FULL-SCALE FLOW VISUALIZATION OVER
A LOW-RISE BUILDING

by

SCOTT ANDREW WAGAMAN, B.S., M.S.

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LIST OF SYMBOLS

13P	13-ft pole
BP	building position
Cov(X, Y)	covariance of X and Y
CZ	cavity zone
EVM	eddy viscosity model
GLCs	ground level concentrations
H	height of building
H _m	maximum length of bubble
HB	height of separation bubble
KW	Kruskal - Wallis test
L	length of building
L _c	length of separation cavity
LB	length of separation bubble
LW	long wall experiment
MEVER	mechanical engineering video editing room
MT	meteorological tower
N	total number of observations in Kruskal - Wallis test
R	characteristic length
R _i	sum of ranks
R(X _{ij})	rank assigned to observation X _{ij}
R1	anemometer 1 ft above the building's roof
R4	anemometer 4 ft above the building's roof
R6	anemometer 6 ft above the building's roof
Re	Reynold's number

SB	separation bubble
SW	short wall experiment
T	test statistic from Krustal - Wallis test
TD	timing devise
TI	turbulence intensity
TTU	Texas Tech University
UWZ	upwind displacement zone
Var	variance
W	width of building (normal to wind)
WERFL	wind engineering research field laboratory
WD	wind direction
X_{ij}	observation
c	percent error
j	integer counter
k	number of points in moving average
m	reference point
n	length of time series
n_i	sample point
u_m	moving average
x	value being averaged
x_m	length from windward wall to separation bubble's maximum height
χ^2	Chi square value
Ω	smallest building dimension normal to wind
β	angle of attack
f	largest building dimension normal to wind
μ	correlation coefficient

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

A building can greatly perturb the wind field near the structure. The change in the wind flow can affect the dispersion of pollutants emitted by that building. As shown in Figure 1.1, the structure has induced a cavity (separation bubble) located at the edge of the roof and windward wall. Recirculating flow occurs within the separation bubble. If an exhaust stack is located in the cavity, as shown in the figure, the cavity can prevent the dispersion of the pollutants into the atmosphere. Pollutant concentrations in the bubble increase. If the intake for the building's ventilation system is also located in the cavity, the fumes reenter the building. The elevated indoor pollutant concentrations can have a serious impact on human health. Prediction of this flow behavior is needed to insure safe emission of exhaust gases.

Researchers employ three techniques in the analysis of flow around buildings. The first technique is to utilize a scale model of the building in a wind tunnel. Airflow patterns are then visualized using smoke or tufts of yarn. This technique has two main advantages. Wind tunnels can model atmospheric flow with acceptable accuracy under neutrally stable conditions. Also, a large number of experiments can be conducted in a short amount of time. The primary disadvantage is that wind tunnels cannot properly represent wind fields for all atmospheric conditions.

The second type of airflow study is through the use of numerical models. Numerical models can calculate wind data at selected points within the discretized study area. Also, many airflow simulations can be performed in a short period of time. Numerical models do have some limitations. The models have difficulty representing turbulence accurately. An approximate numerical simulation of airflow over a building that includes the

Figure 1.1. A depiction of an exhaust stack located in the separation bubble.

separation bubble requires a fine grid with a large number of nodes. Such a simulation would demand a super-computer to complete the calculations in a reasonable length of time.

The third technique is to conduct field tests on specific buildings. Full-scale flow visualization tests utilize either using smoke emitted from point or diffuse generators or a grid of tufts mounted in the test area. The main advantage of field experiments is that the natural phenomenon is being measured as it actually occurs at full-scale. Therefore, the results of this method are the most accurate of the three techniques.

To date, few full-scale airflow studies around buildings have been conducted. No researchers have yet investigated the characteristics of the separation bubble at full scale. The Wind Engineering Research Field Laboratory (WERFL), located on the Texas Tech University campus, was therefore used to conduct full-scale flow visualization tests on the airflow over a full-size test building.

1.2 Research Objectives

The goal of this thesis is to determine the characteristics of airflow over a full-scale, low-rise building for a variety of wind speeds. The specific objectives of this project may be stated as follows:

1. Quantify the height and length dimensions of the separation bubble under various wind speeds and building positions,
2. Describe the flow structure of the separation cavity above the roof, and
3. Relate these observations to previous theoretical and experimental results.

1.3 Summary of Procedures

The data used in this study were collected at the Wind Engineering Research Field Laboratory (WERFL) on the Texas Tech University campus. WERFL consists of a

rotating metal-frame test building. Inside the test structure, there is a concrete block house. A 160-ft meteorological tower is located to the west of the test building. WERFL can be seen in Figure 1.2. A more complete description of WERFL can be found in Section 3.1 of this thesis.

For this study, a metal frame with a grid of yarn tufts was placed on the building's roof. The positions of the tufts, as controlled by spatial wind variations, were recorded on videotape. Simultaneously, a computer recorded wind data from the tower and point wind speed data from the roof. A light bulb timing device allowed synchronization of the video data and computer-recorded data. The periods with wind perpendicular to the desired building face were then analyzed. The characteristics of the separation bubble of each period, as well as the wind information, are presented in this thesis.

Figure 1.2. Picture of the Wind Engineering Research Field Laboratory on the Texas Tech University campus.

CHAPTER 2

LITERATURE REVIEW

2.1 Review of Bluff Body Aerodynamics

Formation of separation zones as air flows around obstacles is a topic within the field of bluff body aerodynamics. Bluff body aerodynamics is the study of obstacles which cause fluid flow to separate from the bodies' surfaces (Simiu and Scanlan, 1986). Typical bluff bodies are automobiles and buildings. As the fluid strikes a bluff body, the object's geometry, such as sharp edges of a building's roof and walls, cause the flow to be deflected away from the object. This is called separation. Flow separation can be seen in Figure 2.1. The flow then begins to curve towards the object. If the obstacle is long enough in the downwind direction, the flow will reattach to the body. The streamlines of reattached flow are generally parallel to the body's surface.

Between the locations of separation and reattachment, a cavity exists. This cavity is called the separation bubble. The separation bubble (SB) is characterized by low mean speeds, high turbulence, recirculation, and long residence times (Hosker, 1984). The flow characteristics of the SB depend upon the turbulence present in the undisturbed fluid.

Flow around buildings has become an increasingly studied phenomenon. In 1984, a review article was published by Hosker. Hosker (1986) later authored another review article which surveyed research related to dispersion near clusters of buildings. Researchers have studied flow patterns resulting from buildings, wind-induced pressures on the buildings, and dispersion of pollutants released from buildings. The results of these studies have enabled designers to create safer buildings.

Figure 2.1. Schematic of the separation bubble (Yeatts, 1992).

The aforementioned research has yielded a conceptual model of airflow around a simple building (Woo et al., 1977). The model is shown in Figure 2.2. There are three main features of this model. The first is an upwind displacement zone (UDZ) in front of the building. The second important characteristic is the cavity zone (CZ) located at the rear of the building. The final feature is flow separation at the roof and wall edges.

The UDZ is located in front of the windward wall. The UDZ extends 5 to 10 building heights ahead of the windward wall (Hosker, 1986). As wind approaches the building, it decelerates. The path the wind follows as it decelerates depends upon the height of the air parcel above the ground. The stagnation point is located at approximately two-thirds of the wall's height. At this point, there is little motion. Below the stagnation point, the air follows a vortex pattern. From the plan view, the vortex pattern resembles a horseshoe, thus the name horseshoe vortex system. Above the stagnation point, the streamlines curve upward.

At the leeward wall, the flow separates from the building to form the cavity zone. The CZ can be 10 to 20 times the building height long (Hosker, 1986). As seen in Figure 2.2, two vortices are formed near the side walls. These vortices are called lateral edge vortices. The lateral edge vortices are paired with vortices parallel to the ground. Elsewhere in the wake cavity, there is a general recirculation pattern. Flow recirculation can cause problems if pollutants become trapped in the wake. For example, elevated pollutant concentrations in the wake zone may cause illness to pedestrians.

At the building's roof and side walls, the streamlines separate from the buildings surface. From Figure 2.2, the distance to the point of reattachment on the side walls decreases with height. The SB has maximum length at ground level on the side walls. On the roof, the reattachment line has an arc shape. The bubble is longest along the roof's centerline (parallel to the wind).

Figure 2.2. Conceptual model of airflow around a simple building (Woo et al., 1977).

Flow reattachment depends on the characteristics of the building. The characteristics of concern are shown in Figure 2.3. In the figure, W is the windward wall dimension. L is the length of the building parallel to the wind direction. H is the height of the building. Researchers have found that the L to H ratio (L/H) determines whether flow reattachment occurs (Hosker, 1986). If L/H is greater than 1, atmospheric flows usually reattach. The location of reattachment depends upon fluctuations in the flow field called turbulence. Since the magnitudes of the wind fluctuations vary, the position of reattachment varies.

The flow above the roof can be divided into three zones. Figure 2.4 shows a two-dimensional representation of the three areas (Wilson, 1979). As shown in the figure, zone I is the recirculation cavity as described previously. Zone II is called the "high" turbulent region. The boundary of this region is not easily defined since the definition of "high" is subjective. In any event, the area is characterized by turbulence and rapid diffusion. Zone II includes zone I. Zone III is the roof wake region. This region is defined by the extending a line from the maximum height of the separation bubble towards the leeward wall. The dispersion characteristics of zone III are similar to those of the incident wind field. Zone III encompasses zones I and II. The three zones indicate where and how the building-induced wind fields will affect exhaust stacks. If the exhaust plume is located in zone II, the plume will be mixed downward. In zone I, the plume will be recirculated to produce a uniform concentration. An exhaust stream located in zone III will act as though it is being dispersed by the free atmosphere. This study will concentrate on zone I, the separation bubble.

2.2 Airflow Studies Around Buildings

There are three methods to study airflow around buildings. The first and most common technique is to use a wind tunnel. Wind tunnels produce a wind profile which is similar to atmospheric winds. A scale model of the building is placed on the wind tunnel's

Figure 2.3. Schematic of the WERFL building listing its characteristics.

Figure 2.4. Two-dimensional representation of the three zones of the separation bubble (Wilson, 1979).

test section. The researcher can then perform experiments on the model. Flow patterns are visualized by either smoke or tufts attached to the model. The advantages of this technique are (1) the researcher has control over the wind profile striking the model, (2) the wind field can be made more or less turbulent depending on the scientist's need, (3) the wind speed can be manipulated by the wind tunnel scientist, and (4) the scale-model can be positioned so that the wind strikes the building at a desired angle (angle of attack). Since the wind tunnel operator can control the characteristics of the wind produced by the tunnel, he can conduct a large number of experiments in a relatively short time using the same wind conditions. The main disadvantage of this method is that wind modeling is more of an art than a science. An accurate wind profile, when compared with field-measured values, is obtained by a trial-and-error process, not by an established procedure. Another problem is that flow-measuring instruments can significantly disturb the flow. Also, wind tunnels cannot represent unstable atmospheric boundary layers. Wind tunnels can simulate neutral conditions since the turbulence present is mainly mechanically-induced. During unstable conditions, thermally produced turbulence is present. Wind tunnels to date can not accurately represent thermal turbulence.

The second and newest technique is numerical modeling. This method involves the solution of Navier-Stokes equations which govern viscous fluid flow. The Navier-Stokes equations consist of the continuity equation, the momentum equations, and an energy equation (Panton, 1984). The equations are a set of partial differential equations made up of nonlinear terms, linear terms, and quasilinear (containing both linear and nonlinear parts) terms.

The convective terms, which represent turbulence in the Navier-Stokes equations, are quasilinear. To simplify the calculation of the convective terms, the models have made various assumptions to simulate turbulence. These assumptions have led to the three most common methods to represent turbulence. The most common approach is the

kappa-epsilon eddy viscosity model (EVM). The EVM solves six equations: an equation for the transport of the dissipation of turbulent kinetic energy, an equation for the transport of turbulent kinetic energy, three components of the Reynolds equation, and the continuity equation (Paterson and Apelt, 1986). The EVM is unique compared to the other models because the model solves the Reynolds equation directly. The other models approximate that equation. The other common turbulence models are the algebraic stress model and the large eddy simulation model (Murakami et al., 1992). A more detailed comparison of typical turbulence models is presented in subsection 2.2.2. Using the results of such models, flow can be visualized by plotting wind vectors or streamlines around the building. The advantages of numerical modeling are that "experimental" results are relatively quick to obtain. The flow is not disturbed by instrumentation in a numerical experiment. Also, data can be obtained for the entire numerical domain. The main problem associated with numerical modeling is discrepancies between field-measured data and numerical simulations, primarily due to the model's inability to exactly represent turbulence (Murakami et al., 1987). Also, numerical modelers must linearize the nonlinear Navier-Stokes equations so that the computer can solve the equations. Therefore, a "true" solution of the Navier-Stokes equations is not possible.

The final method of determining airflow patterns around a building is by conducting full-scale tests. This technique involves the use of a variety of methods to visualize the flow around the test building. The most common flow visualization techniques utilize yarn tufts or smoke generators. Tufts can be attached to the building itself or arranged in a 2-dimensional or 3-dimensional grid. The tufts' orientations change with the flow. Smoke generators can also be used to determine the flow patterns. Generally, smoke is emitted upstream the point of interest. Smoke visualization is not suited for fine-scale circulation structure studies. In addition to flow visualization, wind speeds, directions, and pressures can be measured by a variety of different instruments at selected locations. The advantage

of full-scale testing is the phenomenon of interest can be measured under actual atmospheric conditions. The primary disadvantage is the high cost compared to wind tunnel and numerical studies. A secondary obstacle is that the measuring devices may influence the flow. Also, field tests require a great amount of effort to collect the data. Another inconvenience is the inability to control the wind speed and wind direction.

2.2.1 Wind Tunnel Studies

As mentioned previously, the most common technique to study wind effects on buildings is the wind tunnel. Researchers have studied airflow around many different shaped and sized objects. This literature review will only report on rectangular and cubic bluff bodies. Readers interested in cylindrical-shaped bodies or plates should refer to Apelt, West, and Szewczyk (1973) and Arie and Rouse (1956), respectively. The wind tunnel studies can be split into two categories: flow visualization studies and dispersion studies.

In both flow visualization and dispersion studies, the wind field used in the tests has turbulence. The simplest method of describing turbulence is the turbulence intensity (TI). The equation used to determine turbulence intensity is

$$TI = 100(SD/M) \quad (2.1)$$

where SD is the standard deviation of the wind speed, M is the mean speed of the wind, and TI is in percent.

2.2.1.1 Flow Visualization Studies. Robertson et al. (1978) investigated the behavior of the fluid reattachment zone for uniform (low turbulence) and non-uniform (turbulent) flows on a bluff body. The non-uniform flows had a TI of 10 percent. The experiments were performed on a 5.94-ft wide object (the wide of the test section of the wind tunnel).

The body's length and height were both 6 in. A number of wind directions, relative to building position, were used in their study. A pitot tube was used to measure the wind speed at model height. The speeds ranged from 38.0 to 40.5-miles per hour (mph). It was unclear from the article what the equivalent full-scale wind speeds would be. Building-surface pressures were measured from pressure taps located on the roof in the reattachment zone and corners. The authors also used tufts attached to the model to determine the location of flow reattachment. The authors defined the angle of attack to be the angle between the wind direction and the model's centerline. Therefore, an angle of attack of 0° implied the wind direction was normal to the windward wall. The researchers found reattachment occurred when the angle of attack is greater than or equal to 14° for uniform flows. Under turbulent conditions, reattachment occurred for angles of attack greater than 9°. They also found that both the length of the separation region and the magnitude of the roof pressure fluctuations decreased rapidly with an increase in angle of attack. Reattachment did not occur when the angle of attack was 45°. The authors also found that the chance of reattachment increased for the more turbulent flow.

Fackrell and Pearce (1981) studied the relationship of reattachment to the dimensions of bluff bodies. They related reattachment to the following body ratios: L/H and W/H . They determined that there was a critical value of L/H . The critical value of L/H can be determined from the equation

$$(L/H)_{cr} = (0.72(W/H))/(1 + 0.51(W/H)), \quad (2.2)$$

where $(L/H)_{cr}$ is the critical value of L/H , W is the width of the wall normal to the wind, and H is the height of the body. Fackrell and Pearce found that reattachment occurs when L/H is greater than $(L/H)_{cr}$. A graph of equation 2.2 is shown in Figure 2.5 where $(L/H)_{cr}$ is equal to $(L/H)^*$. The figure also shows later work by Robins and Fackrell

Figure 2.5. Graphical representation of equation 2.2. $(L/H)_*$ is equal to $(L/H)_{cr}$ (Hosker, 1986).

(1983). Unfortunately, the paper by Robins and Fackrell was not obtainable, therefore details of their experiment cannot be described in this thesis.

Using equation 2.2, it can be determined if reattachment will occur on the roof of the TTU building. Equation 2.2 can be solved for the long wall (LW) and short wall (SW) normal to the wind. Table 2.1 shows the results of calculating equation 2.2. For LW, $(L/H)_{cr}$ is 0.90. L/H for this case is 2.3. Since L/H is greater than $(L/H)_{cr}$, reattachment will occur. With the short wall normal to the wind, $(L/H)_{cr}$ is equal to 0.76. L/H is 3.5 for SW. Again, L/H is greater than $(L/H)_{cr}$. Therefore, reattachment will take place.

The effects of stream turbulence on separating and reattaching flows were studied by Hillier and Cherry (1981). Their study involved a model which was 2.2 ft wide, 4.52 ft long, and 1.5 in high. They tested their model in smooth and turbulent flows. The smooth flow had a TI of less than 0.1 percent while the non-uniform flow had an 11 percent turbulence intensity. Hillier and Cherry did not state wind profile information in their paper. Pressure was measured on the roof surface. Hillier and Cherry concluded from smoke flow visualization tests and pressure records that reattachment occurred at the end of pressure recovery (where mean pressure values remained constant with distance from the windward wall). Under uniform flow conditions, the separation bubble was the longest. The reattachment line curved across the span of the roof, similar to the reattachment line shown in Figure 2.2. For the turbulent flow, the bubble was shorter and the reattachment line was straight across the roof span.

Gowda et al. (1983) attempted to determine the influence of a 3-dimensional bluff body on ground-plane flow patterns. Their study considered two types of flows: uniform and turbulent. The models they used had a constant W of 30 millimeters and variable lengths and heights. The models they tested had (L/W) ratios that ranged from 0.5 to 4.0. They also had (H/W) ratios that spanned from 0.1 to 4.0. The tests were conducted using a wind speed of 40.5 mph, measured at the exit of the wind tunnel just before the model.

Table 2.1. Determination of reattachment using equation 2.2.

<u>Parameter</u>	<u>Long Wall</u>	<u>Short Wall</u>
L (ft)	45	30
W (ft)	30	45
H (ft)	13	13
L/H	2.3	3.5
W/H	3.5	2.3
(L/H) _{cr}	0.90	0.76

The height at which the wind speed was measured at was not given. Titanium dioxide solution, petroleum, and detergent were all used for visualization. The exact method of how the flow visualization liquids were used was not described in the paper. Gowda et al. found that for a flat approach velocity profile, increase in model height decreased the length of the wake. Therefore, the ground-plane flow was influenced by the building's dimensions. Also, a horseshoe vortex was present around the building. Finally, the boundary-layer height affected the separation point, but the dimension of the horseshoe vortex remained unchanged.

Castro and Dianat (1983) studied the surface flow over and around a bluff body. The goals of their research were to determine how body geometry and upstream flow affected reattachment. The objects they used all had a height of 60 mm. The width and length of the rectangular bodies varied in an unspecified way, and the wind speed the models were tested under was not given. They measured pressure on the bluff body's roof and used a pulsed-wire anemometer to measure wind speeds at the roof's surface. Castro and Dianat concluded reattachment was unaffected by the Reynold's number (Re). Figure 2.6 is a summary of their conclusions. The figure shows that for a particular (W/H) , $(L/H)_{cr}$ was smaller for the rough flow than the smooth flow. Therefore, reattachment depends on the dimensions of the object and the turbulence intensity of the approaching flow.

2.2.1.2 Dispersion Studies. The dispersion of a building's waste gases by the wind is important to design engineers. Designers want to determine the best location for exhaust and intake equipment. They also strive to specify the proper height of the stack to avoid recirculation of the exhaust gas (exhaust-to-intake problems). Therefore, many people have conducted dispersion studies on scale-models to determine the proper height and location of building effluent stacks.

Figure 2.6. Summary of Castro and Dianat's (1983) research concerning reattachment.

One of the most comprehensive building dispersion studies was conducted by Wilson (1979). He tested 32 aluminum test buildings. Each model was different in size and shape. Most of the models were 5-cm tall. The height of the objects ranged from 5 cm to 30 cm. The aluminum blocks were 5-cm to 30-cm wide. The models ranged from 5-cm to 50-cm long. Instead of using a wind tunnel, Wilson tested his models in a water channel. The flow profile was similar to wind profiles found in suburban areas. Wilson did present the velocity profile of the water table, but he did not provide the information necessary to convert the water velocity into an air velocity. He injected dye at various locations close to the roof in order to study the flow patterns over the models roofs. Figure 2.4, shown previously, is a generalized schematic of Wilson's observations. The three zones, described in detail in section 2.1, are labeled in the figure.

Wilson developed equations to quantify the characteristics he observed. Let f be the larger dimension of H and W . Let Ω be the smaller dimension. Wilson defined the characteristic length (R) of the separation bubble as

$$R = f^{0.67} \Omega^{0.33}. \quad (2.3)$$

The length (L_C) of the separation bubble is then

$$L_C = 0.9R. \quad (2.4)$$

The maximum height of the bubble (H_m) is

$$H_m = 0.22R. \quad (2.5)$$

The distance of H_m from the windward wall (x_m) is

$$x_m = R/2. \quad (2.6)$$

Wilson suggested that the exhaust stack height should be greater than H_m to avoid exhaust-to-intake problems. He also found that the mean wind velocity had no effect on the size of the separation bubble.

Using Wilson's equations, the characteristics of the TTU building separation bubble can be predicted. The values used in the calculations are shown in Table 2.2. For LW, the bubble is 17.63-ft long and 4.31-ft tall. Using the values for SW, the separation bubble is 15.42-ft long and 3.77-ft tall.

Pollutant dispersion in building wakes was studied by Koga and Way (1979). They used a wind tunnel to determine the effects of stack height on dispersion. The model they used was arbitrarily chosen to have the dimensions 4 x 4 x 8 in. The model was tested for a wind speed of 4.5 mph at an undisclosed height. The turbulence intensity of the flow was not given by the authors. Helium was used as the stack gas. The gas was preheated to 212°F. Ground level concentrations (GLCs) were measured using thermal tracers. The tracers consisted of temperature probes which measured changes in temperature due to the heated helium. Smoke was used for flow visualization. A 35-mm camera recorded the experiment. The authors positioned the stack at the following locations: in the middle of the roof, along the windward wall, parallel to the side wall, and beside the edge of the roof and leeward wall. The coordinates of the stack's locations were not given in the paper. Koga and Way determined that the GLCs were greatest for the leeward stack positions. The GLCs were similar at all positions when the stack height was 1.5H. Also, the best stack location was at the center of the model. The stack height should be at least 1.5H to avoid building-induced pollution problems.

Table 2.2. Determination of separation bubble characteristics using Wilson's equations.

<u>Parameter</u>	<u>Long Wall</u>	<u>Short Wall</u>
W (ft)	45	30
H (ft)	13	13
R	19.58	17.13
L_c (ft)	17.63	15.42
H_m (ft)	4.31	3.77

White and Stein (1990) tried to find the best location and height of a stack for a proposed building at Lawrence Livermore National Laboratory in Livermore, California. The model they used had a scale of 1 to 300. Only the height of the proposed building was given in the paper. The height (H) was 60 ft. They tested stack heights of $2H$, $2.5H$, and $3H$. White and Stein tested the dispersion characteristics of the building for the eight basic wind directions. The wind speed they used was 25 mph at $2H$. Smoke, the stack's effluent, was videotaped for 5 minutes. The video was then analyzed frame-by-frame. The plume's position was drawn for 1-sec periods, each separated by 2 sec. Assuming an angle of attack of 0° was produced by a north wind, the authors concluded that angles of attack of 90° and 270° (east and west winds) caused the stack effluent to contact the roof when the stack was $2H$. For a $2H$ -tall stack, the east and west winds caused the effluent to reach the ground a distance of $5H$ from the building. For south and north winds, the plume struck the ground at a distance of $5H$ for all stack heights. They also observed a $0.5H$ -tall separation bubble. The authors suggested the stack should be a minimum of $0.5H$ -tall.

Olivari and Babuska (1990) studied the dispersion of pollutants in the wake of a cube. They used a very low velocity compared to some of the previously mentioned studies. The velocity at 5 cm above the wind tunnel bottom was 2.20 m/sec (4.93 mph). The model shape they used in their study was cubic. The dimensions of the cube were not given by the authors. They used a video camera and digital processing equipment to analyze the smoke as it flowed over the model. The cube was aligned normal to the wind. The smoke was emitted from a flush vent located at the center of the roof. A laser illuminated the smoke. The camera was fitted with a filter that was sensitive only to the light emitted by the laser. From their work, the authors concluded that wake dispersion was dominated by periodic vertical and horizontal motions. Near the model's leeward edges, shed vortices

swept pollutants into the wake. The average distribution of the pollutants in the wake was uniform.

2.2.2 Numerical Studies

Numerical modeling is the second method of studying airflow around buildings. Numerical models solve the equations governing fluid motion. This technique has gained in popularity over the past 20 years due to improvements in computers.

Paterson and Apelt (1990) attempted to simulate flow over a cube in a turbulent boundary layer. They used time-averaging to solve the Navier-Stokes equations. The kappa-epsilon model was used. Also, the authors added a "recirculation promoter" to the model to help the model represent the separation bubble. Paterson and Apelt reported that the model accurately simulated areas of recirculation when the model results were compared with a wind-tunnel flow visualization study the authors conducted. They found that flow structures varied in size and shape due to the following variables: the height of the wind tunnel's simulated boundary layer, the roughness of the model's walls, and the amount of turbulence in the flow.

Qasim et al. (1991) conducted a two-dimensional simulation of flow over the WERFL test building. Their model used the finite-volume method to solve the Navier-Stokes equations. The model grid was non-uniform. The kappa-epsilon turbulence model was used. They compared the numerically derived flow results to water channel flow visualization studies. The model they used in the water channel was a 1 to 50 model of the prototype building. In Figure 2.7, the numerical simulated flow field is compared with the water flow visualization. The water table picture is blurred, making an accurate comparison difficult. Yet, the authors determined the two flows compared well. The model's output did not represent the separation bubble well. It was difficult to determine if the wind vectors indicated recirculating flow. Also, it was impossible to determine the

(a)

(b)

Figure 2.7. A comparison of the computer-generated flow field (a) and the water table flow visualization (b) (Qasim et al., 1991).

length and height of the bubble from the figure. Qasim et al. also found the numerically determined mean pressures were similar to mean pressures measured at the TTU building.

Kamath (1993), a Texas Tech University Mechanical Engineering student, used a commercially available 3-dimensional flow visualization program (Fluent version 3.03) to determine the dispersion characteristics of the TTU building. Fluent utilizes finite differences to solve the Navier-Stokes equations. Kamath studied winds normal to both the long wall and the short wall. For both building positions, Kamath varied the location and height of the stack on the roof. The stack heights he used ranged from $0.25H$ to H . He positioned his stack at the following locations: in the middle of the roof and around the perimeter of the roof. The coordinates of the stack's locations were not given in the paper. The results of the numerical simulation were compared with water table simulations. Kamath stated that both methods of simulation were conducted under similar conditions. His statement was true for the wind velocity. The wind speed was 22.5 mph. Yet, the water channel's turbulence intensity was 4 percent, while the TI used in Fluent was 10 percent. Therefore, there was a significant difference between the two simulations. Kamath found good agreement between the two simulations. Figure 2.8 shows the wind vector fields from one of Kamath's simulations. The overall flow pattern is similar to the conceptual model shown in Figure 2.2. The model simulation fails to represent the separation bubble (typical of numerical modeling experiments). He concluded that changes in wind speed did not affect the size and shape of the building's airflow contours. The flow did vary with the building's aspect ratio (length on wall normal to the wind divided by the height of the wall). He concluded the height of the stack should be greater than H for an isolated building. For a non-isolated building, the stack should be higher than the tallest nearby building.

(a)

(b)

Figure 2.8. Flow fields from Kamath's work (1993) of the following views: (a) the plan view and (b) the side view.

2.2.3 Full-Scale Studies

There have been several full-scale studies of wind effects on buildings. The first attempt was the Aylesbury House Experiment (Eaton and Mayne, 1975). The experiment consisted of an experimental building and 7 two-story residential homes located in Aylesbury, England. The two-story experimental building, located southwest of the 93-home estate, had an adjustable roof pitch which ranged from 5° to 45° . The terrain southwest of the estate was flat and open. The experiment's main emphasis was to determine wind loading on low-rise buildings. Some flow visualization work was performed in the Aylsebury House Experiment. In Newbury and Eaton's (1974) paper, they included sketches of roof corner vortices. They determined that the steeper the pitch of the roof, the smaller the size of the vortices.

Researcher at Texas Tech University are conducting full-scale tests on a low-rise structure. The Texas Tech University Wind Engineering Field Laboratory (WERFL) is located on the TTU campus in Lubbock, Texas. The surrounding terrain of WERFL is basically flat, open farm land. Figure 2.9 shows the land uses near the test site. The building's dimensions are 30 x 45 x 13 ft, as shown in Figure 2.10. The building is a smooth metallic structure with a rigid horizontal steel frame. The frame can be attached to a circular concrete foundation by anchor bolts located in the concrete. Hydraulic jacks are located at each corner of the frame. The building can be raised and then rotated. Two electric motors power the rotation.

The building may be rotated so the wind strikes the building in any desired manner. The building position is defined as an angle. The angle is measured clockwise between true north and the longitudinal axis of the building. The angle between the building position and the wind direction is called the angle of attack. The angle of attack and building position are shown in Figure 2.11.

Figure 2.9. Land uses around the WERFL site (Yeatts, 1992).

Figure 2.10. Dimensions of the WERFL.

Figure 2.11. Definition of wind azimuth and angle of attack.

The test building has pressure transducers located at various points. The transducers are used to measure external surface pressure and internal building pressure. The features of the pressure transducers were described by Levitan and Mehta (1991a, b).

Inside the main building, a small concrete block structure exists. This building houses the data collection system. The data collection system consists of a 20 MHz 80386-based personal computer. LabTech Notebook software is used to perform the data collection. This structure does not rotate with the main building.

The WERFL has a 160-ft meteorological tower, shown in Figure 2.9, west of the test building. The tower has anemometers and wind vanes located at various heights. Also, a 13 ft pole is located approximately 60 ft west of the building between the meteorological tower and the building. The pole is outfitted with an anemometer.

The wind engineering program at Texas Tech University is currently studying wind and its effects on structures and the environment. The research projects include wind loads on low-rise buildings, studies for building ventilation, building roofing studies, nonboundary layer wind simulation, structural glazing performance, prediction of extreme winds, numerical modeling of air flow, and soil erosion.

Some flow visualization work was been conducted for the wind engineering program. Sandri's (1992) work involved flow visualization of the separation bubble formed by the WERFL test building. Using tufts attached to the roof and roof pressures, Sandri determined the location of the reattachment zone for a wind normal to the building's short wall. As shown in Figure 2.12, the reattachment zone begins approximately $0.4L$ (18 ft) and extends to $0.6L$ (27 ft). The shape of Sandri's reattachment zone is significantly different than Woo et al.'s reattachment line shown in Figure 2.2. The conceptual model shows the reattachment line was curved. Sandri's reattachment zone has a rectangular shape. Therefore, the two studies contradict each other.

Figure 2.12. The WERFL test building's roof reattachment zone determined by Sandri (1992).

2.3 Summary of Previous Work

Much work has been accomplished in the area of airflow around buildings. Although most of the research has been conducted in the wake region of the building, some separation bubble studies have been conducted. Wind tunnel researchers have determined that the geometry of the bluff body, the turbulence intensity of the wind field, and the height of the atmospheric boundary layer impact reattachment. Equations have been developed to predict the height and length of the separation bubble. However, since wind tunnels cannot simulate thermal turbulence, such as occurs in the atmosphere, the applications from wind tunnel results are limited. Numerical modelers have had trouble simulating the separation bubble due to difficulty representing turbulence. One researcher has even programmed a recirculation promoter to simulate the separation bubble. As a result of the shortcomings of wind tunnel modeling and computer modeling, more full-scale studies must be undertaken. The full-scale studies that have been undertaken have not included formal studies on the airflow over their test buildings. As a result, this full-scale study will determine the properties of the separation bubble formed by the WERFL test building.

CHAPTER 3

EXPERIMENTAL DESIGN

3.1 The WERFL Wind Instrumentation

The WERFL test site measures wind data at 6 heights for 2 locations. Most of the wind instrumentation is measured on the 160-ft meteorological tower (MT), which is 155 ft west of the test building. Wind speeds are measured at the following elevations on the MT: 3, 8, 13, 33, 70, and 160 ft. Gill Microvanes are used to measure the 13-ft and 160-ft wind direction on the MT. Gill UVW anemometers are used to measure wind speed and wind direction at 8 and 33 ft on the MT. Gill 3-cup anemometers are utilized on the MT (except at 8 and 33 ft). Wind speed is also measured by a Gill 3-cup anemometer at a 13-ft pole, located 80 ft west of the building (between the MT and the building).

3.2 Experimental Apparatus

Additional equipment was required for the flow visualization experiments. The main piece of equipment used in the study was the metallic frame shown in Figure 3.1. The frame was 6.5 x 20 x 4.5 ft. The vertical members and upper horizontal members were constructed of 1-in steel pipe. The lower horizontal members were fabricated from 1.375-in steel slats. Nylon line was tied to the frame at 1-ft intervals. Black yarn tufts were fastened to the nylon line. The tufts were attached every 4 in up to 2 ft in the vertical direction. Above 2 ft, the yarn was attached at 2.5 ft, 3 ft, and 4 ft. A side view of the frame was shown in Figure 3.2. The positions of the yarns are represented in the figure as dots. Only one 20-ft row was used in this study.

Smoke was used a background for the tufts. Figure 3.3 shows the smoke generation system. A gas-powered smoke generator was used. The generator burned diesel fuel to

Figure 3.2. Side view of the metallic frame. The tuft positions are indicated by the dots.

Figure 3.3 Picture of smoke generation system. Included are mast and timing device.

produce the smoke. A 4-in PVC pipe conveyed the smoke to the edge of roof and windward wall. Flow from the pipe was baffled by a small, rectangular flow reducer. The flow reducer decreased the speed of the smoke emitted from the PVC pipe. By decreasing the smoke's velocity, it was thought that the effect of the smoke's exit velocity on the separation bubble would be decreased.

The tuft grid and smoke were recorded by a video camera. The video camera was located at roof height, approximately 20 ft from the grid. This camera position was chosen because it gave the best view of the entire grid. The camera collected data at 30 frames per second.

A steel mast was also used in the study. The mast consisted of a 0.375-in diameter steel rod connected to a 1 x 1 x 0.125 ft steel plate. Anemometers were attached to the mast at heights of 1, 4, and 6 ft. The wind speeds measured by the 3-cup anemometers were recorded by the computer in the block house.

To synchronize the video data and the computer-recorded data, a timing device was built. The timing device was constructed of a standard, 120-volt light socket connected to a relay switch. As the switch was turned on, the light illuminated and was recorded by the video camera. Simultaneously, a small 3-volt current was recorded by the computer. The time at which the light and the voltage were recorded could then be compared as a reference point for each data source.

3.3 Data Collection

3.3.1 Data Sources

Pressure data, wind data, and meteorological data were collected during each data run under the data acquisition mode 98 (M98). The pressure data was collected at 30 Hz. The wind data and meteorological data under M98 were sampled at 10 Hz and 1 Hz, respectively. The data collected by the computer was stored on an optical disk for easy

transport. Section 3.1 described the types of instruments and the instrument locations. More detailed information about the data collection system was presented in papers by Levitan and Mehta (1991 a, b).

3.3.2 Data Collection Procedure

Data were collected for angles of attack of 270° (long wall normal to the wind) and 180° (short wall normal to the wind). The data for this study were collected according to a predetermined procedure. The purpose of the procedure was to ensure the quality and repeatability of the data. The exact procedure is described below.

The first step was to set up the experimental apparatus. The smoke generator was positioned on the roof. The piping was then placed on the roof and connected to the smoke generator. The rectangular box was placed in front of the pipe opening. Next, the mast was fastened to the grid at the desired position. The timing device was placed at the base of the mast. All roof-instrument connections were then checked.

The second step was to raise and rotate the building so the wind would be perpendicular the appropriate wall. The building's position, relative to "true" north in degrees, was recorded. The camera was then set up on an elevated platform. The camera focused so that the entire grid was recorded. Once the camera was positioned, the camera started recording. Next the smoke generator was started. Finally, the computer was initiated. The timing device was switched on for approximately 1 sec in the beginning of the data run and near the end of the data run.

After the 15-min data run ended, the smoke generator was refueled. The mast was moved to a different location. The 1-min average wind direction was checked to make sure the wind was still normal to the building. Once these tasks were completed, another 15-min data run was conducted. Data were collected with the mast positioned 8 in, 7 ft, 14 ft, and 20 ft from the edge of the windward roof edge.

3.4 Data Processing

Once the data were collected on the optical disk, the disk was taken from the field site to the Wind Engineering offices to be processed. The raw data, consisting of voltage readings from the instruments, was transformed into the proper units by a computer processing program. The processing program was previously written by WERFL personnel. The program also flagged potentially bad data readings. A flagged data reading consisted of a data value with an asterisk adjacent to it. A summary of each data run was produced by the program. The summary listed statistical information for each instrument. The summary sheets were analyzed by the author to locate "flagged" data sources and to ensure the unflagged data was acceptable. For the most part, the data was consistently good. At least one pressure transducer malfunctioned in each run. Therefore, the pressure data was not used in this study. A complete description of each data run will be presented in Chapter 4.

CHAPTER 4

DATA ANALYSIS AND DISCUSSION

4.1 Data Collected

To study the separation bubble formed on the WERFL test building under varying wind conditions, 29 data runs were collected on three different dates. Each data run was 15 minutes long. Of the 29 data records that were gathered, 16 were not useful to this study. There were two reasons why those data runs were not beneficial to this thesis. Ten data runs were non-retrievable due to a defective computer disk. Six records were not usable because of video camera problems. Still, 13 successful data records were collected and analyzed. Of the 13 runs, 7 were recorded for an angle of attack (β) of 270° (LW). The remaining records were collected for an β of 180° (SW).

Information concerning the 13 successful records is summarized in Table 4.1. Each data run has a data run number. For example, the first data record number in the table is M98N692. M98 indicated the data run was collected by the data acquisition mode 98. Information concerning data acquisition mode 98 was described in subsection 3.3.1 (i.e., sampling frequency, instruments sampled, etc.). The number 692 stated that this data run was the 692nd data record collected by M98. Also in Table 4.1, each run's date of collection and acquisition time of each run are given. The runs are described by the average wind speed (at the 13-ft pole), wind direction (at 13 ft on the MT), the building position, angle of attack, and weather conditions. The average wind speeds were similar for most data runs, as the means ranged from 8.07 mph to 14.49 mph. Also, the different weather conditions are notable. All LW data runs were collected during sunny sky conditions. A few of the SW data records were collected while showers and thunderstorms were near the WERFL building. Thunderstorms can cause gusty winds. The gusty winds may be the

Table 4.1. Listing of successful data runs collected for this thesis.

<u>Data Run Number</u>	<u>Date</u>	<u>Starting Time</u>	<u>Average 13P Wind Speed (mph)</u>	<u>BP (°)</u>	<u>Average Wind Direction at 13 ft on MT (°)</u>	<u>Average Angle of Attack (°)</u>	<u>Weather Conditions During Run*</u>
M98N692	5/4/1993	11:42	8.53	315	208.11	253.10	1
M98N693	5/4/1993	12:02	10.35	315	196.00	241.00	1
M98N694	5/4/1993	12:19	9.18	315	204.18	249.18	1
M98N695	5/4/1993	12:41	10.00	315	211.32	256.32	1
M98N696	5/4/1993	12:59	11.16	315	213.14	258.14	1
M98N697	5/4/1993	13:18	10.21	315	202.52	247.52	1
M98N698	5/4/1993	13:38	10.78	315	195.32	240.32	1
M98N747	5/17/1993	14:43	10.86	40	213.34	186.66	2
M98N748	5/17/1993	15:02	11.09	40	204.19	195.81	2
M98N749	5/17/1993	15:21	14.49	40	190.62	209.38	2
M98N751	5/19/1993	14:49	8.87	45	209.44	195.56	3
M98N752	5/19/1993	15:07	8.07	45	208.58	196.42	3
M98N753	5/19/1993	15:24	8.69	45	208.71	196.29	3

*Note: 1 - sunny skies
2 - mostly cloudy skies with showers and thunderstorms in the area
3 - partly cloudy skies

reason the mean wind speeds of data runs M98N747 to M98N749 were higher than the other records.

4.2 Data Analysis

As stated in Chapter 3, there were two types of data collected: video data and computer-recorded data. Each type of data was analyzed differently. Therefore, a description of each type of analysis is given in the following subsections.

4.2.1 Wind Analysis

Wind information was measured at three locations and six heights producing 13 wind records. Not all of the wind data were utilized for this study. Only wind data records at five selected positions were analyzed to aid in the definition of the separation bubble's properties. The five selected records were the wind direction time series measured at 13 ft on the MT, the wind speed record on the 13-ft pole, and the three wind speed records collected by the roof anemometers. All other wind records were collected by the preexisting instrumentation, but not utilized in this study.

The first wind data record analyzed was the 13-ft wind direction measured on the MT. This record showed when the wind was normal to the appropriate building face (normal wind). A typical wind direction time series can be seen in Figure 4.1. In the figure, notice the large number of fluctuations in the wind direction. The fluctuations made it difficult to locate periods of normal wind. As a result, all the wind direction time series were then filtered or "smoothed." The data was filtered using the moving average technique (Smithe, 1992). The moving average (u_m) was defined as

$$u_m = \frac{1}{k} \sum_{j=1}^k x_{(m+j-1)}, \quad (4.1)$$

Figure 4.1. Wind direction time series for M98N694.

where k = the number of points used in the average, x = the value being averaged (wind direction), m is an integer and represents the reference point in the time series, and j = an integer counter. From equation 4.1, it can be seen that the moving average value (u_m) was determined by adding values of x from m to $m + k - 1$ in the time series. Then, the sum was divided by k to give u_m . A u_m value was calculated for each point in the time series except near the end of the time series. This boundary problem is handled differently by the various software for time series analysis. Since the commercial program DADISP was utilized to calculate moving averages in this thesis, DADISP's treatment of the boundary problem is discussed in the following paragraph (DSP Development Corporation, 1991).

The net result of applying a moving average is to filter out the high frequency signals in the time series. The remaining signal was a smoothed, easily read time series. Figure 4.2 shows the result of performing a moving average on Figure 4.1 using DADISP (DSP Development Corporation, 1991). DADISP is a program package which was developed to analyze and display time series. The number of points (k) used in the average calculated by DADISP was 101. This averaging interval was chosen because the resulting time series was smooth while it retained the characteristics of the original time series. DADISP manages the moving average boundary problem by setting the first and last point of the time series equal to zero. The program then draws a straight line from the initial time series point ($m = 0$) to the first point ($m = k + 1$) for which the moving average was calculated. Near the end of the time series, a straight line is drawn from the last point in the time series (n) to the value at $n - k$. As shown in Figure 4.2, two such lines exist at the beginning and at the end of the time series.

By knowing the building's position for each data run, the normal wind direction, β , was determined from equation 4.2:

$$\beta = 360^\circ - |BP - WD| \quad (4.2)$$

Figure 4.2 Moving average performed on wind direction time series from M98N694. Averaging interval was 101 data points.

where BP was the building position, relative to "true" north, in degrees and WD was the average 13-ft wind direction at the MT, relative to "true" north, in degrees for the data run. Using the BP and the desired β , the WD normal to the building was calculated for each data record. Once the normal wind direction was determined, the moving-averaged time series was inspected for each data run. Wind directions $\pm 5^\circ$ from the desired wind direction were considered perpendicular to the building. From the 13 successful data runs, 11 records had at least one period which met the following criteria: (1) wind normal to the building for 10 sec or longer and (2) a majority of the tufts were visible. A 10-sec period was chosen for two reasons. First, the observed, 10-sec SB resulted from approximately 150 ft of wind (average 14.67 ft/sec wind for 10 sec). Since 150 ft of wind is 3.3 building dimensions when the short wall is normal to wind, the SB can be considered in a steady state for the period. Second, it was observed during the data collection that the separation bubble collapsed approximately every 45 sec. A 10 sec period, which is smaller than the average duration of a separation bubble, was deemed appropriate for this study. These periods that fulfilled the requirements are listed in Table 4.2. In the table, note that these 11 data runs had 35 acceptable periods. Of those 35 periods, 16 episodes occurred during the LW experiment. The remaining periods in Table 4.2 were collected during the SW experiment.

Once the periods were located, it was necessary to extract wind speed information for each period. Wind speed information was selected from both the 13-ft pole record and the roof anemometer. As stated in section 3.2, the roof anemometers were mounted on a 6-ft mast. The instruments 1 ft, 4 ft, and 6 ft above the roof's surface were labeled R1, R4, and R6, respectively. One hundred data points (10 sec at 10 Hz) from the wind speed data were extracted to determine the statistical properties of the wind that struck the building. The following statistical parameters of the wind speed data were determined: the average, the standard deviation, the variance, the maximum speed, the minimum speed, and the turbulence intensity (defined by equation 2.1).

Table 4.2. Listing of periods of wind normal to building.

<u>Type of Experiment</u>	<u>Data Run Number</u>	<u>Period Number</u>
LW	M98N692	P2
		P3
		P4
		P5
		<u>P6</u>
	M98N694	<u>P2</u>
		P3
		<u>P4</u>
	M98N695	P1
		P2
		P3
		<u>P4</u>
	M98N696	<u>P1</u>
		P2
		P3
		<u>P4</u>
SW	M98N747	<u>P1</u>
		P2
		P3
		P4
		<u>P5</u>
	M98N748	P1
		P2
		P3
		<u>P4</u>
	M98N751	P1
		P2
		<u>P3</u>
	M98N752	P1
		<u>P2</u>
	M98N753	P1
		P2
		P3
		P4
		P5

4.2.2 Video Analysis

The video tape was analyzed using video equipment housed in the Mechanical Engineering Video Editing Room (MEVER) on the Texas Tech campus. The VCR used at this facility was a Panasonic AG-6500, Hi-Fi VCR. The VCR was controlled by a Panasonic AG-650 editing computer. The computer had the capability of advancing or rewinding the video tape on a frame-by-frame basis. The computer also kept track of the elapsed time. The video was viewed on the facility's two Panasonic CT-1030 color video monitors.

The first step in video analysis was synchronization of the video tape with the computer-recorded data using the timing device (TD). The TD consisted of a light socket and a relay switch. The relay switch, when activated, simultaneously illuminated the 120-volt light bulb (which was recorded by the video camera) and emitted a 3-volt signal archived by the computer. The TD's time series was then analyzed to determine the time the device was switched on and then off. To accomplish this, the commercial program DADISP was utilized (DSP Development Corporation, 1991). DADISP allows the user to determine the exact time a data point was recorded during the data run. By using this DADISP feature, the time the TD was activated and deactivated was determined to the nearest tenth of a second for each data run. Once the TD's activation and deactivation times were established for the computer data, the on and off times were determined for the video data for each run using the MEVER equipment. The time the TD's light bulb illuminated was located on the video tape. At that point, the elapsed time, indicated by the editing computer, was recorded. The same technique was used to determine the deactivation time.

The duration of TD activation compared well between the two data sources. As seen in Table 4.3, the difference between the two data sources' activation time duration was generally 0.1 sec. This difference can be attributed to the fact that the light bulb's light

Table 4.3. Comparison of timing device as determined from computer data and from video data.

<u>Run Number</u>	<u>TD Activation Time (sec)</u>		<u>Difference (sec)</u>
	<u>Computer Data</u>	<u>Video Data</u>	
M98N692	1.5	1.6	-0.1
M98N694	1.8	1.6	+0.2
M98N695	2.1	2.1	0.0
M98N696	1.4	1.3	+0.1
M98N697	1.1	1.0	+0.1
M98N698	2.1	2.1	0.0
M98N747	1.1	0.9	+0.2
M98N748	0.9	0.7	+0.2
M98N751	1.4	1.3	+0.1
M98N752	1.0	1.0	0.0
M98N753	1.1	1.0	+0.1

slowly faded after the TD was turned off. Therefore, an exact deactivation time was difficult to determine from the video data.

By comparing the TD's activation times from both data sources, a reference point in each data source was determined to locate the beginning of the data run on the video. Once the start time was determined for the video, the periods determined from the wind analysis were located and analyzed. For example, assume the TD was switched on then off at 37.0sec and 38.5 sec, respectively (as determined from the computer TD time series). From viewing the video tape of the same data run, it was determined that the TD was switched on and off at 2:05.5 min and 2:06.2 min, respectively. Therefore, 1:28.5 min elapsed on the video before the data run began. Therefore, the data run began ($t = 0$) 1:28.5 min into the video.

After the start of each data run was determined, the video could be advanced to the periods of interest. Once the video was at the initial frame for the period, the video image was transferred to a hard copy. The commercial program NMG Take 1 (News Media Graphics Company, 1992), which has the capability to convert video images into a printable digital picture, was initially used to print the video frames. Unfortunately, the resolution of these hard copies was not high enough for tuft differentiation. It was determined that the only feasible method of this transformation was to manually record the orientation of each tuft visible on the TV monitor on standard plots of the grid (as in Figure 3.2). Not all the tufts were visible in each frame on the video tape. Some of the yarns were occasionally obscured due to objects in the background, such as buildings, poles, smoke from the smoke generator, birds, and the grid. Therefore, the obscured tufts were not drawn. Also, tufts oriented parallel to the video camera were not visible. As a result, not all of the tufts were drawn on the paper record for each video tape frame.

The video tape provided 300 frames for each 10 sec period. This large number of snapshots was too large to process. A time interval of 2.5 sec was selected to provide a

manageable number of frames yet still represent variations within the period. Four to five frames were plotted for each run.

4.3 Characterization of the Separation Bubble

4.3.1 Case Studies

As stated in subsection 4.2.1, 35 usable periods of sustained wind normal to the building were discovered. The periods were first sorted into similar groups. Prior to this analysis, the periods were initially separated according to the building orientation. As stated previously, 16 periods were placed in the LW group, and 19 were deposited in the SW group. The hard copies from each group were then inspected. Four distinct flow structure trends were apparent, and four classifications were created. These cases are listed in Table 4.4. Case A represents a stable, idealized separation bubble which is fairly constant in all frames. One period from both experiments was placed in this category. Case B designates periods in which the area of recirculation in the SB increased throughout the entire period. One SW period and two LW periods matched this category's requirements. Periods were classified as Case C if the recirculation first strengthened during the period, then dissipated. Ten SW episodes and eight LW episodes matched the requirements for case C. Case D periods had continuously fluctuating amounts of recirculation. Periods were classified as case D, and not case C, if the cycle of SB's recirculation increase followed by decrease happened more than once during the episode. Five LW periods and seven SW periods were placed in case D. The result of the above classification is listed in Table 4.5, including the data run from which each period originated. Table 4.5 also shows each period's name after classification. The first letter of the new designation indicated from which experiment the period originated. An L indicates the episode was from the LW test. Similarly, an S implies the period was collected during the short wall experiment. The second letter describes in which case the period is placed.

Table 4.4. Description of period classification.

<u>Case</u>	<u>Description</u>	<u>Number of LW Periods</u>	<u>Number of SW Periods</u>
A	Idealized separation bubble	1	1
B	Recirculation increasing throughout period	2	1
C	Recirculation increases, then decreases during period	8	10
D	Recirculation fluctuates during period	5	7

Table 4.5 Classification of periods according to separation bubble flow structure.

<u>Grouping</u>	<u>Run Number</u>	<u>Period Number</u>
LA1	M98N692	P2
LB1	M98N695	P2
LB2	M98N696	P4
LC1	M98N692	P3
LC2	M98N692	P5
LC3	M98N692	P6
LC4	M98N694	P1
LC5	M98N694	P3
LC6	M98N695	P4
LC7	M98N696	P2
LC8	M98N696	P3
LD1	M98N692	P4
LD2	M98N694	P2
LD3	M98N694	P4
LD4	M98N695	P3
LD5	M98N696	P1
SA1	M98N748	P4
SB1	M98N751	P3
SC1	M98N747	P4
SC2	M98N748	P2
SC3	M98N748	P3
SC4	M98N751	P1
SC5	M98N751	P2
SC6	M98N752	P2
SC7	M98N753	P1
SC8	M98N753	P3
SC9	M98N753	P4
SC10	M98N753	P5
SD1	M98N747	P1
SD2	M98N747	P2
SD3	M98N747	P3
SD4	M98N747	P5
SD5	M98N748	P1
SD6	M98N752	P1
SD7	M98N753	P2

The third character is the period's number in the case. Therefore, LA1 indicates the period is the first episode of case A for the LW experiment.

As each period was analyzed, certain general guidelines to characterize the separation bubble were followed. The height of the bubble (HB) was determined by the vertical and lateral orientations of the tufts. The HB was defined as the level at which the orientation of the tufts did not change with height. Since the tufts at the 4-ft level were usually obscured by the upper portions of the frame, it was assumed that when the HB was greater than 3 ft, then HB was equal to 4 ft. The length of the bubble (LB) was determined to correspond with the first column of tufts, relative to the leading edge of the building, for which the tufts' orientations, relative to the horizontal plane, were similar. If that column of tufts had uniform orientation, at least one tuft in the lower 1 ft must have been visible for it to be said that the SB ended at that column. If a column did not meet the above criterion, it was determined that the end of the bubble did not occur at that position. Of course, the tufts' orientation outside of the SB must have been directed towards the leeward wall.

An example of how the HB and LB were determined is shown in Figure 4.3. The area of tufts reviewed in the determination of the HB is enclosed in the rectangle in the figure. In the rectangle, the tufts' orientation is chaotic at 2 ft above the roof. At 2.5 ft, the tufts alignment was more uniform. The 3 ft arrangement of the yarns was similar to the 2.5 ft tufts position. As a result, the bubble was determined to be 2.5 ft tall. The portion of the grid used to determine the LB is encircled on the figure. Two yarns indicated recirculation at 11.5 ft. At 12.5 ft, a majority of the tufts were not visible. Therefore, this column was not chosen as the LB since it did not fit the criterion in the previous paragraph. Looking at the column 13.5 ft from the windward wall, the tufts' vertical arrangement was uniform and the tuft at 1 ft (of that column) was visible. As a result, the LB was set at 13.5 ft.

The assumption that the maximum the SB dimensions were similar to the limits of the grid was used for several reasons. The first reason was the complete exclusion of those

Figure 4.3. Example of the process of determining the height and length of the separation bubble.

frames would result in a bias towards bubbles smaller than the grid, thereby decreasing the mean HB and the mean LB. The second reason was that the assumption was applied to a minority of the frames. Of the 166 frames used in this thesis, the height limitation was applied to 67 frames (38 times in the LW experiment and 29 times in the SW test), while the length assumption was utilized 26 times (14 times and 12 times in the LW and SW experiments, respectively). Clearly, the largest impact the assumptions will have is on the average height from the LW experiments, but it was observed during the collection of data that the SB was generally less than 4 ft tall (as indicated by the 4 ft tufts). The height assumption would likely have been used less if the 4 ft row of tufts had been visible in more frames.

Two types of lines were drawn in each figure to help the reader visualize the flow over the roof. The most important line drawn was the separation bubble boundary. A solid line represents that boundary. The second type of lines drawn were streamlines. These dark lines with arrows were drawn to help the reader visualize the flow since a streamline represents the projected path a small volume of air will follow from a given starting point. The paths of some selected streamlines are shown in each figure of this section. It is important to state that the streamlines do not necessarily represent the boundary of the SB.

After viewing the streamlines from the figures in subsections 4.3.1.1 and 4.3.1.2, it will be apparent that the separation bubble is formed before the windward wall in all cases. This observation is consistent with Woo et al.'s (1977) conceptual model shown in Figure 2.2. Apparently, the streamlines are influenced by the building in the UDZ. As a result, the streamlines are deflected upward before the windward edge of the roof. The streamlines continue their ascent as the air flows over the leading edge of the roof.

4.3.1.1 Long Wall Experiment. This set of tests was conducted for an angle of attack of 270° (i.e., incident wind is normal to the long wall). In this subsection, examples of each category are presented. Also, a description of each example is given. For each case,

a figure displays the grid of tufts. The distances from the windward wall are shown under the grid's template for each frame. The height above the roof's surface is also shown in the figure.

For case A, LA1 is shown in Figure 4.4. The HB was 2 ft in the first frame, while the LB was 7.5 ft. In Figure 4.4 (a), a streamline was drawn. The streamline indicated that air, approximately 2 ft above the roof, flowed parallel to the roof. The streamline then curved toward the roof and reattached approximately 6.5 ft from the windward wall. Within the SB, some recirculation was present near the front of the bubble. The tufts had a fairly uniform orientation outside of the separation bubble. Figure 4.4 (b) implied the LB was still 8.5 ft. The HB was still 2 ft. In Figure 4.4 (c), the SB increased in length and height, with HB of 2.5 ft and LB of 14.5 ft. A second streamline was drawn for a height of 1.33 ft. After this streamline reached a maximum height of 1.5 ft, it curved toward the roof in a circular path, indicating recirculation of the flow. Figure 4.4 (d) shows the HB increased to 3 ft, while the LB was decreased to 10.5 ft. Inside the bubble, the streamline indicated that the incoming air began to reverse its direction approximately 2.5 ft from the windward wall. Again, outside of the SB, the tuft orientations were fairly uniform. Overall for the period, the average HB was 2.38 ft, and the average LB for the period was 9.25 ft. This was the only LW case A.

The wind information for LA1 is shown in Table 4.6. The mast was located 14 ft from the edge of the roof. Statistical values were given for the 13P, R1, R4, and R6. The mean roof speeds for LA1 increased with height, as expected since the roof's frictional effects should be greatest at the roof. R1 indicated a very low average wind speed. The turbulence intensities (TI) at the 13P, R4, and R6 were similar. Therefore, building-induced turbulence was minimal 4 ft above the roof. Less than 4 ft above the roof, building-generated turbulence increased. The extremely high TI at R1 should be ignored since the value has calculated from very small numbers.

(a)

(b)

(c)

(d)

Figure 4.4. Tuft orientations for LA1. Tufts were drawn for the following times: (a) 13:20.7, (b) 13:23.2, (c) 13:25.7, (d) 13:28.2.

Table 4.6. Summary of wind information for LA1.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	7.80	0.05	6.91	7.39
Variance	1.76	0.13	1.50	1.77
Standard Deviation	1.33	0.36	1.23	1.33
Maximum Speed (mph)	11.58	1.11	9.64	9.38
Minimum Speed (mph)	5.83	0.00	3.31	3.95
Turbulence Intensity (%)	17.24	786.96	17.75	18.01

Case B situations were more dynamic than case A. LB1 is presented in Figure 4.5. The initial HB was 3 ft, while the LB was 8.5 ft (Figure 4.5 (a)). A small area of recirculation was present below the shorter streamline. The tuft orientations in and outside the SB were fairly uniform. Figure 4.5 (b) shows the SB grew to a height greater than 3 ft. The LB was approximately 13.5 ft. The streamline initiating 1.67 ft above the roof's edge indicated flow reversal occurred 4.0 ft from the windward wall. Outside of the SB, the tuft orientations were more chaotic than in Figure 4.5 (a). In Figure 4.5 (c), the SB was still greater than 3 ft high, while the LB was 11.5 ft. It was apparent that the area of recirculation was increasing. Also, the shorter streamline indicated recirculation started approximately 3 ft from the edge of the roof. From Figure 4.5 (d), the area of recirculation has again increased. The height of the SB was still greater than 3 ft, while the LB was assumed to be 19.6 ft. The interior streamline indicated flow reversal began less than 3 ft from the windward wall. In Figure 4.5 (e), recirculation dominated most of the grid. The HB and LB cannot be determined for this frame. Therefore, the HB was assumed to be 4 ft, and a 19.6 ft long bubble was assumed. The two streamlines indicated that the position flow reversal began changed with height of the streamline. The streamline that began 2.5 ft above the roof implied flow reversal occurred 6 ft from the roof's edge. The other streamline reversed direction slightly more than 2.5 ft from the windward wall. The average HB and LB for LB1 were 3.8 ft and 14.5 ft, respectively. Another case B example, collected during the long wall experiment, can be seen in the Appendix of this thesis.

The wind statistics for LB1 are shown in Table 4.7. The roof anemometers were positioned 1 ft from the windward wall. The average speeds measured at R1, R4, and R6 were greater than the mean at the 13P. Also, the mean from R1 was greater than the average from R4. The larger mean was probably due to the acceleration of the wind as it flowed over the edge of the building. The acceleration was greatest near the roof. The TIs

(a)

(b)

(c)

(d)

(e)

Figure 4.5. Tuft orientations for LB1. Tufts were drawn for the following times: (a) 1:20.7, (b) 1:23.2, (c) 1:25.7, (d) 1:28.2, and (e) 1:30.7.

Table 4.7. Summary of wind information for LB1.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	8.50	13.67	11.28	13.77
Variance	1.95	1.40	1.15	1.03
Standard Deviation	1.40	1.82	1.07	1.01
Maximum Speed (mph)	12.55	15.78	13.06	15.71
Minimum Speed (mph)	6.28	11.25	9.06	11.32
Turbulence Intensity (%)	16.42	13.32	9.51	7.36

determined from the roof anemometer data were less than the TI at the 13P. Near the building's roof edge, the building effectively reduced the turbulence intensity of the approaching wind.

Case LC7 is presented in Figure 4.6. In Figure 4.6 (a), HB was approximately 4 ft, LB was 13.5 ft. Inside the bubble was a small area of recirculation. As shown by the streamline inside the bubble, flow reversal occurred approximately 5.5 ft into the bubble. Figure 4.6 (b) shows the height of the bubble was still at least 4 ft. The LB increased to 15.5 ft. The area of recirculation had also become larger. Nearly the entire interior of the SB had recirculating flow. The interior streamline indicated that flow reversal began 2.5 ft from the roof edge. In Figure 4.6 (c), recirculation continued to increase in area. Recirculation can be seen 18.6 ft from the windward wall. From this frame, it was impossible to determine HB and LB. As a result, the HB and LB were assumed to be 4 ft and 19.6 ft, respectively. The ellipsoidal-shaped streamline reversed its direction 5 ft from the roof's edge. Again, the bubble did not begin at the edge of the roof. In Figure 4.6 (d), the area of recirculation diminished. HB was approximately 3 ft tall, and LB was 15.6 ft. Flow reversal was present in the front third of the bubble. The interior streamline reversed direction 4.5 ft from the windward wall. Figure 4.6 (e) is similar to Figure 4.6 (d), with HB at 4 ft and LB at 16.6 ft. Flow reversal, as indicated by the shorter streamline, occurred again 4.5 ft. The streamline also indicated the bubble began before the windward wall. For the entire period, the average HB and LB were 3.8 ft and 14.5 ft, respectively. Additional examples of case C can be found in the Appendix.

The wind statistics for LC7 are summarized in Table 4.8. The mast of anemometers was placed 7 ft from the windward wall. The mean speeds measured at this point indicated the wind speed increased with height. R1's mean was 1.38 mph. R6's mean was larger than the 13P and R4. Therefore, the SB's mean height at 7 ft from the roof's edge was probably between 4 ft and 6 ft. On the roof, TI decreased with height. The TI at R1 was

(a)

(b)

(c)

(d)

(e)

Figure 4.6. Tuft orientations for LC7. Tufts were drawn for the following times: (a) 1:54.4, (b) 1:56.9, (c) 1:59.4, (d) 2:01.9, and (e) 2:04.4.

Table 4.8. Summary of wind information for LC7.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	12.25	1.38	6.92	15.61
Variance	1.75	0.29	0.96	1.88
Standard Deviation	1.32	0.54	0.98	1.37
Maximum Speed (mph)	15.71	3.05	9.57	18.38
Minimum Speed (mph)	9.64	0.47	5.37	13.26
Turbulence Intensity (%)	10.79	39.02	14.20	8.79

the greatest TI from this period. It was obvious from the TI value that R1 was located in the SB. Also, R6's TI was lower than 13P's TI. Therefore, the building probably reduced the TI of the wind just above the SB.

LD2, an excellent example of case D, is shown in Figure 4.7. In Figure 4.7 (a), the HB was approximately 3 ft. The bubble extended to 10.5 ft from the windward wall. Figure 4.7 (b) was less chaotic than Figure 4.7 (a). The bubble was 4 ft tall and 19.6 ft long. The top of the SB had a more pronounced wave-like appearance than the previous figure. The interior streamline changed direction 7.5 ft from the roof's edge. Also, recirculation increased in area in the SB. Figure 4.7 (c) shows the area of recirculation decreased. The streamline implied flow reversal had nearly vanished in the SB. The HB was 3 ft and the LB decreased to 10.5 ft. From Figure 4.7 (d), recirculation, located in the front third of the grid, increased. The flow reversal was seen in the interior streamline. Nearly 2 ft from the windward wall, the streamline changed its path. The SB was 3 ft tall and approximately 10.5 ft long. In Figure 4.7 (e), the amount of recirculation increased. Reversal of flow was indicated by the tufts for nearly two-thirds of the SB. The grid of tufts orientations was chaotic until 12.5 ft from the windward wall. Then the grid became more uniform. The chaotic pattern was also indicated by the path of the upper streamline. This streamline abruptly changed direction for most of its course. Once the streamline was 11 ft from the windward wall, the streamline flowed toward the roof. The interior streamline's path was more smooth than the upper streamline. The lower streamline reversed its direction nearly 5 feet from the roof's edge. In Figure 4.7 (e), the HB was greater than 3 ft, and the LB was 14.5 ft. For the period, the average height of the cavity was 3.2 ft, and the SB had an average length of 13.1 ft. The reader can find more case D examples in the Appendix.

Table 4.9 shows the wind statistics for LD2. The roof mast was located 1 ft from the windward wall. The mean speeds were similar for the four anemometers. R1 and R6

(a)

(b)

(c)

(d)

(e)

Figure 4.7. Tuft orientations for LD2. Tufts were drawn for the following times: (a) 10:43.6 (b) 10:46.1, (c) 10:48.6, (d) 10:51.1, and (e) 10:53.6.

Table 4.9. Summary of wind information for LD2.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	11.86	12.31	10.05	12.63
Variance	2.01	1.91	1.03	1.10
Standard Deviation	1.42	1.38	1.01	1.05
Maximum Speed (mph)	13.51	14.94	11.58	10.48
Minimum Speed (mph)	7.64	8.35	7.89	10.48
Turbulence Intensity (%)	11.95	11.24	10.08	8.29

means were greater than R4. R1, R4, and 13P TIs were similar during this period. On the roof, the TI decreased with height. Also, all the roof TIs were less than the 13P TI. The building slightly reduced the turbulence intensity of the previously undisturbed wind.

4.3.1.2 Short Wall Experiment. The short wall experiment (SW) was conducted for an angle of attack of 180° . In this subsection, examples of each category are presented.

From the 19 periods analyzed for the SW experiments, one case A period was identified. For SA1, the SB was initially 2.5-ft tall and 9.5-ft long in Figure 4.8 (a). Outside of the cavity, the tuft orientation was fairly uniform. Inside the bubble, there was some recirculation present. The interior streamline indicated flow near the roof's edge was towards the leeward wall. In Figure 4.8 (b), the tuft positions were still uniform. Recirculation was present near the roof's surface. The HB was 2 ft, and the LB was 7.5 ft. In Figure 4.8 (c), the tufts were uniform in orientation outside of the separation bubble. The bubble was 2.5-ft high., and extended to 9.5 ft in length. Inside the SB, recirculation was located in the rear of the bubble. A few tufts indicated recirculation in the bubble in Figure 4.8 (d). The LB was 9.5 ft, while the SB was 2.5-ft tall. In Figure 4.8 (e), the bubble had grown to a height of 3 ft. Also, the LB was 9.5 ft. Some recirculation can be seen in the bubble. Outside of the cavity, the flow pattern remained uniform. For this period, the average bubble was 2.5-ft tall and 9.1-ft long.

Table 4.10 summarizes the wind information from SA1. For this period, the mast was 14 ft from the windward edge of the roof. The mean speeds from the roof anemometers increased with height as a result of roof friction. R4's mean was nearly equal to 13P's average speed. The TI at the 13P was larger than the previous examples. This was probably due to the influence of the thunderstorms that were within 10 miles of the WERFL test building on this test date. Wind fields can be significantly impacted by a thunderstorm. The high 13P TI was probably a result of the thunderstorms. On the roof, the TIs decreased with height.

(a)

(b)

(c)

(d)

(e)

Figure 4.8. Tuft orientations for SA1. Tufts were drawn for the following times: (a) 9:39.6, (b) 9:42.1, (c) 9:44.6, (d) 9:47.1, and (e) 9:49.6.

Table 4.10. Summary of wind information for SA1.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	8.33	4.09	8.39	10.14
Variance	3.80	1.35	4.06	3.65
Standard Deviation	1.95	1.16	2.02	1.86
Maximum Speed (mph)	10.48	5.83	11.25	13.19
Minimum Speed (mph)	4.92	1.63	5.18	6.80
Turbulence Intensity (%)	23.39	28.44	24.01	18.36

One case B was recorded. Case SB1 was shown in Figure 4.9. Frame one of the period was totally obscured by smoke. Therefore, the frame was not shown in the figure. Frame two is shown in Figure 4.9 (a), and had a HB of 3 ft, and LB of 9.5 ft long. The orientation of the few tufts that were visible was uniform inside and outside of the separation cavity. In Figure 4.9 (b), the size of the cavity increased. The HB was 4 ft-tall. The LB was 13.5 ft. Within the bubble, recirculation has increased in area. At 9.5 ft from the windward wall, the streamline indicated air above the grid curved towards the roof. The SB's structure changed again in Figure 4.9 (c). The area of recirculation increased. Also, the HB and LB increased. The LB was 18.6 ft while the HB was greater than 4 ft. Two streamlines were drawn for this frame. The upper streamline had a path that was directed towards the roof. The second streamline reversed its direction 11 ft from the roof's edge. In Figure 4.9 (d), nearly the entire interior of the SB had recirculation. The HB was 4 ft, and the LB was 17.6 ft long. Two air trajectories were drawn. The interior streamline reversed direction 5 ft from the edge of the roof. For the period, the average HB was 3.75 ft, and the mean length of the bubble was 14.8 ft.

The wind statistics for SB1 are shown in Table 4.11. The mast was located 7 ft from the windward wall for this period. The roof anemometers' mean speeds increased with height. The 13P's average speed was greater than R1's mean. Apparently, R4 and R6 were outside the SB as indicated by the mean speeds. The TIs calculated from the roof wind data decreased with height. R1's TI was the largest since R1 was located in the SB, the TI for 13P, which was located in the free wind field, was slightly smaller than R1's TI. Apparently, the free wind field was nearly as turbulent as the SB. The other roof TIs were less than the undisturbed wind's TI.

Among the SW experiments, case C occurred the most. SC10 was a good example of case C. SC10 is shown in Figure 4.10. Initially, Figure 4.10 (a) shows a large area of recirculation was present in SC10. The upper streamline indicated the SB did not have the

(a)

(b)

(c)

(d)

Figure 4.9. Tuft orientations for SB1. Tufts were drawn for the following times: (a) 10:29.4, (b) 10:31.9, (c) 10:34.4, and (d) 10:36.9.

Table 4.11. Summary of wind information for SB1.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	9.61	4.44	10.91	14.28
Variance	5.58	1.57	2.34	3.28
Standard Deviation	2.36	1.25	1.53	1.81
Maximum Speed (mph)	13.26	7.76	14.22	18.29
Minimum Speed (mph)	5.50	1.95	8.60	11.45
Turbulence Intensity (%)	24.58	28.20	14.03	12.69

(a)

(b)

(c)

(d)

(e)

Figure 4.10. Tuft orientations for SC10. Tufts were drawn for the following times: (a) 8:23.1, (b) 8:25.6, (c) 8:28.1, (d) 8:30.6, and (e) 8:33.1.

idealized shape shown in Chapter 2. Instead, the streamline was parallel to the roof, then curved upward. The maximum height of the cavity was assumed to be 4 ft. The streamline attached to the roof at least 19.6 ft from the windward wall. The lower streamline indicated flow reversal occurred 2 ft from the roof's edge. In the Figure 4.10 (b), recirculation decreased in area. The back third of the grid of tufts displayed a more chaotic pattern. The HB decreased to approximately 4 ft. The LB was not determinable for this frame. Therefore, the LB was assumed to be 19.6 ft. Two streamlines were drawn for this frame. Both lines reverse their direction. The upper streamline reversed its path 12 ft from the windward wall. The lower line changed direction 3 ft from the roof's edge. Figure 4.10 (c) shows the tufts positions continued to decrease in variability. Also, the recirculation decreased, and was mainly present near the roof's surface. The HB was 2.5 ft, and the LB was approximately 17.6 ft. In this figure, only the lower streamline reversed its direction. In Figure 4.10 (d), the area of recirculation diminished. The height and length of the cavity also decreased. The HB was 4 ft, while the LB decreased to 14.5 ft. Both streamlines' trajectories were towards the windward wall. Figure 4.10 (e) shows the recirculation continued to decrease in area. Flow reversal was located throughout the bottom 8 in of the SB. The HB was 3 ft, while the LB was 14.5 ft. The inner line reversed its direction 3 ft from the roof's edge. The bubble was still began off the windward roof edge. For the entire period, the average LB was 17.2 ft. The mean HB was 3.5 ft. Nine more examples of case C can be found in the Appendix.

The wind statistical information for SC10 is summarized in Table 4.12. The roof mast was positioned 1 ft from the windward wall. The mean roof speeds increased with height. Both R4 and R6 average speeds were greater than the 13P's mean speed. The TI for R1 was very large, because R1 was at the boundary of recirculation and leeward flowing air. At such boundaries, additional turbulence was generated, as implied by the large TI. The

Table 4.12. Summary of wind information for SC10.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	5.13	2.64	5.64	8.61
Variance	0.14	3.89	0.19	0.55
Standard Deviation	0.37	1.97	0.43	0.74
Maximum Speed (mph)	6.15	6.28	6.67	10.41
Minimum Speed (mph)	4.28	0.00	4.79	6.80
Turbulence Intensity (%)	7.24	74.78	7.64	8.62

TIs at R4 and at R6 were comparable to the TI from the 13P. Therefore, little extra turbulence was generated by the building at R4 and R6.

Several examples of case D were found during the analysis of the SW data. Period SD6 was a good example of case D. In Figure 4.11 (a), the tuft positions were fairly uniform. Little recirculation was present in the SB. The height of the cavity was 2.5 ft, and the length of the bubble was 9.5 ft. In the figure, two streamlines were drawn. Both streamlines had similar appearances, indicating air would flow towards the leeward wall. Figure 4.11 (b) shows the recirculation intensified. The height of the cavity increased to 4 ft, and the LB increased to 17.6 ft. In Figure 4.11 (c), the area of recirculation reduced in size. Flow reversal was located in the rear third of the SB. The HB was 3 ft while the LB was 11.5 ft. Two streamlines were drawn. The lower line reversed its direction 4 ft from the roof's edge. The recirculation redeveloped in Figure 4.11 (d), encompassing nearly two-thirds of the bubble. The HB was 3 ft, and the LB was 17.6 ft. Again, two lines were drawn. The upper streamline was nearly parallel to the top of the grid for most of its path. The lower streamline changed its direction 5 ft from the roof's edge. In Figure 4.11 (e), recirculation was still present. The HB increased to 4 ft. The length of the cavity was approximately 17.6 ft. The streamline was parallel to the grid for one half of its path, then the streamline gently curved towards the roof. A small vortex was centered 2.75 ft above the roof. The SB formed before the roof's edge. For the period, the average SB was 3.2 ft tall and 14.9 ft long.

Statistical data for SD6 are presented in Table 4.13. The roof wind speeds were measured 1 ft from the building's windward edge. The mean speeds increased with height above the roof. The average wind speed at the 13P was greater than the roof's mean speeds. The TIs decreased with height on the roof. Only R1's TI was greater than the 13P's TI. Apparently, some additional turbulence was present at R1. The building tended to reduce the turbulence in the wind at R4 and R6.

(a)

(b)

(c)

(d)

(e)

Figure 4.11. Tuft orientations for SD6. Tufts were drawn for the following times: (a) 7:37.4, (b) 7:39.9, (c) 7:42.4, (d) 7:44.9, and (e) 7:47.4.

Table 4.13. Summary of wind information for SD6.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	12.43	5.49	11.12	11.56
Variance	5.26	1.24	3.72	3.42
Standard Deviation	2.29	1.24	1.93	1.85
Maximum Speed (mph)	15.32	8.02	14.81	14.94
Minimum Speed (mph)	7.96	3.24	8.22	7.76
Turbulence Intensity (%)	18.44	22.55	17.34	16.00

4.3.1.3 Comparison of Long Wall Experiment to Short Wall Experiment. The two experiments were compared to determine the relative similarities of the separation bubbles. The comparison required a statistical test if the similarities' statistical significance was to be judged objectively. Determining which statistical test to utilize was difficult because wind data and roof pressure data are not normally distributed (Simiu and Scanlan, 1986). Therefore, it is inappropriate to assume separation bubble data is normally distributed. As a result, a non-parametric statistical test which does not assume a distribution must be employed to compare data related to the separation bubble.

The statistical test that was chosen to compare the separation bubble information was the Kruskal-Wallis (KW) test (Conover, 1990). As with all non-parametric tests, the data did not need to be normally distributed. The procedure for performing the KW test is described below. Assume there are k samples of an independent experiment to be investigated. The data for these k samples can be arranged as shown in Table 4.14. Let N equal the total number of observations, and rank is assigned in ascending order to the entire data set. Each sample is then summed so that

$$R_i = \sum_{j=1}^{n_i} R(X_{ij}) \quad (4.3)$$

where j is an integer which represents position in the sample, n_i is the length of the sample (which has to be greater than 7 but can vary between samples), $R(X_{ij})$ represents the rank assigned to the observation X_{ij} and R_i is the sum of the ranks. R_i is calculated for each level (1 to k).

The hypotheses tested are:

H_0 : All the k level distribution functions are equal, and

H_1 : The k levels do not all have identical means.

The test statistic, T, is defined as

Table 4.14. Arrangement of data for Kruskal-Wallis test.

<u>Sample 1</u>	<u>Sample 2</u>	<u>...</u>	<u>Sample k</u>
$X_{1,1}$	$X_{2,1}$		$X_{k,1}$
$X_{1,2}$	$X_{2,2}$		$X_{k,2}$
...	...		...
$X_{1,n1}$	$X_{2,n2}$		$X_{k,nk}$

$$T = \frac{1}{S^2} \left[\sum_{i=1}^k \frac{R_i^2}{n_i} - \frac{N(N+1)}{4} \right] \quad (4.4)$$

where n_i and R_i are as defined above and

$$S^2 = \frac{N(N+1)}{12}. \quad (4.5)$$

The null hypothesis is unfulfilled at a particular confidence level $(1 - c)$ if $T > \chi_{1-c}^2$. The chi square distribution is calculated from the following equation:

$$\chi(x) = \frac{1}{\Gamma\left(\frac{k}{2}\right) * 2^{k/2}} x^{k/2} * e^{(-x/2)} \quad (4.6)$$

where k is the degrees of freedom, x is variable, and Γ is the gamma function from the gamma distribution (Milton and Arnold, 1986). Solutions of the chi square distribution are presented in a table in most statistical books such as Milton and Arnold, and Table 4.15 lists the chi square values at various confidence levels with one degree of freedom.

The wind statistics, averaged over different cases, are presented in Table 4.16. Comparing each experiment's cases, the LW experiment's cases had a higher average wind speed compared to the SW experiment's cases. Also, the SW's cases had a higher average turbulence intensity than the LW's cases. The KW Test was performed on the TI data to determine if LW's TIs were statistically different to SW's TIs. T_{TI} (the T-value calculated from the TI data) is 3.69. T_{TI} is less than $\chi_{0.95}^2$ from the Table 4.15, and the KW test showed the SW TIs were statistically similar to the LW TIs for a confidence level of 95%. Therefore, the average wind climate was apparently similar for each experiment.

Table 4.15. Selected values from χ^2 table (Milton and Arnold, 1986) for 1 degree of freedom, and the T values calculated from selected LW and SW parameters.

<u>(1-c)</u>	<u>$\chi^2_{(1-c)}$</u> ²
0.10	0.0158
0.20	0.0642
0.30	0.148
0.40	0.275
0.50	0.455
0.60	0.708
0.70	1.07
0.80	1.64
0.90	2.71
0.950	3.84
0.975	5.02
0.990	6.63
0.995	7.88
0.999	10.80

Table 4.16. Comparison between long wall experiments and short wall experiments wind conditions, measured at the 13 ft pole, by case.

<u>Case</u>	<u>Experiment</u>	<u>Average Wind Speed (mph)</u>	<u>Average Variance</u>	<u>Average Standard Deviation</u>	<u>Average Maximum (mph)</u>	<u>Average Turbulence Intensity at 13 ft Pole (%)</u>
A	LW	7.70	1.76	1.33	22.58	17.24
	SW	8.33	3.80	1.95	10.48	23.39
B	LW	9.08	1.12	0.97	11.67	10.98
	SW	9.61	5.58	2.36	13.26	24.58
C	LW	9.87	0.86	0.89	11.63	9.28
	SW	6.92	5.58	2.36	13.26	12.87
D	LW	8.51	1.40	1.17	11.16	13.68
	SW	8.46	2.39	1.45	4.76	16.88

The period-averaged HBs and LBs for both experiments are shown in Table 4.17. For the LW test, the HBs ranged from 2.38 ft to 4.00 ft, while the LBs extended from 10.5 ft to 18.6 ft. The standard deviation (SD) was 0.54 and 2.26 for the LW's HBs and LBs, respectively. The average SW bubble's HB and LB ranged from 2.5 ft to 3.75 ft and 9.1 ft to 19.2 ft, respectively, and the SD of the HBs and LBs were 0.48 and 2.66, respectively.

The characteristics of the separation bubble for each test were compared. From Table 4.18, the average SB for the long wall test was 3.34 ft tall. The mean SW experiment's HB was 3.06 ft. The KW test (Conover, 1990) was performed using the HB data from both experiments. The T value calculated from the HB data (T_{HB}) was 3.44, which was less than $\chi_{0.95}^2$; therefore, the two HBs were statistically similar for a confidence level of 95%. The mean LB of the LW test was 14.5 ft. The SW experiment's LB was 13.9 ft. Again, the KW test was performed on both experiment's LB data. The test determined the two experiment's LBs were not statistically different at 95% confidence.

Each case was compared for the two experiments. Table 4.19 shows the case-averaged separation bubble's height and length for each test. For each particular case, the separation bubble's height and length from both experiments were similar. From the table, the difference between the average length of the bubble for a case ranged from 1.4 ft to 0.59 ft for cases A and D, respectively. Such differences are relatively small and not statistically significant, as proved by the KW test previously. When the average height of the bubble is compared between cases in Table 4.17, the differences ranged from 0.66 ft for case B to 0.12 ft for case A. Again, these differences for each case are minor and not statistically significant. As a result, the cases' HBs were similar for each experiment. The WERFL's test building's geometry normal to the wind had little impact on the height and length of the SB in the range of wind speeds observed.

The flow structures in the separation bubble were compared. It was determined that the general trend of the flow structures (i.e., enlargement of the area of recirculation,

Table 4.17. Listing of the period-averaged HBs and LBs for each period.

<u>Grouping</u>	<u>HB (ft)</u>	<u>LB (ft)</u>
LA1	2.38	10.5
LB1	3.80	14.5
LB2	2.46	13.3
LC1	4.00	15.8
LC2	3.13	18.6
LC3	3.63	17.6
LC4	3.30	15.3
LC5	3.40	15.1
LC6	2.83	11.1
LC7	4.00	16.2
LC8	3.25	14.7
LD1	3.80	15.8
LD2	3.70	13.1
LD3	3.10	14.7
LD4	3.40	11.1
LD5	2.46	14.1
SA1	2.50	9.1
SB1	3.75	14.8
SC1	3.10	12.5
SC2	2.83	12.7
SC3	2.80	14.6
SC4	2.90	16.1
SC5	3.63	17.4
SC6	3.20	14.9
SC7	3.50	15.3
SC8	3.03	15.2
SC9	2.73	12.1
SC10	3.50	17.2
SD1	2.75	11.3
SD2	2.30	9.3
SD3	2.20	12.7
SD4	2.87	11.5
SD5	3.30	13.5
SD6	3.30	14.8
SD7	4.00	19.2
Mean LW	3.34	14.5
Standard Deviation LW	0.54	2.26
Mean SW	3.06	13.9
Standard Deviation SW	0.48	2.66

Table 4.18. Comparison of full-scale separation bubble characteristics to calculated separation bubble characteristics using Wilson's equations.

<u>Test</u>	<u>Separation Bubble Property</u>	<u>Full-scale Study's Results (ft)</u>	<u>Calculated Results (ft)</u>
Long Wall	Length	14.5	17.6
	Height	3.34	4.31
Short Wall	Length	13.9	15.4
	Height	3.06	3.77

Table 4.19. Comparison of bubble structure from long wall and short wall experiments.

<u>Case</u>	<u>Experiment</u>	<u>Average Length of Bubble (ft)</u>	<u>Average Height of Bubble (ft)</u>
A	LW	10.50	2.38
	SW	9.10	2.50
B	LW	13.93	3.09
	SW	14.80	3.75
C	LW	15.50	3.43
	SW	14.81	3.13
D	LW	13.78	3.50
	SW	13.19	2.95

fluctuating recirculation area, etc.) were similar for both tests. This was due to the fact that both experiments' periods were grouped by the same classification system. Each test had examples of cases A, B, C, and D. Even though the number of periods in each case was different for the tests, similar flow trends were observed in each experiment. Therefore, the flow structures observed in both experiments were similar.

In both tests, the separation bubble was not a totally enclosed structure. As the streamlines indicated in every figure shown in this subsection, the SB did not begin at the roof's edge. Instead, the SB did not have a well defined beginning within the tufts. This observation agrees with the Woo et al. (1977) conceptual model shown in Figure 2.2.

4.4 Comparison to Previous Studies

A correlation test was performed on the statistical data from all the periods . The correlation was performed using the commercial software CSS:STATISTICA (StatSoft, 1991). The purpose of the correlation work was to determine if the SB's height and length were related to any of the wind's statistical properties. Since correlation is a measure of relation between two variables, the coefficient which results from the correlation indicate the degree of the variables relation. The correlation coefficient (μ) can range from -1.00 to 1.00 and is calculated by the following equation:

$$\mu = \frac{\text{Cov}(X,Y)}{\sqrt{(\text{Var}X)(\text{Var}Y)}} \quad (4.7)$$

where X and Y are random variables, Cov(X,Y) is the covariance of X and Y, and Var is the variance of X or Y. A value of 1.00 indicates a perfect positive correlation. The value of 0.00 represents a lack of correlation.

The following 13P wind speed parameters, averaged for each period, were used in the correlation: mean, variance, standard variation, maximum, minimum, and TI. Also, the average HB and LB from each period were included in the correlation. The result of the correlation test are shown in Table 4.20. The correlation test on the data yielded low correlation coefficients, except for a quantity correlated with itself which resulted in a coefficient of 1.00. Looking at the table's columns labeled LB and HB, the coefficients ranged from -0.16 to 0.60. Therefore, the quantities, such as turbulence intensity and mean wind speed, were not related to the properties of the SB. Therefore, any one wind parameter did not have an impact on the SB. From Table 4.20, the largest correlation coefficient occurred for HB and LB with a coefficient was 0.6. As a result, the height and length of the SB were correlated. Therefore, as the height increased, the length generally increased.

The lack of correlation of mean speeds to HBs and LBs is consistent with Castro and Dianat's work (1983). They stated that Reynold's number (Re) changes do not affect reattachment. Since Re changes with velocity, the low coefficients in Table 4.20 imply Re changes do not effect the SB's properties.

As stated in Chapter 2, Wilson (1979) developed some predictive equations which calculated the height and length of the separation bubble. Using Wilson's equations, the height and length of the SB for each experiment were calculated. The results of the calculations were also presented in Table 4.18. From the table, Wilson's equations slightly over-predicted the HB and the LB for both experiments. The largest difference occurred for the full-scale LW test. Wilson's equations slightly over-predicted the length of the LW's bubble by 3.18 ft. The full-scale SW SB length was 1.51 ft shorter than the length determined by Wilson's equations. The difference between the full-scale bubble heights and the equation derived heights were 0.93 ft and 0.69 ft for the LW and SW, respectively. Wilson's equations predicted values which were close, generally within 17 percent, to the

Table 4.20. Correlation coefficients determined from 13P wind parameters and SB properties of both experiments.

Parameter	Mean	Variance	Standard Deviation	Maximum	Minimum	Turbulence Intensity	LB	HB
Mean	1.00	0.24	0.25	0.72	0.77	-0.20	0.12	-0.00
Variance	0.24	1.00	0.97	0.56	0.02	--0.74	-0.06	-0.13
Standard Deviation	0.25	0.97	1.00	0.59	0.03	0.79	-0.03	-0.13
Maximum	0.72	0.56	0.59	1.00	0.79	0.05	0.19	0.03
Minimum	0.77	0.02	0.03	0.79	1.00	-0.51	0.21	0.14
Turbulence Intensity	-0.20	0.74	0.79	0.05	-0.51	1.00	-0.12	-0.16
LB	0.12	-0.06	-0.03	0.19	0.21	-0.12	1.00	0.60
HB	0.00	-0.13	-0.13	0.03	0.14	-0.16	0.60	1.00

full-scale values. The differences may be a result of the method Wilson used to obtain his equations. Wilson used a water channel to conduct his experiments. Water channels produce stable, reproducible conditions. In the field, nature dictates the wind conditions. Therefore, the full-scale tests were conducted under much more random conditions when compared to water channel or wind tunnel tests. Therefore, natural variations, not reproduced in water channels, may contribute to the differences between the full-scale results and Wilson's equations.

As reported in Chapter 2, Sandri (1992) found the reattachment zone, using pressure data and tufts attached to the roof, on the WERFL test building to be between 18 ft and 27 ft for an β of 180° and a mean wind speed of 17.2 mph. Table 4.17 shows that the mean reattachment point for the SW ($\beta = 180^\circ$) to be 13.91 ft. There is a large difference between Sandri's results and this study's observations. A reason for the difference may be because Sandri used only 2 data runs to develop his reattachment zone. More data may have changed his results.

4.5 Possible Application of Observations

The goal of most research is to apply research results to everyday life. This research can be applied to the design of heating/ventilation systems. For isolated buildings, the standard exhaust stack design practice was to set the stack height equal to $1.5H$, supported by Koga and Way's (1979) work, to ensure the stack opening was above the SB. Therefore, a stack on the WERFL building should be 19.5 ft tall. The results of this experiment show that a 19.5-ft stack would be a very conservative design. Since the largest average HB from Table 4.16 was 3.75 ft, the stack would be nearly 15 ft taller than the SB. As a result, it is suggested that the minimum stack of an isolated, low-rise building should be $0.5H$, which is the stack height White and Stein (1990) recommended. A stack $0.5H$ tall would safely emit its exhaust into the free atmosphere.

This research may also help computer modelers through the comparison of their flow fields with field-derived flow visualization data. By comparing numerical results with full-scale observations, numerical models can be verified. If differences result from the comparison, numerical researchers can modify their models to more accurately represent flow over a low-rise building.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The Wind Engineering Research Field Laboratory (WERFL), located on the Texas Tech University campus in Lubbock, TX, provided an excellent opportunity to conduct full-scale, wind-related tests on a low-rise building. As a result, experiments were performed at WERFL to examine the separation bubble characteristics as wind passed over the roof.

To determine the properties of the separation bubble (SB), two experiments were conducted: The first experiment was arranged so the wind struck the building perpendicular to the long wall (45 ft), seven data runs were collected for this experiment. During the second test, the building was positioned so that the wind direction was normal to the short wall (30 ft), for which six data runs were collected. The following information was collected during each data run: wind direction and wind speed at various locations, and orientations of a grid of tufts as recorded on videotape. The tufts were used to help visualize the flow over the roof.

The 15-minute data runs were analyzed to determine the periods in the record when the wind direction was directly normal to the building for 10 or more seconds. From both experiments, 35 periods were located. Once this was accomplished, a reference point in the video tape and computer-recorded data was determined. Using the reference point, the video image was transferred to paper.

The periods were then grouped together according to evolution of the SB flow structure during the 10 sec. Four classes were developed. After the period were classified, the height (HB) and length (LB) of the separation bubble were determined. The average LB and HB were 3.34 ft and 14.5 ft, respectively, for periods in the long

wall test. The short wall experiment's average LB was 3.06 ft, and the average HB was 13.9 ft.

5.1 Conclusions

The two experiments, conducted for this thesis, yielded the following results.

1. The average height of the separation bubble for the long wall experiment was 3.34 ft with the range of 2.38 ft to 4.00 ft and a standard deviation of 0.54. The average length was 14.5 ft (range of 10.5 ft to 16.6 ft) for the mean wind speed range from 8.53 mph to 11.16 mph at 13P. The standard deviation calculated from the length data was 2.26. The mean height of the bubble formed during the short wall experiment was 3.06 ft with the range of 2.5 ft to 3.75 ft and a standard deviation of 0.48. The cavity was 13.9 ft long (range of 9.1 ft to 19.2 ft) for the mean wind speed range from 8.07 mph to 14.49 mph at the 13-ft pole. The standard deviation calculated from the length data was 2.66. The average height and length of the bubble formed by the long wall was statistically similar at the 95% confidence level when compared to the short wall bubble's physical attributes.
2. The WERFL test building's width had little impact on the length and height of the separation bubble in the range of observed wind speeds.
3. The interior flow structure of the separation bubble was similar for both experiments because both experiments contained the four distinct flow patterns in the separation bubble.
4. The streamlines drawn for each period indicated the bubble extended beyond the windward roof edge. This observation agreed with Woo et al.'s (1977) conceptual model of air flow over and around a bluff body.
5. Correlation test indicated the height of the bubble was positively correlated with the length of the cavity. The correlation coefficient was 0.6. The test did not show

significant relationships between the wind statistical properties and the separation bubble characteristics.

6. Wilson's (1979) predictive equations slightly over-predicted the separation bubble's physical characteristics.

7. The stack height for the WERFL test building can be $0.5H$. This stack height is less than the conventional $1.5H$.

5.2 Recommendations

After conducting the experiments described above, several recommendations were made. The suggestions are listed below.

1. It is suggested that the grid's height and length should be enlarged, perhaps to 6.5-ft high and 30-ft long.

2. Once the expansion is completed, the grid should be positioned so that the frame extends beyond the windward roof edge. By enlarging the frame, the entire separation bubble can be measured.

3. An additional camera should be used. The camera should be placed perpendicular to the grid. The two cameras can be positioned on the building closer to the grid. The closer the cameras are to the frame, the more visible the tufts will be on the video tape. Commercial programs, which convert video images to printable graphic files, can then be utilized to produce hard copies of the tufts.

4. A white backdrop should be constructed and positioned opposite the cameras. The backdrop would enhance the visibility of the tufts while reducing background visual obstructions.

5. Data should be collected for a wider range of wind speeds. This study's data had a relatively narrow range of wind speeds. Although this study proved the wind's properties

were not related to the separation bubble's characteristics, data should be collected for other average wind speeds to support this study's observations.

6. Although limited pressure data was collected during this study, the pressure data from this study and futures studies can be used along with the hard copies of the tufts' to determine if flow patterns in the separation bubble cause peak roof pressure.

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APPENDIX

This appendix contains the periods not shown in Chapter 4. The appendix is organized so that the long wall experiment cases are presented first. The short wall experiment periods are shown after the LW test. Each occurrence's facts are displayed by a figure and a table. The figure contains the video frames that were drawn for the period. The wind information and other significant data is listed in the table.

(a)

(b)

(c)

(d)

Figure A.1. Tuft's orientation for LB2 during the following times: (a) 14:05.0, (b) 14:07.5, (c) 14:12.5, (d) 14:15.0.

Table A.1. Summary of wind information for LB2.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	9.67	1.55	7.97	13.94
Variance	0.29	1.06	1.11	2.39
Standard Deviation	0.53	1.03	1.05	1.55
Maximum Speed (mph)	10.80	3.63	9.51	15.58
Minimum Speed (mph)	8.41	0.00	6.09	10.22
Turbulence Intensity (%)	5.53	66.43	13.21	11.72

Note: LB2 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 2.46 ft and 13.3 ft, respectively.

(a)

(b)

(c)

(d)

Figure A.2. Tuft's orientation for LC1 during the following times: (a) 13:41.3, (b) 13:43.8, (c) 13:46.3, (d) 13:48.8.

Table A.2. Summary of wind information for LC1.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	13.14	0.24	4.95	5.15
Variance	0.71	0.39	1.81	1.61
Standard Deviation	0.84	0.63	1.35	1.27
Maximum Speed (mph)	15.00	1.63	7.44	8.93
Minimum Speed (mph)	10.99	0.00	2.40	2.92
Turbulence Intensity (%)	6.40	259.09	27.15	24.67

Note: LC1 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 4.00 ft and 15.8 ft, respectively.

(a)

(b)

(c)

(d)

Figure A.3. Tuft's orientation for LC2 during the following times: (a) 14:18.5 (b) 14:21.0, (c) 14:23.5, (d) 14:26.0.

Table A.3. Summary of wind information for LC2.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	9.63	0.00	5.12	4.59
Variance	1.19	0.78	7.17	5.62
Standard Deviation	1.09	0.88	2.68	2.37
Maximum Speed (mph)	11.19	1.76	10.87	10.93
Minimum Speed (mph)	7.57	0.00	2.27	1.69
Turbulence Intensity (%)	11.30	-	52.34	51.62

Note: LC2 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 3.13 ft and 18.6 ft, respectively.

(a)

(b)

(c)

(d)

Figure A.4. Tuft's orientation for LC3 during the following times: (a) 14:26.0, (b) 14:28.5, (c) 14:31.0 (d) 14:33.5.

Table A.4. Summary of wind information for LC3.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	10.44	1.93	9.34	9.77
Variance	0.65	0.55	3.24	6.64
Standard Deviation	0.81	0.74	1.80	2.58
Maximum Speed (mph)	11.90	3.31	12.29	14.16
Minimum Speed (mph)	9.12	0.21	6.28	5.12
Turbulence Intensity (%)	7.73	38.44	19.27	26.37

Note: LC3 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 3.63 ft and 17.6 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.5. Tuft's orientation for LC4 during the following times: (a) 3:01.8, (b) 3:04.3, (c) 3:06.8, (d) 3:09.3, and (e) 3:11.8.

Table A.5. Summary of wind information for LC4.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	8.82	9.41	8.26	10.70
Variance	0.91	1.97	0.82	1.36
Standard Deviation	0.96	1.40	0.91	1.17
Maximum Speed (mph)	10.54	11.39	10.41	13.00
Minimum Speed (mph)	6.54	6.41	6.28	8.48
Turbulence Intensity (%)	10.83	14.90	10.95	10.90

Note: LC4 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 3.30 ft and 15.3 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.6. Tuft's orientation for LC5 during the following times: (a) 11:19.3, (b) 11:21.8, (c) 11:24.3, (d) 11:26.8, and (e) 11:29.3.

Table A.6. Summary of wind information for LC5.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	7.20	8.85	7.88	9.70
Variance	1.16	1.26	0.82	0.95
Standard Deviation	1.08	1.12	0.91	0.97
Maximum Speed (mph)	8.86	12.16	10.16	11.77
Minimum Speed (mph)	5.63	7.18	6.41	8.09
Turbulence Intensity (%)	14.96	12.68	11.53	10.05

Note: LC5 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 3.40 ft and 15.1 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.7. Tuft's orientation for LC6 during the following times: (a) 10:04.6, (b) 10:07.1, (c) 10:09.6, (d) 10:12.1, and (e) 10:14.6.

Table A.7. Summary of wind information for LC6.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	7.58	7.46	5.66	6.33
Variance	0.31	2.29	0.64	2.02
Standard Deviation	0.56	1.51	0.80	1.42
Maximum Speed (mph)	8.67	10.48	7.96	8.60
Minimum Speed (mph)	6.38	4.53	4.34	3.18
Turbulence Intensity (%)	7.33	20.27	14.14	22.49

Note: LC6 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 2.83 ft and 11.1 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.8. Tuft's orientation for LC8 during the following times: (a) 6:12.6, (b) 6:15.1, (c) 6:17.6, (d) 6:20.1, and (e) 6:22.6.

Table A.8. Summary of wind information for LC8.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	7.58	7.46	5.66	6.33
Variance	0.31	2.29	0.64	2.02
Standard Deviation	0.56	1.51	0.80	1.42
Maximum Speed (mph)	8.67	10.48	7.96	8.60
Minimum Speed (mph)	6.38	4.53	4.34	3.18
Turbulence Intensity (%)	7.33	20.27	14.14	22.49

Note: LC8 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 3.40 ft and 14.7 ft, respectively.

(a)

(b)

(c)

(d)

Figure A.9. Tuft's orientation for LD1 during the following times: (a) 14:08.5, (b) 14:11.0 (c) 14:13.5 (d) 14:16.0.

Table A.9. Summary of wind information for LD1.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	8.17	1.12	6.13	6.84
Variance	0.72	0.74	0.51	1.27
Standard Deviation	0.85	0.86	0.71	1.13
Maximum Speed (mph)	10.74	3.31	7.57	8.99
Minimum Speed (mph)	7.12	0.00	4.47	4.53
Turbulence Intensity (%)	10.39	76.63	11.63	16.51

Note: LD1 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 3.25 ft and 15.8 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.10. Tuft's orientation for LD3 during the following times: (a) 14:43.1, (b) 14:45.6, (c) 14:48.1, (d) 14:50.6, and (e) 14:53.1.

Table A.10. Summary of wind information for LD3.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	8.51	11.22	9.12	12.31
Variance	1.22	2.05	0.89	1.12
Standard Deviation	1.11	1.43	0.94	1.06
Maximum Speed (mph)	10.74	13.97	11.96	14.22
Minimum Speed (mph)	6.41	8.80	8.41	10.48
Turbulence Intensity (%)	12.98	12.75	10.35	8.60

Note: LD3 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 3.70 ft and 14.7 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.11. Tuft's orientation for LD4 during the following times: (a) 9:34.8, (b) 9:37.3, (c) 9:39.8, (d) 9:42.3, and (e) 9:44.8.

Table A.11. Summary of wind information for LD4.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	6.35	11.01	9.65	12.12
Variance	1.42	0.52	0.62	0.64
Standard Deviation	1.19	0.72	0.79	0.80
Maximum Speed (mph)	8.67	12.35	11.06	14.10
Minimum Speed (mph)	4.73	9.51	8.35	10.61
Turbulence Intensity (%)	18.79	6.52	8.15	6.59

Note: LD4 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 3.10 ft and 11.1 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.12. Tuft's orientation for LD5 during the following times: (a) 0:39.9, (b) 0:42.4, (c) 0:44.9, (d) 0:47.4, and (e) 0:49.9.

Table A.12. Summary of wind information for LD5.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	8.97	0.45	9.26	12.48
Variance	1.64	0.83	0.99	2.33
Standard Deviation	1.28	0.91	0.99	1.53
Maximum Speed (mph)	12.16	3.24	10.93	15.13
Minimum Speed (mph)	6.93	0.00	7.05	10.22
Turbulence Intensity (%)	14.27	204.04	10.74	12.23

Note: LD5 was collected on May 4, 1993. The skies were mostly sunny. The average height and length of the separation bubble were 3.40 ft and 14.1 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.13. Tuft's orientation for SC1 during the following times: (a) 11:18.6, (b) 11:21.1, (c) 11:23.6, (d) 11:26.1, and (e) 11:28.6.

Table A.13. Summary of wind information for SC1.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	9.81	5.24	8.77	9.09
Variance	0.63	1.81	0.91	1.73
Standard Deviation	0.80	1.35	0.95	1.32
Maximum Speed (mph)	11.25	7.64	10.61	11.32
Minimum Speed (mph)	7.70	2.14	6.09	6.09
Turbulence Intensity (%)	8.10	25.68	10.86	14.47

Note: SC1 was collected on May 17, 1993. The skies were mostly cloudy with thunderstorms and showers in the immediate area. The average height and length of the separation bubble were 3.10 ft and 12.5 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.14. Tuft's orientation for SC2 during the following times: (a) 8:19.8, (b) 8:22.3, (c) 8:24.8, (d) 8:27.3, and (e) 8:29.8.

Table A.14. Summary of wind information for SC2.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	7.11	3.50	8.10	7.79
Variance	0.57	5.01	0.56	2.19
Standard Deviation	0.76	2.24	0.75	1.48
Maximum Speed (mph)	8.93	8.02	9.44	10.35
Minimum Speed (mph)	5.70	0.40	6.60	4.21
Turbulence Intensity (%)	10.62	64.00	9.28	18.97

Note: SC2 was collected on May 17, 1993. The skies were mostly cloudy with thunderstorms and showers in the immediate area. The average height and length of the separation bubble were 2.83 ft and 12.7 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.15. Tuft's orientation for SC3 during the following times: (a) 9:09.2, (b) 9:11.7, (c) 9:14.2 (d) 9:16.7, and (e) 9:19.2.

Table A.15. Summary of wind information for SC3.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	7.93	2.40	6.15	6.74
Variance	0.27	1.90	1.67	2.12
Standard Deviation	0.52	1.38	1.29	1.46
Maximum Speed (mph)	8.99	5.12	9.19	9.77
Minimum Speed (mph)	6.99	0.27	4.08	4.28
Turbulence Intensity (%)	6.60	57.40	21.03	21.59

Note: SC3 was collected on May 17, 1993. The skies were mostly cloudy with thunderstorms and showers in the immediate area. The average height and length of the separation bubble were 2.80 ft and 14.6 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.16. Tuft's orientation for SC4 during the following times: (a) 7:57.0, (b) 7:59.5, (c) 8:02.0, (d) 8:04.5, and (e) 8:07.0.

Table A.16. Summary of wind information for SC4.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	7.14	0.84	7.36	10.25
Variance	1.99	0.55	0.69	1.40
Standard Deviation	1.41	0.74	0.83	1.19
Maximum Speed (mph)	9.96	2.08	9.38	12.67
Minimum Speed (mph)	4.99	0.00	5.89	7.64
Turbulence Intensity (%)	19.73	88.34	11.31	11.56

SC4 was collected on May 17, 1993. The skies were partly cloudy. The average height and length of the separation bubble were 2.90 ft and 16.14 ft, respectively.

(a)

(b)

(c)

(d)

Figure A.17. Tuft's orientation for SC5 during the following times: (a) 8:39.7, (b) 8:42.2, (c) 8:44.7, (d) 8:47.2.

Table A.17. Summary of wind information for SC5.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	5.05	0.65	5.13	6.72
Variance	0.21	0.38	0.29	1.05
Standard Deviation	0.45	0.62	0.54	1.02
Maximum Speed (mph)	6.09	2.09	6.41	8.54
Minimum Speed (mph)	4.08	0.00	3.95	4.15
Turbulence Intensity (%)	8.98	95.97	10.53	15.23

Note: SC5 was collected on May 17, 1993. The skies were partly cloudy. The average height and length of the separation bubble were 3.63 ft and 17.4 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.18. Tuft's orientation for SC6 during the following times: (a) 8:53.2, (b) 8:55.7, (c) 8:58.2, (d) 9:00.7, and (e) 9:03.2.

Table A.18. Summary of wind information for SC6.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	4.87	2.73	5.50	8.32
Variance	0.20	1.02	1.15	0.89
Standard Deviation	0.45	1.01	1.07	0.94
Maximum Speed (mph)	6.41	4.92	8.67	11.25
Minimum Speed (mph)	3.89	0.85	3.82	7.05
Turbulence Intensity (%)	9.24	37.12	19.48	11.34

Note: SC6 was collected on May 17, 1993. The skies were partly cloudy. The average height and length of the separation bubble were 3.20 ft and 14.9 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.19. Tuft's orientation for SC7 during the following times: (a) 0:12.0, (b) 0:14.5, (c) 0:17.0, (d) 0:19.5, and (e) 0:22.0.

Table A.19. Summary of wind information for SC7.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	12.33	3.84	8.60	11.78
Variance	3.62	8.31	1.42	1.80
Standard Deviation	1.90	2.88	1.19	1.34
Maximum Speed (mph)	15.65	8.80	11.38	15.39
Minimum Speed (mph)	8.35	0.00	5.83	9.06
Turbulence Intensity (%)	15.43	75.14	13.83	11.40

Note: SC7 was collected on May 17, 1993. The skies were partly cloudy. The average height and length of the separation bubble were 3.50 ft and 15.3 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.20. Tuft's orientation for SC8 during the following times: (a) 4:35.4, (b) 4:37.9, (c) 4:40.4, (d) 4:42.9, and (e) 4:45.4.

Table A.20. Summary of wind information for SC8.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	4.60	1.26	5.95	8.93
Variance	1.34	1.46	0.56	0.53
Standard Deviation	1.16	1.21	0.75	0.73
Maximum Speed (mph)	6.54	4.02	7.51	10.74
Minimum Speed (mph)	2.86	0.00	4.73	6.99
Turbulence Intensity (%)	25.20	95.72	12.53	8.13

Note: SC8 was collected on May 17, 1993. The skies were partly cloudy. The average height and length of the separation bubble were 3.03 ft and 15.2 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.21. Tuft's orientation for SC9 during the following times: (a) 4:49.8, (b) 4:52.3, (c) 4:54.8, (d) 4:57.3, and (e) 4:59.8.

Table A.21. Summary of wind information for SC9.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	5.28	5.20	7.93	10.24
Variance	0.86	2.13	0.30	0.94
Standard Deviation	0.93	1.46	0.55	0.97
Maximum Speed (mph)	6.80	8.54	8.80	11.96
Minimum Speed (mph)	3.57	2.53	6.73	8.28
Turbulence Intensity (%)	17.57	28.11	6.87	9.45

Note: SC9 was collected on May 17, 1993. The skies were partly cloudy. The average height and length of the separation bubble were 2.73 ft and 12.1 ft, respectively.

(a)

(b)

(c)

(d)

Figure A.22. Tuft's orientation for SD1 during the following times: (a) 0:57.3 (b) 0:59.8, (c) 1:02.3 (d) 1:04.8.

Table A.22. Summary of wind information for SD1.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	7.15	3.41	6.01	7.10
Variance	0.43	1.49	1.91	1.76
Standard Deviation	0.66	1.22	1.38	1.33
Maximum Speed (mph)	8.73	5.44	8.02	8.73
Minimum Speed (mph)	5.76	1.11	2.92	4.21
Turbulence Intensity (%)	9.16	35.80	23.00	18.71

Note: SD1 was collected on May 17, 1993. The skies were mostly cloudy with thunderstorms and showers in the immediate area. The average height and length of the separation bubble were 2.75 ft and 11.3 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.23. Tuft's orientation for SD2 during the following times: (a) 8:43.8, (b) 8:46.3, (c) 8:48.8, (d) 8:51.3, and (e) 8:53.8.

Table A.23. Summary of wind information for SD2.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	9.36	3.36	8.75	9.46
Variance	2.76	3.04	0.56	1.24
Standard Deviation	1.66	1.74	0.75	1.11
Maximum Speed (mph)	11.51	5.96	10.48	11.51
Minimum Speed (mph)	6.09	0.47	7.38	6.99
Turbulence Intensity (%)	17.77	51.91	8.52	11.77

Note: SD2 was collected on May 17, 1993. The skies were mostly cloudy with thunderstorms and showers in the immediate area. The average height and length of the separation bubble were 2.30 ft and 9.3 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.24. Tuft's orientation for SD3 during the following times: (a) 10:39.5, (b) 10:42.0, (c) 10:44.5, (d) 10:47.0, and (e) 10:49.5.

Table A.24. Summary of wind information for SD3.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	12.43	5.49	11.12	11.56
Variance	5.26	1.54	3.72	3.42
Standard Deviation	2.29	1.24	1.93	1.85
Maximum Speed (mph)	15.32	8.02	14.81	14.94
Minimum Speed (mph)	7.96	3.24	8.22	7.76
Turbulence Intensity (%)	18.44	22.55	17.34	16.00

Note: SD3 was collected on May 17, 1993. The skies were mostly cloudy with thunderstorms and showers in the immediate area. The average height and length of the separation bubble were 2.20 ft and 12.7 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.25. Tuft's orientation for SD4 during the following times: (a) 11:38.6, (b) 11:41.1, (c) 11:43.6, (d) 11:46.1, and (e) 11:48.6.

Table A.25. Summary of wind information for SD4.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	8.76	2.36	6.07	6.72
Variance	2.26	1.64	1.53	1.48
Standard Deviation	1.50	1.28	1.24	1.22
Maximum Speed (mph)	13.51	5.70	8.22	8.60
Minimum Speed (mph)	6.47	0.92	3.82	4.41
Turbulence Intensity (%)	17.16	12.09	20.38	18.12

Note: SD4 was collected on May 17, 1993. The skies were mostly cloudy with thunderstorms and showers in the immediate area. The average height and length of the separation bubble were 2.87 ft and 11.5 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.26. Tuft's orientation for SD5 during the following times: (a) 7:26.2 (b) 7:28.7, c) 7:31.2, (d) 7:33.7, and (e) 7:36.2.

Table A.26. Summary of wind information for SD5.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	6.79	2.36	6.20	6.07
Variance	2.48	1.30	9.10	5.57
Standard Deviation	1.57	1.14	3.02	2.36
Maximum Speed (mph)	8.82	4.73	11.12	12.55
Minimum Speed (mph)	4.28	0.27	1.43	4.15
Turbulence Intensity (%)	23.19	48.22	48.65	38.84

Note: SD5 was collected on May 17, 1993. The skies were mostly cloudy with thunderstorms and showers in the immediate area. The average height and length of the separation bubble were 3.30 ft and 13.5 ft, respectively.

(a)

(b)

(c)

(d)

(e)

Figure A.27. Tuft's orientation for SD7 during the following times: (a) 1:18.7 (b) 1:21.2, (c) 1:23.7, (d) 1:26.2, and (e) 1:28.7.

Table A.27. Summary of wind information for SD7.

<u>Quantity</u>	<u>13P</u>	<u>R1</u>	<u>R4</u>	<u>R6</u>
Mean Speed (mph)	9.10	1.35	7.24	10.02
Variance	2.92	1.09	1.11	0.64
Standard Deviation	1.71	1.04	1.05	0.80
Maximum Speed (mph)	11.71	4.34	9.19	11.77
Minimum Speed (mph)	6.15	0.00	5.12	8.41
Turbulence Intensity (%)	18.78	77.36	14.54	7.97

Note: SD7 was collected on May 17, 1993. The skies were partly cloudy. The average height and length of the separation bubble were 4.00 ft and 19.2 ft, respectively.