-edged, elongated, two-dimensional bluff body placed in uniform upstream flow. .......................... 13

Figure 2.2: Schematic diagram of the building models, location of the pressure taps, and coordinate system. .................................................................................................................. 17

Figure 2.3: Velocity and turbulence intensity profiles for upstream conditions “3S” and “3L” ........................................................................................................................................ 20

Figure 2.4: Velocity spectra at $y = H_1$ for the (a) streamwise, $u$, and (b) vertical, $v$, components. ........................................................................................................................................ 21

Figure 2.5: Photograph of experimental set-up, including the arrangement of the Particle Image Velocimetry components and the locations of the fields of view. .............................. 22

Figure 2.6: Mean streamlines around Building-1 for upstream condition 2L, along with the distribution of reduced pressure coefficients ($C_p^*$) on the roof. .............................. 24

Figure 2.7: Distribution of reduced pressure coefficient ($C_p^*$) for Building-1. ............ 27

Figure 2.8: Variation of the reduced pressure coefficient, $C_p^*$, at the reattachment point with turbulence intensity, $I_u$. ........................................................................................................ 28

Figure 2.9: Variation of mean reattachment length with aspect ratio for NIST data for roof slopes of (a) 1:12 and (b) 1:48. ............................................................................................................. 32

Figure 2.10: Variation of mean reattachment length, corrected to infinite aspect ratio, ($X_r/h_1)_{AR=\infty}$, as a function of streamwise turbulence intensity. A polynomial fit through the 2D bluff-body data is also shown for clarity................................................................. 34

Ruderich & Fernholz (1986), Case-1
Ruderich & Fernholz (1986), Case-2
polynomial fit through the Hudy et al. (2003) and Ruderich & Fernholz (1986)
NIST data legends are listed in Table 2.6.

Figure 2.12: Variations of minimum mean pressure coefficient with turbulence intensities. A polynomial fit through the dataset of Building-1 and Building-2 are shown on the figure with a dashed curve.

Figure 2.13: Streamwise velocity spectra for $H = 4m$ and $U = 30m/s$ and various integral scales and turbulence intensities.

Figure 3.1: Schematic representation of the axial locations and the reference locations used for variable normalization.

Figure 3.2: Contours of $U/U_r$ for upstream conditions (a) 1S, (b) 1L, (c) 2S (d) 2L (e) 3S and (f) 3L.

Figure 3.3: Vertical profiles of $U/U_r$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$.

Figure 3.4: Horizontal distribution of $U_r/U_{r,LE}$ at $H_r$.

Figure 3.5: contours of $V/V_{r,LE}$ for upstream conditions (a) 1S, (b) 1L, (c) 2S (d) 2L (e) 3S and (f) 3L.

Figure 3.6: Vertical profiles of $V/V_r$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$.

Figure 3.7: Horizontal distribution of $V_r/V_{r,LE}$ at $H_r$.

Figure 3.8: Vertical profiles of $V/U_{r,LE}$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$.

Figure 3.9: Contours of $|V|/|V_r|$ for upstream conditions (a) 1S, (b) 1L, (c) 2S (d) 2L (e) 3S and (f) 3L.
Figure 4.5: Distribution of standard deviation of pressure coefficients ($Cp'$) under the separation bubble for Building-2. ................................................................. 108

Figure 4.6: Comparisons of the distributions of $Cp'$ with simple Quasi-Steady theory predictions for Building-1 model................................................................. 110

Figure 4.7: Comparisons of the distributions of $Cp'$ with simple Quasi-Steady theory predictions for Building-2........................................................................ 111

Figure 4.8: Statistical distribution of $-Cp/Cp'$ at $x=0.22H_1$ for upstream condition (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L. ................................................................. 113

Figure 4.9: Instantaneous position of the separated shear layer and velocity contours of (a) streamwise and (b) vertical velocity components. ........................................... 115

Figure 4.10: Conditionally averaged positions of separated shear layer at $x=0.22H_1$....116

Figure 4.11: Contours of correlation coefficients of $|v|$ with surface pressures at $x=0.22H_1$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L. ...................... 119

Figure 4.12: Variations of conditionally-averaged pressure coefficients ($<Cp>/Cp_{mean}$) at $x=0.22H_1$ with area-averaged velocity magnitude in the highly correlated region ($|V|_{CA}/U_{r,LE}$)........................................................................................................ 121

Figure 4.13: Instantaneous contour of swirling strength and the position of the separated shear layer. ........................................................................................................ 124

Figure 4.14: Contours of correlation coefficients of $\lambda$ with surface pressures at $x=0.22H_1$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L. ......................... 125

Figure 4.15: Variations of $<Cp>/Cp_{mean}$ at $x=0.22H_1$ with area-averaged swirling strength in the highly correlated region ($\lambda_{CA}$)......................................................................................................... 127

Figure 4.16: Statistical distributions of $\lambda_{CA}$ with surface pressures at $x=0.22H_1$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L......................... 128
Figure 4.17: Variation of $<Cp>/C_{p\text{mean}}$ with both $|V|_{CA}/U_{r,LE}$ and $\lambda_{CA}$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L. The contours indicate the levels of $<Cp>/C_{p\text{mean}}$. ...............................................................130

Figure 4.18: Variation of $<Cp>/C_{p\text{mean}}$ with $|V|_{CA}/U_{r,LE}$ at two different levels of $\lambda_{CA}$ for upstream condition 3S. ........................................................................................................131

Figure 4.19: Variation of $<Cp>/C_{p\text{mean}}$ with $|V|_{CA}/U_{r,LE}$ at two different levels of $\lambda_{CA}$ for upstream condition 3L. ........................................................................................................131

Figure 4.20: Variation of $<Cp>/C_{p\text{mean}}$ with $|V|_{CA}/U_{r,LE}$ at two different levels of $\lambda_{CA}$ for all six upstream conditions. ........................................................................................................132

Figure 4.21: Fluctuating velocity vector field ($<u'>$ and $<v'>$) and contour of $<|V|/U_{r,LE}>$ during extremely high suctions at $x=0.22H_1$ for upstream conditions (a) 3L and (b) 1S. 135

Figure 4.22: Fluctuating velocity vector field ($<u'>$ and $<v'>$) and contour of $<\lambda>$ during extremely high suctions at $x=0.22H_1$ for upstream conditions (a) 3L and (b) 1S........135
List of Appendices

Appendix A: Measurement Uncertainties..................................................145
Appendix B: Velocity Profiles.................................................................149
Appendix C: Correlation Coefficients of $|v|$ and $\lambda$ with Surface Pressures.....154
Appendix D: Statistical Distributions of $|V|_{CA}/U_{r,LE}$................................164
Appendix E: Reuse of Copyrighted Material............................................165
## Nomenclature

### Notations and symbols

- $|V|, |v|$ Mean and instantaneous velocity magnitudes
- $|V'|$ Standard deviation of velocity magnitudes
- $|V|_A$ Area-averaged velocity magnitude
- $|V|_{CA}$ Area-averaged velocity magnitude in highly correlated area
- $C_p$ Pressure coefficient referenced to model height
- $C_p^*$ Reduced pressure coefficient
- $C_p'$ Standard deviation of pressure coefficient
- $C_p_{mean}$ Mean pressure coefficient
- $C_p_{min}$ Minimum pressure coefficient
- $C_p_{ref}$ Pressure coefficient referenced to 1.5m above the ground
- $D$ Thickness of two-dimensional bluff bodies
- $H$ General symbol for heights of model/low-rise building
- $H_1$ Height of surface mounted prism model (Building-1)
- $H_2$ Height of surface mounted prism model (Building-2)
- $h_f$ Model height above stagnation streamline
- $H_r$ Reference height
- $I_u$ Turbulence intensity
- $J_e$ Jensen number
- $L$ Length
- $L_x$ Integral length scale
- $T_{b,\text{max}}$ Maximum mean thickness of the separation bubble
- $T_x$ Uncertainties in the measurement of any variable ‘$x$’
- $u^*$ Friction velocity
- $U, V$ Mean streamwise and vertical velocity components
- $u, v,$ Instantaneous streamwise and vertical velocity components
- $u'u'$ Reynolds normal stress in streamwise direction
$u'v'$  Reynolds shear stress

$\nu'\nu'$  Reynolds normal stress in vertical direction

$V_H$  Velocity at model height

$V_R$  Velocity at a height 1.5m above the ground

$W$  Width

$x$  Horizontal distance

$X_r$  Mean reattachment length

$y$  Vertical distance

$y_0$  Roughness length

$\lambda$  Swirling strength

$\lambda_A$  Area-averaged swirling strength

$\lambda_{CA}$  Area-averaged swirling strength in highly correlated area

$\sigma_x$  Standard deviation in any variable ‘x’

Abbreviations

AR  Aspect Ratio
LE  Leading edge
NIST  National Institute of Standards and Technology
TR-PIV  Time Resolved Particle Image Velocimetry
Chapter 1

1 Introduction

1.1 Background

Separation of flow from the surface of bluff bodies is a fundamental phenomenon in the area of bluff body aerodynamics. For bluff bodies with sharp edges, flow separation can occur under a large variety of conditions; even at low Reynolds numbers (Tritton, 1988). For flows over sharp-edged bluff bodies, there is a point on the windward face where the flow stagnates, i.e., the flow is brought to rest. The streamline connected to the stagnation point is known as the stagnation streamline. Away from the stagnation point, a boundary layer is formed on the windward surface. When these boundary layers reach a (sharp) edge, they separate from the body and move downstream. The separated flow often bends towards the surface and reattaches on the surface, if the bluff body is sufficiently long in the streamwise direction. The point on the bluff body surface where the mean flow reattaches is known as the reattachment point. Upstream of the reattachment point, back flow occurs near the surface and recirculates to form a highly turbulent recirculation region known as separation bubble. The distance between the separation point and the mean reattachment point is defined as the reattachment length while the streamline connecting the separation point and the reattachment point is known as the separating – reattaching streamline. For two-dimensional bluff bodies placed in a uniform flow, there are boundary layers both above and below the stagnation streamline, which behave similarly. However, for surface-mounted bluff bodies, the flow beneath the stagnation streamline forms an additional recirculating region at the base of the bluff body due the presence of the solid boundary. For surface-mounted, three-dimensional bluff bodies this recirculating flow follows the sides of the bluff body as the flow moves downstream (Martinuzzi & Tropea, 1993).

Investigation of the separated flow near the leading edge of the bluff bodies has received special attention by researchers since there are large pressure fluctuations on the surface
beneath the separation bubble. Examples of this phenomenon are the generation of large uplifting loads on the roofs of low-rise buildings or on roof-mounted structures such as solar panels. This is one of the major causes of the damage during windstorms (Saathoff & Melbourne, 1997). Flow properties in the separated flow region and the aerodynamic forces acting on a bluff body depend largely on the characteristics of the upstream flow. Researchers have shown that, for two-dimensional bluff bodies placed in uniform upstream flow, the structure of the separation bubble, pressure fluctuations underneath the separation bubble, the length of the separation bubble and forces exerted on the bluff bodies are strongly dependent on the turbulence parameters in the free stream (Gartshore, 1973; Hillier & Cherry, 1981). Free stream turbulence properties affecting the separation bubble properties are turbulence intensities and the turbulent scales. Turbulence intensity is a measure of the velocity fluctuations in the flow while the turbulent integral length scale is a measure of the size of the energy containing eddies in the flow.

Many of the engineered structures which experience the effects of separated and reattaching flows are three-dimensional and mounted on earth’s surface (e.g., low-rise buildings). The flow around these structures is caused by the highly turbulent atmospheric surface layer. Whereas there have been a number of studies focusing the separating – reattaching flows over sharp-edged, two-dimensional bluff bodies placed in uniform flows with comparatively lower levels of turbulence, separated and reattaching flows over three-dimensional bluff bodies in high turbulent boundary layer flows have received comparatively less attention in literature. There are some similarities in the flow features and surface pressures of two-dimensional and three-dimensional bluff bodies. However, as will be discussed in the following chapters, there are significant differences as well. Due to the numerous practical applications, flow features and surface pressures on surface-mounted three-dimensional bluff bodies (e.g., buildings) are required to examine in detail. Also, the influences of turbulence properties in the incident boundary layer flows on the flow features and aerodynamic loads on surface-mounted three-dimensional bluff bodies need to be investigated as the turbulence properties in the incident boundary layer flows vary over a wide range, depending on location and other structures in the surroundings.
The lack of significant experimental data for separation bubbles on bluff bodies in highly turbulent streams is perhaps due to the challenges of conventional flow measurement techniques (e.g., Pitot tubes, hot-wire anemometry) in highly turbulent and recirculating flow regions (Agelinchaab & Tachie, 2008). Since many conventional techniques are either point measurement or qualitative (e.g., flow visualization) flow measurement techniques, it has been difficult to capture reliable quantitative information of the flow features in the whole separation bubble. In addition, one-dimensional computational models fail to predict flow separation (Sherry et al., 2010). Hence, it is necessary to employ modern experimental flow measurement techniques, Particle Image Velocimetry (PIV) being but one example, to measure the separating – reattaching flows with high accuracy.

Whereas a number of studies have focussed on surface pressure measurements on sharp-edged bluff bodies (two-dimensional bluff bodies in particular) in a variety of upstream condition, few studies have involved measurements of the flow fields in relation to surface pressures; especially for surface-mounted, three-dimensional bluff bodies. For surface-mounted, three-dimensional bluff bodies the effects of different incident flow conditions on the velocity field and surface pressures together have received less attention in literature. Hence, the relationships between upstream turbulence properties with separated and reattaching flow fields and surface pressures for surface-mounted three-dimensional bluff bodies have not been systematically developed.

Various features of the separation bubble formed on the surface of two-dimensional bluff bodies in uniform upstream flows, including surface pressure distributions, have been investigated in the literature. The experimental studies of Hillier & Cherry (1981), Kiya & Sasaki (1983a), Nakamura & Ozono (1987) and Saathoff & Melbourne (1997) reveal some of the basic features of two-dimensional separation bubbles over a wide range of upstream turbulence intensity and length scale, when the results are considered together. The experimental studies mentioned here demonstrate that the mean reattachment lengths of the two-dimensional separation bubble in uniform upstream flows are dependent on the turbulence intensity in the upstream flow. Increasing turbulence intensities in the upstream causes a reduction in the mean size of the separation bubble while turbulence...
length scales do not alter the mean size of the separation bubble. However, Nakamura & Ozono (1987) speculate, based on surface mean pressure measurements, that for large values of turbulence length scales in the upstream (relative to the size of the body) the mean reattachment lengths may be affected. Similarly, mean pressure distributions under the two-dimensional separation bubble are observed to be dependent on turbulence intensity. Increasing turbulence intensity is observed to increase the magnitudes of mean suction, cause quicker recovery, and move the location of the maximum mean suction closer to the leading edge (Hillier & Cherry, 1981; Kiya & Sasaki, 1983a; Nakamura & Ozono, 1987; Saathoff & Melbourne, 1989). Turbulence length scales affect surface mean pressures only at large values due to relatively slow fluctuations in the incident flow, leading the surface mean pressure distributions to become similar to the distributions for smooth upstream flow (Bearman & Morel, 1983; Nakamura & Ozono, 1987). However, for surface-mounted three-dimensional bluff bodies, even though some of the basic flow features were studied (e.g., Castro & Robins, 1977 and Martinuzzi & Tropea, 1993), less information is known about the effects of turbulence properties in the boundary layer upstream on the distributions of surface mean pressures and the reattachment lengths.

Investigations of the flow field in and around the separation bubbles are of fundamental importance as the unsteady flows over bluff bodies give rise to unsteady aerodynamic loads on bluff bodies. The features of the flow field in and around the two-dimensional separation bubble have been studied extensively. For example Kiya & Sasaki (1983a and 1985), Cherry et al. (1984), Castro & Haque (1987), Saathoff & Melbourne (1997) have investigated the flow around two-dimensional bluff bodies placed in uniform smooth and comparatively low turbulence upstream flows. The existence of the Kelvin-Helmholtz vortices in the separated shear layer, the pairing of these vortices and impingement on the surface near the reattachment point has been well established in these studies. The surface pressures at the reattachment point are primarily characterized by the impingement of these vortices, whereas surface pressures close to the leading edge are affected by shear layer flapping (Kiya & Sasaki, 1985). The flow fields over two-dimensional bluff bodies are also affected by the turbulence properties in the upstream. Upstream flow interacts with the separated flow to alter the characteristics of the separated shear layer. Hillier &
Cherry (1981) and Bearman & Morel (1983) describe that turbulence in the upstream has the potential to alter the separated flow in two different ways: (i) causing earlier transition of the separated shear layer to turbulent, and (ii) by interacting with the turbulent structures present in the separated shear layer. Lander et al. (2016) show that turbulence on the stagnation streamline causes a bypass transition in the separated shear layer. In addition, Saathoff & Melbourne (1997) observe that turbulence intensity in the upstream causes the separated shear layer to roll-up closer to the leading edge as a result of increased perturbations in the separated shear layer. They also found the increased strengths of the shear layer vortices as turbulence intensity in the upstream is increased.

There are some similarities in the flow characteristics of surface-mounted bluff bodies with two-dimensional bluff bodies placed in uniform upstream flows. For example, Sherry et al. (2010) observe the presence of shear layer flapping in the separated flow over a forward facing step. However, there are significant dissimilarities as well. The main difference is the presence of a recirculating region near the base of the surface-mounted bluff body which, for three-dimensional bluff bodies, follows the sides of the bluff body, forming a large horseshoe-like vortex (Martinuzzi & Tropea, 1993), which, for forward facing step, moves over the step occasionally (Pearson et al., 2013). Similar to two-dimensional bodies in uniform upstream flows, separated flows over surface-mounted three-dimensional bluff bodies also respond to upstream turbulence properties. Whereas few studies are observed to measure the flow field over three-dimensional surface-mounted bluff bodies (e.g., Kim et al., 2003) in order to extract some of the basic flow features, the effects of turbulence properties in the boundary layer upstream has not been investigated in detail. A more comprehensive experimental study is required to be performed in a variety of boundary layer upstream conditions in order to better understand the responses of the mean and fluctuating flows over surface-mounted three-dimensional bluff bodies to the turbulence properties in the approach flow.

It is understood that turbulence in the upstream interacts with the separated flows to alter the surface pressures (both mean and fluctuating). However, the effects upstream turbulence on fluctuating pressures are different than mean pressures. For two-dimensional bluff bodies in uniform upstream flows, an increment in turbulence intensity
increases the magnitude of surface pressure fluctuations and causes the location of maximum fluctuations to occur closer to the leading edge (Hillier & Cherry, 1981; Kiya & Sasaki, 1983b; Saathoff & Melbourne, 1997). Unlike mean pressures, increased turbulence length scales in the upstream also cause the magnitude of surface pressure fluctuations to increase (Hillier & Cherry, 1981; Saathoff & Melbourne, 1997). The mechanism by which the surface pressures are affected by turbulence in the upstream has been studied by few researchers. Upstream turbulence intensity is observed to cause earlier transition of the shear layer to turbulence causing the movement of the location of maximum fluctuations closer to the leading edge (Hillier & Cherry, 1981; Bearman & Morel, 1983). As speculated by Saathoff & Melbourne (1997), larger integral scales in the upstream allow more time for the shear layer vortices to grow in size and strength, causing higher pressure fluctuations. In comparison to two-dimensional bluff bodies in uniform upstream flows, fewer numbers of studies are present in literature focusing the effects of upstream turbulence properties on surface pressure fluctuations for three-dimensional surface-mounted bluff bodies. Some Quasi-Steady theory based models have been developed to predict the surface pressures on surface-mounted three-dimensional bluff bodies (e.g., Richards & Hoxey, 2004). However, these models are inaccurate for predicting the surface pressures in the regions of separated flow (Richards & Hoxey, 2004).

Whereas a number of studies have focussed on measuring the aerodynamic loads on the three-dimensional surface-mounted bluff bodies exposed to different boundary layer flows, a complete understanding of the dependence of pressure fluctuations on upstream turbulence properties has not been developed. Due to the immense practical importance, the pressure fluctuations on the surfaces of surface-mounted three-dimensional bluff bodies and the dependence of these fluctuations on turbulence properties in the boundary layer incident flows are required to be investigated in detail. The key parameters involved in characterizing the surface pressure fluctuations on surface-mounted three-dimensional bluff bodies need to be identified. The responses of these parameters to the turbulence properties in the incident boundary layer flows also need to be investigated in order to acquire a better knowledge about the surface pressure fluctuations on surface-mounted three-dimensional bluff bodies.
1.2 Thesis Objectives

The primary objective of this thesis is to develop a comprehensive understanding of the effects of boundary layer turbulence on the separating-reattaching flows above surface-mounted three-dimensional bluff bodies and roof surface pressures. A detailed examination of the roof surface mean pressures, mean reattachment lengths, mean flow fields, fluctuating flow fields and surface pressure fluctuations is performed in relation to turbulence intensity and length scale in the upstream boundary layer flows in order to achieve the objective. The dominant flow parameters in the separating-reattaching flows involved in characterizing the pressures on surface-mounted three-dimensional bluff bodies will be identified and their responses to the turbulence properties in the upstream flow will also be investigated to fulfill the objective.

1.3 Thesis Layout

The experimental study presented here in an Integrated Article format involves Time-Resolved PIV measurements of the separating – reattaching flows formed on the roof-surface of a surface-mounted, three-dimensional, low-rise-shaped bluff body with synchronized surface pressure measurements for six different upstream, turbulent boundary layer conditions. Additionally, only surface pressure measurements on the roof-surface of a second surface-mounted three-dimensional bluff body, exposed to same six boundary layer upstream conditions, were also taken. The results were analyzed to reveal various features of the separation bubbles and the roof-surface pressures. The influences of the turbulence properties in the approaching boundary layer flows on these features were also investigated.

In Chapter 2, the mean reattachment lengths along with the distributions of mean surface pressures in the separation bubble, and their dependence on the turbulence properties in the incident flow, are presented and discussed. Along with these data, mean surface pressure data along the roof centre-line from the NIST aerodynamic database were utilized to propose a method of estimating the mean reattachment length on the roof of low-rise buildings from measured surface pressures and roof height turbulence intensity and building aspect ratio. In this chapter, the characteristics of the upstream boundary
layer properties, the details of experimental models and the experimental techniques used in the present experimental study are also presented. The literature relevant to the mean flow is also reviewed in this chapter, rather than separating the literature review into a distinct chapter.

Chapter 3 contains the detailed statistical analysis of the mean and fluctuating flow fields over a three-dimensional surface-mounted bluff body, including a review of the relevant literature. The results presented in this chapter reveal various characteristics of the mean flow along with the turbulence statistics of the flow field in and around the separated and reattaching flows. The results were used to identify the significant features and characteristics of the mean and fluctuating velocities in the flow fields in and around the separated and reattaching flow.

The instantaneous and conditionally-averaged fluctuations in the surface pressures, and the effects of the upstream turbulence properties on these, are presented and discussed in Chapter 4, including a review of the relevant literature. These results are compared to similar data from two-dimensional bluff bodies in uniform incident flow. Synchronized surface pressure data and velocity field data in and around the separated flow regions were utilized to determine the key parameters involved in conditionally-averaged surface pressure fluctuations on the surfaces of three-dimensional surface-mounted bluff bodies. How these parameters respond to upstream turbulence properties in characterizing the surface pressure fluctuations is examined.

Conclusions from the current work and recommendations for future research are presented in Chapter 5.

In summary, some of the fundamental features of the separated and reattaching flows on the roof surface of surface-mounted, three-dimensional, low-rise-building-shaped bluff bodies have been investigated along with the surface pressure distributions in order to develop relationships between the upstream turbulence properties, surface pressures and flow fields. It is hoped that the present work will contribute to this area of fluid mechanics and wind engineering to better understand the responses of the surface
pressures (both mean and fluctuating) and the velocity fields in separated and reattaching flow to the incident turbulence in atmospheric boundary layer flows.
References


Chapter 2

2 Mean pressure distributions and reattachment lengths for roof-separation bubbles on low-rise buildings

2.1 Introduction

Separating and reattaching flows on the surface of sharp-edged, elongated bluff bodies are of fundamental importance to the aerodynamic loads for these shapes. The flow near the leading edge of such bodies has received special attention by researchers since there are large pressure fluctuations on the surface beneath the separating – reattaching flow (Lyn & Rodi, 1994; Saathoff & Melbourne, 1997). These cause large uplifting loads (e.g., on the roofs of low-rise buildings, Tieleman et al., 1996) or can interact with the trailing edge, leading to the flow instabilities such as vortex streets in the wake (e.g., on long-span bridges, Taylor et al., 2014). In the present chapter, the focus is on the mean pressure field beneath separation bubbles on surface-mounted prisms in turbulent boundary layers. Figure 2.1 shows a schematic representation of the terminologies used to describe separating-reattaching flows over sharp-edged, elongated, bluff bodies. In particular, the point on the bluff-body surface where the mean flow reattaches is known as the reattachment point, the distance between the separation point and the reattachment point is defined as the reattachment length.

2.1.1 Two-dimensional bluff bodies

Ruderich and Fernholz (1986) investigated the nature of the mean pressure field beneath separating – reattaching flows and found similarity of the distribution when the mean pressure coefficients are normalized by the minimum pressure such that the reduced pressure coefficient is:

\[ C_p^* = \frac{(C_{p_{mean}} - C_{p_{min}})}{1 - C_{p_{min}}} \]  

(2.1)

\[ \text{A version of this chapter has been published in “Journal of Wind Engineering and Industrial Aerodynamics”. Copyright release is provided in Appendix E.} \]
Figure 2.1: Schematic diagram of a separating and reattaching flow over a sharp-edged, elongated, two-dimensional bluff body placed in uniform upstream flow.

where $C_{p_{\text{mean}}}$ is the mean pressure coefficient, $C_{p_{\text{min}}}$ is the minimum value of the mean pressure coefficient on the surface under the separation bubble, while streamwise distance, $x$, is normalized by the reattachment length, $X_r$. Eq. (2.1) was first proposed by Roshko & Lau (1965). The experimental results of Hudy et al. (2003) were found to be similar to the results of Ruderich and Fernholz (1986). These authors found that, for a smooth (i.e., low turbulence) free stream, irrespective of Reynolds numbers, body shape, blockage ratio, over a large range of reattachment lengths, the distribution of reduced pressure coefficients fall on the same curve. However, the reasons for the particular shape of the curve, or how surface pressures arise, were not explained.

Researchers have shown that the flow structure of separation bubbles, the surface pressure and aerodynamic forces on the body beneath the separation bubble, and the reattachment length are strongly dependent on the turbulence parameters in the upstream flow (e.g., Gartshore, 1973; Hillier & Cherry, 1981). Upstream properties affecting the separation bubble properties are turbulence intensities, $I_u = \frac{\sigma}{U}$ (where, $\sigma$ is the standard deviation of the velocity fluctuations and $U$ is the streamwise mean velocity), and the turbulent scales, particularly the integral scales, $L = \int_0^{\infty} r(\xi) \, d\xi$, relative to the dimensions of the body, where $r(\xi)$ is the correlation coefficient of the velocities separated by some distance, $\xi$. Usually the integral scale, $L_x$, formed by the streamwise
velocities separated in the streamwise direction, $x$, is considered to be the most important integral scale.

Hot-wire measurements in the separation bubble by Hillier & Cherry (1981) for different turbulence intensities and integral length scales show that higher levels of the free-stream turbulence intensity causes a reduction in the reattachment length, but that the reattachment length tends to be insensitive to the integral scales. Kiya & Sasaki (1983) and Saathoff & Melbourne (1997) also found similar trends in the reduction of the reattachment length with turbulence intensity. These authors suspected that the higher levels of entrainment in the turbulent flow cases are responsible for the smaller reattachment lengths. These studies were performed on two-dimensional bluff bodies of thickness, $D$, in uniform flow over a range of turbulence intensities up to 15% and length scales, $L_x/D$, up to 2.1. However, the effects of length scales on mean reattachment lengths for larger ranges of turbulence length scales have not yet been investigated. Nakamura & Ozono (1987) investigated the mean surface pressures under the separated and reattaching flows for an extended range of integral length scales ($L_x/D = 0.4$ to 24), focussing on the maximum turbulence-intensity levels investigated by Hillier & Cherry (1981) and Kiya & Sasaki (1983). Their investigation indicated an independence of the surface mean pressure distribution at smaller ratios of integral scale to body thickness. However, for higher ratios of integral scales to body thickness, they observed dependence of the mean surface pressures to the integral scales. These results indicate that larger integral scales may have some effect on the mean reattachment length, particularly when the turbulence intensity is fixed.

Perhaps the most investigated property of separation bubbles is the surface pressure field because of the practical importance. The properties of free-stream turbulence are known to significantly affect the mean pressure field. For example, Hillier & Cherry (1981) have shown that for smooth flow in the free stream, the maximum value of the mean suction coefficient is smaller in magnitude and occurs further away from the leading edge. Increased levels of free-stream turbulence tend to increase the maximum values of the mean suction coefficients near the leading edge to a significant extent, while moving the location of the maximum closer to the leading edge. However, pressure recovery for the
smooth upstream case is slower than for the turbulent case because of the larger reattachment lengths in smooth flow.

Integral scale effects on the mean pressure appear to be more complex. For example, Hillier & Cherry (1981) do not observe any effects of the turbulent integral scales, at fixed levels of turbulence intensity, up to values of \( L_x/D = 1.95 \). Kiya & Sasaki (1983) and Saathoff & Melbourne (1989) make similar observations. However, the study by Nakamura & Ozono (1987) found that there is dependence of mean pressures over a large range of integral length scales (i.e., over the range of their study with \( L_x/D = 0.4 \) to 24. For values of \( L_x/D \) up to 2, these authors found similar results to those obtained by Hillier & Cherry (1981). However, at larger integral length scales, the mean pressure distribution begins to behave more like those with smooth upstream flow conditions. The reason for this is that the free-stream fluctuations become relatively slower, with reduced fluctuating energy at the smaller-scales. Thus, these relatively slow fluctuations in the upstream flow are unable to influence the mean flow and the mean pressure over the bodies (Bearman & Morel, 1983; Nakamura & Ozono, 1987) and the combination of both scale and intensity are important parameters for the character of the separation bubble.

2.1.2 Surface-mounted, three-dimensional bluff bodies

Many of the engineering applications of bluff body aerodynamics are for buildings, i.e., surface-mounted, three-dimensional prisms, placed in the atmospheric boundary layer. In this case, there are both relatively high turbulence levels along with high levels of mean shear. However, similar flow patterns occur with flow separations, mean flow reattachment and separation bubbles. Despite the similarities in these flow patterns, there are also some significant differences. The main difference arises due to the streamwise vorticity generated in the separated shear layer from the sides of the body (Martinuzzi & Tropea, 1993). For example, Martinuzzi & Tropea (1993) show that, in addition to a recirculation region on the top surface, there is also a recirculation region formed in front of the body (a cube in their particular case). This recirculation region in front of the body extends around the sides of the body, forming a “horseshoe” vortex (Castro & Robins, 1977; Martinuzzi & Tropea, 1993). The aspect ratio of the body is also observed to alter the reattachment lengths. Martinuzzi & Tropea (1993) and Kim et al. (2003) both report
shorter reattachment lengths for three-dimensional, surface-mounted prisms than those observed for two-dimensional bodies. This is attributed to a mean flow that has a higher acceleration at separation for two-dimensional bodies than for three-dimensional bodies of similar thickness.

So, in contrast to two-dimensional, sharp-edged bluff bodies, the effects of turbulence on surface-mounted bodies have not been systematically investigated. The objective of the present chapter is to examine the relationships between upstream turbulence conditions on the mean surface-pressure distributions and mean reattachment lengths for relatively low (i.e., with heights less than the plan dimensions), surface-mounted prisms. In order to do so, pressure measurements on two prisms were taken for six different upstream, boundary-layer flows. For one of the prisms (which we will call Building-1), Particle Image Velocimetry (PIV) measurements were made, synchronized with surface pressure measurements. In addition, pressure data from the NIST Low-Rise Building Aerodynamic Database (Ho et al., 2005) are utilized.

### 2.2 Experimental Set-Up

#### 2.2.1 Building Models and Pressure Measurements

The dimensions of the two models used in the current study are presented in Table 2.1. Building-1 is a scaled version of the Texas Tech University “WERFL” Building, which is described in Levitan & Mehta (1992a, b). For this model, a row of 9 pressure taps on the roof surface along the centreline of the building was used. The height of Building-1 is denoted as $H_1$. A schematic diagram of the models is provided in Figure 2.2, which also defines the coordinate system. Building-2 is a more generic building, but was previously used in the study by Pratt & Kopp (2014). This was constructed with 96 pressure taps along the centreline. The height of Building-2 is denoted as $H_2$. Both models were placed in the high-speed test section of Boundary Layer Wind Tunnel II at the University of Western Ontario, with the wind direction normal to the wide face for each of the two buildings.

The pressure taps were connected to the pressure scanners by a tubing system, which had a flat frequency response up to about 200 Hz; a complete description of the tubing system
can be found in Ho et al. (2005). Pressure measurements were taken for approximately 180 seconds at a frequency of 1108 Hz after being low pass filtered at 200 Hz. The pressure measurement system records pressure coefficients referenced to the dynamic pressure at a height of 57 inches (~1.5m) from the wind tunnel floor (in a uniform and low turbulence region). These pressure coefficients were converted to obtain the pressure coefficients referenced to dynamic pressure at model height using

\[ C_p = Cp_{ref} \left( \frac{V_R}{V_H} \right)^2 \]  

(2.2)

<table>
<thead>
<tr>
<th>Model Label</th>
<th>Height, H [cm]</th>
<th>Width, W [cm]</th>
<th>Length, L [cm]</th>
<th>Number of pressure taps</th>
<th>Aspect Ratio, AR (=W/H)</th>
<th>Reynolds number, Re (( \rho U H H/\mu ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building-1</td>
<td>7.8</td>
<td>27.5</td>
<td>18.4</td>
<td>9</td>
<td>3.5</td>
<td>~35,000</td>
</tr>
<tr>
<td>Building-2</td>
<td>24</td>
<td>75.1</td>
<td>53.3</td>
<td>96</td>
<td>3.1</td>
<td>~110,000</td>
</tr>
</tbody>
</table>

Figure 2.2: Schematic diagram of the building models, location of the pressure taps, and coordinate system.
Here, $C_{p_{\text{ref}}}$ is the pressure coefficient referenced to the dynamic pressure at the reference height, $V_R$ is the velocity at the reference height, and $V_H$ is the velocity at the model height. Ho et al. (2005) demonstrated that pressure coefficients referenced to the dynamic pressure at the model height, which is common wind engineering practice, show the least variability. The uncertainty in the measurements of $Cp$ is dependent on the measurement uncertainties of $C_{p_{\text{ref}}}$, $V_R$ and $V_H$. The maximum value of measurement uncertainty in the pressure coefficients referenced to the model height dynamic pressure was observed to be less than 7%, which is controlled by the uncertainty for the square of the velocity ratio in Eq. (2.2). The procedures and calculations associated with the measurements of $Cp$ are provided in Appendix A.

2.2.2 Terrain simulation

In wind-tunnel experiments of surface-mounted bluff bodies in deep turbulent boundary layers, characterizing the approaching turbulent boundary layer is important. Such experiments are challenging since proper simulation of atmospheric boundary layers in wind tunnels requires either long and large test sections or small models with small details (Tieleman, 2003). In most boundary layer wind tunnels, the turbulence in the oncoming flow is generated by controlling the heights of roughness elements distributed on the floor of the test section, along with additional turbulence-generating elements, such as spires and barriers, which are usually placed near the entrance of the test section. These roughness elements and turbulence generating elements are chosen in such a way that the desired velocity profiles and turbulence characteristics are achieved. Often the roughness elements are varied in height along the length of the section in order to obtain desired characteristics. During a change in the roughness, an internal boundary layer develops as the flow adjusts. Since it takes time for the turbulence to come into equilibrium with the new roughness (see Tieleman, 2003; Beljaars et al. 1983), two distinct regions in the boundary layer are formed with the internal layer growing at slower rate than the outer layer (e.g., Tieleman, 2003). Flow parameters obtained from the lower part of the profile are representative of the local flow characteristics and parameters obtained from the outer part of the profile are representative of flow characteristics over a longer distance upstream (Tieleman, 2003).
Boundary Layer Wind Tunnel II at University of Western Ontario has a high-speed test section that is 3.4 m wide with a nominal height of 2.4 m. The surface of the wind tunnel is provided with surface roughness blocks, which have maximum heights of 200 mm. The high-speed test section is 39 m long from inlet to the centre of the turntable. For the present experiments, a total of six different upstream conditions were developed. These are made up of three different ground roughness configurations, each of which is repeated with and without a 0.38m tall barrier at the test-section inlet. Velocity profile measurements were taken using a Cobra Probe (TFI, Model No. 900311) at a sampling frequency of 1250Hz. The three upstream conditions with the 0.38m tall barrier are labelled as 1L, 2L and 3L while the three without any barrier at the entrance to the test section are labelled as 1S, 2S and 3S, i.e., the number in these labels indicates the terrain roughness while “L” indicates the presence of the barrier (and a Larger integral scale) and “S” indicates no barrier (and a Smaller integral scale).

In the velocity profiles for the present experiments, two distinct profile regions are observed because of the presence of the barrier and changes in block heights along the test section length. For all of the upstream conditions, the outer layers were found to be located within a range of heights above the tunnel floor not exceeding 1m from the floor. The velocity measurements only up to the heights of the internal boundary layers are considered and the profile parameters could be obtained by fitting the mean velocity measurements into the logarithmic velocity profile,

\[
U = \frac{u^*}{K} \ln(y) - \frac{u^*}{K} \ln(y_o)
\]  

(2.3)

where \(U\) is the mean velocity at height, \(y\), from the wind tunnel floor, \(u^*\) is the friction velocity, \(K = 0.41\) is the von Karman constant and \(y_o\) is the aerodynamic roughness height. Representative velocity and turbulence intensity profiles are shown in Figure 2.3, in this case for terrain conditions 3S and 3L. It is observed that while both velocity profiles are similar, there is some increase in the turbulence intensity when the barrier is present. However, for some of the other upstream conditions considered here, the roof-height turbulence intensities were not found to be altered significantly due to presence of
the barrier. Table 2.2 provides roof-height turbulence intensities and aerodynamic roughness lengths for each of the six profiles. As can be seen, the inclusion of the barrier increases the integral length scale without substantially altering the turbulence levels or the roughness length, although there are some variations.

Figure 2.4 shows plots of the velocity spectra for the streamwise and vertical velocity components at height, $H_1$. These plots confirm that the changes in integral length scale depend primarily on the barrier, while the turbulence intensities and spectral content depend primarily on the terrain roughness, with the barrier increasing the integral scales by up to 100%. The Jensen number, $Je = H/y_o$, is usually used as the scaling parameter for low-rise buildings (Holmes & Carpenter, 1990). Using the measured $y_o$ values, $Je$ values for the current experiments are indicated in Table 2.2.

![Graph](image)

**Figure 2.3:** Velocity and turbulence intensity profiles for upstream conditions “3S” and “3L”.
Figure 2.4: Velocity spectra at $y = H_1$ for the (a) streamwise, $u$, and (b) vertical, $v$, components.

Table 2.2: Characteristics of the atmospheric Boundary Layer Simulations

<table>
<thead>
<tr>
<th>Terrain</th>
<th>Barrier Length, $y_0$ [m]</th>
<th>Roughness</th>
<th>$I_u$</th>
<th>$L_x$</th>
<th>$J_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L$</td>
<td>0.38</td>
<td>0.00013</td>
<td>14</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>$S$</td>
<td>0</td>
<td>0.00014</td>
<td>13</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>$L$</td>
<td>0.38</td>
<td>0.00014</td>
<td>17</td>
<td>13</td>
<td>11</td>
</tr>
<tr>
<td>$S$</td>
<td>0</td>
<td>0.00027</td>
<td>17</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>$L$</td>
<td>0.38</td>
<td>0.0111</td>
<td>27</td>
<td>25</td>
<td>12</td>
</tr>
<tr>
<td>$S$</td>
<td>0</td>
<td>0.0014</td>
<td>26</td>
<td>22</td>
<td>7</td>
</tr>
</tbody>
</table>

2.2.3 Particle Image Velocimetry measurements

In order to find the mean reattachment lengths on the upper surface of Building-1, the Time Resolved-PIV (TR-PIV) measurements were made. The TR-PIV system has the ability to sample PIV velocity field data at a rate of 500 Hz. Olive oil is atomized, seeded in the flow and illuminated by a double-head, diode-pumped Q-switched Nd:YLF laser operating at a frequency of 1000 Hz. The average pulse energy is 22 mJ. Two 1 Mb
Photron FASTCAM-1024PCI CMOS cameras were used to capture the PIV images. A more detailed description of the TR-PIV system can be found in (Taylor et al., 2010). Two fields of view with 20% overlap, one on the upstream side and the other on the roof, were selected. Figure 2.5 shows the photograph of Building-1 placed inside the Boundary Layer Wind Tunnel, the locations of the fields of view and the arrangement of the Time-resolved Particle Image Velocimetry setup. Pressure measurements along the roof centreline were taken for Building-1 with and without placing the particle image velocimetry optics inside the wind tunnel in order to assess the effects of the particle image velocimetry optics on the flow field and surface pressures. The surface pressures were observed to be unaltered by the presence of particle image velocimetry optics inside the wind tunnel. Hence, it can be assumed that the flow fields over the model are also unaffected by the presence of the particle image velocimetry optics.

Figure 2.5: Photograph of experimental set-up, including the arrangement of the Particle Image Velocimetry components and the locations of the fields of view.
A time delay of 85µs was applied between the two images of a single image pair so that the particles did not move more than one-fourth of the intended interrogation area. A total of 80000 pairs of PIV raw images of the separated and reattaching flow were captured for each of the six upstream conditions considered in this experiment. TSI Insight 4G, a commercial image processing software package, was used to find the velocity fields, utilizing an FFT cross-correlation algorithm. Interrogation windows of 32x32 pixels with 50% overlap were used during processing the PIV raw images. The post processing on the raw vector data was done by a global standard deviation filter, followed by local mean and median filters. Spurious vectors numbered less than 5% after masking off the visible laser reflection regions and were replaced by interpolated vectors. Standard cross-correlation algorithms have a spatial uncertainty of less than approximately 0.1 pixels (Huang et al., 1997).

2.3 Mean reattachment lengths

2.3.1 Reattachment lengths from the PIV data

The PIV measurements of the flow around Building-1 were taken in order to determine the mean flow field, particularly the reattachment lengths and locations of the stagnation points. Figure 2.6 shows the mean streamlines around Building-1 for one upstream condition, 2L. From the figure it can be seen that the flow separates at the edge of the roof and reattaches downstream between 1.0 to 1.1\(H_1\). The mean reattachment points for all six upstream conditions for Building-1 were obtained by identifying the point on the roof surface where the flow changes direction (from reverse to the forward flow). The uncertainties associated with these measurements mainly arise due to lack of velocity data in the masked-off regions (because of laser reflections from the surface) and due to the resolution of the PIV measurements, which have a spacing of 0.02\(H_1\). The uncertainties in the measurements of mean reattachment lengths (\(X_r\)) due to masked off regions near the surface and vector spacing are estimated to be within a range of 3% to 5% of \(X_r\). Table 2.3 provides the mean reattachment lengths with the corresponding upstream flow properties. Note that the sizes of the reattachment lengths for the “1L” and “1S” conditions were large enough that they extended beyond the field of view of the
Figure 2.6: Mean streamlines around Building-1 for upstream condition 2L, along with the distribution of reduced pressure coefficients ($C_p^*$) on the roof.

Table 2.3: Mean reattachment lengths, $X_r$, obtained via PIV measurements for Building-1.

<table>
<thead>
<tr>
<th>Upstream Condition</th>
<th>$(I_u)_{H1}$ (%)</th>
<th>$L_x/H_1$</th>
<th>$X_r/H_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1L</td>
<td>14</td>
<td>13</td>
<td>~1.4</td>
</tr>
<tr>
<td>1S</td>
<td>13</td>
<td>6</td>
<td>~1.4</td>
</tr>
<tr>
<td>2L</td>
<td>17</td>
<td>11</td>
<td>1.05</td>
</tr>
<tr>
<td>2S</td>
<td>17</td>
<td>8</td>
<td>1.05</td>
</tr>
<tr>
<td>3L</td>
<td>27</td>
<td>12</td>
<td>0.88</td>
</tr>
<tr>
<td>3S</td>
<td>26</td>
<td>7</td>
<td>0.88</td>
</tr>
</tbody>
</table>

PIV camera. In these cases, the reattachment points were approximated by extrapolating the streamlines along the centre of the separated shear layer, which obviously increases the uncertainty for these points.
From Table 2.3, it can be seen that, for higher levels of the streamwise turbulence intensity, the mean reattachment length is smaller. For example, there is a reduction of about 35% in the reattachment length when the turbulence intensity is changed from 12% to 26% (from upstream condition “1L” to “3S”). A closer look at the data reveals that integral length scales do not significantly affect the mean reattachment length over the range examined. Noting that the spectra are similar for each terrain configuration, this result appears to be consistent with the findings of Hillier and Cherry (1981) over the limited range of tested integral scales.

In addition to the reattachment length on the roof, the location of the stagnation point on the front face of Building-1 is necessary in order to compare reattachment lengths with those from two-dimensional bluff bodies. It is the distance from the stagnation point to the roof edge that is the important geometric length scale (Hillier & Cherry (1981), Kiya & Sasaki (1983), Saathoff & Melbourne (1997)). It is observed that, irrespective of the flow details, the mean location of the front-face stagnation point is at $y = 0.65H_1$ in the current experiments. Thus, the distance from the stagnation point to the roof edge, $h_f = 0.35H$ for these surface-mounted bodies. This contrasts with $h_f = 0.5H$ for two-dimensional bodies (of total height $H$) in a uniform stream. In addition, from the present experimental results, the upstream turbulence levels and scales do not appear to have significant influence on the height of the stagnation point above the ground plane. The experimental results of Kim et al. (2003) for a surface-mounted, three-dimensional prism with a roof height turbulence level of 20% show that the location of the stagnation point on the front surface of the model is at $0.7H$ from the ground plane, indicating a reasonable consistency between the two studies.

### 2.3.2 Mean reattachment lengths from pressure data

Eq. (2.1) was first proposed by Roshko & Lau (1965) as an appropriate normalization of the pressure distribution within separation bubbles. Ruderich & Fernholz (1986) showed that, for separating – reattaching flows, irrespective of the blockage ratios and Reynolds numbers, when the reduced pressure coefficients are plotted against the distance from the leading edge normalized by the mean reattachment length, there is similarity of the profile. Using their own experimental results, along with a series of results obtained from
literature, Hudy et al. (2003) showed that there is a constant value of reduced pressure coefficient of 0.35 at the reattachment point. The datasets considered in their analysis were for two-dimensional bluff bodies with relatively long reattachment lengths (e.g., the maximum $X_r/h_f$ being 33.6 and the minimum being 4.9) and with a maximum turbulence intensity of 4\% (and the maximum Reynolds number of $3.2 \times 10^4$). For the present experiments on surface-mounted prisms, the upstream conditions have much higher turbulence intensities, ranging from 9\% to 27\% with the size of the separation bubbles being small compared to the data considered by Hudy et al. (2003). Hence, the present experiments are rather different from the data considered previously. This leads to some different outcomes, as discussed below.

Figure 2.6 depicts the distribution of the reduced pressure coefficients, $C_p^*$, as defined in Eq. (2.1) for the roof of Building-1 in upstream terrain condition 2L, along with the mean streamlines. Comparing the pressure distribution with the location of the reattachment point, it is observed that $C_p^* = 0.24$ at reattachment for this terrain configuration. Using the observed reattachment points from the PIV data, the reduced pressure coefficient, $C_p^*$, distributions are plotted versus $x/X_r$ for the six terrain configurations in Figure 2.7. It can be observed that the distributions of the reduced pressure coefficients are broadly similar between the six cases, although there are significant differences in magnitudes of the reduced coefficients. There are also significant differences when compared to the distributions found by Ruderich & Fernholz (1986) and Hudy et al. (2003) for uniform, low turbulence flow. The minimum value of the mean pressure coefficient, and of $C_p^*$, occurs near $x/X_r = 0.25$, after which the pressure recovers, with $C_p^*$ increasing to values between 0.2 and 0.3 at reattachment point. These data indicate that, at the reattachment point, the values of $C_p^*$ depend on the upstream conditions. In fact, increasing the turbulence intensity appears to reduce the value of $C_p^*$ at $x/X_r = 1$ so that it has a value of about 0.2 for $I_u = 26-27\%$, about 0.3 at $I_u = 13-14\%$, and about 0.35 in the smooth flow data of Ruderich & Fernholz (1986) and Hudy et al. (2003). Considering the distributions in Figure 2.7, it appears that the integral scales in the upstream flow do not have significant effect on the value of $C_p^*$ at the reattachment point, at least over the range tested. Thus, the normalized pressure distribution in separation bubble appears to depend significantly on the turbulence level in the free stream.
Figure 2.7: Distribution of reduced pressure coefficient ($Cp^*$) for Building-1.

Figure 2.8 shows the variation of reduced pressure coefficients at the reattachment point versus the roof-height turbulence intensities for Building-1. Included in the graph are also the results of Ruderich & Fernholz (1986) and Hudy et al. (2003) (for two-dimensional bodies in low turbulence). While the true functional variation of $Cp^*$ at $x/X_r = 1$ is unknown, it is approximated here with a linear equation, also shown on the figure. It is observed that the fit satisfactorily approximates the variation of reduced pressure coefficients at the mean reattachment point for Building-1. Using the fitted linear equation, the reattachment lengths are estimated and presented in Table 4 along with the error in the estimates. As can be seen, the errors are reasonably small and similar to the measurement uncertainty for the pressure coefficients. (It should also be noted that an extension of the linear fit nearly falls on the data of Hudy et al. (2003), which has turbulence levels of up to 4%. Further research is required to establish whether or not this is fortuitous.)

Since the errors and uncertainties from using $Cp^*$ to estimate $X_r$ appear to be reasonably small, the linear fit from Figure 2.8 is used to estimate the reattachment lengths for Building-2. Table 2.4 presents these values, which will be examined in greater detail below. In addition to the current data, the wind tunnel pressure data stored by the
Figure 2.8: Variation of the reduced pressure coefficient, $C_p^*$, at the reattachment point with turbulence intensity, $I_u$.

Table 2.4: Estimated reattachment lengths, $X_r$, for Building-1 and Building-2 using the fit from Figure 2.8.

<table>
<thead>
<tr>
<th>Upstream</th>
<th>$(I_o)_{H1}$</th>
<th>$L_o/H_1$</th>
<th>$X_r/H_1$ (error)</th>
<th>$C_p^*$ at $X_r$ Building-1 (directly measured)</th>
<th>$(I_o)_{H2}$</th>
<th>$L_o/H_2$</th>
<th>$C_p^*$ at $X_r$ Building-2</th>
<th>$X_r/H_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1L</td>
<td>14</td>
<td>13</td>
<td>1.29 (-3.9%)</td>
<td>0.27 (0.30)</td>
<td>10</td>
<td>4</td>
<td>0.31</td>
<td>1.49</td>
</tr>
<tr>
<td>1S</td>
<td>13</td>
<td>6</td>
<td>1.42 (+0.7%)</td>
<td>0.28 (0.28)</td>
<td>9</td>
<td>2</td>
<td>0.32</td>
<td>1.50</td>
</tr>
<tr>
<td>2L</td>
<td>17</td>
<td>11</td>
<td>1.09 (+1.8%)</td>
<td>0.25 (0.24)</td>
<td>13</td>
<td>5</td>
<td>0.28</td>
<td>1.12</td>
</tr>
<tr>
<td>2S</td>
<td>17</td>
<td>8</td>
<td>1.08 (+1.3%)</td>
<td>0.25 (0.24)</td>
<td>13</td>
<td>2</td>
<td>0.28</td>
<td>1.18</td>
</tr>
<tr>
<td>3L</td>
<td>27</td>
<td>12</td>
<td>0.87 (-0.5%)</td>
<td>0.21 (0.21)</td>
<td>25</td>
<td>3.5</td>
<td>0.22</td>
<td>0.62</td>
</tr>
<tr>
<td>3S</td>
<td>26</td>
<td>7</td>
<td>0.87 (-0.5%)</td>
<td>0.21 (0.21)</td>
<td>22</td>
<td>3</td>
<td>0.23</td>
<td>0.67</td>
</tr>
</tbody>
</table>

National Institute of Standards and Technology (NIST) were analyzed. This database, which is described in detail by Ho et al. (2005), contains a series of measured surface pressures building models of different heights, plan dimensions and gable-roof slopes for two different upstream terrain conditions. From the NIST dataset only the data for slope of the roof less than or equal to 1:12 (i.e., 4.8°) were extracted in order to compare with present experiments. The mean reattachment lengths were estimated based on the values provided by Figure 2.8, along with the measured roof-height turbulence intensities. These values are reported in Table 2.5 and will also be examined in greater detail below.
Table 2.5: Flow characteristics and estimated $X_r/H$ for buildings from the NIST dataset (Ho et al., 2005). All dimensions are in full-scale; the roof slope is 1:12 unless otherwise stated. $y_o$ for open and suburban terrains are 0.03m and 0.3m respectively.

<table>
<thead>
<tr>
<th>$H$ [m]</th>
<th>Plan dimensions [m x m]</th>
<th>($I_u)_H$ (open)</th>
<th>$X_r/H$, Open Terrain (estimated)</th>
<th>($I_u)_H$ (suburban)</th>
<th>$X_r/H$, Suburban Terrain (estimated)</th>
<th>$\Delta X_r/H$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>19x12</td>
<td>20</td>
<td>0.65</td>
<td>28</td>
<td>0.52</td>
<td>20.1</td>
</tr>
<tr>
<td>5.5</td>
<td>19x12</td>
<td>19</td>
<td>0.66</td>
<td>27</td>
<td>0.56</td>
<td>14.7</td>
</tr>
<tr>
<td>7.3</td>
<td>19x12</td>
<td>19</td>
<td>0.7</td>
<td>26</td>
<td>0.55</td>
<td>21.6</td>
</tr>
<tr>
<td>12.2</td>
<td>19x12</td>
<td>18</td>
<td>0.71</td>
<td>25</td>
<td>0.47</td>
<td>33.8</td>
</tr>
<tr>
<td>4.9</td>
<td>38x24</td>
<td>19</td>
<td>0.93</td>
<td>27</td>
<td>0.75</td>
<td>20.2</td>
</tr>
<tr>
<td>7.3</td>
<td>38x24</td>
<td>19</td>
<td>0.81</td>
<td>26</td>
<td>0.65</td>
<td>20.2</td>
</tr>
<tr>
<td>9.8</td>
<td>38x24</td>
<td>18</td>
<td>0.72</td>
<td>25</td>
<td>0.59</td>
<td>18.6</td>
</tr>
<tr>
<td>12.2</td>
<td>38x24</td>
<td>18</td>
<td>0.69</td>
<td>25</td>
<td>0.54</td>
<td>22.2</td>
</tr>
<tr>
<td>5.5</td>
<td>38x24 (roof slope 1:48)</td>
<td>19</td>
<td>1.11</td>
<td>27</td>
<td>0.86</td>
<td>22.4</td>
</tr>
<tr>
<td>7.3</td>
<td>38x24 (roof slope 1:48)</td>
<td>19</td>
<td>1.03</td>
<td>26</td>
<td>0.78</td>
<td>24.1</td>
</tr>
<tr>
<td>9.8</td>
<td>38x24 (roof slope 1:48)</td>
<td>18</td>
<td>0.94</td>
<td>25</td>
<td>0.72</td>
<td>23.9</td>
</tr>
<tr>
<td>12.2</td>
<td>38x24 (roof slope 1:48)</td>
<td>18</td>
<td>0.9</td>
<td>25</td>
<td>0.65</td>
<td>28.0</td>
</tr>
<tr>
<td>3.7</td>
<td>57x36</td>
<td>20</td>
<td>1.01</td>
<td>28</td>
<td>0.86</td>
<td>14.7</td>
</tr>
<tr>
<td>4.9</td>
<td>57x36</td>
<td>19</td>
<td>0.97</td>
<td>27</td>
<td>0.8</td>
<td>17.2</td>
</tr>
<tr>
<td>5.5</td>
<td>57x36</td>
<td>19</td>
<td>0.92</td>
<td>27</td>
<td>0.76</td>
<td>17.5</td>
</tr>
<tr>
<td>7.3</td>
<td>57x36</td>
<td>19</td>
<td>0.92</td>
<td>26</td>
<td>0.69</td>
<td>24.9</td>
</tr>
<tr>
<td>12.2</td>
<td>57x36</td>
<td>18</td>
<td>0.75</td>
<td>25</td>
<td>0.56</td>
<td>24.6</td>
</tr>
<tr>
<td>5.5</td>
<td>76x48</td>
<td>19</td>
<td>1</td>
<td>27</td>
<td>0.73</td>
<td>26.9</td>
</tr>
<tr>
<td>7.3</td>
<td>76x48</td>
<td>19</td>
<td>0.92</td>
<td>26</td>
<td>0.71</td>
<td>23.3</td>
</tr>
<tr>
<td>12.2</td>
<td>76x48</td>
<td>18</td>
<td>0.78</td>
<td>25</td>
<td>0.57</td>
<td>27.7</td>
</tr>
</tbody>
</table>
Table 2.6: Symbols used for NIST data in Figure 2.11.

<table>
<thead>
<tr>
<th>$H$ [m]</th>
<th>Plan dimensions [m x m]</th>
<th>Symbol in Fig. 2.11 (open)</th>
<th>Symbol in Fig. 2.11 (suburban)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>19x12</td>
<td>▼</td>
<td>▼</td>
</tr>
<tr>
<td>5.5</td>
<td>19x12</td>
<td>▼</td>
<td>▼</td>
</tr>
<tr>
<td>7.3</td>
<td>19x12</td>
<td>▼</td>
<td>▼</td>
</tr>
<tr>
<td>12.2</td>
<td>19x12</td>
<td>▼</td>
<td>▼</td>
</tr>
<tr>
<td>4.9</td>
<td>38x24</td>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>7.3</td>
<td>38x24</td>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>9.8</td>
<td>38x24</td>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>12.2</td>
<td>38x24</td>
<td>□</td>
<td>■</td>
</tr>
<tr>
<td>5.5</td>
<td>38x24 (roof slope 1:48)</td>
<td>◊</td>
<td>◆</td>
</tr>
<tr>
<td>7.3</td>
<td>38x24 (roof slope 1:48)</td>
<td>◊</td>
<td>◆</td>
</tr>
<tr>
<td>9.8</td>
<td>38x24 (roof slope 1:48)</td>
<td>◊</td>
<td>◆</td>
</tr>
<tr>
<td>12.2</td>
<td>38x24 (roof slope 1:48)</td>
<td>◊</td>
<td>◆</td>
</tr>
<tr>
<td>3.7</td>
<td>57x36</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>4.9</td>
<td>57x36</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>5.5</td>
<td>57x36</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>7.3</td>
<td>57x36</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>12.2</td>
<td>57x36</td>
<td>○</td>
<td>●</td>
</tr>
<tr>
<td>5.5</td>
<td>76x48</td>
<td>△</td>
<td>▲</td>
</tr>
<tr>
<td>7.3</td>
<td>76x48</td>
<td>△</td>
<td>▲</td>
</tr>
<tr>
<td>12.2</td>
<td>76x48</td>
<td>△</td>
<td>▲</td>
</tr>
</tbody>
</table>

2.3.3 Effects of aspect ratio

Aspect ratio, defined as the width-to-height ratio, i.e., $AR = \frac{W}{H}$, is a parameter that is also known to affect mean reattachment lengths. For example, Gu & Lim (2012) show
that for an incremental increase of the aspect ratio for surface-mounted prisms, mean suction coefficients increase and the pressure recovery is delayed. Cherry et al. (1984) found that increasing the aspect ratio of bluff bodies in a uniform stream increases the reattachment length up to the point when an asymptotically-limiting value is reached. However, they also found that the asymptotically-limiting aspect ratio depends on blockage ratio.

Figure 2.9 depicts the variation of mean reattachment lengths \((X_r/h_f)\) as a function of aspect ratios for the NIST data obtained for the “open” (with an average roof height turbulence intensity of 19%) and “suburban” (with an average roof height turbulence intensity of 26%) terrains, with 1:12 and 1:48 roof slopes. Since the flow field was not measured for these cases, the explicit assumption that the \(Cp^*\) value at \(X_r\) versus \(I_u\) relationship from Figure 2.8 holds for these data and is not altered by the aspect ratio. Several observations can be made. First, there is clearly scatter in the plots, which may be due to the pressure tap resolution for the NIST data, in addition to measurement uncertainty, and variations and errors associated with the relationship between \(Cp^*\) at \(x = X_r\) and the turbulence intensity (Figure 2.8). Second, from Figure 2.9(a), for gable-roofed buildings with 1:12 roof slope, it is observed that for turbulence intensities consistent with an open terrain, increasing the aspect ratio increases the mean reattachment length. This relationship can be described satisfactorily by an exponential equation (with an upward trend), although there is substantial extrapolation to the asymptotic limit. For the higher level of turbulence intensity characteristic of a suburban terrain, the variation of mean reattachment length with aspect ratio follows a similar trend. In fact, both fits are nearly parallel to each other. Similar observations can also be made from the data presented in Figure 2.9(b) for gable roofs with 1:48 roof slopes. Third, it is estimated that for both upstream conditions, the asymptotic limit of the mean reattachment length occurs at aspect ratios between 50 and 80 (considering the asymptotic limit as 99% of maximum value of \(X_r\)) for 1:12 and 1:48 roof slopes. Finally, Figures 2.9(a) and 2.9(b) indicate that \(X_r/h_f\) is ~0.5 larger for the flatter roof slope of 1:48, when compared the more-highly sloped 1:12 data.
Figure 2.9: Variation of mean reattachment length with aspect ratio for NIST data for roof slopes of (a) 1:12 and (b) 1:48.
2.3.4 Discussion

In order to compare experimental data for different aspect ratios, it is necessary to adjust the results to a common aspect ratio and roof slope. Here we choose to use the asymptotic limit and the 1:48 roof slope so that the reattachment lengths for the current, three-dimensional, surface-mounted prisms can be compared to two-dimensional prisms in uniform flow. As discussed by Essel et al. (2015), it has been established that this asymptotic value of mean reattachment length \( \langle X_r \rangle \) practically reaches at aspect ratio higher than 10. Hence, even though Figures 2.9(a) and 2.9(b) suggest very high values of asymptotic-limits, the mean reattachment lengths for the NIST data and present experimental data were converted to the mean reattachment lengths equivalent to infinite aspect ratio considering the asymptotic limit for the mean reattachment lengths reaches at \( W/H=20 \). These are plotted in Figure 2.10 as a function of turbulence intensity. Included in Figure 2.10 are the results from Saathoff & Melbourne (1997) for two-dimensional bluff bodies placed in four uniform flows with different upstream turbulence levels and the results obtained by Kim et al. (2003) for a surface-mounted, three-dimensional prism with a 20% roof-height turbulence intensity (and also modified to account for aspect ratio).

Several observations can be made. First, as discussed above, there is a strong trend for decreasing reattachment lengths with increasing turbulence intensity. Most of the changes occur for \( I_u < \sim 17-18\% \), with relatively little change in the reattachment lengths for larger values of \( I_u \). In fact, the range of the scatter is greater than the underlying trend for \( I_u > \sim 17-18\% \).

Second, it appears that surface-mounted prisms have a different trend-line than those placed in a uniform stream with the reattachment lengths for surface-mounted prisms being a little larger at the turbulence intensities where there is overlap. It should be emphasized that there is considerable uncertainty in the extrapolation to large aspect ratio for the surface-mounted bodies, with the largest aspect ratios being about 16 in the experiments. Nevertheless, the evidence suggests that the curve for true two-dimensional bodies in a uniform stream is distinct from that for three-dimensional surface-mounted bodies extrapolated to large aspect ratios. While the uniform flow results end at \( I_u = 15\% \),
it appears that the uniform flow data and the current data have similar magnitudes beyond this point; however, there are no data to examine this point further. At lower turbulence intensities, it appears that the trend-lines for the two classes of bluff bodies are diverging, with larger reattachment lengths for the surface-mounted prisms. However, the first data point is at only $I_u = 9\%$. It seems likely that this difference is due to the nature of the vortical structures formed around surface-mounted prisms, which do not exist for two-dimensional bodies in a uniform stream, as discussed in the Introduction, although it could be due to other differences including the effects of the mean shear and anisotropic turbulence of the atmospheric boundary layer. Since the streamwise dimension of the surface-mounted low-rise building is comparatively small (e.g., $L/H=2.36$ for Building-1), the interaction between vortices shed at the trailing edge with the separation bubble may also have some effect on the mean reattachment length for surface-mounted three-dimensional bluff bodies, and the underlying assumptions for the aspect ratio corrections. These points merit further study in future work.

Figure 2.10: Variation of mean reattachment length, corrected to infinite aspect ratio, $(X_r/h_f)_{AR=\infty}$, as a function of streamwise turbulence intensity. A polynomial fit through the 2D bluff-body data is also shown for clarity.
2.4 Mean pressure distribution

Having established the variation of the reattachment length as a function of aspect ratio and turbulence intensity, we re-visit the normalization of the mean pressure distribution via Eq. (2.1). Figure 2.7 shows the variation of the reduced pressure coefficient, \( C_p^* \) versus \( x/X_r \) for Building-1. As discussed above, the value of \( C_p^* \) at \( x/X_r = 1 \) varies significantly (Figure 2.8). Adding to Figure 2.7, the Building-2 and NIST data are included, based on the model for the reattachment lengths indicated by Figure 2.8. The results are shown in Figure 2.11.

Figure 2.11 indicates that there is dependence of the reduced pressure curves on the turbulence intensity. The clear trend of larger values of \( C_p^* \) for smaller \( I_u \) values is apparent, notwithstanding the scatter in these plots. In general, those having similar levels of turbulence have similar shapes and magnitudes, although they do not fall perfectly onto a single curve. These results, when compared to those of Hudy et al. (2003) and Ruderich and Fernholz (1986), are clearly different. Thus, one can conclude that the normalized pressure distributions depend on more than distance normalized by the reattachment length, with the turbulence intensity significantly affecting the normalized distribution. Given the variations in the curves, other parameters (such as integral scales) must also affect the distributions, but to a lesser extent. In general, the pressure begins to recover earlier, i.e., at smaller \( x/X_r \) values (i.e., \( x/X_r \sim 0.2 \) to \( 0.3 \) compared to \( x/X_r \sim 0.4 \) to \( 0.5 \) for low turbulence) but beyond this point, the turbulence level slows the pressure recovery so that there are significantly lower values of \( C_p^* \) at the reattachment point. So, while higher levels of turbulence intensity reduce the reattachment length, the mean pressure on the surface does react as quickly resulting in lower \( C_p^* \) values at reattachment.

While Figure 2.11 highlights the changes in the normalized pressure distribution, it should also be noted that \( C_{p_{min}} \) varies significantly, depending on the turbulence intensity. For both buildings measured in the current study, it is observed that the minimum pressure coefficient for all of the upstream conditions falls between values of -0.9 to -1.3 with the lower values occurring at the higher turbulence intensities. Following reattachment, the pressure drop is nearly recovered with values of the pressure coefficient
between -0.1 and -0.2 for these experiments. Figure 2.12 depicts the $C_{p_{\text{min}}}$ values (along with a curve fit). The data show quite a lot of scatter, although the trend is clearly discernible, consistent with other experimental observations (e.g., Castro & Robins, 1977; Tieleman et al., 1996) and the measurement uncertainty.

Figure 2.11: Distribution of the reduced pressure coefficient ($C_{p^*}$) under the separation bubble. Legends: Building-1: 1L ––; 2L ––; 3L ––; 1S ––; 2S ––; 3S ––; Building-2: 1L ––; 2L ––; 3L ––; 1S ––; 2S ––; 3S ––; Hudy et al. (2003) ––; Ruderich & Fernholz (1986), Case-1 ––; Ruderich & Fernholz (1986), Case-2 ––; polynomial fit through the Hudy et al. (2003) and Ruderich & Fernholz (1986), Case-2* ––; NIST data legends are listed in Table 2.6.
Figure 2.12: Variations of minimum mean pressure coefficient with turbulence intensities. A polynomial fit through the dataset of Building-1 and Building-2 are shown on the figure with a dashed curve.

2.5 Discussion

From the Particle Image Velocimetry and surface pressure data for Building-1 it is observed that the building height turbulence intensity in the upstream boundary layer flow is the key turbulence parameter affecting the size of the separation bubble. For the range of turbulence length scales considered in this experiment ($L_x/H = 6$ to 13), no significant effect of turbulence length scales on the size of the separation bubble was observed. However, for very large values of integral scales in the upstream boundary layer, similar effects may not be observed. For two-dimensional bluff bodies placed in uniform upstream flows, it is observed in the literature that, at significantly larger values of turbulence length scale (relative to the body thickness, $L_x/H$), the surface mean pressure distributions behave more like smooth upstream flow over bluff bodies (Nakamura & Ozono, 1987). Bearman & Morel (1983) and Nakamura & Ozono (1987) suggest that, at these large values of upstream scales, the slowly fluctuating velocities are unable to alter the mean flow inside the separation bubble and that this may lead to larger separation bubbles. For surface-mounted bodies, similar effects would be expected.
For a fixed turbulence intensity, larger integral scales imply lower energy levels at the higher frequencies (smaller scales). Consider, for example, the von Kármán spectrum,

\[
\frac{f S_{uu}}{\sigma^2} = \frac{4 \left( \frac{L_x f}{U} \right)}{\left[ 1 + 7.8 \left( \frac{L_x f}{U} \right)^2 \right]^{5/6}}
\]

which indicates that the normalizing parameters for the power spectral density of the streamwise velocity are the variance, \(\sigma^2\), and the integral time scale, \(L_x / U\). One can rewrite this in terms of the turbulence intensity and \(L_x / H\),

\[
\frac{f S_{uu}}{U^2} = \frac{4 \left( \frac{L_x f}{U} \right) I_u^2}{\left[ 1 + 7.8 \left( \frac{L_x f}{U} \right)^2 \right]^{5/6}}
\]

Figure 2.13 illustrates the spectra for \(H = 4\) m and \(U = 30\) m/s. For the spectrum with \(L_x / H = 200\) and \(I_u = 17\%\), the energy is shifted to larger wavelengths relative to the size of the building compared to the spectrum with \(L_x / H = 10\) and \(I_u = 17\%\). At wavelengths similar to the building size, i.e., \(f H / U \sim 1\) there is an order of magnitude more energy for \(L_x / H = 10\) than for \(L_x / H = 200\). While this undoubtedly affects the fluctuating pressures, one may also expect a change towards lower-turbulence-level (i.e., smoother) mean-flow results, based on the Nakamura & Ozono (1987) data. Quasi-steady theory results suggest that the cut-off for “passive” fluctuations is at about \(f H / U \sim 0.1\) (e.g., Wu & Kopp, 2016, for a building with the same geometry as Building-1). If this holds generally, then the \(L_x / H = 200, I_u = 17\%\) flow would yield similar aerodynamics (i.e., similar reattachment lengths and pressure distributions) as for the \(L_x / H = 2\) and \(I_u = 4\%\) spectrum shown in Figure 13. This is the argument made by Irwin (2008; see his Figure 9) regarding the “partial turbulence simulation” method. Clearly, such results would have significant implications on how scale-model wind tunnel tests are conducted, particularly for large model scales.

For low-rise buildings in the range from \(H = 4\) m to 20 m, in open (\(I_u \sim 17\%) or suburban (\(I_u \sim 27\%\)) terrain, \(L_x / H\) is in the range from 7 to 33, based on the integral scales found by Counihan (1975) for the atmospheric boundary layer. The experiments for Building-1 are within this range (but do not fully span it). Thus, the current data for Building-1 (i.e.,
Figure 2.13: Streamwise velocity spectra for $H = 4\text{m}$ and $U = 30\text{m/s}$ and various integral scales and turbulence intensities.

Tables 2.3 and 2.4 and Figures 2.7 and 2.8) are of practical relevance for typical wind engineering applications for low-rise buildings. In general, further research is required to more fully assess the impact of integral scales outside the range tested, although it should be emphasized that there are challenges with respect to the size of boundary layer wind tunnels achieving larger integral scales relative to reasonably sized building models, as discussed by Tieleman (2003).

2.6 Conclusions

The objective of this chapter is to examine the effects of turbulence intensity and scale in upstream boundary layers on the mean reattachment length and pressure distributions for low-rise buildings. PIV and surface pressure measurements were made on a model building in six distinct terrain simulations, along with a detailed analysis of the pressure measurements from another low-rise building model for similar six terrains. The roof centre-line pressure for low-rise buildings with roof slopes less than or equal to 1:12 extracted from the NIST dataset (Ho et al., 2005) were also utilized in the analysis. The following conclusions can be drawn from the results:
➢ The mean location of the stagnation streamline on the front wall of a low rise building is found to be at $0.65H$ and is unaffected by the turbulence properties in the upstream flow.

➢ The mean reattachment length is primarily dependent on the streamwise turbulence intensity upstream of the building and the building aspect ratio. For the low-rise building models considered in the present experiment, it is seen that increasing the roof height turbulence intensities causes the mean reattachment lengths to decrease. For instance, increasing roof height turbulence from $I_u = 9\%$ to $25\%$ reduced the size of the separation bubble by more than $30\%$.

➢ It was found that the reduced pressure coefficient, $Cp^*$, distribution within separation bubbles depends primarily on the reattachment length, but also depends on the turbulence intensity. Values of $Cp^*$ at $x/X_r = 1$ range from about 0.35 for low turbulence (from Hudy et al., 2003) to about 0.20 at $I_u \sim 25\%$. Thus, while high turbulence levels cause earlier reattachment, the pressure does not recover at the same rate, relative to the reattachment point.

➢ Larger aspect ratios also yield larger mean reattachment lengths. For example, with $I_u \sim 18\%$, changing the aspect ratio from 2 to 16 increased the reattachment length by about $50\%$ under the assumption that the $Cp^*$ value at reattachment is unaltered by aspect ratio. Further research is required to confirm this point.

➢ The reattachment length was found to be largely unaffected by the integral length scales over the range of values examined (i.e., $L_x/H = 6$ to 13). However, for significantly larger integral scales, at a fixed turbulence intensity the reattachment length is also expected to be an important parameter.
References


Gu, D. and Lim, H. C. 2012 Wind flow around rectangular obstacles and the effects of aspect ratio. The Seventh International Colloquium on Bluff Body Aerodynamics and Applications (BBAA7). Shanghai, China; September 2-6.


Chapter 3

3 The effects of turbulence on the mean and fluctuating velocity fields within the separated-reattaching flow of a surface-mounted prism

3.1 Introduction

Flows over sharp leading edge bluff bodies have received special attention by researchers because of their numerous practical applications. Some of the practical applications of flows over sharp leading edge bluff bodies include atmospheric boundary layer flows over low-rise buildings, surface-mounted solar panels and flows over large sharp edged cliffs. One of the most unique features for flows over sharp-leading-edge bluff bodies, compared to other bluff bodies (e.g., spheres, circular cylinders, etc.), is the presence of the fixed separation point at the leading edge. However, as discussed in earlier chapters, flows over sharp leading edged bluff bodies typically reattach on the surfaces of the body if the streamwise dimension of the bluff bodies is long, forming a turbulent separation bubble. This turbulent separation bubble exhibits completely different flow behavior than the flow further away from the bluff body. The separated and reattaching flows over the sharp-leading-edge bluff bodies can be divided into three distinct regions; namely the separated shear layer, the recirculation region under the separated shear layer and the outer flow region above the separated shear layer.

There are a comparatively larger number of studies focussing on separated and reattaching flows over two-dimensional bluff bodies in low turbulence uniform upstream flows in contrast to complex incident flows with high turbulence. Kiya & Sasaki (1983) investigated the velocity fields in and around the separation bubble formed on the top surface of a two-dimensional blunt flat plate placed in uniform upstream flow with very low turbulence intensity. Their investigations reveal the shedding of large scale vortices near the reattachment point, which is associated with a shrinkage and elongation process of the separation bubble, causing the flapping motion of the separated shear layer. The
shedding of these vortices influences the surface pressures under the separation bubble. The experimental results of Kiya & Sasaki (1983) and Kiya & Sasaki (1985) show that for a two-dimensional bluff body placed in uniform upstream flow, the vortices shed from the reattachment point influence surface pressure fluctuations near the reattachment point while the pressure fluctuations close to the separation point are related to the Kelvin-Helmholtz instability. In these studies, the effects of turbulence properties in the upstream on the flow characteristics in the separation bubble have not been investigated. Saathoff & Melbourne (1997) investigated the effects of upstream turbulence properties on the flow field inside the separation bubble formed on the surface of two-dimensional bluff bodies over a range of turbulence intensity and lengths scales. Their investigations reveal that turbulence properties in the upstream interact with the separated shear layer in a variety of manners. An upstream with higher turbulence intensities causes greater perturbations in the separated shear layer and causes the rolling up of vortices to occur closer to the leading edge. This leads to larger surface pressure fluctuations for larger turbulence intensities. However, these authors speculate that for smaller scales of turbulence in the upstream the gusts are more frequent to carry away the vortices in the shear layer downstream not allowing the vortices to grow in strength. In contrast, for larger turbulence length scales, the gusts are less frequent and allow more time for the vortices to grow in strength, which causes the surface pressures to fluctuate more.

The velocity field around surface-mounted bluff bodies have been received comparatively less attention by fluid mechanics researchers, although some simplified geometries with smooth incident flow have received extensive study, particular for benchmarking cases of computational fluid dynamics (CFD); for example, some experimental and computational studies focussing on the separated and reattaching flows over forward facing steps include Agelinchaab & Tachie (2008), Hattori & Nagano (2010), Sherry et al. (2010), Ren & Wu (2011), Pearson et al. (2013), Iftekhar & Agelin-Chaab (2016). One fundamental difference in the flow features of the forward-facing step, in contrast to two-dimensional bluff bodies in uniform stream, is the formation of a recirculation region at the base of the front wall of the step. Pearson et al. (2013) observed that intermittent shedding from the recirculation region at the base of the forward-facing step spills over the step and interacts with the separation bubble formed
on the top surface of the step. The interactions of these kinds are absent for two-dimensional bluff bodies in uniform upstream flow. However, in the similar manner of the separation bubbles of two-dimensional bluff bodies in the uniform upstream flow, Sherry et al. (2010) observed the flapping of the separated shear layer caused by accumulation of vortices in the separation bubble and it’s shedding from the reattachment point. Sherry et al. (2010) also investigated the presence of high streamwise Reynolds normal stress and Reynolds shear stress regions along the separated shear layer. In any case, the effects of the turbulence properties in the incident flow on the formation and decay of these turbulence components were not investigated. Also, the mechanisms by which the flow fields in and around the separation bubble affect the fluctuating pressures on the surface remains to be studied.

There have been a limited number of studies present in literature investigating the separated and reattaching flows over sharp leading edge three-dimensional bluff bodies in turbulent boundary layer upstream conditions. Castro and Robins (1977) show that for surface-mounted cubes placed in turbulent boundary layer flows, there is intermittent reattachment on the upper surface and that the Reynolds stress components play important role in characterization of surface aerodynamic loading. Simultaneous pressure and velocity field measurements on the surface of a gable-roofed building (Kopp et al., 2012) show the formation and convection of a vortex near the leading edge is responsible for the high instantaneous uplift on the roof surface. However, the effects of upstream turbulence properties on the formation of these vortices have not been investigated in detail. Martinuzzi & Tropea (1993) investigated the flow fields around surface-mounted three-dimensional prisms of different aspect ratios and found the presence of a large vortex at the base of the front surface of the three-dimensional prism which flows downstream along the sides of the prism and forms a horseshoe-like vortex. There is a possible interaction of this horseshoe-like vortex with the flow above the three-dimensional prism and the interaction reduces as the spanwise dimension of the prism increases. The presence of the horseshoe vortex is a unique feature of the three-dimensional surface-mounted bluff bodies as these are not observed for forward facing steps and two-dimensional bluff bodies in uniform upstream flows. Kim et al. (2003) took detailed velocity field measurements around a surface-mounted rectangular prism in
a turbulent boundary layer upstream. Their analysis reveals that along the separated shear layer a very short distance downstream from the separation point, turbulent kinetic energy attains its maximum value and then gradually reduces in the downstream direction as the reattachment point is approached. However, the effects of turbulence properties in the upstream on the flow fields and the distribution of turbulent kinetic energy in and around the separation bubble have not been well addressed in literature.

In this chapter, the mean and fluctuating velocity fields along with the turbulence energy budget in and around the separation bubble formed on the top surface of a surface-mounted prism are investigated for six different turbulent boundary upstream conditions using the Time-Resolved Particle Image Velocimetry measurements described in Chapter 2. The effects of the turbulence properties in the approaching boundary layer flow on both mean and fluctuating velocity fields are examined in detail.

3.2 Normalization of the velocity field

3.2.1 Variable normalization

The mean and fluctuating velocity fields along with the mean and fluctuating vorticity fields are investigated for the six upstream boundary layer conditions. The results are normalized by the corresponding quantities at a vertical location sufficiently far from the body surface, i.e., at a location where the quantities do not change in magnitude with distance from the roof surface. This vertical location is labelled as the reference height \( H_r \) in the following sections. The flow characteristics of the reference height \( H_r \) represent the characteristics of the flow immediately surrounding the model. The reference height is located at \( y = H_r = 1.8H_1 \) from the wind tunnel floor, as shown in Figure 3.1. The subscript, ‘r’, with the variables represents the local normalizing value. As well, the subscript ‘r,LE’ represents a normalizing value at \( H_r \) above the leading edge, i.e., at \( x = 0 \). Normalizing the mean and fluctuating velocity fields and the mean and fluctuating vorticity fields in and around the separation bubble by corresponding quantities at \( H_r \) indicate how the flow properties vary with respect to the surrounding flow. The flow properties investigated are:

a. Mean streamwise velocity component \( (U) \)
b. Mean vertical velocity component ($V$)
c. Mean velocity magnitude ($|V| = (U^2 + V^2)^{1/2}$)
d. Standard deviation of velocity magnitude ($|V'|$)
e. Mean streamwise Reynolds normal stress ($\overline{u'u'}$)
f. Mean vertical Reynolds normal stress ($\overline{v'v'}$)
g. Mean Reynolds shear stress ($-\overline{u'v'}$)

In addition to these flow properties, the production, convection and diffusion terms in the turbulence energy budget are also investigated.

Figure 3.1: Schematic representation of the axial locations and the reference locations used for variable normalization.

3.2.2 Vertical axis normalization and thickness of the separation bubbles

In the contour plots of the investigated variables, the horizontal and vertical axes represent the axial distance from the leading edge of the model and vertical distance from the roof surface respectively. In these plots both the horizontal and vertical axes are normalized by the model height, $H_1$. However, in the vertical distribution of the investigated variables, the vertical axis represents the distance from the model’s roof surface whereas the horizontal axis represents the normalized investigated variable. In these plots, the vertical axis is normalized by the maximum thickness of the mean separation bubble ($T_{b,max}$). In Table 3.1, the values of $T_{b,max}/H_1$ are for all six upstream conditions presented. It is observed that a larger turbulence intensity decreases the
maximum mean thickness of the separation bubble as a proportion of the model height, $H_1$. However, the values of $T_{b,max}/X_r$ indicate that the ratio of $T_{b,max}$ to $X_r$ is almost identical for all of the upstream conditions, with a mean values of about 0.19. The small differences observed in the values of $T_{b,max}/X_r$ are primarily due to the spatial resolution of the PIV measurements ($0.02H_1$).

Table 3.1: Maximum thickness of the mean separation bubble.

<table>
<thead>
<tr>
<th>Upstream Conditions</th>
<th>Maximum thickness of mean separation bubble, $T_{b,max}/H_1$</th>
<th>Maximum thickness of mean separation bubble, $T_{b,max}/X_r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1S</td>
<td>0.25</td>
<td>0.18</td>
</tr>
<tr>
<td>1L</td>
<td>0.25</td>
<td>0.18</td>
</tr>
<tr>
<td>2S</td>
<td>0.19</td>
<td>0.18</td>
</tr>
<tr>
<td>2L</td>
<td>0.21</td>
<td>0.2</td>
</tr>
<tr>
<td>3S</td>
<td>0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>3L</td>
<td>0.19</td>
<td>0.21</td>
</tr>
</tbody>
</table>

3.2.3 Axial measurement locations

The vertical distributions of normalized variables were investigated at six different axial locations. The axial locations were chosen in such a manner that each of the axial locations show almost same values of $x/X_r$. However, the actual axial distances from the leading edge ($x/H_1$) of the chosen locations may vary from one upstream condition to the other, as shown in Chapter 2, the mean reattachment length ($X_r$) varies for different upstream conditions. In Figure 3.1, in the schematic representation of the axial locations, the locations are numbered as 1, 2, 3, 4, 5 and 6. In Table 3.2 the axial locations with respect to the mean separation bubble ($X_r$) are presented.

Table 3.2: Axial locations considered for velocity profile investigations.

<table>
<thead>
<tr>
<th>Axial location</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position with respect to the separation bubble, $x/X_r$</td>
<td>0.05</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>1</td>
</tr>
</tbody>
</table>
3.3 Results and discussions

3.3.1 Mean streamwise velocity ($U$)

In Figure 3.2 the mean streamwise velocity contours, $U/U_r$ are shown for the six upstream conditions. On these contour plots, mean streamlines are also plotted. The mean streamlines show that the flow separates at the leading edge, moves upwards and then curves back towards the roof surface, and reattaches on the surface. It is observed that for higher turbulence intensities in the upstream, the mean reattachment lengths ($X_r$) decrease. A detailed investigation of this can be found in Chapter 2. It is also evident that the centre of the recirculation region under the separated and reattaching streamline moves closer to the leading edge as the model height turbulence intensity is increased.

The contours of mean streamwise velocities ($U/U_r$), indicate that, close to the roof surface, the mean streamwise velocities are negative within the separation bubble i.e, there is reverse flow. With increasing vertical distance from the roof surface the magnitude of mean streamwise velocities increases and gradually blends into the surrounding mean flow. The zero contour of $U/U_r$ starts at the leading edge, passes through the centre of the separation bubble and ends at the mean reattachment point. A closer look at the plots reveals that, along the separating - reattaching streamline, the magnitude of $U$ is 40% of the mean streamwise velocity of the surroundings ($U_r$) up to the axial location where the mean thickness of the separation bubble attains its maximum value. As the separating and reattaching streamline curves back towards the roof surface, the 40% mean streamwise velocity contour deviates from the separating and reattaching streamline into the outer flow.

Figure 3.3 shows the mean streamwise velocity $U/U_r$ profiles above the roof surface at six different streamwise locations. These profiles indicate the development of the flow indicating that the recovery of mean streamwise velocity into the surrounding values. It is observed that, irrespective of the turbulence intensity and length scale, the recovery of mean streamwise velocity to the mean streamwise velocities of the surroundings occurs at almost at the same vertical distance above the model’s roof surface, when the vertical
Figure 3.2: Contours of $U/U_r$ for upstream conditions (a) 1S, (b) 1L, (c) 2S (d) 2L (e) 3S and (f) 3L.
Figure 3.3: Vertical profiles of $U/U_r$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 

Distance from the surface, $y/T_{b,max}$

$U/U_r$
axis is normalized by $T_{b,\text{max}}$. Thus, considering the constancy of $T_{b,\text{max}}/X_r$ ratio, normalizing the vertical distance in this manner shows the similarity of the mean streamwise velocities in and around the separation bubble since the profiles for all six upstream conditions collapse on each other at all locations. These results also reveal that $T_{b,\text{max}}$ is the appropriate parameter for normalizing the vertical distances in these flows. (In contrast, when the distance from the roof surface is normalized by the height of the model ($H_1$), it is observed that recovery of the mean streamwise flow into the surrounding flow occurs at different vertical heights from the roof surface. These figures are presented in Appendix B, Figure B.1.) This parameter, $T_{b,\text{max}}$, has previously been used by Castro & Haque (1987) to normalize the vertical distance from the surface. Hence, the mean thickness of the separation bubble is reduced by increasing the turbulence intensity because of the reduced reattachment length. Integral length scales do not significantly affect the thickness of the separated flow.

In Figure 3.4, the variation of $U_r$ is presented. Here the values of $U_r$ are presented normalized by $U_{r,\text{LE}}$ and the horizontal axis, representing the axial distance from the leading edge, is normalized by the model height, $H_1$. It is observed that with the increment of axial distance from the leading edge, for all six upstream conditions, the mean streamwise velocities do not change significantly from $U_{r,\text{LE}}$ and the horizontal distribution of $U_r/U_{r,\text{LE}}$ at $H_1$ does not show significant change with changing the upstream conditions. The maximum deviation of $U$ from $U_{r,\text{LE}}$ is observed to be about 7%. Hence, normalizing the parameters with $U_{r,\text{LE}}$ instead of $U_r$ does not significantly affect the results. In order to compare the turbulence and flow properties for different upstream cases, variables normalized by $U_{r,\text{LE}}$ will also be used in addition to local normalizing values in the following sections.

3.3.2 Mean vertical velocity component ($V$)

The contour plots of normalized mean vertical velocity component ($V/V_{r,\text{LE}}$) (Figure 3.5) show that, at the leading edge, the mean vertical velocity component has its highest magnitude, after which it decreases as flow moves downstream. Due to the interaction of the upstream flow with the model’s front surface, flow moves upwards giving rise to the
Figure 3.4: Horizontal distribution of $U_r/U_{r,LE}$ at $H_r$.

vertical component of the velocity. With increasing vertical distance from the leading edge, due to the interaction with the high streamwise component in the upstream flow, the vertical component of the velocity decrease. The contour of the zero mean vertical velocity passes through locations where the flow only has the streamwise component including the centre of the separation bubble. Downstream of the zero mean vertical velocity contour, flow moves towards the surface of the model where regions of negative mean vertical velocity component are observed. As discussed earlier, due to the shortening of the separation bubble with upstream turbulence intensity, the centre of the separation bubble moves towards the leading edge causing movement of the zero mean vertical velocity contour towards the leading edge with increasing the model height turbulence intensity in the upstream.

Figure 3.6 shows the profiles of $V/V_t$ at six different axial locations from the leading edge where the vertical distance from the roof surface is normalized by $T_{b,max}$. The vertical locations of maximum $V/V_t$ move away from the roof surface as flow moves downstream. At axial locations less than 0.5$x_r$ (locations 1, 2 and 3) closer to the roof the values of $V/V_t$ are positive, whereas at axial locations greater than 0.5$x_r$ (locations 4, 5 and 6) the magnitudes of $V/V_t$ are negative closer to the surface. These are because of the upward movement of the flow after separation close to the separation point and downward movement of the flow as reattachment is approached. It is also observed that, unlike the
Figure 3.5: contours of $V/V_{r,LE}$ for upstream conditions (a) 1S, (b) 1L, (c) 2S (d) 2L (e) 3S and (f) 3L.
Figure 3.6: Vertical profiles of $V/V_r$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
distribution of $U/U_r$, the distribution of $V/V_r$ does not collapse for all six upstream conditions even though the mean vertical velocity components are normalized by the mean vertical velocity component at the reference height ($H_r$) and the distance from the surface is normalized by $T_{b, \text{max}}$. Hence, the distribution of $V/V_r$ in and around the separation bubble is not self-similar. However, the fact that the distributions of $V/V_r$ showing a decreasing trend beyond the reference height suggests that the reference height chosen for normalizing the mean vertical velocity components does not perfectly represent the mean vertical velocity component of the surroundings.

In Figure 3.7 the horizontal distribution of $V_r/V_{r, \text{LE}}$ is presented. For each of the upstream conditions, the magnitude of $V_r$ reduces from $V_{r, \text{LE}}$ as axial distance from the leading edge is increased. The magnitudes of $V_r/V_{r, \text{LE}}$ for higher turbulent upstream conditions (‘3S’ and ‘3L’) drop at higher rate compared to lower turbulence upstream cases. The effect of turbulence length scales in the upstream is only observed for upstream conditions ‘3S’ and ‘3L’, where the magnitudes of $V_r/V_{r, \text{LE}}$ decrease at slower rate as upstream turbulence length scale is increased.

![Figure 3.7: Horizontal distribution of $V_r/V_{r, \text{LE}}$ at $H_r$.](image)
Figure 3.8: Vertical profiles of $V/U_{r,LE}$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
In Figure 3.8 the vertical profiles of mean vertical velocity component normalized by \( U_{r,LE} \) are presented. It is observed that the magnitudes of \( V \) are very small compared to \( U_{r,LE} \) in most of the regions within the separation bubble. Along the separated shear layer at the axial location closer to the leading edge (‘Location 1’), the value of \( V/U_{r,LE} \) is observed as the maximum 0.6. Vertically away from the surface and also downstream of the separation point the magnitudes of \( V/U_{r,LE} \) drop significantly. Hence, in most of the regions of the separation bubble, except for the regions very close to the leading edge, the vertical mean velocity components are not significant when compared to the mean streamwise velocity component at the reference height (\( U_{r,LE} \)).

### 3.3.3 Mean velocity magnitude, \(|V|\)

The contours of the mean velocity magnitudes in and around the separation bubble, \(|V|/|V|_r\) are presented in Figure 3.9. These figures show that along the separating - reattaching streamline the mean velocity magnitude is approximately 0.45\(|V|_r\) over that of the mean streamwise velocity component (\( U \)). However, it is observed from the contours of mean streamwise velocity component that the 0.4\(U\) contour follows the separated and reattaching streamline until the maximum thickness of the separation bubble is obtained. Clearly, the major contributor to the mean velocity magnitude along the separated shear layer is the mean streamwise velocity component.

The profiles of \(|V|/|V|_r\) for the six upstream conditions are presented in Figure 3.10. It is observed that closer to the surface the mean velocity magnitude has the minimum value for all upstream conditions and it gradually increases away from the roof surface. For all of the upstream conditions, \(|V|\) reaches the mean velocity magnitude of the reference height (\(|V|_r\)) almost at the same height from the roof surface when the vertical axis is normalized by \( T_{b,max} \). However, the actual heights at which \(|V|\) reaches \(|V|_r\) is different for different upstream conditions. This can be observed from the plots of \(|V|/|V|_r\) (presented in Appendix B, Figure B.2) where the vertical distance from the roof surface is normalized by the model height (\( H_1 \)). For larger values of the upstream turbulence intensity, the heights to reach the outer mean velocity magnitudes decrease. The vertical distance at which the mean velocity magnitude equals the reference magnitude increases.
Figure 3.9: Contours of $|V|/|V_r|$ for upstream conditions (a) 1S, (b) 1L, (c) 2S (d) 2L (e) 3S and (f) 3L.
Figure 3.10: Vertical profiles of $|V|/|V_r|$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
as flow moves downstream from the leading edge due to the movement of the separated shear layer away from the surface. Like the mean streamwise velocity distributions, the vertical distribution of normalized mean velocity magnitude $|\mathbf{V}|/|\mathbf{V}|_r$ does not change with changing the upstream conditions. Hence, the distribution of velocity magnitudes in and around the separation bubble is essentially self-similar, even though the vertical component is not.

In the following figure (Figure 3.11), the horizontal distribution of $|\mathbf{V}|_r/|\mathbf{V}|_{r,\text{LE}}$ is presented. As axial distance from the leading edge increases $|\mathbf{V}|_r$ show very little deviation from $|\mathbf{V}|_{r,\text{LE}}$, with the maximum deviation being around 7%.

![Figure 3.11: Horizontal distribution of $|\mathbf{V}|_r/|\mathbf{V}|_{r,\text{LE}}$ at $H_r$.](image)

3.3.4 Streamwise Reynolds normal stresses $(\overline{u'u'})$

The contours of the Reynolds normal stress in the streamwise direction $(\overline{u'u'})$, normalized by the reference values $(\overline{(u'u')_r})$ for the six upstream conditions are presented in Figure 3.12. On the contour plots the mean streamlines are also plotted in order to observe the regions of fluctuating streamwise velocity components with respect to the mean flow in and around the separation bubble. The results demonstrate that, for each of the upstream condition, closer to the model surface the magnitude of Reynolds normal stresses in streamwise direction are small and it gradually increases as distance from the roof surface approaches the separated shear layer. With further increment of
Figure 3.12: Contours of $\overline{u'w'/(u'\overline{u'})}$, for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L (e) 3S and (f) 3L.
vertical distance from the model’s surface, \( \overline{u' \cdot u'} \) gradually reduces to match \( \langle \overline{u' \cdot u'} \rangle_r \). It is also observed from the present experimental results that very close to the leading edge the streamwise velocity fluctuations are low compared to the maximum streamwise velocity fluctuations observed along the separated shear layer. As flow moves downstream, the region of maximum streamwise velocity fluctuations are observed along the separated shear layer and the region of maximum streamwise velocity fluctuations start to occur at an axial distance around 0.2\( H_1 \) from the leading edge. As the mean separating - reattaching streamline moves towards the roof surface after attaining the maximum thickness of separation bubble \( (T_{b,\text{max}}) \), the regions of streamwise velocity fluctuations moves away from the mean separating and reattaching streamline, reducing and blending into the outer flow.

There are qualitative similarities with the results for the forward-facing step obtained by Sherry et al. (2010) in a very low turbulence upstream flow \( (I_u=1\%) \). However, there is some dissimilarity as well. For example, the regions with high streamwise Reynolds normal stresses for the forward-facing step are found to be spread over a longer region in the streamwise direction when compared to the current experimental results. This difference is mainly due to the formation of longer separation bubbles for forward facing step as observed by Sherry et al. (2010). (Sherry et al. (2010) observed a mean size of separation bubble very close to 3\( H \), whereas for the present experimental results the maximum and minimum mean sizes of the separation bubbles were observed to be \(~1.4H_1 \) and 0.88\( H_1 \) respectively.)

As discussed by Martinuzzi & Tropea (1993), for a forward facing step, in contrast to surface mounted three dimensional prisms, the streamwise flow accelerates more over the step causing a delay in reattachment. The turbulence intensities in the upstream also plays important role in characterizing the mean size of the separation bubble (Chapter 2). High turbulence upstream flow interacts with the separated shear layer resulting higher entrainment of high velocity upstream flow in the separation bubble to overcome the momentum deficit caused by the leading edge of the bluff body by the mechanism known as turbulence mixing. This mechanism in turn causes earlier reattachment on the surface for higher turbulence upstream cases (Sherry et al., 2010). Due to the geometry and
considerably low turbulence upstream, longer mean size of the separation bubble is observed by Sherry et al. (2010) where the mean separating and reattaching streamline reaches its maximum height from the model’s surface at a higher streamwise distance from the leading edge before moving downwards towards surface compared to smaller separation bubbles observed in the present experiment. However, the spread of Reynolds normal stress in the streamwise direction of Sherry et al. (2010) with respect to the mean size of the separation bubble \(X_r\) is observed to be qualitatively similar with the present experimental results.

It is observed from the contour plots that with the increment of the turbulence intensities in the upstream, the magnitude of streamwise velocity fluctuations decrease. It is worth noting here that the magnitudes of streamwise velocity fluctuations are normalized by the streamwise velocity fluctuations at the reference height \(H_r=1.8H_1\). Hence, the results presented in Figure 3.12 represent the ratio of streamwise velocity fluctuations to the streamwise velocity fluctuations at the reference height. Keeping this in mind, the results in Figure 3.12 show that the magnitude of streamwise velocity fluctuations along the separated shear layer compared to the outer flow is maximum for upstream condition ‘1S’ and minimum for upstream condition ‘3L’.

In Figure 3.13, the vertical profiles of \(\frac{\bar{uu}}{(u'u')_r}\) are presented. For all upstream conditions, it is observed that as flow moves downstream from the leading edge, the regions of high \(\frac{\bar{uu}}{(u'u')_r}\) spread wider in the vertical direction as compared to the regions of \(\frac{\bar{uu}}{(u'u')_r}\) closer to the leading edge. The recovery of the outer flow values occurs almost at the same height for all of the upstream conditions when the distance from the roof is normalized by \(T_{b,max}\). However, normalizing the vertical distance from the roof surface by the model height \(H\) reveals that the actual distances to the outer flow values decrease with increasing turbulence intensity in the upstream. (Plots are presented in Appendix B, Figure B.3.) For the upstream with lowest turbulence intensity and turbulence length scale (upstream ‘1S’), the magnitude of \(\frac{\bar{uu}}{(u'u')_r}\) generated in the separated shear layer is the highest while
Figure 3.13: Vertical distribution of $\frac{u'u'}{(u'u')_r}$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
for the highest model eight turbulence intensity and turbulence length scale (upstream ‘3L’), the magnitude of $\frac{u^\prime u^\prime}{(u^\prime u^\prime)_r}$ along the separated shear layer compared to the reference height is found lowest. Effects of the model height turbulence length scales are also observed in the results as decreasing turbulence length scales in the upstream increases the streamwise velocity fluctuations along the separated shear layer compared to the streamwise velocity fluctuations in the surrounding flow. Hence, it can be concluded that the relative levels of the body-generated streamwise velocity fluctuations along the separated shear layer, compared to the velocity fluctuations in the surrounding flow, are highest for the smoothest (i.e., lowest turbulence) cases.

It is also evident from these plots that for six different upstream conditions, the distribution of $\frac{u^\prime u^\prime}{(u^\prime u^\prime)_r}$ under the separated shear layer do not collapse on the same curve even though the distance from the surface is normalized by $T_{b,\text{max}}$. However, a satisfactory collapse of the distribution of $\frac{u^\prime u^\prime}{(u^\prime u^\prime)_r}$ is observed in the regions above the shear layer where the streamwise velocity fluctuations match the streamwise velocity fluctuations of the outer flow. Hence, the distributions of streamwise velocity fluctuations under the separated flow are not observed to be self-similar.

Figure 3.14 shows the axial variation of $\frac{u^\prime u^\prime}{(u^\prime u^\prime)_{r,\text{LE}}}$ at the reference height ($H_r$). It is observed that, except for the upstream condition ‘1S’, $\frac{u^\prime u^\prime}{(u^\prime u^\prime)_{r,\text{LE}}}$ does not show significant variation as the axial distance from the leading edge increases. However, for the upstream condition ‘1S’, the magnitude of $\frac{u^\prime u^\prime}{(u^\prime u^\prime)_{r,\text{LE}}}$ initially decreases showing a maximum deviation of about 10% in $(u^\prime u^\prime)_r$ from $(u^\prime u^\prime)_{r,\text{LE}}$ and increase to match $(u^\prime u^\prime)_{r,\text{LE}}$ further downstream.

In Figure 3.15, the vertical profiles of streamwise normal stresses $(u^\prime u^\prime)$ normalized by the square of the mean streamwise velocity at the reference height above the leading edge $(U_{r,\text{LE}}^2)$ are presented. These plots represent the absolute differences in magnitudes of
Figure 3.14: Horizontal distributions of $(\overline{u'u'})/\overline{(u'u')}_{r,LE}$ at $H_r$.

$\overline{u'u'}$ from one upstream condition to the other. The plots reveal that at all the six locations, the upstream condition ‘3S’ and ‘3L’ (the highest turbulence intensity cases considered in this experiment) show the maximum values in the magnitude of $(\overline{u'u'})_{r,LE}$ everywhere in and around the separation bubble. The maximum value of $(\overline{u'u'})_{r,LE}$ is observed to be around 0.2 at every axial location. At most of the axial locations, slightly higher values of $(\overline{u'u'})_{r,LE}$ are observed for the upstream conditions ‘2S’ and ‘2L’ when compared to the upstream conditions ‘1S’ and ‘1L’. No significant effects of the turbulence length scales in the upstream flow are observed in the vertical distributions of $(\overline{u'u'})_{r,LE}$. Hence, even though the streamwise velocity fluctuations in the separated - reattaching flows, compared to the streamwise velocity fluctuations in the outer flow, are highest for the lowest turbulence intensities and length scales in the upstream flow (as discussed above), the absolute magnitudes of streamwise velocity fluctuations are observed to be highest for the upstream conditions with the highest turbulence intensities.
Figure 3.15: Vertical profiles of $\overline{u'w'}/U^2_{r,LE}$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
3.3.5 Vertical velocity fluctuations, $v'v'$

In Figure 3.16 the contours of the Reynolds normal stresses in the vertical direction ($v'v'$) normalized by the Reynolds normal stresses in the vertical direction at the reference height ($\overline{(v'v')}_{r}$) are presented. It is observed that for all six upstream conditions the vertical velocity fluctuations are high very close the leading edge. However, as flow moves downstream from the leading edge, the vertical velocity fluctuations decrease in a small region along the separated shear layer and then gradually increase again, further downstream.

Figures 3.17 show the vertical profiles of $\frac{v'v'}{(v'v')_{r}}$ for all six upstream conditions at six different axial locations from the leading edge. It is observed that, at all streamwise locations, closer to the surface the magnitude of $v'v'$ is lower, increases as the vertical distance from the surface reaches the separated shear layer and then gradually reduces to match $\overline{(v'v')}_{r}$ further away from the surface. The vertical locations where $v'v'$ match $\overline{(v'v')}_{r}$ is closer for higher turbulence upstream cases when compared to lower turbulence upstream cases. This is more prominent when the distributions of $\frac{v'v'}{(v'v')_{r}}$ are plotted against the vertical distance normalized by the model height ($H_1$). (Plots are presented in Appendix B, Figure B.4.) The magnitudes of $\frac{v'v'}{(v'v')_{r}}$ are observed to be higher for lower turbulence upstream cases and lower for the higher turbulence upstream cases. This indicates that the generation of vertical velocity fluctuations along the separated shear layer, when compared to the vertical velocity fluctuations in the outer flow, is higher for lower turbulence intensity upstream. Increasing turbulence length scales in the upstream also increases the magnitudes of $\frac{v'v'}{(v'v')_{r}}$ along the separated shear layer and these phenomena can be more clearly observed for lower turbulence upstream conditions (upstream conditions ‘1S’ and ‘1L’) and at axial locations away from the leading edge. It can also be noted from these plots that the vertical distributions of $\frac{v'v'}{(v'v')_{r}}$ under the separated and reattaching flows for the six upstream conditions do not collapse on a
Figure 3.16: Contours of $\frac{\overline{v'v'}}{(\overline{v'v'})_r}$ for upstream conditions (a) 1S, (b) 1L, (c) 2S (d) 2L (e) 3S and (f) 3L.
Figure 3.17: Vertical profiles of $\frac{v'v'}{v'v'}_r$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
single curve and hence, the distribution of the Reynolds normal stresses in the vertical direction \((v'v')\) are not self-similar.

In Figure 3.18 the horizontal distributions of \(\frac{(v'v')_r}{(v'v')_{r,LE}}\) at reference height \((H_r)\) are presented. It is observed that the magnitudes of \(\frac{(v'v')_r}{(v'v')_{r,LE}}\) initially increases for upstream conditions ‘1S’ and ‘1L’ and then decreases further away from the leading edge. For upstream conditions ‘2S’, ‘2L’, ‘3S’ and ‘3L’, the magnitudes of \(\frac{(v'v')_r}{(v'v')_{r,LE}}\) remains almost constant up to an axial distance of \(x/H_1=0.5\) from the leading edge and then gradually decreases in magnitude as axial distance from the leading edge is further increased. The maximum deviation of \((v'v')_r\) from \((v'v')_{r,LE}\) is observed to be 15% for the upstream condition ‘3S’.

The vertical profiles of \(\frac{\overline{v'v'}}{U_{r,LE}}\) (Figure 3.19) reveal that there are no significant differences in the magnitude of \(\frac{\overline{v'v'}}{U_{r,LE}}\) close to the surface as the turbulence properties in the upstream are varied, except for ‘Location 1’ where increased upstream turbulence intensities

![Graph](image-url)

**Figure 3.18:** Horizontal distribution of \(\frac{(v'v')_r}{(v'v')_{r,LE}}\) at \(H_r\).
Figure 3.19: Vertical profiles of $\overline{v'v'}/U_{r,LE}^2$ (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
causes higher magnitudes of $\frac{\overline{v'^{2}}}{U_{r,LE}^2}$. However, further away from the surface the higher magnitudes of $\frac{\overline{v'^{2}}}{U_{r,LE}^2}$ for upstream conditions with higher turbulence intensities are observed. It is also observed from the plots that the magnitudes of $\frac{\overline{v'^{2}}}{U_{r,LE}^2}$ at any axial location and for any upstream condition are never higher than 0.05. Comparing these results with the distributions of $\frac{\overline{U'^{2}}}{U_{r,LE}^2}$ reveal that the magnitudes of $\frac{\overline{v'^{2}}}{U_{r,LE}^2}$ are always significantly lower than the magnitudes of $\frac{\overline{U'^{2}}}{U_{r,LE}^2}$ (the maximum value of $\frac{\overline{U'^{2}}}{U_{r,LE}^2}$ was observed to be 0.23). Hence, the streamwise Reynolds stresses are significantly larger than the vertical Reynolds normal stresses, and are the major contributor of the fluctuating flow field.

3.3.6 Reynolds shear stress, $\overline{-u'v'}$

The contours of Reynolds shear stresses ($\overline{-u'v'}$) normalized by the Reynolds shear stress at the reference height ($\overline{-u'v'}_r$) are presented in Figure 3.20. It is observed that near the separation point, the Reynolds shear stresses show negative values. These negative regions of Reynolds shear stresses indicate regions of production of Reynolds stresses (Hattori & Nagano, 2010; Sherry et al., 2010). The turbulence energy budget will be examined further below. As flow moves downstream of the separation point, the magnitude of Reynolds shear stresses increases, attain positive values, these positive contours spread into the outer flow and gradually mixes into the Reynolds shear stresses at the reference height ($\overline{(u'v')_r}$). These results agree qualitatively with the experimental results of Sherry et al. (2010) and the DNS results of Hattori & Nagano (2010) for flows over forward-facing steps.

The DNS results of Hattori & Nagano (2010) demonstrate that the positive values of Reynolds shear stresses occur at the locations where the vertical velocity fluctuations and the gradients of mean velocity are positive. Observations on the contour plots Reynolds shear stresses and Reynolds normal stresses in vertical direction for the present experiment reveal that the regions where the positive values of Reynolds shear stresses start to occur in the regions where the Reynolds normal stresses in the vertical direction
Figure 3.20: Contours of $\frac{\overline{u'v'}}{(u'v')_r}$ for upstream conditions (a) 1S, (b) 1L, (c) 2S (d) 2L (e) 3S and (f) 3L.
start to increase in magnitude. Hence, the present experimental results are qualitatively in good agreement with the numerical results of Hattori & Nagano (2010).

The contour plots of the present experimental results also reveal that with increasing turbulence intensity and length scale in the upstream flow, the regions of negative Reynolds shear stresses spread more widely into the outer flow. These results indicate larger production regions of Reynolds stress components near the leading edge at higher turbulence intensity and length scale upstream cases.

The vertical profiles of \(\frac{u'v'}{(u'v')}_{r}\) are presented in Figure 3.21. Closer to the surface the magnitudes of \(\frac{u'v'}{(u'v')}_{r}\) are smaller and gradually increase to maximum values as distance from the surface increases to the location of the separated shear layer. The magnitudes of \(-u'v'\) gradually match the values of \(-\overline{(u'v')}_{r}\) as the distance from the surface is further increased. However, the vertical distance at where \(-u'v'\) matches the surrounding values are higher for lower turbulent upstream cases. These results can more clearly be observed when the distance from the surface is normalized by the model height \((H_i)\). These plots are presented in Appendix B (Figure B.5). It is also from the plots that at ‘Location 1’ and ‘location 2’, the magnitudes of \(\frac{u'v'}{(u'v')}_{r}\) show negative values whereas for other four axial locations the magnitudes of \(\frac{u'v'}{(u'v')}_{r}\) are positive along the separated shear layer.

Along the separated shear layer, the lower turbulent upstream conditions (upstream conditions ‘1S’ and ‘1L’) show higher values of \(-u'v'\) compared to \(-\overline{(u'v')}_{r}\). The effects of turbulence length scales in the upstream are also observed, as with increasing turbulence length scales in the upstream, the magnitude of Reynolds shear stresses increase within the separation bubble when compared to the reference height. However, the effects of turbulence length scales in the upstream flow cannot be observed for the upstream conditions with highest turbulence intensities in the upstream flow (upstream conditions ‘3S’ and ‘3L’). Even though above the separated shear layer the profiles show very good match for all six upstream conditions, in the flow under the separated shear layer the profiles significantly vary with each other. Hence, the distributions of Reynolds shear stresses under the separated and reattaching flows are not self-similar.
Figure 3.21: Vertical profiles of $u'v'/(u'v')_r$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
Figure 3.22 shows the horizontal distribution of $\frac{(u'v')_r}{(u'v')_{r,LE}}$ at reference height ($H_r$). For upstream conditions ‘1L’ and ‘2L’ the distributions of $\frac{(u'v')_r}{(u'v')_{r,LE}}$ does not change significantly whereas for the other four upstream conditions the magnitude of $-(u'v')_r$ gradually reduces from $-(u'v')_{r,LE}$ as the distance from the leading edge is increased. The maximum deviation of $-(u'v')_r$ from $-(u'v')_{r,LE}$ is observed as 40% for upstream condition ‘1S’.

The vertical distributions of $-\frac{w'v'}{u_{r,LE}^2}$ at six axial locations (Figure 3.23) indicate that the magnitudes of Reynolds shear stresses in and around the separation bubble vary slightly with changing the upstream conditions. However, it is also observed that the magnitudes of $-\frac{w'v'}{u_{r,LE}^2}$ are small compared to the magnitudes of $\frac{w'w'}{u_{r,LE}^2}$ anywhere in the flow field except very close to the surface for ‘Location 1’. Except for ‘Location 1’ the magnitude of $-\frac{w'v'}{u_{r,LE}^2}$ were observed always less than 0.03. Comparing all three Reynolds stress components reveal that Reynolds normal stress in the streamwise direction is the largest within and around the separated - reattaching flow for surface-mounted bluff bodies in turbulent boundary layer upstream flows.

![Figure 3.22: Horizontal distributions of $\frac{(u'v')_r}{(u'v')_{r,LE}}$ at $H_r$.](image-url)
Figure 3.23: Vertical profiles of $-u'v'/U_{r,LE}^2$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
3.3.7 Fluctuations in velocity magnitude, $|V'|$

The contours of the standard deviations of velocity magnitude ($|V'|$) in and around the separation bubble, normalized by the standard deviation of velocity magnitude at the reference height ($|V'|_r$), are presented in Figure 3.24. For all upstream conditions, along the mean separating - reattaching streamline, the highest fluctuations in velocity magnitude are observed to occur over a streamwise extent from the separation point to the location of maximum mean thickness of the separation bubble. As the mean separating and reattaching streamline curves towards the surface the contour of the fluctuations in velocity magnitude moves in the outer flow and decrease in magnitude downstream. As the turbulence intensity in the upstream is increased, the region of maximum fluctuations in velocity magnitude shrinks near the leading edge. Increasing the turbulent length scales in the upstream also shows an indication of shortening of the regions of high fluctuations in velocity magnitude along the separated shear layer towards the separation point.

The vertical profiles of $|V'|/|V'|_r$ are presented in Figure 3.25. The plots indicate that the values of $|V'|/|V'|_r$ are higher along the separated shear layer for upstream conditions with lower turbulent intensities and lower turbulence length scales. Self-similarity of the vertical profiles of $|V'|/|V'|_r$ is not observed.

The vertical profiles of $|V'|/U_{r,LE}$ (Figure 3.26) reveal that closer to the surface the magnitudes of $|V'|/U_{r,LE}$ does not change much with changing upstream conditions. However, vertically further away from the surface, fluctuations in velocity magnitudes are observed to be increased as turbulence intensities in the upstream are increased.

Figure 3.27 shows the horizontal distribution of $|V'|/|V'|_{r,LE}$ at the reference height ($H_r$). For all of the upstream conditions the magnitude of $|V'|_r$ do not significantly vary from $|V'|_{r,LE}$. The maximum deviation of $|V'|_r$ from $|V'|_{r,LE}$ is observed to be less than 5%.
Figure 3.24: Contours of $|V'|/|V'|$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Figure 3.25: Vertical profiles of $|V'|/|V|_r$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
Figure 3.26: Vertical profiles of $|V|/U_{r,LE}$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
3.3.8 Turbulence energy budget

The transport equation of turbulent kinetic energy can be expressed as follows (Kasagi & Matsunaga, 1995)

\[
\frac{\partial k}{\partial t} = -U_j \frac{\partial k}{\partial x_j} - u'_i u'_j \frac{\partial U_i}{\partial x_j} - v \frac{\partial u'_i}{\partial x_j} \frac{\partial u'_j}{\partial x_j} + \frac{\partial}{\partial x_j} \left( -\frac{1}{2} u'_i u'_j - \frac{1}{\rho} p u'_j + \nu \frac{\partial k}{\partial x_j} \right)
\]

The terms on the right-hand side of the kinetic energy budget equation are convection, production, dissipation, turbulent diffusion, pressure diffusion and viscous diffusion respectively. The convection, production, dissipation and turbulent diffusion terms and their forms for two-dimensional velocity fields are as follows,

Convection term: \(-U_j \frac{\partial k}{\partial x_j}\)

For a two-dimensional velocity field the convection terms is:

\[
\text{Convection} = -U \frac{\partial (u^2 + v^2)}{\partial x} - V \frac{\partial (u^2 + v^2)}{\partial y}
\]
Production: \(-u'_i u'_j \frac{\partial U_i}{\partial x_j}\)

For a two-dimensional velocity field the production term is:

\[
\text{Production} = -u'' \frac{\partial U}{\partial x} - u'v' \frac{\partial U}{\partial y} - u'v' \frac{\partial V}{\partial x} - v'' \frac{\partial V}{\partial y}
\]

Dissipation: \(-v \frac{\partial u'_i}{\partial x_j} \frac{\partial u'_i}{\partial x_j}\)

For a two-dimensional velocity field the dissipation is:

\[
\text{Dissipation} = -v \left[ \left( \frac{\partial u'}{\partial x} \right)^2 + \left( \frac{\partial u'}{\partial y} \right)^2 + \left( \frac{\partial v'}{\partial x} \right)^2 + \left( \frac{\partial v'}{\partial y} \right)^2 \right]
\]

Turbulent diffusion: \(\frac{\partial}{\partial x_j} \left( -\frac{1}{2} u'_i u'_i u'_j \right)\)

For a two-dimensional velocity field the turbulent diffusion term is:

\[
\text{Turbulent Diffusion} = -\frac{1}{2} \left( \frac{\partial (u'^3 + u'v'^2)}{\partial x} + \frac{\partial (u'^2 v' + v'^3)}{\partial y} \right)
\]

The gradients of both the streamwise and vertical components were determined with a finite-difference approximation from the PIV velocity field data. The values of \(u'\) and \(v'\) at any given point inside the PIV field of view are known from the PIV measurements. Hence, taking the spatial derivatives in both directions the corresponding term is evaluated at the midpoint of the points considered in the calculation.

The experimental measurements in the wake of a cylinder (Browne et al., 1987) and in the wake of a splitter plate (Liu & Thomas, 2004) show that the magnitude of the pressure diffusion term is very small. The experimental measurements of Liu & Thomas (2004) also confirm that the magnitude of the viscous diffusion term is very small in
magnitude and does not contribute significantly in turbulence energy budget. The pressure diffusion and the viscous diffusion terms were not considered in the analysis of present data. The magnitudes of the dissipation term (not presented here) measured in the present experiment are observed to be very small compared to convection, production and turbulent diffusion terms. As discussed by Liu & Thomas (2004) that the dissipation terms are highly sensitive to the resolution of measurements because of the mean-square derivatives associated with dissipation term. It is understood that the dissipation term could not be estimated properly from the present experiment and requires further investigation. In the following sections the distribution of the production, convection and diffusion terms at six different axial locations are presented. The results are normalized by $U_{r,LE}^3/H_1$, here, $U_{r,LE}$ is the mean streamwise velocity at reference height ($H_r$) above the leading edge.

**Convection**

In Figure 3.28 the vertical profiles of the convection of the turbulence kinetic energy are presented. It is observed that at streamwise locations $x < \sim 0.5X_r$, closer to the surface, as distance from the surface is increased; the convection term initially attains negative values, then gains positive values of small magnitude and again reaches maximum negative values further away from the surface. At streamwise locations further downstream than $0.5X_r$, the convection term shows similar distribution except for the absence of the negative values close to the surface. With flow moving downstream, the location of maximum negative convection moves away from the surface, the magnitude of maximum negative convection term reduces and also the regions of high negative convection spreads in the vertical direction. At all six axial locations, as distance from the surface is further increased, the convection term approaches to zero. The rate at which the convection term reaches to zero is dependent on the turbulence intensities in the upstream. For higher levels of turbulence intensities, the convection term reaches to zero at a rate slower than lower turbulence upstream cases. Also, the magnitudes of
Figure 3.28: Vertical profiles of convection at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
convection term along the separated shear layer increases as turbulence intensities in the upstream are increased.

Production

In Figure 3.29 the vertical profiles of production term are presented. Closer to the surface the production is very small in magnitude, increasing to maximum values at the location of separated shear layer and then reducing to zero further away from the surface. As flow moves downstream after separation, the magnitudes of maximum production are reduced, the higher production regions spread in the vertical direction and the location of maximum production moves away from the surface. It is also observed that under the separated shear layer the magnitudes of production are not affected much by the upstream conditions. However, with increasing turbulence intensities in the upstream increases the maximum value of production along the separated shear layer and reduces the rate at which the production term decays to zero. The length scales in the upstream flow does not significantly alter the production of turbulence along the separated shear layer.

Turbulent diffusion

Figure 3.30 show the vertical distributions of the turbulent diffusion term. Regions of turbulent diffusion term in the vertical direction consists of a positive region closer to the surface, a negative region little away from the surface and a positive region further away from the surface before reducing to zero into the outer flow. In all regions mentioned above, the magnitude of diffusion is observed to increase with increasing model height turbulence intensities in the upstream flow, whereas the magnitudes of diffusion are not affected by the turbulence length scales in the upstream. In addition to this, the rate at which the diffusion term decays in to the outer flow is also delayed by increasing turbulence intensities in the upstream.
Figure 3.29: Vertical profiles of production at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
Figure 3.30: Vertical profiles of diffusion at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. 
3.3.9 Growth of the separated shear layer

The growth of the separated shear layer is typically investigated in terms of the growth of the vorticity thickness ($\delta_o$) (e.g., Hancock, 2000; Agelinchaab & Tachie, 2008). The vorticity thickness ($\delta_o$) is defined as, $\delta_o = (U_{\text{max}} - U_{\text{min}})/\left(\frac{\partial U}{\partial y}\right)_{\text{max}}$. However, for separated flows the growth of the separated shear layer can also be investigated in terms of the maximum slope thickness ($\delta_{ms}$) defined by $\delta_{ms} = U_{\text{max}}/\left(\frac{\partial U}{\partial y}\right)_{\text{max}}$ (Cherry et al., 1984). The main difference of the maximum slope thickness in contrast to the vorticity thickness is the way how $U_{\text{min}}$ is treated inside the separated flow region. In calculations of the maximum slope thickness the values of $U_{\text{min}}$ is considered as zero in contrast to the calculations of the vorticity thickness.

In Figure 3.31 the axial variations of maximum slope thickness ($\delta_{ms}$) for six upstream conditions as obtained from present experiment are presented. On the figure, the results obtained by Cherry et al. (1984), Ota & Itasaka (1976) and Kiya et al. (1982) for two-dimensional bluff body placed in uniform upstream flows are also presented. The results of Ota & Itasaka (1976) and Kiya et al. (1982) are obtained from Cherry et al. (1984). For the present experimental data and the data for two-dimensional bluff bodies the growth rate of the separated shear layer ($\frac{\partial \delta_{ms}}{\partial X}$) can be satisfactorily described by a linear relationship. However, from the present experimental data, it is observed that increasing model height turbulence intensities in the upstream boundary layer flows increases the growth rate whereas, upstream turbulence length scales do not significantly affect the growth rates of the maximum slope thickness. It is also observed that the present experimental data show significantly higher values of the growth rate compared to the two-dimensional bluff bodies in uniform upstream flows. The two-dimensional bluff bodies show a very similar value of growth rate of the separated shear layer ($\frac{\partial \delta_{ms}}{\partial X} \sim 0.15$) to that for plane mixing layer. As reported by Brown & Roshko (1974), the growth rate of the separated shear layer for a plane mixing layer is in the range of 0.14-0.22.
Figure 3.32: The growth of maximum slope thickness ($\delta_{ms}$).

Figure 3.32 shows the axial variations of the vorticity thickness for the present experiment with the results of Hancock (2000), Hancock & McCluskey (1997) and Castro & Haque (1988) obtained for two-dimensional blunt flat plate with a long splitter plate placed in uniform upstream flows. The results of Hancock & McCluskey (1997) are obtained from Hancock (2000). It is observed from the results of Hancock (2000) and Hancock & McCluskey (1997) that the growth rate of the vorticity thickness ($\frac{\partial \delta_\omega}{\partial x}$) shows two distinct regions of different growth rates. Up to an axial location of $x=0.7X_r$ the growth rate is very similar to that for a plane mixing layer ($\frac{\partial \delta_\omega}{\partial x} \approx 0.18$) and further downstream the growth rate is reduced. The experimental results of Castro & Haque (1988) is, however, different from the findings of Hancock (2000) and Hancock & McCluskey (1997). Castro & Haque (1988), in uniform and turbulent upstream flows, observe that the growth rates of the vorticity thickness is not linear and the authors conclude that the complex separated flows should not exhibit the linear, plane mixing layer like behavior. However, a series of experimental results for two-dimensional bluff bodies in uniform upstream flows in literature with different bluff body geometries discussed above, show the similarity of the separated shear layers with plane mixing layers at least up to an axial distance of $x=0.7X_r$ from the leading edge.
The present experimental results of three-dimensional bluff body in a turbulent boundary layer upstream, the growth rate of the vorticity thickness is observed to be higher than the plane mixing layer and the growth rate is increased significantly as the model height turbulence intensity is increased. However, turbulence length scales in the upstream does not significantly affect the growth rates of the vorticity thickness. It is interesting to observe that, similar to blunt flat plate with a long splitter plate placed in uniform upstream flows, the present experimental results also show two distinct regions of different growth rates of vorticity thickness; upstream and downstream of \( x \sim 0.7X_r \). This is more prominent for upstream conditions ‘3S’ and ‘3L’. The experimental results of Agelinchaab & Tachie (2008) also observe two separate regions where the growth rates of the vorticity thickness are different for surface mounted obstacles of different geometries.

Hence, from the above results and discussions it is clear that irrespective of the parameter used to investigate the growth rates of the separated shear layer (the vorticity thickness or the maximum slope thickness), the growth rate of the separated shear layer for three-dimensional bluff bodies in turbulent boundary layer flows is linear at least up to an axial distance of \( x = 0.7X_r \) from the leading edge and is significantly higher when compared to two-dimensional bluff bodies in uniform upstream flows.

![Figure 3.32: The growth of vorticity thickness (\( \delta_\omega \)).](image-url)

Figure 3.32: The growth of vorticity thickness (\( \delta_\omega \)).
3.4 Discussions on the results

From the results presented for a three-dimensional bluff body placed in turbulent boundary layer upstream, it is observed that the mean flows in and around the separation bubble are self-similar as the vertical distance from the bluff body surface is normalized by the maximum mean thickness of the separation bubble ($T_{b,\text{max}}$). The mean size of the separation bubble is strongly dependent on the model height turbulence intensities (as discussed in Chapter 2) and in order to maintain the self-similarity of the mean flow the mean thickness of the separation bubble is also reduced. Hence, in the regions of separated and reattaching flows the parameter, $T_{b,\text{max}}$ is an appropriate normalizing parameter of the vertical distance. Hancock (2000) show that for a two-dimensional blunt plate with a long splitter plate, in a range of Reynolds numbers the mean streamwise flow at the reattachment point is self-similar when the vertical axis is normalized by the mean reattachment length, $X_r$. This is qualitatively in agreement with the present experimental results as it is observed that the ratio of the $T_{b,\text{max}}$ to $X_r$ is approximately constant.

Unlike the mean flow, the fluctuating flows in the separated shear layer are very sensitive to the turbulence properties in the upstream and the most dominant Reynolds stress in the separating-reattaching flow region is the streamwise Reynolds stress. Increasing turbulence intensities in the upstream significantly increases the streamwise fluctuations in the separation bubble. These results are in consistent qualitatively with the results obtained for two dimensional blunt plate with a splitter plate (Castro & Haque, 1988) and also for the separated shear layers from a circular cylinder (Khabbouchi et al., 2014). Castro & Haque (1988) explains that upstream turbulence increases the velocity fluctuations in the separated shear layer by increasing flapping motions of the separated shear layer and also by increasing entrainment rates of in the separated flow regions.

From the present experimental results for three-dimensional bluff bodies in boundary layer upstream flows, the vertical Reynolds normal stresses are observed to be very small compared to the streamwise Reynolds normal stresses. Similar observations are made in the experimental results of Iftekhar & Agelincaab (2016) and Ren & Wu (2011) for forward facing steps. However, as observed by Castro & Haque (1987), for two-
dimensional blunt plate with splitter plate placed in uniform upstream flows, the vertical Reynolds normal stresses are comparable with streamwise Reynolds normal stresses in and around the separation bubble. Hence, unlike for surface-mounted obstacles, Reynolds normal stresses in both directions are dominant for two-dimensional blunt plates with splitter plates placed in uniform upstream flows.

The experimental results of Castro & Haque (1987) show that vertical locations of the maximum velocity fluctuations in the separated shear layer move closer to the surface (the splitter plate attached to the blunt plate in this particular case) as the separated flow moves towards the reattachment point. However, in addition to the present experimental results, the results of Iftekhar & Agelinchaab (2016) and Ren & Wu (2011) for forward facing steps and Kiya & Sasaki (1983) for two-dimensional bluff body placed in uniform upstream flows reveal that vertical locations of the maximum velocity fluctuations in the separated shear layer move away from the surface as the reattachment point is approached. These differences in the flow features may be due to the bluff body geometry chosen by Castro & Haque (1987). For the blunt plate attached to a long splitter plate, as chosen by Castro & Haque (1987), the flow separation occurs at the leading edge of the blunt plate and reattaches on the splitter plate a vertical distance below the separation point. This geometry shows some similarities with a backward facing step, except for a backward facing step a boundary layer separates at the edge of the step. For a backward facing step (e. g., Kasagi & Matsunaga, 1995) the locations of maximum fluctuation moves closer to the surface as reattachment point is approached. Hence, the direction of the separated shear layer can be expected as a function of the bluff body geometry.

The growth of the separated shear layer is observed to be linear for three-dimensional surface-mounted bluff body used in the present experiment, which is in consistent with the growth of plane mixing layers. The rate at which the separated shear layer grows is strongly dependent on model height turbulence intensity and for the present experimental results the growth rates are observed to be significantly higher than two-dimensional bluff bodies in uniform upstream flows and for plane mixing layer. One of the reasons of the differences of present experimental results from the two-dimensional bluff bodies in
uniform upstream flows observed in literature is due to the different levels of turbulence intensities considered in different experiments.

The choice of the parameter (vorticity thickness or maximum slope thickness) assessing the growth of the separated shear layer affects the results as regions of different growth rates are observed when vorticity thickness is considered. However, for the estimation of the growth of separated shear layer from the leading edges of sharp-edged bluff bodies, the negative values of $U_{\text{min}}$ is more appropriate to neglect as the regions of negative $U$ values within the recirculating regions are not really part of the separated shear layer. Hence, for the separation bubbles formed on the top surface of the bluff bodies the use of maximum slope thickness ($\delta_{\text{ms}}$) can be considered to be more accurate in assessing the growth of the separated shear layer.

### 3.5 Conclusions

From the results and the discussions presented above, the following conclusions can be drawn:

- The distributions of mean streamwise velocity and mean velocity magnitude in and around the separation bubble are essentially self-similar over the range of upstream boundary layer conditions. However, the distributions of mean vertical velocity components and the Reynolds stresses are not self-similar.
- Increasing the turbulence intensity reduces the mean thickness of the separation bubble, whereas the turbulence length scales do not significantly affect it.
- Increasing turbulence intensity in the upstream shrinks the region of maximum streamwise velocity fluctuations along the separated shear layer, with highest values near the leading edge.
- The magnitudes of streamwise velocity fluctuations along the separated shear layer increase with increasing turbulence intensity upstream. However, when compared to the fluctuations in the outer flow, velocity fluctuations in the separated shear layer is observed to be higher for lower turbulent upstream cases.
➢ Reynolds normal stresses in the streamwise direction are the most significant Reynolds stress within and around the separated and reattaching flow for surface-mounted bluff bodies in turbulent boundary layers.

➢ The growth of the separated shear layer is observed to be linear at least up to an axial location of $x=0.7X_r$ from the leading edge. Increasing model height turbulence intensity increases the growth rate of the separated shear layer and turbulence length scales in the upstream do not significantly alter the growth rate.

➢ With increasing turbulence intensities in the upstream the magnitudes of convection, production and diffusion terms in the turbulence energy budget increases. However, the rate at which these terms reduce to zero far above the surface is decreased by increasing turbulence intensities in the upstream.
References


Chapter 4

4 Effects of boundary layer turbulence on roof-surface pressure fluctuations for a three-dimensional prism

4.1 Introduction

Surface pressure fluctuations occurring on the roof surfaces of low-rise buildings are of particular importance as these may cause severe effects on the roof-mounted structures (e.g., solar panels) and on the roof structure itself, especially during the extreme wind conditions. The fluctuating pressure field on the surface under the separation bubble occurs because of the fluctuating flow in the high turbulent recirculation region. Changes in turbulence properties in the upstream have significant effects on pressure fluctuations and hence, the aerodynamic loads on the surface underneath the separating and reattaching flows for two-dimensional bluff bodies (Gartshore, 1973; Hillier & Cherry, 1981; Saathoff & Melbourne, 1989 and 1997). There have been a number of studies addressing this issue for two-dimensional bluff bodies placed in uniform upstream flows.

Experimental results of Hillier & Cherry (1981) show that, for two-dimensional bluff bodies placed in uniform upstream flows, the surface pressure fluctuations under the separation bubble are strongly dependent on the free stream turbulence intensity. Similar results were found by Kiya & Sasaki (1983b) and Saathoff & Melbourne (1989 and 1997). It was also observed by Hillier & Cherry (1981) that, despite the independence of the mean pressures to free stream integral length scale changes, the fluctuating pressures under the separation bubble are strongly dependent on the free stream turbulence length scales. The dependence of fluctuating pressures on free stream turbulence intensity and integral length scale observed by Saathoff & Melbourne (1997) is presented in Figure 4.1. The uniform upstream conditions in the experiment of Saathoff & Melbourne (1997) consist of smooth and turbulent upstream conditions with two different turbulence length scales. The experimental results of Cherry et al. (1984), obtained for two-dimensional bluff bodies placed in smooth upstream flow, are also presented in Figure 4.1. The
horizontal axis represents the distance from the leading edge normalized by the mean reattachment length ($X_r$). It is observed that the distributions of the standard deviations of pressure coefficient ($Cp'$) under the separation bubble for smooth upstream conditions obtained by Cherry et al. (1984) and Saathoff & Melbourne (1997) are in very good agreement. For smooth upstream conditions the pressure fluctuations are very low close to the leading edge and gradually increase further downstream as the mean reattachment point is approached. Increasing turbulence intensity in the upstream increases the magnitude of surface pressure fluctuations under the separation bubble by a large extent. In addition to this, the location of maximum pressure fluctuations is observed to move towards the leading edge. The movement of the location of maximum pressure fluctuations towards the leading edge for uniform turbulent upstream conditions are also observed by Hillier & Cherry (1981). Hence, for two-dimensional bluff bodies in uniform upstream flows, turbulence intensities in the upstream affect the distribution of surface pressure fluctuations in two different ways; by increasing the magnitude of pressure fluctuations and by shifting the location of maximum pressure fluctuations towards the separation point (leading edge).

It is evident from Figure 4.1 that turbulence length scales in the upstream flow affect the surface pressure fluctuations for two-dimensional bluff bodies placed in uniform upstream flows by increasing the magnitudes of pressure fluctuations. However, for
similar levels of turbulence intensities in the upstream, increasing the turbulence length scales do not alter the location of maximum surface pressure fluctuations. Hence, the magnitude of surface pressure fluctuations is a combined effect of freestream turbulence intensities and length scales, whereas the location of maximum pressure fluctuation is only dependent on turbulence intensities in the upstream in these two-dimensional flows.

In order to formulate the combined effects of turbulence intensity and length scale on surface pressure fluctuations at the separation point, Saathoff and Melbourne (1997) found a relation of the empirical parameter (first proposed by Taylor (1936) as cited in Bearman and Morel (1983)), \( \eta = (\sigma/U)(L_x/D)^n \), (where \( \sigma/U = I_u \), is the turbulence intensity, \( n=0.15 \) and \( L_x/D \) is the streamwise turbulence length scale normalized by the bluff body thickness). Saathoff and Melbourne (1997) found that the variation of fluctuating pressure near separation varies linearly with the empirical parameter (\( \eta \)). Bearman (1971) shows that for a square plate, placed normal to the upstream flow the correlation to the empirical relation is valid for the turbulent scale exponent of 2. Bearman & Morel (1983) suggest that the empirical relation is also a function of the thickness of the separated shear layer for a separated flow.

The mechanisms by which the large magnitude surface pressure fluctuations under two-dimensional separation bubbles in smooth flow arise have been investigated experimentally in many studies. Cherry et al. (1984), Kiya & Sasaki (1983b) and Hillier & Cherry (1981) conclude that the primary source of pressure fluctuations on the surface under the separation bubble is associated with the convection of shear layer vortices. It is well established in literature that separated shear layers from bluff bodies experience transition from laminar shear layer to turbulent shear layer. It is observed that the laminar shear layer rolls up to form Kelvin-Helmholtz vortices (K-H vortices) short distance downstream of the separation point and further downstream from separation, pairing of the K-H vortices into larger and stronger vortices occur. The measurements along the separated and reattaching shear layer by Kiya & Sasaki (1983a) also reveal the incremental size of these vortices as separated shear layer moves downstream from separation. Kiya & Sasaki (1983a, 1983b and 1985) show that, near the separation point the K-H vortices are primarily responsible for the surface pressure fluctuations. However,
as the K-H vortices start to roll up and form stronger vortices further downstream the surface pressure fluctuations increase. The stronger vortices also enhance the entrainment of higher momentum outer flow into the separated flow which in turn leads the separated flow to reattach on the surface (Hillier & Cherry, 1981; Bearman & Morel, 1983; Kiya & Sasaki, 1983b). At the reattachment point, comparatively larger and stronger vortices impinge on the surface causing higher pressure fluctuation for these two-dimensional bluff bodies (Kiya & Sasaki, 1983a and 1985).

Formation and impingement of vortices is not the only mechanism characterizing the surface pressure fluctuations for two-dimensional bluff bodies in uniform smooth upstream flows. Kiya & Sasaki (1985) observed that the size of the separation bubble increases due to the accumulation of small scale rolled up vortices. When a sufficiently large separation bubble is formed, a large vortex is shed from the separation bubble causing the separation bubble to reduce in size. This mechanism induces a low-frequency flapping motion of the separated shear layer. The existence of these intermittent shedding of large scale vortices from the reattachment zone is also observed by Cherry et al. (1984). The flapping motion of the separated shear not only affects surface pressures near the leading edge, but also the pressures under the entire separation bubble (Kiya & Sasaki, 1985).

Comparatively fewer studies have focussed on the aerodynamic mechanisms by which the turbulence properties in the upstream (turbulence intensities and length scales) affect the distribution of surface pressure fluctuations (e.g., the increase in magnitude of fluctuations, movement of the location of maximum pressure fluctuations closer to the leading edge). Hillier & Cherry (1981) and Bearman & Morel (1983) indicate that the possible ways by which the turbulent upstream interacts with the separated flows for two-dimensional bluff bodies are by promoting the transition of the separated shear layer and by influencing the structures present in the separated shear layer. Kiya & Sasaki (1983b) reach similar conclusions as they observe increased growth rate of the rolled up vortices in the shear layer as turbulence in the upstream is increased. However, the process by which the length scales in the upstream influences the magnitude of surface pressure fluctuations is not understood. Saathoff & Melbourne (1989 and 1997) speculate that
increasing turbulence length scales in the upstream allows more time for the vortex in the shear layer to grow both larger and stronger since the larger scales in the freestream reduce the high frequency disturbances of the small scale turbulence. The presence of these larger and stronger shear layer vortices is responsible for large pressure fluctuations on the surface.

Few studies are found in the literature addressing the effects of turbulence in thick boundary layer flows on the surface pressure fluctuations on three-dimensional surface-mounted bluff bodies. The effects of boundary layer turbulence on surface pressure fluctuations on three-dimensional bluff bodies are important to study as this resembles the low-rise buildings exposed to highly-turbulent atmospheric surface layers. Due to the challenges in controlling the turbulence intensities and turbulence length scales independently in an experiment, there is not a complete understanding of the independent effects of turbulence intensity and length scale on aerodynamic forces on low-rise buildings. Data for a low-rise building model in a simulated atmospheric boundary layer (Pratt, 2012) are included in Figure 4.1. These data indicate an even higher magnitude of standard deviation of pressure coefficients ($C_p'$) with peak values even closer to the leading edge. The mechanisms of these have not been examined in the literature. However, it is worth noting that the model height turbulence intensity and length scale is significantly higher in the incident boundary layer considered by Pratt (2012) than the uniform upstream flow cases presented in the figure (Figure 4.1).

Some models, based on the Quasi-Steady (Q-S) theory, have been developed in the literature in order to predict surface pressure fluctuations and surface peak pressures. As explained by Cook (1990), cited in Richards & Hoxey (2004), the Quasi-Steady theory based models predict the peak pressures by taking into account the mean pressures and upstream flow conditions. In addition to the upstream velocity field, the elevation angle and the azimuth angle of the velocity vectors are also incorporated in the models (e.g., Letchford et al., 1993, Richards & Hoxey, 2004; Wu & Kopp, 2016). Even though there are several upstream flow parameters included in these models to increase accuracy of the Quasi-Steady theory based models, lack of wind tunnel experimental data restricts these models to incorporate some simplifications (Richards & Hoxey, 2004).
it is observed that the surface pressure fluctuations cannot be predicted with higher accuracy by these models, especially when vortices are present (Banks & Meroney, 2001b). For example, the predictions of the surface peak pressures by the model developed by Richards & Hoxey (2004) show significant dissimilarities with the experimental measurements in the regions of separated and reattaching flows. They indicate towards the dynamic behavior of the separated flows due to the generation of vortices from the leading edge. Incorporating an additional parameter related to the strength of the vortices, Banks & Meroney (2001a and 200b) observe an improved accuracy of a Quasi-Steady theory based model; however, for a ‘classical’ corner vortex. Whereas the importance of the vortices present in the separated flow regions on surface pressures has been demonstrated by several researchers, a complete understanding of effects of these vortices in relation to surface pressures for three-dimensional surface-mounted bluff bodies has not been well developed.

The objective of this chapter is to examine the effects of turbulence intensity and length scale in the turbulent boundary layer upstream flows on the surface pressure fluctuations for surface-mounted three-dimensional bluff bodies, to identify the key flow parameters involved in characterization of surface pressure fluctuations and to investigate the responses of these parameters to the turbulence properties in the boundary layer upstream flows. Time-Resolved Particle Image Velocimetry measurements of the flow field in and around the separation bubble formed on the roof surface of a surface-mounted three-dimensional bluff body, synchronized with the measurements of surface pressures under the separation bubble will be utilized to achieve the above mentioned objectives. A detailed description of the upstream conditions, experimental procedures and experimental models are provided in section 2.2 of Chapter 2.

4.2 Surface pressure fluctuations under the separation bubble

In Figures 4.2, 4.3, 4.4 and 4.5 the distribution of the standard deviations of surface pressure fluctuations ($C_p'$) along the roof centreline are presented for Building-1 and Building-2, respectively. It is observed that increasing both turbulence intensities and
Figure 4.2: Distribution of standard deviation of pressure coefficients ($C_p$') along roof centreline for Building-1.

Figure 4.3: Distribution of standard deviation of pressure coefficients ($C_p$') along roof centreline for Building-2.
length scales in the incident flow increase the magnitude of surface pressure fluctuations while the location of maximum pressure fluctuations moves closer to the separation point. These results qualitatively match the results of two-dimensional bluff bodies
placed in uniform upstream flows. In Figure 4.2 and Figure 4.3, the horizontal axis, representing the distance from the leading edge, is normalized by the model heights (H) while in Figure 4.4 and Figure 4.5 the distance from the leading edge is normalized by the mean reattachment lengths (X). Hence, the differences in the locations of peak fluctuations (Cp’_max) in Figure 4.2 and Figure 4.3 are the absolute distance, whereas the differences in the locations of peak fluctuations (Cp’_max) in Figure 4.4 and Figure 4.5 are the differences in locations of the peak fluctuations with respect to the mean reattachment lengths (X). The locations of Cp’_max for Building-1 and Building-2 are presented in Table 4.1 with the magnitudes of the peak fluctuations. It is observed from the table that increasing the turbulence intensity in the upstream causes the location of Cp’_max to move closer to the leading edge (both absolute and with respect to the mean reattachment length). This observation is more prominent for Building-2 where the resolution of the pressure taps is significantly higher than Building-2.

<table>
<thead>
<tr>
<th>Upstream condition</th>
<th>Building-1</th>
<th>Building-2</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cp’_max</td>
<td>x/X at Cp’_max</td>
</tr>
<tr>
<td>1L</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>1S</td>
<td>0.21</td>
<td>0.29</td>
</tr>
<tr>
<td>2L</td>
<td>0.34</td>
<td>0.21</td>
</tr>
<tr>
<td>2S</td>
<td>0.3</td>
<td>0.21</td>
</tr>
<tr>
<td>3L</td>
<td>0.61</td>
<td>0.24</td>
</tr>
<tr>
<td>3S</td>
<td>0.47</td>
<td>0.24</td>
</tr>
</tbody>
</table>

A very simple form of the Quasi-Steady model described in Holmes (2001) can be rearranged to establish a relationship between the turbulence intensity in the upstream (I_u), the mean pressure coefficient (Cp\text{mean}) and the standard deviation of pressure coefficient (Cp’) of the form, Cp’ = 2I_uCp\text{mean}. The distributions of Cp’ for the present experiments and the predictions of Cp’ by the simple Quasi-Steady model are compared in Figure 4.6 and Figure 4.7 for Building-1 and Building-2 respectively. It can be observed that the predictions of Cp’ by the simple Quasi-Steady model does not hold for
Figure 4.6: Comparisons of the distributions of $C_p'$ with simple Quasi-Steady theory predictions for Building-1 model.
Figure 4.7: Comparisons of the distributions of $C_p'$ with simple Quasi-Steady theory predictions for Building-2.
the upstream conditions considered in this experiment. The simple Quasi-Steady model sometimes under predicts and sometimes over predicts the magnitudes of $Cp'$. In addition to that, the distribution of $Cp'$ on the surface under the entire separation bubble cannot be predicted by the Quasi-Steady theory of this simple form. The upstream conditions considered in the present experiment, in addition to different turbulence intensities, consist of different ranges of turbulence length scales. The differences in the experimental results from the Quasi-Steady predictions indicate real changes in aerodynamic behavior depending on the properties in the incident flow which are not accounted for in the simple Quasi-Steady theory based model.

4.3 Effects of flow parameters on surface pressure fluctuations

In order to better understand the differences discussed in the previous section, the surface pressure fluctuations on the roof surface of Building-1 as a function of different flow parameters in and around the separation bubble and separation bubble properties were investigated in more detail. The results are presented in the following sections. It is observed from the figures of Building-1 (presented in the earlier sections) that the pressure tap located at $x=0.22H_1$ (pressure tap 2) show the maximum values of pressure fluctuations (except for upstream conditions ‘1S’ and ‘1L’) compared to other locations where surface pressures were measured. Hence, the pressure tap located at $x=0.22H_1$ will be investigated with more emphasis in the following sections. The location of the pressure tap chosen for analysis, at $x=0.22H_1$, is a fixed location on the surface which varies with respect to the mean reattachment length ($X_r$) as the mean reattachment length was observed to decrease with turbulence intensity in the upstream (Chapter 2).

In Figure 4.8 the statistical distributions of the suction coefficients normalized by the standard deviations the suction coefficients ($-Cp/Cp'$) recorded over a time period of approximately 160s at $x=0.22H_1$ is presented for all six upstream conditions. It is observed that for all of the upstream conditions the distributions of $-Cp/Cp'$ are positively skewed. In Table 4.2 the skewness in the distributions of $-Cp/Cp'$ are presented. However, a systematic variation of the skewness with upstream conditions has not been
Figure 4.8: Statistical distribution of $-\frac{C_p}{C_p'}$ at $x = 0.22H_1$ for upstream condition (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
observed. It is also interesting to observe from Figure 4.8 that increasing turbulence intensities increases number of samples \(-Cp/Cp'\) closer to zero. For upstream conditions ‘3S’ and ‘3L’ even the negative values of \(-Cp/Cp'\) occur (i. e., there are positive pressures).

<table>
<thead>
<tr>
<th>Table 4.2: Skewness in (-Cp) at pressure tap 2.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Condition</td>
</tr>
<tr>
<td>Skewness in (-Cp)</td>
</tr>
</tbody>
</table>

4.4 Examination of Separated-Shear-Layer Dynamics

It was discussed earlier that several researchers have found the flapping motion of the separated shear layer affecting the surface pressures under the separation bubble, including pressures closer to the leading edge, for two-dimensional bluff bodies in uniform smooth upstream flows. In order to investigate the equivalence of this phenomenon for three-dimensional surface-mounted bluff bodies in turbulent upstream flows, it is necessary to track the movement of the separated shear layer in time, which is possible to do with the use of TR-PIV data.

4.4.1 Identification of the instantaneous positions of the separated shear layer

The instantaneous vertical position of the centre of the separated shear layer is identified based on the location of the local maxima of the streamwise velocity gradient in the vertical direction. A similar technique was used by Lander et al. (2016) to identify the instantaneous position of the shear layer separated at the leading edge of a two-dimensional square prism. One specific example is shown in Figure 4.9, where the identified centre of the separated shear is plotted (black line) along with the instantaneous streamlines and contours of streamwise (Figure 4.9(a)) and vertical velocity (Figure 4.9(b)). It is observed (from an analysis of the full data set) that the location of the centre of the separated shear layer up to a streamwise distance of about \(x \sim 0.4H_1\) can be satisfactorily identified, although there are occasional points that are clear outliers. For \(x > \sim 0.4H_1\), the method fails to predict the location of the shear layer because of large
gradients in the vortex core. However, the location of the particular pressure tap under investigation (pressure tap 2, at $x=0.22H_1$), where the maximum surface pressure fluctuations are observed, being located within the streamwise range where the separated shear layer can be satisfactorily identified, it is possible to investigate the relationships between the pressure fluctuations at pressure tap 2 with the movement of the separated shear layer above it.

Figure 4.9: Instantaneous position of the separated shear layer and velocity contours of (a) streamwise and (b) vertical velocity components.

4.4.2 Influence of shear layer movement on surface pressures

In order to understand the relationships between the pressure fluctuations at pressure tap 2 (at $x=0.22H_1$) with the movement of the separated shear layer above it, the conditionally-averaged vertical positions of the separated shear layer based on surface pressure coefficients recorded at pressure tap 2 were investigated. In the conditional-averaging process, the instantaneous pressure coefficients at pressure tap 2 were divided into a number of segments from the minimum value to the maximum value (where the width of each segment was set to be 0.1). The vertical positions of the shear layer during the occurrences of pressure coefficients within each segment of pressure coefficients ($\langle C_p \rangle$) were recorded and averaged to identify the conditionally-averaged positions of
the separated shear layer. Data for \( <C_p> \) ranges where less than 500 velocity data (data equivalent to one second of PIV data) were obtained were not included in the analysis (in order to obtain a reliable statistics). The results are presented in Figure 4.10. In Figure 4.10, the 25\(^{th}\) and 75\(^{th}\) percentiles of the data in each segment are also presented to display the variability in the conditionally-averaged pressure coefficients (\( <C_p> \)). In the figure the vertical axis represents the conditionally averaged positions of the separated shear layer with respect to the maximum mean thickness of the separation bubble (\( T_{b,\text{max}} \)).

Figure 4.10 demonstrates that, even though there is a significant variability in the positions of the conditionally-averaged shear layer (as observed from the 75\(^{th}\) and 25\(^{th}\) percentiles of the data presented in the figure), during the occurrence of high suctions (i.e., low \( C_p \) values) the position of the shear layer is observed to be closer to the surface. In contrast, the shear layer tends to be further away from the surface during low suction events. For upstream conditions ‘2’ and ‘3’ the ranges in which the conditionally-averaged positions of the separated shear layer vary are observed approximately \( 0.1T_{b,\text{max}} \) and \( 0.15T_{b,\text{max}} \) respectively. For upstream conditions ‘1’ this range is approximately \( 0.05T_{b,\text{max}} \). Hence, the movement of the separated shear layer is observed to affect the surface pressures to some extent.

![Figure 4.10: Conditionally averaged positions of separated shear layer at x=0.22H1.](image-url)
It is also worth noting that for higher model height turbulence intensities the positions of the separated shear layer tend to be located further away from the surface and turbulence length scales in the upstream do not affect the locations of the separated shear layer. These differences arise mainly due to the choice of the location (at $x=0.22H_1$) above which the positions of the separated shear layer are considered in the analysis. As increasing turbulence intensity in the upstream causes reduction in the maximum mean thickness of the separation bubble ($T_{b,\text{max}}$) as well as the mean reattachment length ($X_r$), the location of the pressure tap 2 ($x=0.22H_1$) is closer to the axial location where $T_{b,\text{max}}$ occurs for upstream conditions ‘3’ compared to upstream conditions ‘1’ and ‘2’. Hence, the positions of the separated shear layer at $x=0.22H_1$ is always closer to $T_{b,\text{max}}$ considered for scaling the vertical axis in the figure.

4.5 Influence of velocity gusts on surface pressure fluctuations

In Figure 4.9(a) and Figure 4.9(b), it is observed that there are regions of high velocity, both streamwise and vertical, just outside the separated shear layer near the leading edge. The state of the velocity in these regions has the potential to affect the surface pressure fluctuations. In order to understand how the upstream turbulence properties interact with the separated flow from the leading edge and the formation of surface pressure fluctuations the statistical relationships between the outer velocities and the magnitude of the surface pressure fluctuations are required to be understood.

Quasi-Steady models (e. g., Richards & Hoxey, 2004; Banks & Meroney, 2001a and 2001b) developed to predict the surface pressures on the roof surfaces of surface-mounted three-dimensional bluff bodies, exposed to a variety of wind directions, the effects of velocity fields around the bluff bodies has always been found to produce significant effects on surface pressures. However, some studies have correlated the velocities at a point far away from the surface (Richards & Hoxey, 2004) whereas some studies were found to correlate the velocities at a point closer to the surface (Banks & Meroney, 2001a and 2001b). Due to the difficulties involved in experiments, the effects of the velocities over a large region closer to the surface and inside the highly turbulent separated flow regions have not been developed. As discussed by Hillier & Cherry (1981)
and Kiya & Sasaki (1985), the information of the velocity field in a larger region is important to understand the effects of velocities on surface pressures. Even though point velocity measurement techniques placed within the shear layer (e.g., hot-wire anemometry) provide reliable data, at a point instead of over a large region, they tend to interact with the separated flow and alter it. From the present experiment, which involves Time-Resolved Particle Image Velocimetry measurements of the separated flow, it is possible to extract the velocity field information in a larger region around the separated flow without altering the flow. The results are presented and discussed in the following.

At first, the correlations of the velocity fields (streamwise (u), vertical (v) and magnitude of velocities (|v|)) with surface pressures at \(x=0.22H_1\), 0.4\(H_1\) and 0.8\(H_1\) (pressure tap 2, 3 and 4 respectively) are investigated. The distributions of the correlation coefficients of |v| around the model with surface pressures at \(x=0.22H_1\) are presented in Figure 4.11. The distributions of the correlation coefficients of u and v with pressure tap 2 are presented in Appendix C (Figures C.1 and C.2) and the distributions of the correlation coefficients of |v|, u and v with pressure taps 3 and 4 are presented in Appendix C (Figures C.3 to C.8).

It is observed (comparing Figure 4.11 with Figures C.1 to C.8 in Appendix C) that |v| shows the highest values of correlation coefficients compared to u and v almost everywhere in the flow field. However, the vertical velocity component (v) shows the weakest correlation with surface pressures for all of the pressure taps, whereas the magnitudes of the correlation coefficients of the streamwise velocity component (u) is comparable with the correlation coefficients of |v|. It was discussed in Chapter 3 that the vertical component (v) of the velocity field is small in magnitude around the separated flow and does not contribute much to the velocity magnitude (|v|). Hence, only the effects of the velocity magnitudes (|v|) are utilized in the analysis.

Figure 4.11 reveals that the magnitude of the correlation coefficients of |v| with pressure tap 2, is very high close to the leading edge and just outside the mean separating and reattaching streamlines. For larger model height turbulence intensities and length scales in the approaching boundary layer flows, the magnitudes of the correlation coefficients
Figure 4.11: Contours of correlation coefficients of $|v|$ with surface pressures at $x=0.22H_1$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
increase considerably, from a peak of about 0.45 for upstream condition ‘1S’ to about 0.7 for ‘3L’. In addition to that, the regions of high correlation coefficients are observed to spread over larger areas for larger turbulence intensities and length scales.

It has been well established in the literature that the surface pressure fluctuations are dependent on the velocity fluctuations in a region over the surface instead of a particular point (e. g., Kiya & Sasaki, 1985; Hillier & Cherry, 1981). For the present experiment, in order to find the region around the flow field, a search was conducted within the flow field and the region of the highest value of correlation coefficient of area averaged velocity magnitude ($|V|_A$) with surface pressure measurements was identified. The area averaged velocity magnitude ($|V|_A$) is defined as $|V|_A = \frac{\sum |V|_i A_i}{\sum A_i}$. Here, $|V|_i$ is the velocity magnitude around a point $i$ in the flow field, $A_i$ is the small area in between two adjacent points. The area averaged velocity in the highly correlated area is expressed as $|V|_{CA}$ and this region is observed to be located just outside the shear layer little above the leading edge for all six upstream conditions. This region is marked on Figure 4.11(f). For cornering wind over a surface-mounted three-dimensional bluff body Banks & Meroney (2001a and 2001b) observed the maximum value of the correlation coefficients of streamwise velocity ($u$) with surface pressures to be 0.82 at a vertical location above the pressure tap considered in their experiment. For the present experiment the maximum value of the correlation coefficient of ($|V|_{CA}$) with pressure tap 2 was observed to be 0.75 and the minimum value was observed to be 0.5 for upstream conditions ‘3L’ and ‘1S’ respectively.

The surface pressures recorded at tap 2 (at $x=0.22H_1$) were conditionally-averaged based on the area averaged velocity magnitude in the highly correlated region ($|V|_{CA}$) in order to understand the variation of surface pressures with the velocity field around the model. The results are presented in Figure 4.12. In the figure $|V|_{CA}/U_{t,LE}$ is presented along the horizontal axis and the vertical axis represents the conditionally-averaged surface pressure coefficients ($<C_p>$) normalized by the corresponding mean pressure coefficients.
Figure 4.12: Variations of conditionally-averaged pressure coefficients \((<C_p>/C_{p\text{mean}})\) at \(x=0.22H_1\) with area-averaged velocity magnitude in the highly correlated region \((|V|_{CA}/U_{r,LE})\).

\((C_{p\text{mean}})\). Hence, any value along the vertical axis is an indication of the deviation of the conditionally-averaged pressure coefficients from the mean pressure coefficients. It is observed from the figure that for all of the upstream conditions the surface pressures equal to the mean pressures \((<C_p>/C_{p\text{mean}} = 1)\) occur at a when \(|V|_{CA}\) is observed to be close to \(U_{r,LE}\). During the occurrences of \(|V|_{CA}\) less than the \(U_{r,LE}\) the surface pressures start to show values less than the mean pressures and as \(|V|_{CA}\) increases, the surface pressures show higher values than \(C_{p\text{mean}}\). Increasing turbulence intensities in the upstream gives rise to broader ranges of \(|V|_{CA}/U_{r,LE}\) (this can also be observed from the statistical distributions of \(|V|_{CA}/U_{r,LE}\) presented in Figure D.1 in Appendix D) and hence, pressures on the surface also deviate from the mean in a broader range giving higher values of standard deviations of pressure coefficients. Increasing the turbulence length scales increases the range of \(|V|_{CA}/U_{r,LE}\) by a significantly small amount, if at all. Hence, the contributions of turbulence length scale in surface pressure fluctuations by altering the velocity fields in the highly correlated region are significantly smaller compared to the contributions of turbulence intensity in the upstream.
A solid line representing the quadratic variation of $\langle Cp \rangle/\langle Cp \rangle_{\text{mean}}$ with $|V|_{CA}/U_{r,LE}$ is superimposed on the plots in Figure 4.12. It is observed that the experimental results match very well with the quadratic line, except the regions close to extreme ends. Hence, the general conjecture that surface pressures vary with square of velocity magnitudes hold well for the experimental results. On the figure the 25th and 75th percentiles of $\langle Cp \rangle/\langle Cp \rangle_{\text{mean}}$ are also plotted to show the amount of scatter present in the data of each $|V|_{CA}/U_{r,LE}$ segment used for conditional-averaging process. The amount of variability associated with the data in the segments of $|V|_{CA}/U_{r,LE}$ higher than 1.5 is considerably high. However, the variations in the other segments are observed to be small. One of the sources of this variations in the data are the presence of insufficient amount of $\langle Cp \rangle/\langle Cp \rangle_{\text{mean}}$ samples in each of segments of $|V|_{CA}/U_{r,LE}$ higher than 1.5. However, the variations in the data may also refer to some other dynamics involved in surface pressure fluctuations which cannot be explained in terms of fluctuations in the velocity field.

4.6 Influence of vortices on surface pressure fluctuations

It is clearly observed from the above results and discussions that even though the gust velocities around the bluff bodies have significant effects on surface pressures, velocity fluctuations are not the only parameter involved in the process of characterizing the surface pressures. This is one of the key reasons the simple Quasi-Steady theory show less accuracy to predict the surface pressures on bluff bodies where significant amount of body generated effects are present (e. g., in the separated flow regions) (Cook, 1990; as cited in Richards & Hoxey, 2004). It is demonstrated in the studies investigating the surface pressures of two-dimensional bluff bodies in uniform upstream flows, reviewed in the Introduction, that the vortices in the separated shear layer play important role in the fluctuations of surface pressures. The experimental results of Banks & Meroney (2001a and 2001b), for a classical corner vortex over surface-mounted three-dimensional bluff body, also demonstrate the relationship of surface pressures fluctuations with the vorticity field above it. Hence, for the present experiment the effects of the vortices present in the separated flow and the separation bubble are needed to be investigated in relation to surface pressures.
As described by Chakraborty et al. (2005), a compelling definition of a vortex is a topic of argument. However, Chong et al. (1990) have prescribed a method to effectively identify a vortex by using the second eigenvalue of the velocity gradient tensor, \( u_{ij} = \frac{\partial u_i}{\partial x_j} \).

In order to identify the vorticity in a turbulent boundary layer, Adrian et al. (2000) applied this technique successfully on their PIV data. Similar technique was used in the two-dimensional PIV measurements of Taylor et al. (2010) around elongated bluff bodies to identify the location of vortices during flutter. For a two dimensional velocity fields, the presence of complex eigenvalues of the velocity gradient tensor indicates the swirling motion of the fluid about the point, an indication of the presence of a vortex (Taylor, 2011). As described by Adrian et al. (2000), Zhou et al. (1996) quantified the strength of any local swirling motion by the positive complex portion of the eigenvalues of the velocity gradient tensor. They defined this as swirling strength, \( \lambda \). In identification of vortices from the vorticity contours, the regions of high shear may show high values of vorticity without the presence of a real vortex in the region. However, identification of vortices in terms of swirling strength (\( \lambda \)) has been observed to less sensitive to this kind of error (Taylor, 2011).

For the present experiment, a similar technique was applied to identify the vortices present in the flow field around the surface-mounted prism. In Figure 4.13 an instantaneous contour of the swirling strength (\( \lambda \)) is presented. On the contour plot, instantaneous streamlines and the positions of the separated shear layer (yellow lines, up to an axial location of \( x=0.4H_1 \)) are superimposed. It is observed that most of the vortices are associated with the instantaneous position of the separated shear layer.

From the investigations on the time series of the full set of data, for all six upstream conditions, it was visually observed that high swirling strength contours are present at the leading edge and convect downstream. Lander et al. (2016) have shown that turbulence originating at the stagnation streamline causes a by-pass transition of the turbulence at the leading edge of the separated shear layer, as speculated by Gartshore (1973). This leads to distinct turbulent vortices already present in the shear layer at the leading edge, rather
than the Kelvin-Helmholtz vortices which form in a separated shear layer generated in smooth flow. It was also observed that pressure fluctuations are related to the vortices present in the separated flow.

In Figure 4.14, the contours of correlation coefficients of surface pressures at pressure tap 2 with $\lambda$ are presented for all six upstream conditions. The contours of correlation coefficients of surface pressures at pressure tap 3 and 4 with $\lambda$ are presented in Figure C.9 and Figure C.10 (in Appendix C). It is observed that the magnitudes of the correlation coefficients are very small, especially when compared to the correlation coefficients of velocity magnitudes ($|V|$). However, when the area averaged swirling strengths were considered, the magnitudes of the correlation coefficients increased significantly.

Area-averaging of the swirling strength was performed in the similar manner of area-averaging of the velocity magnitudes discussed in the previous section. The area averaged swirling strength can be defined as, $\lambda_A = \frac{\sum \lambda_i A_i}{\sum A_i}$. Here, $\lambda_i$ is the swirling strength at point $i$ in the velocity field and $A_i$ is the small area in between two adjacent
Figure 4.14: Contours of correlation coefficients of $\lambda$ with surface pressures at $x=0.22H_1$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
The search for the best correlated area within the flow field reveals that as the area from the leading edge towards the mean reattachment point is increased the magnitude of correlation coefficients of $\lambda_A$ with surface pressures is also increased significantly. The maximum value of the correlation coefficients, for each of the upstream conditions, were found when the total area from the leading edge to the mean reattachment point, vertically bound by the maximum thickness of the mean separation bubble, was considered in the area-averaging process. The area-averaged swirling strength in this highly correlated area is denoted by $\lambda_{CA}$. This region is marked on Figure 4.14(f). The maximum value of the correlation coefficient of $\lambda_{CA}$ with surface pressures at tap 2 was recorded to be around 0.56 for upstream condition ‘3L’ and the minimum value was observed to be 0.38 for upstream condition ‘1S’. These values of correlation coefficients are significantly higher than the value when a small area around pressure tap 2 was considered. For example, for upstream condition ‘3L’, an area of $0.2H_1 \times 0.1H_1$ in the separated shear layer region above pressure tap 2 shows the correlation coefficient of about 0.32 (about 43% smaller than the maximum value reported earlier). Hence, the pressures on a particular location on the surface under the separation bubble are correlated with the total swirling strength present within the separation bubble, not only by the local swirling strength. In further analysis of the dependence of surface pressures on swirling strength, area averaged swirling strengths within the highest correlated area ($\lambda_{CA}$) are considered.

In order to better understand the variations of surface pressures at tap 2 with $\lambda_{CA}$, surface pressure coefficients normalized by corresponding mean pressures ($<Cp>/Cp_{mean}$) were conditionally-averaged based on $\lambda_{CA}$. The results are shown in Figure 4.15 along with the 25th and 75th percentiles of the data. The figure reveals that for most of the upstream conditions the values of $<Cp>$ equals $Cp_{mean}$ for a value of $\lambda_{CA}$ very close to 1, except for upstream condition ‘3S’. Increments in the values of $\lambda_{CA}$ from 1, increases the deviation of $<Cp>$ from $Cp_{mean}$. Also, a reduction in the values of $\lambda_{CA}$ causes increment in the deviation of $<Cp>$ from $Cp_{mean}$; however, in the opposite direction. Hence, the fluctuations in surface pressures are observed to be strongly affected by $\lambda_{CA}$. Increasing turbulence intensities in the upstream increases the range of $\lambda_{CA}$ (this can also be observed from the statistical distributions of $\lambda_{CA}$ presented in Figure 4.16), particularly in
the higher end of $\lambda_{CA}$, and hence, the pressure fluctuations also increase. This indicates that higher turbulence intensities in the upstream forms stronger vortices inside the separated flow regions and these stronger vortices contribute to the surface pressure fluctuations. These findings are in consistent with the speculations of Kiya & Sasaki (1983b).

4.7 Combined effects of both velocity gust and vortices on surface pressure fluctuations

It has been observed in the previous sections that the surface pressures at pressure tap 2 ($x=0.22H_1$) are strongly dependent on the area averaged velocity magnitudes ($|V|_{CA}/U_{r,LE}$) outside the separated shear layer and the area averaged swirling strength ($\lambda_{CA}$) under the mean separation bubble. However, in the previous sections the individual effects of $|V|_{CA}/U_{r,LE}$ and $\lambda_{CA}$ were investigated in detail. It can be observed from Table 4.3 that $|V|_{CA}$ and $\lambda_{CA}$ show satisfactory correlations for all upstream conditions. It is understood that the combined effects of $|V|_{CA}$ and $\lambda_{CA}$ play role in characterization of surface pressures.
Figure 4.16: Statistical distributions of $\lambda_{CA}$ with surface pressures at $x=0.22H_1$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Table 4.3: Correlation coefficients of $|V|_{CA}/U_{r,LE}$ with $\lambda_{CA}$.

| Upstream Condition | Correlation Coefficients of $|V|_{CA}/U_{r,LE}$ and $\lambda_{CA}$ |
|---------------------|-------------------------------------------------|
| 1L                  | 0.50                                            |
| 1S                  | 0.46                                            |
| 2L                  | 0.50                                            |
| 2S                  | 0.51                                            |
| 3L                  | 0.61                                            |
| 3S                  | 0.61                                            |

In order to understand the combined effects of $|V|_{CA}/U_{r,LE}$ and $\lambda_{CA}$ on surface pressure fluctuations, the surface pressures ($<Cp>/Cp_{mean}$) recorded at pressure tap 2 were conditionally-averaged based on both $|V|_{CA}/U_{r,LE}$ and $\lambda_{CA}$. The contour plots of conditionally-averaged $<Cp>/Cp_{mean}$ based on both $|V|_{CA}/U_{r,LE}$ and $\lambda_{CA}$ are presented in Figure 4.17. It is observed that at lower values of $|V|_{CA}/U_{r,LE}$ and $\lambda_{CA}$ the magnitudes of $<Cp>/Cp_{mean}$ are lower and increasing magnitudes of both $|V|_{CA}/U_{r,LE}$ and $\lambda_{CA}$ increase the magnitudes of $<Cp>/Cp_{mean}$. However, there are some regions which do not follow this trend. It is observed that in these regions the number of samples is very low to obtain reliable statistics.

The variation of $<Cp>/Cp_{mean}$ with $|V|_{CA}/U_{r,LE}$ for upstream conditions ‘3S’ and ‘3L’ are presented in Figure 4.18 and Figure 4.19 respectively. Results of two different levels of $\lambda_{CA}$ (0.9 and 1.8) are shown on the plots and the 25th and 75th percentiles in the conditionally-averaged $<Cp>/Cp_{mean}$ data are also presented in order to demonstrate the levels of variations present in the data. These figures more clearly reveal the effects of both $|V|_{CA}/U_{r,LE}$ and $\lambda_{CA}$ on $<Cp>/Cp_{mean}$ discussed in the earlier sections. For similar levels of $|V|_{CA}/U_{r,LE}$, a change in the magnitudes of $\lambda_{CA}$ causes $<Cp>$ to deviate from the $Cp_{mean}$. Similar observations as Figure 4.18 and Figure 4.19 were observed for all six upstream conditions considered in this experiment.

As, similar observations were observed for all of the upstream conditions, Figure 4.20 was plotted taking into account the results of all six upstream conditions for two different levels of $\lambda_{CA}$ (0.9 and 1.8). The variations of $<Cp>/Cp_{mean}$ with $|V|_{CA}/U_{r,LE}$, for both the
Figure 4.17: Variation of $<Cp>/Cp_{\text{mean}}$ with both $|V|_{CA}/U_{r,LE}$ and $\lambda_{CA}$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L. The contours indicate the levels of $<Cp>/Cp_{\text{mean}}$. 
levels of $\lambda_{CA}$, are observed to be satisfactory described by quadratic equations. Even though there is a considerable amount of variability present in the dataset (as observed from the 25$^{th}$ and 75$^{th}$ percentiles of the datasets presented in the figure), there is a convincing trend that a change in $\lambda_{CA}$ is responsible for a deviation of $<Cp>$ from $C_{p\text{mean}}$. The best fit quadratic curve for both the levels of $\lambda_{CA}$ are observed to be parallel for most of the $|V|_{CA}/U_{r,LE}$ range and they are observed to be separated by a value of $<Cp>/C_{p\text{mean}} \sim 0.2$. From the above analysis, it has been convincingly demonstrated that both velocity fields outside the separated shear layer and swirling strengths in the separated flow produce significant effects on surface pressure fluctuations.
4.8 Discussions on the findings

From the results presented in the sections above it has been established that for three-dimensional bluff bodies exposed to turbulent boundary layer flows the surface pressure fluctuations are strongly dependent on both turbulence intensities and length scales. The mechanisms by which turbulence intensities and length scales influence surface pressure fluctuations are different. Comparing these results with the results obtained for two-dimensional bluff bodies in uniform smooth and uniform turbulent upstream flows in different studies, it can be understood that some mechanisms involved in the process of surface pressures fluctuations are similar and some mechanisms are different. The results obtained from the present experiment are discussed below. Comparisons with the features of two-dimensional separated and reattaching flows placed in uniform upstreams (discussed in Introduction with appropriate references) are also made.

For two dimensional bluff bodies in uniform upstream flows, the presence of Kelvin-Helmholtz vortices in the separated shear layer are observed to be rolled up and eventually these vortices are paired to form larger eddies. These eddies are responsible for surface pressure fluctuations near the reattachment point. Turbulence intensities in the
upstream causes the separated shear layer to become turbulent at shorter distance from the leading edge compared to smooth upstream flows. However, for considerably higher turbulent upstream conditions, Lander et al. (2016) clearly demonstrates that the transition to turbulent shear layer occurs very close to leading edge that it appears to be turbulent right at the leading edge. The present experiment involves turbulent boundary layer upstream conditions with model height turbulence intensities ranging from 13% to 28% for Building-1 (used for PIV measurements). For the present experiment the presence of the turbulent eddies were observed to be generated from very close to the separation point as the separated shear layer is turbulent very close to the leading edge. These turbulent eddies are responsible for surface pressure fluctuations very close to the leading edge. This contrasts the flows over two-dimensional bluff bodies in smooth upstream flows where the large pressure fluctuations are observed further away from the leading edge.

The simple Quasi-Steady theory fails to predict the surface pressure fluctuations closer to the leading edge, in the regions of separated flow, due to the presence of the vortices generated from the leading edge. It has been demonstrated in the results that the strength of these vortices (swirling strength is used a measure of the strength of the vortices here) can alter the surface pressures to a great extent. However, it has also been shown that the contributions of the velocity fields outside the separated shear layer is also an important parameter to consider in characterizing surface pressure fluctuations near the leading edge.

Upstream turbulence intensities cause earlier transition of the separated shear layer to turbulence, for two-dimensional bluff bodies in uniform upstream flows, and also contribute to gaining strength of the vortices present in the separated shear layer responsible for high pressure fluctuations. In contrast, for three-dimensional bluff bodies in turbulent boundary layer flows, as the separated shear layer is turbulent from the leading edge, increased turbulence intensities are observed only to increase the strength of the vortices. However, turbulence intensities also increase the correlation of the velocity fields around the shear layer with surface pressures. The effects of turbulence
length scales on the velocity fields and vortices in the separation bubble and could not be explained clearly from the present experiment.

The onset of turbulence very close to the leading edge is observed to have significant influence in surface pressure fluctuations closer to the leading edge. The turbulence along the stagnation streamline is responsible for the shear layer to be turbulent at the leading edge (Lander et al., 2016). Hence, the turbulence properties along the stagnation streamline on the front face of the surface-mounted three-dimensional bluff bodies in relation to the vortices present in the separated shear layer is required to be studied with greater emphasis to better understand the mechanisms by which the free stream turbulence properties affects surface pressures closer to the leading edge. This remains a topic of further study.

In the conditional-averaging to investigate the combined effects of area averaged velocity magnitudes ($|\mathbf{V}|_{CA}/U_{r,LE}$) and swirling strength ($\lambda_{CA}$) on surface pressure fluctuations (e. g., Figure 4.20), data in the extreme ends of both $|\mathbf{V}|_{CA}/U_{r,LE}$ and $\lambda_{CA}$ were excluded from analysis because of the presence of significantly fewer amounts of data to obtain reliable statistics. However, the number of data excluded from analysis was calculated to be less than 0.5% of the total data and were assumed not to affect the overall trend of the results. There exist very few amounts of very extreme surface pressures in the datasets excluded from analysis. These extreme events of surface pressures are very rare events and are not responsible to determine overall pressure fluctuations on the surface (Kiya & Sasaki, 1985); however, one practical implication of these extreme low pressure events is triggering failure of the roofs of low-rise buildings.

Examples of the conditionally-averaged fluctuating vector fields ($<u'>$ and $<v'>$) based on the surface pressures recorded at pressure tap 2 during the occurrences of $-Cp/Cp' \sim 5.5$ and $-Cp/Cp' \sim 10$ (very high suction) for upstream condition ‘3L’ and ‘1S’ respectively along with the contours of $<|\mathbf{V}|>/U_{r,LE}$ are presented in Figure 4.21(a) and Figure 4.21(b). On Figure 4.22(a) and Figure 4.22(b) the contours $<\lambda>$ are presented for the same two upstream conditions. During these peak events considered at $x=0.22H_1$, there exists a rotating system (in clockwise sense) in the separated flow region with very
high curvature positioned on the location of the pressure tap (at \( x=0.22H_1 \)). It is also observed that just upstream of the rotating system the velocity fields are also very high in magnitude. These magnitudes are higher for upstream condition ‘3L’ compare to ‘1S’. The contours of high magnitudes of swirling strength are also observed around pressure tap. Hence, these extremely rare high suction events are affected by localized events. The mechanism by which these extreme events are influenced by the turbulence properties in the upstream requires further attention due to its important practical implications discussed above.

**Figure 4.21**: Fluctuating velocity vector field \((<u'> \text{ and } <v'>)\) and contour of \(<|V|/U_{r,LE}\) during extremely high suctions at \( x=0.22H_1 \) for upstream conditions (a) 3L and (b) 1S.

**Figure 4.22**: Fluctuating velocity vector field \((<u'> \text{ and } <v'>)\) and contour of \(<\lambda>\) during extremely high suctions at \( x=0.22H_1 \) for upstream conditions (a) 3L and (b) 1S.
4.9 Conclusions

In this chapter, the influence of turbulence properties in the upstream flows on surface pressure fluctuations for surface-mounted three-dimensional bluff bodies are examined in detail. The key parameters involved in characterizing the surface pressures are investigated and the responses of these parameters to turbulence properties in the upstream are also studied. From the results and discussions presented in the preceding sections following conclusions can be drawn-

➢ Surface pressure fluctuations for three-dimensional bluff bodies exposed to turbulent boundary layer upstreams are sensitive to turbulence intensities and length scales in the incident flow. Increasing length scales in the upstream flow increases the magnitude of surface pressure fluctuations as shown by Saathoff & Melbourne (1997). In addition, increasing turbulence intensities in the upstream flow causes the location of maximum pressure fluctuations to move closer to the separation point (leading edge). This phenomenon is qualitatively similar to the results obtained for two-dimensional bluff bodies in uniform upstream flows (Hillier & Cherry, 1981; Saathoff & Melbourne, 1997). However, for three-dimensional bluff bodies in turbulent boundary layer flow, the location of maximum surface pressure fluctuations are observed to occur closer to the leading edge. This appears to be more of a function of turbulence intensity than the scale of turbulence.

➢ The positions of the separated shear layer closer to the leading edge, for surface-mounted three-dimensional bluff bodies, is observed to produce some effects on the surface pressure close to the leading edge.

➢ Surface pressure fluctuations near the leading edge are observed to be highly correlated with the streamwise component of the velocity just outside the separated shear layer. This correlation increases with increased turbulence intensity and length scale in the approach flow. The vertical component of the velocity field is observed to be poorly correlated with pressure fluctuations close to the leading edge.
➢ The area-averaged swirling strength (a measure of vortex strength) in the area comparable with the size of the mean separation bubbles is observed to show satisfactory correlation with surface pressure fluctuations. Hence, not only the local vortices, but also the vortices present in the whole separation bubble are observed to influence the surface pressure fluctuations. In contrast, individual, local shear layer vortices are less related to the surface pressure fluctuations, which is distinct from the findings of Saathoff & Melbourne (1997) for two-dimensional bluff bodies in uniform, turbulent flow.

➢ Overall, higher turbulence intensities in the upstream affects surface pressure fluctuations by inducing higher ranges of velocity fluctuations in the regions outside the separated shear layer and also by increasing the strengths of the vortices inside the separation bubble.

➢ Extreme high suctions are observed to be very rare events which do not significantly contribute to the surface pressure fluctuations. A localized rotating system of flow with very high curvature associated with magnitudes of velocity outside the shear layer is observed during these extreme high suction events.
References


Chapter 5

5 Conclusions and Recommendations

5.1 Conclusions

The general objective of the thesis is to develop a better understanding of the effects of turbulence in upstream boundary layer flows on separating-reattaching flows over surface-mounted three-dimensional bluff bodies (resembling low-rise buildings) and the resulting roof surface pressures (both mean and fluctuating). Several key features of the flow fields and the surface pressures of surface-mounted bluff bodies have been studied. Detailed investigations on the effects of turbulence intensity and length scale on mean reattachment lengths, mean surface pressures, mean flow fields, fluctuating flow fields and surface pressure fluctuations have been performed. The dominant flow parameters in the separating and reattaching flows, along with several key flow characteristics responsible for surface pressure fluctuations have been identified and examined as functions of turbulence properties in the upstream. Quantitative and qualitative comparisons of the present experimental results with the results for two-dimensional bluff bodies in uniform upstream flows were made where applicable. Time-Resolved Particle Image Velocimetry measurements, synchronized with surface pressure measurements, have served as a useful tool in achieving the objective. The major conclusions deduced from the analysis of the experimental data are presented below.

In Chapter 2, the mean reattachment lengths and the mean surface pressures in relation to the turbulence intensity and length scale were investigated. The location of the stagnation point on the front (windward) surface of the surface-mounted three-dimensional body is unaffected by the turbulence parameters in the upstream. Reductions in the mean reattachment lengths were observed as for increased values of turbulence intensity. In contrast, turbulence scales in the upstream were found not to alter the mean reattachment lengths, over the range examined. However, it was speculated that for significantly larger turbulent scales in the upstream for similar turbulence intensities, not examined in the
present experiments, integral scales in the upstream may alter the mean reattachment lengths. The distributions of reduced pressure coefficients ($C_p^*$) under the mean separation bubble are observed to be a function of mean reattachment length and turbulence intensity in the upstream, and are, therefore, not universal. Based on the present experimental results and utilizing the mean pressure data along the roof-centerline from the NIST database for a number of low-rise buildings (Ho et al. 2005), a method of estimating the mean reattachment lengths on the roof of low-rise buildings (surface-mounted three-dimensional bluff bodies) from measured surface pressures and roof height turbulence intensity is proposed.

Detailed investigations of the mean and fluctuating flow fields in and around the separation bubble formed on the roof surface for one bluff body were made in Chapter 3. The results of the mean reattachment lengths obtained in Chapter 2 were used to demonstrate the similarity of the mean velocity field of the mean separation bubbles formed on the top surface of the surface-mounted three-dimensional bluff bodies under a variety of boundary layer upstream conditions. It is observed that, whereas the distributions of mean streamwise velocities in and around the separation bubbles show self-similarity, neither the fluctuating flow field (Reynolds stresses) or the mean pressure field (chapter 2) are self-similar. The magnitudes of Reynolds stresses in the separated shear layer increase with upstream turbulence intensity. The streamwise Reynolds normal stress is the most dominant of the Reynolds stresses in the separated flow region.

The effects of upstream turbulence on the distributions of the fluctuating pressures under the separation bubble were studied in Chapter 4. The effects of both turbulence intensity and length scale were observed to be present in the surface pressure fluctuations. Similar to two-dimensional bluff bodies in uniform upstream flows, an increment in turbulence intensity is observed to increase the magnitudes of pressure fluctuations and cause the location of maximum fluctuations to occur closer to the leading edge. Surface pressure fluctuations are observed to be highly correlated with the streamwise velocity outside the separated shear layer and with the area-averaged swirling strength within the whole separation bubble. These findings are distinct from the findings of Saathoff & Melbourne (1997) for two-dimensional bluff bodies in uniform upstream flows, where they observe
the effects of only local vortices on surface pressure fluctuations. Increased turbulence intensity in the upstream alters surface pressure fluctuations by increasing the strengths of the vortices inside the separation bubble and also by increasing fluctuations in the velocity field outside the separated shear layer. However, the mechanisms whereby the turbulence length scales alter the velocity field and vortices in the separation bubble and could not be explained from the present experiments.

5.2 Recommendations for future work

Based on the analysis, results and understanding from the present study, the following recommendations for future work can be made:

- The resolution of velocity vectors the PIV data in the current was 0.02\(H_1\). Certain portions of the analysis presented in this thesis involve the velocity gradients (e.g., swirling strength). Experiments with a higher resolution of the PIV data is required to be performed in order to achieve better details of the flow field right near the leading edge separation point. This will improve the tracking of the movements of the separated shear layer and shear layer vortices near the leading edge.

- An improved algorithm is necessary to track the positions of the separated shear layer at distances further away from the leading edge, notwithstanding that the current analysis may suggest that the definition of the separated shear layer has little meaning beyond \(x/X_r \sim 0.5\).

- The separation bubble is three-dimensional, as is turbulence generally. For example, Kiya & Sasaki (1983) observed correlations of the surface pressures with the transverse velocity component. The use of conventional two-dimensional PIV measurements cannot reveal the three-dimensional features of the separation bubbles. To understand the effects of the transverse velocity component on surface pressures, stereoscopic PIV measurements of the surface pressures would be necessary. There are significant challenges with this in large boundary layer wind tunnels which would need to be resolved.
➢ Swirling strength is an indirect measurement of the vortices in a flow. A better estimate of the strengths of the vortices present in the separation bubble (e.g., an improved measure of circulation) is required to be employed in order to achieve more accurate information about the vortices.

➢ Lander et al. (2016) observe the presence of the turbulent eddies at the onset of separation as a result of turbulence originating along the stagnation streamline. To better understand the effects of turbulence on the shear layer vortices, investigations of the flow features along the stagnation streamline would be necessary.
References


Appendices

Appendix A: Measurement Uncertainties

The measurement uncertainties embedded within the measurements of pressure coefficients referenced to the roof-height \((Cp)\) are calculated and presented below.

A.1 Uncertainties in the measurements of \(Cp_{ref}\)

The pressure coefficients referenced to the roof-height is defined by the following equation

\[
\text{Pressure coefficient referenced to roof-height, } Cp = Cp_{ref} \left( \frac{V_R}{V_H} \right)^2 = Cp_{ref} R \quad (A.1)
\]

Here, \(Cp_{ref}\) is the pressure coefficient referenced to the reference height, \(V_R\) is the velocity at the reference height, \(V_H\) is the velocity at the roof-height and \(R\) is the velocity ratio squared. It is observed that \(Cp\) depends on \(Cp_{ref}\) and velocity ratio, \(R = \left( \frac{V_R}{V_H} \right)^2\). Hence, the overall uncertainty in the measurement of \(Cp\) is,

\[
T_{Cp} = \pm \left[ \left( \frac{\partial Cp}{\partial Cp_{ref}} T_{Cp_{ref}} \right)^2 + \left( \frac{\partial Cp}{\partial R} T_R \right)^2 \right]^{1/2} = \pm \left[ \left( RT_{Cp_{ref}} \right)^2 + \left( Cp_{ref} T_R \right)^2 \right]^{1/2} \quad (A.2)
\]

Here, \(T_{Cp}\) is the uncertainty in the measurement of \(Cp\), \(T_{Cp_{ref}}\) is the uncertainty in the measurements of \(Cp_{ref}\) and \(T_R\) is the uncertainty in the measurements of \(R\). Quiroga (2006) assessed the uncertainties in the measurement of pressure coefficients referenced to the roof-height \((Cp)\) on models placed in the high speed test section of the Boundary Layer Wind Tunnel-II at the University of Western Ontario. In the analysis of the uncertainties, Quiroga (2006) considered the uncertainties from each of the components associated with pressure measurement system in order to estimate the uncertainties in the measurements of pressure coefficients referenced to the reference height \((Cp_{ref})\). Incorporating these results with the uncertainties in the velocity measurements by two
single-wire hot-wire, the uncertainties in the measurements of pressure coefficients referenced to the roof-height \((C_p)\) were estimated. It was observed that the uncertainties in the pressure coefficients referenced to the roof-height \((C_p)\) were dominated by the uncertainties associated with the velocity measurements. Hence, it was recommended by Quiroga (2006) that the velocity measurements are needed to be resolved with lower uncertainties in order to estimate \(C_p\) with greater accuracy. The measurement system of \(C_{p_{ref}}\) for the present experiment being the same as Quiroga (2006), the uncertainties related to \(C_{p_{ref}}\) for the present experiment is considered as measured by Quiroga (2006). However, the measurements of the velocity profiles, in order to find the velocity ratio \((R)\), were taken by means of a Cobra probe (TFI, Model No. 900311). Quiroga (2006) observed the uncertainty of \(C_{p_{ref}}\) as \(\pm 0.07C_{p_{ref}}\). Hence, \(T_{C_{p_{ref}}} = \pm 0.07C_{p_{ref}}\). This value was used in the calculations of uncertainty in \(C_p\).

A.2 Uncertainties in the measurements of velocity by Cobra probe

In order to estimate the uncertainties associated with the velocity measurements, the performance of the cobra probe used in this experiment was assessed in a separate experiment by comparing with a pitot tube in the range of velocities considered in the original experiment. In the performance assessment experiment of the Cobra probe, Cobra probe readings were sampled at 1250Hz for approximately 30s for 11 different wind tunnel speeds. In order to account for the error due misalignment of the cobra probe during the experiments of velocity profile measurements, the cobra probe in the uncertainty test experiment was intentionally placed at an angle of approximately 15°. However, during the velocity profiles measurements the cobra probes were set aligned with the flow by visual inspection. From the cobra probe readings and comparing with the pitot tube readings the bias limit, the precision limit and total uncertainties in the velocity measurements by the cobra probe was calculated for each of the 11 performance-test cases considered. The number of samples for each of the test cases being larger than 30, in the calculation of precision limits for the cobra probe the value of \(t\) was considered to be 1.96. In the following table (Table A.1) the uncertainties associated in the velocity measurements by the cobra probe are presented. Here, \(B\) is the bias limit and \(P\) is the precision limit.
Table A.1: Uncertainties in velocity measurements by cobra probe.

<table>
<thead>
<tr>
<th>Pitot tube reading (m/s)</th>
<th>Cobra probe reading (m/s)</th>
<th>Total uncertainty (m/s)</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.29</td>
<td>5.30</td>
<td>0.10</td>
<td>1.87</td>
</tr>
<tr>
<td>6.59</td>
<td>6.52</td>
<td>0.12</td>
<td>1.86</td>
</tr>
<tr>
<td>7.37</td>
<td>7.32</td>
<td>0.14</td>
<td>1.96</td>
</tr>
<tr>
<td>8.23</td>
<td>8.21</td>
<td>0.12</td>
<td>1.45</td>
</tr>
<tr>
<td>9.01</td>
<td>9.01</td>
<td>0.13</td>
<td>1.52</td>
</tr>
<tr>
<td>10.35</td>
<td>10.12</td>
<td>0.28</td>
<td>2.76</td>
</tr>
<tr>
<td>11.07</td>
<td>10.80</td>
<td>0.33</td>
<td>2.99</td>
</tr>
<tr>
<td>11.79</td>
<td>11.51</td>
<td>0.33</td>
<td>2.81</td>
</tr>
<tr>
<td>12.35</td>
<td>12.09</td>
<td>0.32</td>
<td>2.65</td>
</tr>
<tr>
<td>13.02</td>
<td>12.82</td>
<td>0.29</td>
<td>2.27</td>
</tr>
<tr>
<td>14.19</td>
<td>13.98</td>
<td>0.33</td>
<td>2.33</td>
</tr>
</tbody>
</table>

It is observed that even at a misalignment angle equal to 15°, the maximum uncertainty in the velocity measurement that the cobra probe shows is less than 3% and the uncertainties are significantly lower at velocities less than 10 m/s. However, in the calculations of uncertainties in the measurements of \( C_p \) (\( T_{C_p} \)) and \( R \) (\( T_R \)), the value of 3% uncertainty in the velocity measurements is used.

### A.3 Uncertainties in the measurements of velocity ratio \( (T_R) \) and \( C_p \)

Velocity ratio was defined in the previous section as, \( R = \left( \frac{V_R}{V_H} \right)^2 \)

Hence, the uncertainty in \( R \),

\[
T_R = \pm \left[ \left( \frac{\partial R}{\partial V_R} T_{V_R} \right)^2 + \left( \frac{\partial R}{\partial V_H} T_{V_H} \right)^2 \right]^{1/2} = \pm \left( \frac{2V_R^2}{V_H^2} T_{V_R} \right)^2 + \left( -\frac{2V_H^2}{V_H^3} T_{V_H} \right)^2 \quad (A.3)
\]

Here, \( T_{VR}=3\% \) of \( V_R \) and \( T_{VH}=3\% \) of \( V_H \). \( V_R \) and \( V_H \) were obtained from the velocity profiles measured by the cobra probes. Using these values in Eq. (A.3), the values of \( T_R \) were obtained. Now, using the values of \( T_{C_{pref}}, \) \( R, \) \( C_{pref} \) and \( T_R \) in Eq. (A.2), the overall...
maximum uncertainties in the measurements of $T_{Cp}$ is obtained for each of the six upstream conditions considered in this experiment. For each of the six upstream conditions, the maximum observed values of $Cp_{ref}$ is considered in order to estimate the maximum uncertainties associated with the measurements of $Cp$. The results are presented in Table A.2 and Table A.3.

Table A.2: Uncertainties in the measurements of velocity ratio ($R$).

<table>
<thead>
<tr>
<th>Upstream Condition</th>
<th>$V_R$</th>
<th>$T_{VR}$</th>
<th>$V_H$</th>
<th>$T_{VH}$</th>
<th>$R$</th>
<th>$(V_R/V_H)^2$</th>
<th>Max. $T_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1S</td>
<td>10.34</td>
<td>0.31</td>
<td>6.81</td>
<td>0.20</td>
<td>2.30</td>
<td>0.195</td>
<td></td>
</tr>
<tr>
<td>1L</td>
<td>10.03</td>
<td>0.30</td>
<td>7.97</td>
<td>0.23</td>
<td>1.58</td>
<td>0.134</td>
<td></td>
</tr>
<tr>
<td>2S</td>
<td>10.92</td>
<td>0.32</td>
<td>6.62</td>
<td>0.19</td>
<td>2.71</td>
<td>0.230</td>
<td></td>
</tr>
<tr>
<td>2L</td>
<td>10.34</td>
<td>0.31</td>
<td>7.45</td>
<td>0.22</td>
<td>1.92</td>
<td>0.163</td>
<td></td>
</tr>
<tr>
<td>3S</td>
<td>10.99</td>
<td>0.32</td>
<td>5.74</td>
<td>0.17</td>
<td>3.65</td>
<td>0.310</td>
<td></td>
</tr>
<tr>
<td>3L</td>
<td>10.90</td>
<td>0.32</td>
<td>5.73</td>
<td>0.17</td>
<td>3.61</td>
<td>0.306</td>
<td></td>
</tr>
</tbody>
</table>

Table A.3: Uncertainties in the measurements of $Cp$ ($T_{Cp}$).

<table>
<thead>
<tr>
<th>Upstream Condition</th>
<th>Max. $Cp$ (suction)</th>
<th>Max. $Cp_{ref}$</th>
<th>Max. $T_{Cp_{ref}}$</th>
<th>Max. $T_{Cp}$ (absolute)</th>
<th>Max. $T_{Cp}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1S</td>
<td>0.93</td>
<td>0.17</td>
<td>0.012</td>
<td>0.044</td>
<td>4.78</td>
</tr>
<tr>
<td>1L</td>
<td>1.04</td>
<td>0.41</td>
<td>0.03</td>
<td>0.072</td>
<td>6.95</td>
</tr>
<tr>
<td>2S</td>
<td>1.02</td>
<td>0.13</td>
<td>0.009</td>
<td>0.041</td>
<td>4.04</td>
</tr>
<tr>
<td>2L</td>
<td>1.07</td>
<td>0.29</td>
<td>0.02</td>
<td>0.06</td>
<td>5.71</td>
</tr>
<tr>
<td>3S</td>
<td>1.11</td>
<td>0.08</td>
<td>0.0058</td>
<td>0.033</td>
<td>3.00</td>
</tr>
<tr>
<td>3L</td>
<td>1.30</td>
<td>0.10</td>
<td>0.007</td>
<td>0.039</td>
<td>3.04</td>
</tr>
</tbody>
</table>

It is observed that the maximum uncertainty in the measurement of pressure coefficients referenced to the roof-height is 6.95%.

Appendix B: Velocity Profiles

Figure B.1: Vertical profiles of $U/U_r$ at (a) $x/X_r=0.05$, (b) $x/X_r =0.2$, (c) $x/X_r =0.4$, (d) $x/X_r=0.6$, (e) $x/X_r =0.8$, (f) $x/X_r =1$. Here the vertical distance is normalized by model height ($H_1$).
Figure B.2: Vertical profiles of $|V|/V_r$ at (a) $x/X_r=0.05$, (b) $x/X_r =0.2$, (c) $x/X_r =0.4$, (d) $x/X_r=0.6$, (e) $x/X_r =0.8$, (f) $x/X_r =1$. Here the vertical distance is normalized by model height ($H_1$).
Figure B.3: Vertical profiles of $\frac{u'u'_{\tau}}{(u'u'_{\tau})_r}$ at (a) $x/X_r = 0.05$, (b) $x/X_r = 0.2$, (c) $x/X_r = 0.4$, (d) $x/X_r = 0.6$, (e) $x/X_r = 0.8$, (f) $x/X_r = 1$. Here the vertical distance is normalized by model height ($H_1$).
Figure B.4: Vertical profiles of $\frac{v'v'}{(v'v')_r}$ at (a) $x/X_r=0.05$, (b) $x/X_r=0.2$, (c) $x/X_r=0.4$, (d) $x/X_r=0.6$, (e) $x/X_r=0.8$, (f) $x/X_r=1$. Here the vertical distance is normalized by model height ($H_1$).
Figure B.5: Vertical profiles of $\frac{\overline{u'v'}}{(u'v')_r}$ at (a) $x/X_r=0.05$, (b) $x/X_r =0.2$, (c) $x/X_r =0.4$, (d) $x/X_r=0.6$, (e) $x/X_r =0.8$, (f) $x/X_r =1$. Here the vertical distance is normalized by model height ($H_1$).
Appendix C: Correlation coefficients of velocities and λ with surface pressures

Figure C.1: Contours of correlation coefficients between \(-C_p\) at \(x/H=0.22\) and \(u\) for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Figure C.2: Contours of correlation coefficients between $-C_p$ at $x/H_1=0.22$ and $v$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Figure C.3: Contours of correlation coefficients between \(-C_p\) at \(x/H_1=0.4\) and \(|v|\) for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Figure C.4: Contours of correlation coefficients between $-C_p$ at $x/H_1=0.4$ and $u$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Figure C.5: Contours of correlation coefficients between \(-C_p\) at \(x/H_1=0.4\) and \(v\) for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Figure C.6: Contours of correlation coefficients between -$C_p$ at $x/H_1=0.8$ and $|v|$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Figure C.7: Contours of correlation coefficients between $-C_p$ at $x/H_1=0.8$ and $u$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Figure C.8: Contours of correlation coefficients between $-C_p$ at $x/H_1=0.8$ and $v$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Figure C.9: Contours of correlation coefficients between \(-Cp\) at \(x/H_1=0.4\) and \(\lambda\) for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Figure C.10: Contours of correlation coefficients between $-C_p$ at $x/H_1=0.8$ and $\lambda$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Appendix D: Statistical distributions of $|V|_{CA}/U_{r,LE}$

![Distributions of $|V|_{CA}/U_{r,LE}$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.](image)

Figure D.1: Statistical distributions of $|V|_{CA}/U_{r,LE}$ for upstream conditions (a) 1S, (b) 1L, (c) 2S, (d) 2L, (e) 3S and (f) 3L.
Appendix E: Permissions for reuse of copyrighted material

<table>
<thead>
<tr>
<th>License Number</th>
<th>401440830985</th>
</tr>
</thead>
<tbody>
<tr>
<td>License date</td>
<td>Dec 22, 2016</td>
</tr>
<tr>
<td>Licensed Content Publisher</td>
<td>Elsevier</td>
</tr>
<tr>
<td>Licensed Content Publication</td>
<td>Journal of Wind Engineering and Industrial Aerodynamics</td>
</tr>
<tr>
<td>Licensed Content Title</td>
<td>Mean pressure distributions and reattachment lengths for roof-separation bubbles on low-rise buildings</td>
</tr>
<tr>
<td>Licensed Content Author</td>
<td>Abul Fahad Akon, Gregory A. Kopp</td>
</tr>
<tr>
<td>Licensed Content Date</td>
<td>August 2016</td>
</tr>
<tr>
<td>Licensed Content Volume Number</td>
<td>155</td>
</tr>
<tr>
<td>Licensed Content Issue Number</td>
<td>n/a</td>
</tr>
<tr>
<td>Licensed Content Pages</td>
<td>1</td>
</tr>
<tr>
<td>Start Page</td>
<td>115</td>
</tr>
<tr>
<td>End Page</td>
<td>125</td>
</tr>
<tr>
<td>Type of Use</td>
<td>reuse in a thesis/dissertation</td>
</tr>
<tr>
<td>Portion</td>
<td>full article</td>
</tr>
<tr>
<td>Format</td>
<td>both print and electronic</td>
</tr>
<tr>
<td>Are you the author of this Elsevier article?</td>
<td>Yes</td>
</tr>
<tr>
<td>Will you be translating?</td>
<td>No</td>
</tr>
<tr>
<td>Order reference number</td>
<td></td>
</tr>
<tr>
<td>Title of your thesis/dissertation</td>
<td>Effects of turbulence on the separating-reattaching flow above surface-mounted, three-dimensional bluff bodies</td>
</tr>
<tr>
<td>Expected completion date</td>
<td>Dec 2016</td>
</tr>
<tr>
<td>Estimated size (number of pages)</td>
<td>200</td>
</tr>
<tr>
<td>Elsevier VAT number</td>
<td>GB 494 6272 12</td>
</tr>
<tr>
<td>Requestor Location</td>
<td>Abul Fahad Akon</td>
</tr>
<tr>
<td>Total</td>
<td>0.00 CAD</td>
</tr>
</tbody>
</table>

INTRODUCTION

1. The publisher for this copyrighted material is Elsevier. By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms and conditions apply to this transaction (along with the Billing and Payment terms and conditions)

https://s100.copyright.com/CustomerAdmin/PrintableLicense.jsp?appSource=ocoAdmin&licenseId=orderSelection=201612140244110909/705925d...
established by Copyright Clearance Center, Inc. ("CCC"), at the time that you opened your Rightslink account and that are available at any time at [https://myaccount.copyright.com]

**GENERAL TERMS**

2. Elsevier hereby grants you permission to reproduce the aforementioned material subject to the terms and conditions indicated.

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol / edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

4. Reproduction of this material is confined to the purpose and/or media for which permission is hereby given.

5. Altering/Modifying Material: Not Permitted. However figures and illustrations may be altered/adapted minimally to serve your work. Any other abbreviations, additions, deletions and/or any other alterations shall be made only with prior written authorization of Elsevier Ltd. (Please contact Elsevier at permissions@elsevier.com). No modifications can be made to any Lancet figures/tables and they must be reproduced in full.

6. If the permission fee for the requested use of our material is waived in this instance, please be advised that your future requests for Elsevier materials may attract a fee.

7. Reservation of Rights: Publisher reserves all rights not specifically granted in the combination of (i) the license details provided by you and accepted in the course of this licensing transaction, (ii) these terms and conditions and (iii) CCC's Billing and Payment terms and conditions.

8. License Contingent Upon Payment: While you may exercise the rights licensed immediately upon issuance of the license at the end of the licensing process for the transaction, provided that you have disclosed complete and accurate details of your proposed use, no license is finally effective unless and until full payment is received from you (either by publisher or by CCC) as provided in CCC's Billing and Payment terms and conditions. If full payment is not received on a timely basis, then any license preliminarily granted shall be deemed automatically revoked and shall be void as if never granted. Further, in the event that you breach any of these terms and conditions or any of CCC's Billing and Payment terms and conditions, the license is automatically revoked and shall be void as if never granted. Use of materials as described in a revoked license, as well as any use of the materials beyond the scope of an unrevoked license, may constitute copyright infringement and publisher reserves the right to take any and all action to protect its copyright in the materials.

9. Warranties: Publisher makes no representations or warranties with respect to the licensed material.

10. Indemnity: You hereby indemnify and agree to hold harmless publisher and CCC, and their respective officers, directors, employees and agents, from and against any and all claims arising out of your use of the licensed material other than as specifically authorized pursuant to this license.

11. No Transfer of License: This license is personal to you and may not be sublicensed, assigned, or transferred by you to any other person without publisher's written permission.

12. No Amendment Except in Writing: This license may not be amended except in a writing signed by both parties (or, in the case of publisher, by CCC on publisher's behalf).

13. Objection to Contrary Terms: Publisher hereby objects to any terms contained in any purchase order, acknowledgment, check endorsement or other writing prepared by you, which terms are inconsistent with these terms and conditions or CCC's Billing and Payment terms and conditions. These terms and conditions, together with CCC's Billing and Payment terms and conditions (which are incorporated herein), comprise the entire agreement between you and publisher (and CCC) concerning this licensing transaction. In the event of
any conflict between your obligations established by these terms and conditions and those established by CCC's Billing and Payment terms and conditions, these terms and conditions shall control.

14. Revocation: Elsevier or Copyright Clearance Center may deny the permissions described in this License at their sole discretion, for any reason or no reason, with a full refund payable to you. Notice of such denial will be made using the contact information provided by you. Failure to receive such notice will not alter or invalidate the denial. In no event will Elsevier or Copyright Clearance Center be responsible or liable for any costs, expenses or damage incurred by you as a result of a denial of your permission request, other than a refund of the amount(s) paid by you to Elsevier and/or Copyright Clearance Center for denied permissions.

LIMITED LICENSE

The following terms and conditions apply only to specific license types:

15. Translation: This permission is granted for non-exclusive world English rights only unless your license was granted for translation rights. If you licensed translation rights you may only translate this content into the languages you requested. A professional translator must perform all translations and reproduce the content word for word preserving the integrity of the article.

16. Posting licensed content on any Website: The following terms and conditions apply as follows: Licensing material from an Elsevier journal: All content posted to the web site must maintain the copyright information line on the bottom of each image; A hyper-text must be included to the Homepage of the journal from which you are licensing at http://www.sciencedirect.com/science/journal/xxxxx or the Elsevier homepage for books at http://www.elsevier.com; Central Storage: This license does not include permission for a scanned version of the material to be stored in a central repository such as that provided by Heron/XanEdu.

17. Posting licensed content on Electronic reserve: In addition to the above the following clauses are applicable: The web site must be password-protected and made available only to bona fide students registered on a relevant course. This permission is granted for 1 year only. You may obtain a new license for future website posting.

18. For journal authors: the following clauses are applicable in addition to the above:

Preprints:
A preprint is an author's own write-up of research results and analysis, it has not been peer-reviewed, nor has it had any other value added to it by a publisher (such as formatting, copyright, technical enhancement etc.).

Authors can share their preprints anywhere at any time. Preprints should not be added to or enhanced in any way in order to appear more like, or to substitute for, the final versions of articles however authors can update their preprints on arXiv or RePec with their Accepted Author Manuscript (see below).

If accepted for publication, we encourage authors to link from the preprint to their formal publication via its DOI. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help users to find, access, cite and use the best available version. Please note that Cell Press, The Lancet and some society-owned have different preprint policies. Information on these policies is available on the journal homepage.

Accepted Author Manuscripts: An accepted author manuscript is the manuscript of an article that has been accepted for publication and which typically includes author-incorporated changes suggested during submission, peer review and editor-author communications.

Authors can share their accepted author manuscript:

- immediately
  - via their non-commercial person homepage or blog
  - by updating a preprint in arXiv or RePec with the accepted manuscript
1. Licensed deposit is permitted in the institutional repository for internal institutional use or as part of a research collaboration work-group.
2. For private scholarly sharing as part of a research group, use commercial sites with Elsevier's agreement.
3. In all cases, accepted manuscripts should:
   - Link to the formal publication via its DOI.
   - Use a CC-BY-NC-ND license if aggregated with other manuscripts.
   - Be shared in alignment with our hosting policy.

Published Journal Article (PJA): A published journal article (PJA) is the definitive final record of published research that appears in the journal and embodies all value-adding publishing activities including peer review, co-ordination, copy-editing, formatting, (if relevant) pagination and online enrichment.

Policies for sharing publishing articles differ for subscription and gold open access articles:

Subscription Articles: If you are an author, please share a link to your article rather than the full-text. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help your users find, access, cite, and use the best available version.

Theses and dissertations which contain embedded PJAs are part of the formal submission and can be shared publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

If you are affiliated with a library that subscribes to ScienceDirect you have additional private sharing rights for others' research accessed under that agreement. This includes use for classroom teaching and internal training at the institution (including use in course packs and courseware programs), and inclusion of the article for grant funding purposes.

Gold Open Access Articles: May be shared according to the author-selected end-user license and should contain a CrossRef logo, the end user license, and a DOI link to the formal publication on ScienceDirect.

Please refer to Elsevier's posting policy for further information.

18. For book authors, the following clauses are applicable in addition to the above:

Authors are permitted to place a brief summary of their work online only. You are not allowed to download and post the published electronic version of your chapter, nor may you scan the printed edition to create an electronic version. Posting to a repository: Authors are permitted to post a summary of their chapter only in their institution's repository.

19. Thesis/Dissertation: If your license is for use in a thesis/dissertation, your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of the complete thesis and include permission for Proquest/UMI to supply single copies, on demand, of the complete thesis. Should your thesis be published commercially, please reapply for permission. Theses and dissertations which contain embedded PJAs are part of the formal submission and can be shared publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

Elsevier Open Access Terms and Conditions

You can publish open access with Elsevier in hundreds of open access journals or in nearly 2000 established subscription journals that support open access publishing. Permitted third party re-use of these open access articles is defined by the author's choice of Creative Commons user license. See our open access license policy for more information.
Terms & Conditions applicable to all Open Access articles published with Elsevier:
Any reuse of the article must not represent the author as endorsing the adaptation of the article nor should the article be modified in such a way as to damage the author's honour or reputation. If any changes have been made, such changes must be clearly indicated. The author(s) must be appropriately credited and we ask that you include the end user license and a DOI link to the formal publication on ScienceDirect. If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgment to another source it is the responsibility of the user to ensure their reuse complies with the terms and conditions determined by the rights holder. Additional Terms & Conditions applicable to each Creative Commons user license:
CC BY: The CC-BY license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article and to make commercial use of the Article (including reuse and/or resale of the Article by commercial entities), provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, and the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by/4.0.
CC BY-NC-SA: The CC BY-NC-SA license allows users to copy, create extracts, abstracts and new works from the Article, to alter and revise the Article, provided this is not done for commercial purposes, and that the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, and the licensor is not represented as endorsing the use made of the work. Further, any new works must be made available on the same conditions. The full details of the license are available at http://creativecommons.org/licenses/by-nc-sa/4.0.
CC BY-NC-ND: The CC BY-NC-ND license allows users to copy and distribute the Article, provided this is not done for commercial purposes and further does not permit distribution of the Article if it is changed or edited in any way, and provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, and the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by-nc-nd/4.0.
Any commercial reuse of Open Access articles published with a CC BY NC-SA or CC BY NC-ND license requires permission from Elsevier and will be subject to a fee. Commercial reuse includes:
- Associating advertising with the full text of the Article
- Charging fees for document delivery or access
- Article aggregation
- Systematic distribution via e-mail lists or share buttons

Posting or linking by commercial companies for use by customers of those companies.

20. Other Conditions:

v1.9
Questions? copyright@copyright.com or +1-855-239-3415 (toll free in the US) or +1-978-646-2777.
Curriculum Vitae

Name: Abul Fahad Akon

Post-secondary Education and Degrees:
Bangladesh University of Engineering and Technology
Dhaka, Bangladesh
2004-2009 B. Sc.

University of Saskatchewan
Saskatoon, Saskatchewan, Canada
2010-2012 M. Sc.

The University of Western Ontario
London, Ontario, Canada
2012-2017 Ph.D.

Honors and Awards:
Bangladesh Education Board Merit Scholarship
2001-2009

University of Saskatchewan Graduate Scholarship
2011-2012

Western Graduate Research Scholarship
2012-2016

Related Work Experience
Teaching Assistant
University of Western Ontario
2012-2016

Teaching Assistant
University of Western Ontario
2012-2016

Research Assistant
University of Western Ontario
2012-2016

Research Assistant
University of Saskatchewan
2010-2012
Publications:

Journal articles


Conference Proceedings


