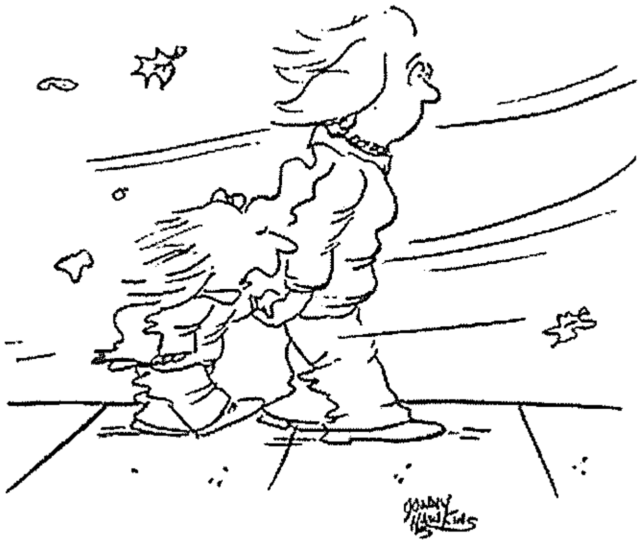
BBSc 433
Reading Assignment 2

Assessing comfort using Wind tunnel



"I wish the wind would breathe in."

Fang Wang
05/06/07

Assessing Comfort using the Wind Tunnel

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1. How to Measure Comfort?

Why comfort is important?

Wind comfort is essential to consider when designing buildings in the city. Poor building designs create bad situations and even a dangerous pedestrian level. A shop can be left vacant if the wind environment is really bad such as if wind gusts near the shop occur frequently. There are a number of cases around the world of wind accidents in which people sustained serious injury or were killed.

In May of 1972 in Portsmouth, England, an elderly lady died by a gust of wind at the corner of a 16 storey building. The local station recorded wind speed during that period ranged from 13 to 20m/s, gust to 25m/s [1]. In June of the same year in Birmingham, England, another elderly woman was lifted off her feet by a gust of wind near a tall block of apartments and died as well [2]. In 1982 in the United States, a woman was blown to the ground by a gust of wind seriously injuring her shoulder near one of New York's tallest buildings. As a consequence of being injured, she sued the building's owners, manager, design engineer, architect as well as New York City for $6.5 million [3]. This problem was caused by them allowing the building to be built which created dangerous situations for pedestrians.

City governments have to take responsibilities for controlling the existing wind problems within the area and preventing the future dangerous incidents from happening when proposing any new development. It is necessary to focus on the problems and identify the probabilities of the pedestrian wind problems. Regulations and wind tunnel tests should be used to identify whether the new development is within the acceptable pedestrian wind level or not.

It seems that tall buildings have a major impact on the wind conditions in the surrounding areas. It often creates high wind speeds at the pedestrian level around itself, therefore the pedestrian level can be experienced as uncomfortable or even dangerous. The design of a building is not enough if designers only look at the building envelope, the effect of the outdoor environment has to be included as well. A single limit on height does not address the problem of pedestrian wind, but a combination of building height limits has an impact on the acceptance of the level wind speed.

The wind comfort does not only address the life quality in urban areas, it also specifies the economic aspect in terms of how far the planned activities serve the use of the area, and how the wind comfort influences people in the existing or future built environment while walking within that area.

Comfort components

Ted Stathopoulos (2006) [4] states *"the wind comfort differences range from the speed averaging period (mean or gust) and its probability of exceedance (frequency of occurrence) to the evaluation of its magnitude (experimental or computational)"*.

Comfort measurement is not dependent on the wind speed itself, it also depends on the outside temperature and sunlight, as well as clothing value. To ensure that location is comfortable, all of the factors must keep within certain acceptable ranges. Comfort criteria vary depending on the different level of activities. People do tolerate the variation in outdoor conditions and they prefer to sit as long as they feel comfortable.
The Beaufort scale is used for estimating wind speeds on land and presents the effect of wind on people. The original version of the scale was developed to assist sailors, and a new modified scale (Figure 1) expresses the mean speeds in open terrain at the 10m height. Lawson and Penwarden [5] have provided an extended ''Land Beaufort Scale'' showing wind effects on people (Figure 2). The value that is measured at pedestrian height (h =1.75 m) over open terrain with an aerodynamic roughness length z0 of 0.03m. The measurement values are averaged over periods of 10 min or 1 h (steady wind). The Beaufort scale measured wind speeds at 1.75m which is more useful to determine the wind effects on people than the speeds measured at 10m above the ground. By comparing both scales, it can be seen that strong breeze (Beaufort 6) at 10m is 10.8-13.6m/s whereas at pedestrian height, people will strong breeze (Beaufort 6) when wind speed is only 7.6-9.7m/s.

	Beaufort number	Speed (m/s)	Effects
Calm, light air	0, 1	0·1·5	Calm, no noticeable wind
Light breeze	2	1·6–3·3	Wind felt on face
Gentle breeze	3	3·4–5·4	Wind extends light flag Hair is disturbed Clothing flaps
Moderate breeze	4	5·5–7·9	Raises dust, dry soil and loose paper Hair disarranged
Fresh breeze	5	8·0–10·7	Force of wind felt on body Drifting snow becomes airborne Limit of agreeable wind on land
Strong breeze	6	10·8–13·8	Umbrellas used with difficulty Hair blown straight Difficult to walk steadily Wind noise on ears unpleasant Windborne snow above head height (blizzard)
Near gale	7	13·9–17·1	Inconvenience felt when walking
Gale	8	17·2–20·7	Generally impedes progress Great difficulty with balance in gusts
Strong gale	9	20·8–24·4	People blown over by gusts

Figure 1: Summary of wind effects on people based on the Beaufort Scale
Source: p40, A.D Penwarden and AFE Wise (1975) Wind environment around buildings. Department of the Environment Building Research Establishment, London

Beaufort Number	Description	Wind Speed at 1.75m height (m/s)	Effect
0	Calm	0.0–0.1	
1	Light air	0.2–1.0	No noticeable wind
2	Light breeze	1.1–2.3	Wind felt on face
3	Gentle breeze	2.4–3.8	Hair disturbed, clothing flaps, newspaper difficult to read
4	Moderate breeze	3.9–5.5	Raises dust and loose paper, hair disarranged
5	Fresh breeze	5.6–7.5	Force of wind felt on body, danger of stumbling when entering a windy zone
6	Strong breeze	7.6–9.7	Umbrellas used with difficulty, hair blown straight, difficult to walk steadily, sideways wind force about equal to forwards walking force, wind noise on ears unpleasant
7	Near gale	9.8–12.0	Inconvenience felt when walking
8	Gale	12.1–14.5	Generally impedes progress, great difficulty with balance in gusts
9	Strong gale	14.6–17.1	People blown over

Figure 2: Extended land Beaufort scale showing wind effects on people
Source: p4, Bert Blocken, Jan Carmeliet Pedestrian wind environment around buildings: literature review and practical examples, In Building Physics Group, Faculty of Building and Architecture,The Netherlands

Types of wind

People do not only respond to the mean wind speed, but also to the random fluctuations in speed caused by turbulence. It is difficult for people to maintain balance when strong winds change suddenly. Bottema [6] investigates the mechanical wind effects caused by three types of wind: Steady wind; non-uniform wind; gusts wind.

Murakami et al. [7] studied the steady wind and non-uniform wind, they have found that in the steady wind: 5m/s cause minor disturbance of hair and clothes and wind is felt on the face; 10m/s cause hair to be disturbed and fluttering clothes; 25-33m/s will blow people away.

In the non-uniform wind, these irregularities were roughly comparable with wind effects in uniform flow with a speed of 1.5 times the wind speed in a jet.

Bottema [6] states that in gust wind, 4m/s for 5second cause hair to be disturbed and cloth to flap; 7m/s during 5second can cause hair to be disarranged; 15m/s during 2second can bring people out of balance and is dangerous for elderly and the infirm; 20m/s can be dangerous even for young people; 23m/s will blow people over. A high gust speed is often immediately produced and it is likely to blow the pedestrian over.

It is necessary to compare the three types of wind speed. For the same wind effect, gust wind speeds are significantly less [7]. In reality, gust wind is more common and most of the wind assessment is measured in gust wind rather than steady wind. Durgin (1991) [8] states that a steady wind speed is less difficult to walk in, than a wind speed with high turbulence intensities and 3 second gusts. Non uniform wind is not commonly used as a parameter to account for any observations, because it is really hard to determine the size of the windess.

The high speed gust has adverse effects. People have difficulty with balance when wind gusting up to 20m/s. Gusts speeds in the range of 20 to 30m/s is estimated as enough to cause people to blow over. If the gust speed is exceeded for more than 2 times a year, then the pedestrian comfort level is considered as an unacceptable and even dangerous wind condition in the area [9].

Many of the effects of wind action, such as blowing papers and loss of balance tend to be primarily noticed during gusts. For activities like standing or sitting for short or long periods of time, the effective gusts or peak gusts are more likely to be critical, so in this case it is appropriate to use gust wind. Whereas the wind effect is more dependent on the mean speed, the speed acts as an indicator of comfort in areas such as outdoor café areas. To sum it up, for the wind force assessment, it is necessary to use mean and gust speeds. Criteria based on mean wind speed is required for the thermal comfort and wind chill assessment [10]. Criteria based on gust wind speed are used in more complex design and applications. Furthermore, Durgin (1991) [8] suggests that gust wind can be classified as gustiness (Effective Gust) and Rarely occurring Peak Gust.

It is not adequate to tell the wind speeds measured at the gust speed or mean speed, therefore the effective wind speed is sufficient to predict the wind condition in a site.

The effective gust speed integrates both mean and gusts speed, it is the most adequate way to quantify wind speed for pedestrian comfort.

$$\hat{U} = \overline{U} + g\,\sigma \quad [11]$$

$\hat{U}$ an effective gust speed,

$\overline{U}$ is the mean speed;

σ is the root-mean-square of velocity fluctuations and

g is a selected multiplier (constant)

g is normally in the range 1.0 - 4.0. A low value is selected when the wind condition is best characterised as the more common gusts; a high value such as in the range of 3 to 4 is used when the occasional peak gust is considered as the most important factor to comfort [12]. g = 1.5 appears in most of the reports. The effective gust can be shown in this case to be approximately the fastest one minute gust [13].

The effective gust speed can be presented as the equivalent wind speed. The idea of the Equivalent Average is using one single parameter to account for three types of windiness. The base equation for the Equivalent wind speed is

$$U_e = U + k \cdot \sigma_u > U_{\mathrm{THR}} \quad [14]$$

Ue is the equivalent wind speed,

U is the mean wind speed,

k is the peak factor (gust factor= gust/ mean)

σ_u is the standard deviation of the wind speed (turbulence) and

UTHR is the threshold value (all at pedestrian height).

k can be calculated by using gust wind speed divided by the mean wind speed. If the factor is 2 in the range of high wind speed, and 1.5 is the factor in the low wind speed range. These values can be interpreted as at the high wind speed, gust speed is 2 times higher than the average speed, whereas at the low wind speed, the gust speed is only 1.5 times higher than the average speed.

Lawson (1978) [15] proposed the value of *g* gives the best characterization of the wind conditions that people feel. In the case of the effect of gusts is totally ignored, g=0; the characteristic gust speed is that which is exceeded about 10% of the time, g=1.5 is used. When g=3.5, the characteristic gust speed becomes the peak gust speed exceeded only about 0.1% of the time. It seems that value of g ranging from 1 to 1.75 being the most common, 3.5 is used in Japan [16].

There is only less than 2% difference between predicted equivalent averages calculated using the raw data or predicted average, effective gust, and peak gust wind speeds. The data suggests that the currently used ratios of 1.4 for effective gust to average wind speed and 2 for peak gust to average predicted wind speed are reasonable [16].

Usually, the wind comfort criteria consisted of a discomfort threshold and an exceedence probability of the threshold. Different authors measure the comfort level in different type of wind speed. The value of the discomfort threshold and an exceedence probability of the threshold are different as proposed by each author. In the case of using the equivalent wind speed, the values vary depending on different author's option.

Classification of pedestrian areas, activities

Most of the threshold wind speeds for discomfort are varied depending on the human activities at a particular location. Hours of the day during which pedestrians are active for various pedestrian use areas within the city are the factors which influence the criteria on comfort.

Williams (1990) [17] proposed dividing pedestrian areas into two groups: Option use and Required use. Option use is defining the areas such as parks and plazas that pedestrians have the option of using depending on the weather. Whereas the Required use is primarily defined on sidewalks or areas that people are required to use. He suggests the acceptability of the wind conditions occur for a majority of the time differently depending on the two groups. In some cases, the comfort criteria consider two main aspects: Safety and Levels of comfort for various pedestrian activities such as walking, sitting and standing. The wind speed acceptable for people walking is higher than areas where people sitting. For the areas that people prefer to sit outside, the wind speed should remain as low as possible.

Ted Stathopoulos (2006) [18] describes pedestrian-level winds in terms of velocities in the presence and absence of a new building within a specific urban environment. Developers of buildings, such as shops, are more interested in the pedestrian volume that passes along the shops in the building. The pedestrian level wind is regarded as the important part involved in the building design. Penwarden (1973) [19] found that substantial complaints occurred when the limit of comfortable wind speed was exceeded for more than 10% of the time. It is important to evaluate the effect of any new building on pedestrian level wind. All places in or near the area where pedestrian activities are involved have to estimate the probability of occurrence in order to make sure the probability is within the acceptance level.

Probability of occurrence

People will start to feel discomfort when the wind effects become so strong and occur so frequently. In most of the studies, the way to measure the pedestrian conditions are either comfortable or uncomfortable or unsafe which is based on the probability of occurrence. Because in general, comfortable conditions cannot always be met and uncomfortable conditions must be accepted for a certain percentage of time. Therefore the information on the local wind for the probability distribution of the wind speed is essential. The threshold value is defined in combination with specific type of activities, particular area and probability of occurrence within a certain duration of time [20]. It is common to use the percentage of hours during a year rather than the week.

If the frequency of occurrence at a particular area for a pedestrian activity exceeds the threshold value, the area will be classified as unacceptable or uncomfortable. The exceedence level specifies whether the area is unacceptable/uncomfortable or dangerous. If any value exceeds the threshold value, action should be taken to provide pedestrian comfort and safety. The threshold speeds for safety are higher than for comfort and the frequency of occurrence is set at a much lower level.

Most of the authors agree that wind speed below 5m/s will have little to no effect on people's comfort regardless of the frequency of occurrence. But any wind speed above 5m/s with frequency of occurrence for each area varies depending on different authors. The goal of all the authors is to measure the pedestrian level comfort. The main difference between different authors is how they measure it. The different method is the way of defining activities, areas and the corresponding threshold values in terms of local pedestrian level wind speed.

Comfort criteria measurement by different approaches

Wind comfort criteria has been studied by many of people for years. It is unfair to judge the different approaches whether right or wrong, good or bad.

Penwarden 1973 [19] defined comfort on mean speed for three main parameters (onset of discomfort, definitely unpleasant and dangerous). There is no probability occurrence involved in this approach. The minimum mean speed allowed is 5m/s and the maximum speed is 20m/s.

Davenport 1972, Isyumov and Davenport 1975b [21] measurements based on the type of activity at each location. There are 4 activities associated with 4 areas, as well as 4 relative comfort parameters in the criteria. The frequency of occurrence is involved. They use the Beaufort scale number to determine the relative comfort. Therefore the measurement is quantified with wind speed range rather than specific speed values. The Beaufort scale is measured in mean wind speed once a week or once a month. Any location with mean winds reaching Beaufort 8 once a year is designated as dangerous.

Lawson and Penwarden 1975 [5] specified the activities as acceptable and unacceptable. There are three activities classified as acceptable. Comfort is measured in terms of Beaufort scale and probability occurrence. In the criteria measured in terms of peak gust over a 3 second average time, the probability of less than 4% is used for all acceptable conditions, and more than 2% is only used for unacceptable condition. The peak gust speed is defined with a gust factor of 2.68: Mean+2.68σ. The measurement of using mean speed is include in the criteria as well.

Hunt, Poulton and Mumford 1976 [22] looked at comfort on two categories of activities (Safe, sure walking, and tolerable conditions and unaffected performance). They offer criteria based on wind tunnel tests on human subjects. The mean speed and gust speed are all involved, and the probability of occurrence is measured in the criteria as well. The gust speed is higher than the mean speed when comparing the same activity at one time. An equivalent steady wind speed defined with a gust factor of 3: Mean+3σ.

Melbourne 1978 [23] proposed the criteria of 4 types of activities. He measured in mean speed as well as gust speed and probability of occurrence. He defined the gust speed with a gust factor of 3.5: Mean +3.5σ. For all the activities, the maximum wind speed should occur no more than once per year. The minimum value used for Mean speed is 5m/s and 10m/s for Gust speed. The maximum value used for Mean speed is 11.5m/s and 23m/s for Gust speed. The area for the activity is not stated in this measurement. Furthermore, he considered the probability of occurrence at different times of day. He assumed that daylight hours are more useful to determine the comfort level rather than at night. Penwarden found that average wind speeds are 10% higher in daylight hours [24]. Therefore Melbourne's comfort criteria looked at the probability for the event occurring during daylight hours and all hours.

Murakami, Iwasa and Morikawa 1986 [25] presented criteria based on occurrence frequency of daily maximum gust speed. There are three classes classified by types of areas, because the criteria is based on a two year survey of residents living near a high rise building, the areas are more focued on the central city. For the daily maximum gust speed, the minimum level of speed is 10m/s and the maximum speed is 20m/s. The probability varies depending on different classes. The probability for low speed is larger than the probability for high speed. The typical value of g in cities is in the range of 2 to 3.5, whereas in high wind speed areas, the value is in the range of 1.6 to 2.5. No activities are specified in this case.

Comfort criteria defined by Durgin from 1997 to 2002 [26] are based on types of activity. 5 categories are used to specify the activities. Equivalent average speed is defined as the highest of: the average wind speed divided by 1.103; the effective gust (mean +1.5RMS) divided by 1.434 and the peak gust divided by 1.875. He assumed 2.6% of probability is optimum when evaluating conditions for all types of activity, except for dangerous conditions, the probability is 0.01%. He recommends the speed can be measured by Equivalent Average, Average, Effective Gust and Peak Gust. The threshold value of Peak Gust speed for each activity is higher than the other values, and the value of Equivalent Average is the lowest. In this case, the area is not involved in the measurement.

Bottema [27] and Gandemer [24] both use 6m/s of wind speed to express their subjective parameters in terms of a frequency of occurrence. Bottema states the comfort criteria by using the equivalent wind speed, and the equivalent wind speed defined with a gust factor of 3: Mean+3σ. 20m/s is the speed for danger situation. The maximum allowed discomfort probability is Pmax=15% (P= threshold + maximum discomfort probability).

All of the approaches deal with how to determine comfort. To sum up all the criteria by Durgin (1997) [28], for sitting and long time standing, the limit of average speed is between 2- 6m/s; for activity such as sitting and short time standing, the limit is in the range of 3- 8m/s; for comfortable walking and strolling, 4- 11m/s is the average restriction; for tolerable walking and walking fast, the acceptable range is between 9-14m/s; any wind speed above, the condition is regarded as unacceptable and dangerous.

Ratcliff 1990 [29] discusses and compares the pedestrian wind acceptable criteria. It appears that there are currently no suitable criteria available in published form. Koss 2006 [20] concludes that the comparison of comfort criteria based on gust wind speeds shows a fundamental difficulty in the consideration of the local turbulence. The local condition has to consider and involve in the comfort criteria. Wind speed and probability of occurrence in terms of types of activity and different areas are more effective to measure the comfort. It is inadequate for measure any criteria only exceed for a small percentage of time, such as if only 1% of the time the area is not comfort, the remainder of the time is comfort. The wind speed at a particular area with an activity should permit to be exceeded at a minimum probability of occurrence of 5% [30].

City rules

As discussed in the previous section, the local wind condition is one of the key factors of the pedestrian comfort level. Different cities have to analyze the wind data first, then set the regulations or rules to evaluate the pedestrian comfort, and to make sure any developer has to take action if the developments worsen the condition and become uncomfortable or dangerous for pedestrians.

In Bristol [31], there are 6 standard categories of use area for assessing the acceptability of comfort criteria. It accounts the probability of occurrence according to the Beaufort scale. For any sitting area if wind speed exceeds Beaufort scale 4 for 6% of the time, the area is unacceptable.

In Boston [32], an effective gust wind speed of 13.86m/s with an occurrence rate of 1% of time is the maximum acceptable pedestrian level wind caused by new buildings.

Under San Francisco's plan [32], the regulation for wind criteria is measured wind speeds should not be greater than 4.9m/s for most of the time for areas with public seating. An overall upper limit is that no building should cause wind to reach or exceed 7.2m/s for more than one hour per year. An effective gust wind speed of 8.6m/s with an occurrence rate of 1% of time is the maximum acceptable pedestrian level wind caused by new buildings.

In North America [33], the criteria for three levels of activity based probability of exceedance on 20%. Any speed above 5.4m/s in terms of Mean speed and Gust Equivalent Mean speed is classified as uncomfortable for any activity.

In London, especially on the Canary Warf development [34], the comfort level is based on 5% probability of exceedance. A wind speed above 10m/s exceeds 10% of the time is recognised as uncomfortable in this case. Mean speed and Gust Equivalent Mean speed are both measured. The approximate speed ranges corresponding to 20% probability is listed as well.

There is a wind regulation in Wellington City. The Figure3 below indicates the variation of wind conditions at different wind speeds occurring for 6 hours per year in Wellington. The Effective Gust speed of 18m/s is the maximum speed accepted by the Wellington City Council.

Effective gust speed (m/s) occurring for 6 hours per year	Description
11 and below	Very low
12 - 14	Low
15 - 17	Moderate
18 - 20	Moderately high
21 - 23	High
24 - 26	Very high
27 and above	Extremely high

Figure 3:Suggested descriptive terms for the range of net effective gust speeds which typically occur at different locations within Wellington City
Source: Penwarden, A.D(1983): Acceptable wind Speed in Town, Building Science, Vol.8

If the proposed building creates wind problems, the city council will require developers to fix or minimise the problems. In Wellington District Plan [35], if the wind speeds in the development proposal exceed the existing wind condition, the developer should take some actions to reduce the wind speeds. The Figure4 below shows that any wind speed above 18m/s, the rule is requires the developer to reduce it to a maximum 18m/s.

13.1.2.11.1 New buildings or structures above 4 storeys in height shall be designed to comply with the following standards:

Existing wind speeds	Wind speeds resulting from development proposal	Requirements on developer
Up to 10 m/sec	If exceeding 10m/sec in any public space	Reduce to 10m/sec in the public space
Up to 15m/sec	If exceeding 15m/sec	1. Reduce to 15m/sec 2. Although other directional speeds may be increased towards 15m/sec, overall impact is to be no worse than existing
15-18m/sec	If exceeding 15m/sec	Reduce to max 15m/sec
Above 18m/sec	If more than 18m/sec	Reduce to max 18m/sec

For information, the effects of wind at various speeds are:

10 metres/second -	*Generally the limit for comfort when standing or sitting for lengthy periods in an open space*
15 metres/second -	*Generally the limit of acceptability for comfort whilst walking*
18 metres/second -	*Threshold of danger level*
23 metres/second -	*Completely unacceptable for walking*

Figure 4:Central area rules for wind
Source: Wellington City Council (2000): Wellington District Plan

2. How to Measure wind

Using Power Law to predict the wind speed in the city

When wind flows over an open area, it approaches the boundaries of the urban area and increases the roughness of the surfaces. Within the city the wind speed is much lower than in the open country at the same height because the roughness is higher than the sub rural area. As the surface gets rougher, more turbulence occurs.

Power Law is generally used to calculate the wind amplification factor at a certain reference height in the urban boundary layer. The increase with height can approximately be represented by this law.

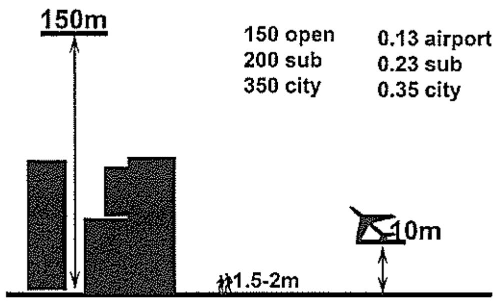
$$\frac{U(z)}{U_{ref}} = \left(\frac{z}{z_{ref}}\right)^{\alpha} \quad [36]$$

U(z) is the horizontal wind speed at height z,
Uref is the reference wind speed at reference height zref

z is the height
ztef is the reference height
α is the power law exponent, =0.35 for Southerly wind, =0.45 Northerly wind.

The Power law predicts a certain wind speed even near the ground level. To predict the wind velocity in the urban boundary layer in the central city, Power law can be applied by using available airport wind data. If the measurements of the wind speed and wind direction at a height at the airport are used then from the Power Law it is simple to calculate the wind speeds at a particular height in the city centre. The standard height for meteorological measurement is always 10m above the ground at the airport. The airport is an open terrain where the wind speed is not affected by the obstacles such as buildings. In general the mean wind speed increases with height above the ground, the wind is two to four times less at the pedestrian level than measured 10m in the airport [37].

By applying the Power Law, Figure5 shows that the wind speeds at 10m above the airport are equivalent to the speeds 150m above the city. If the wind information at 10m above the airport is available, then the wind speed at 1.5m and 2m above the city can be predicted. 1.5m is the pedestrian height, and 2m is just above people's head. Assume the wind speed at 10m above the airport is 7.5m/s, then at 1.5m above the city the wind speed is 1.59m/s and at 2m the speed is 1.76m/s. the wind is moving faster above our head than around our body.



$U_{Airport} = 7.5 m/s$

$$\frac{U_{10m,\ Airport}}{U_G} = \left(\frac{10m}{150}\right)^{0.13} = 0.7\ U_G$$

$$\frac{U_{150,\ City}}{U_G} = \left(\frac{150m}{350}\right)^{0.35} = 0.74\ U_G$$

$U_{10m,\ Airport} = U_{150m,\ City}$

$U_{2m,\ city} = 0.164 U_G$
$U_{1.5m,\ city} = 0.148 U_G$

$$U_{2m,\ city} = 0.164x\ (7.5/0.7) = 1.76 m/s$$
$$U_{1.5m,\ city} = 0.148x\ (7.5/0.7) = 1.59 m/s$$

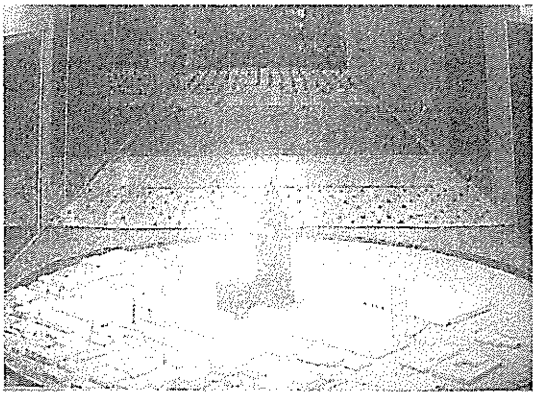
Figure 5: Calculate the pedestrian level speed by using the Power Law

From the calculation is can be seen and predicted that the wind speed at 10m above airport is 4-5 times higher than the speed at the pedestrian height of 1.5m to 2m. It becomes easy and quick to measure the wind speed at any height in the city area. In reality because of complex building shape, street layout, the speed may not be exactly accurate.

Measurements in Wind Tunnel Test

For some of the approaches on the comfort criteria, investigations are based on the wind tunnel test. In the case of whether a pedestrian condition is favourable or not, the full wind tunnel test has to be carried out in order to solve the problem. If the results indicate that wind conditions are unfavourable, remedial measures should be taken.

Wind tunnel test determines the wind effects on pedestrian level and improves the wind condition if the test result is exceed the standards. For the case in Portsmouth, England, the lady died at the corner of a high building by a gust of wind. After she died, the model of that site has been tested in the wind tunnel. The speed estimated at the corner of the building in the wind tunnel is in the range of 15 to 24m/s, gusting to 30m/s which is in average 5m/s higher than the speed at the local station [38]. Therefore wind tunnel test is useful to describe the relative behaviour of the pedestrian comfort criteria. The impact of the new buildings on the pedestrian level can be identified from the wind tunnel test. The evaluation of the wind tunnel test can be used to specify the specific design features as well.



A physical scale model will be tested in the wind tunnel should comprise of building forms, landscape, local features of the area and surroundings. The impact of the new buildings can be identified from the wind tunnel test. The closer to the boundary layer, the more accurate the result will be.

Figure6: City model in the wind tunnel test
Source: A.S.C.E, 2003, ***Outdoor human comfort and its assessment****, published by the American Society of Civil Engineers, US, pp19*

Methods for studying pedestrian level wind conditions in wind tunnels can be divided into two groups: point methods and area methods [39]. Point methods provide quantitative data at discrete locations in the flow field. Commonly, point method includes hotwire/ hot film anemometer and pressure sensor. Area methods provide spatially continuous qualitative information. For instance, scour techniques, the use of oil streaks or infrared thermography is used for area measurement. The advantage of area methods is that a complete visualisation of the pedestrian level wind flow over the entire area of concern is obtained. In practice, point method tends to be used much more widely and routinely than area methods [40].

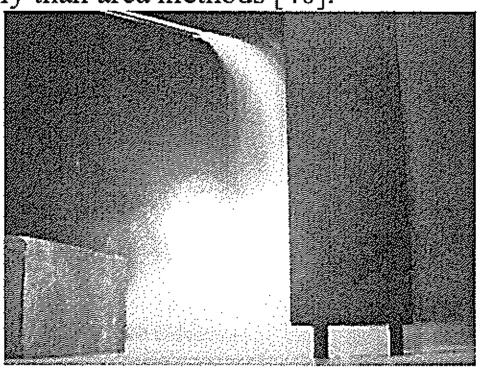


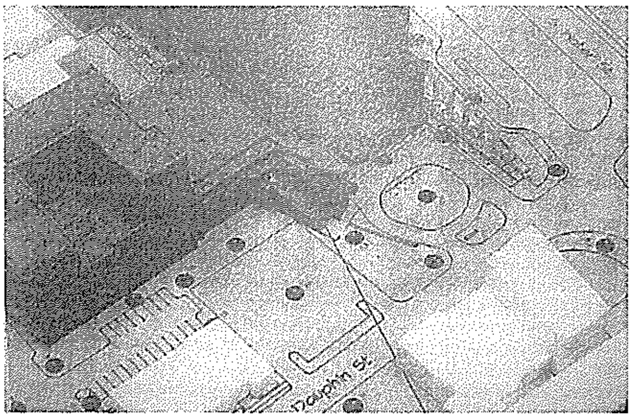
Figure 7: Example of area method: Flow visualisation using smoke

Source: A.D Penwarden and AFE Wise, 1975, ***Wind environment around buildings****, Department of the Environment Building Research Establishment, London*

Usually the tests start from a low wind speed to a very high wind speed at a particular area for a certain wind direction. In typical wind tunnel tests, the wind speed above the boundary layer is in the range 10 to 30m/s. 1 to 5second is the range of gust durations which is commonly used for measuring pedestrian comfort and safety [39].

Irwin Probe

Irwin's omnidirectional pedestrian level wind probe is one of the point methods used for wind measurement in the wind tunnel test. A simple pressure sensor has proposed by Irwin in 1981 [41]. The pressure sensor is used in the pedestrian level studies. The main component of the sensor consists of one circular base, two circular tubes.



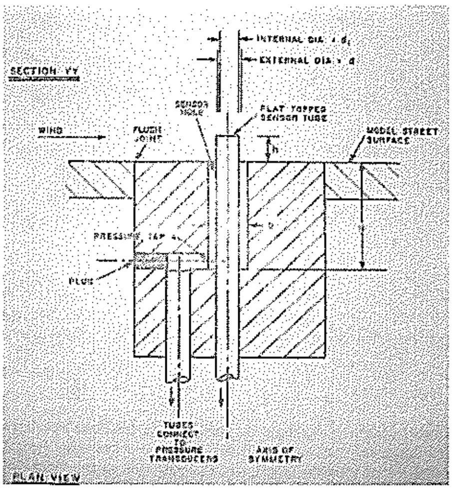


Figure 8(left): Example of point method: Irwin sensor installed around a wind tunnel model.
Figure 9(right): Diagram of Irwin Probe section
Source: A.S.C.E, 2003, ***Outdoor human comfort and its assessment****, published by the American Society of Civil Engineers, US, pp20-23*

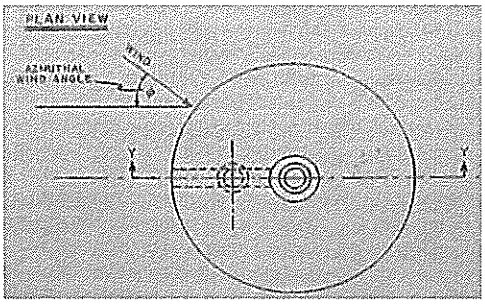
On the upper of the base, a hole is slightly larger diameter than the hole at the bottom of the base. The larger hole is in the center and about 3/5 of the base. The smaller hole is in the center as well and is about 2/5 of the base. At bottom of the base next to the center hole also contain another hole with the same size.

The pressure difference is measured between the top of the tube and the bottom of the tube. Wind speed level at the top of the tube can be converted by using a calibration function. Irwin Probe is measures not only the mean speed, as well as the speed fluctuations [42]. However the pressure difference is not dependent on the wind direction. The frequency responses are high enough to cover the range of interests for pedestrian studies.

The advantage of the probe is relatively easy and cheap to conduct, but in order to achieve high level of accuracy, geometry must be considered. Durgin et al. [42] agreed the more sensitive the sensor is, the zero drift will be eliminated because the pressure signals are very low in the low speed regions. Durgin 1991 [41] states that the probe provides the pressure sensing measurement and the expected error is Ug with standard derivation 7% and the total maximum wind speed error is less than 1m/s within the range of -20 to +20m/s.

Construct an Irwin Probe

It is simple to conduct an Irwin Probe. There are no requirements on the material of the base as long as the base is not so light to move in the wind tunnel. The pressure port of the stainless steel or brass tube is used in the probe. There is no relevant document on the size of the Irwin Probe. The technician in the workshop estimated the size of the tube is 0.16mm diameter and the base is 250mm diameter. The small hole must tighten the tube, therefore the small hole should be drill no more than 0.16mm and the large hole should be drill 25mm. The larger hole will be drill about 3/5 of the base and the rest the length will be drill as a smaller hole. It is about half way from the center of the base to the edge of the base, another smaller hole will be drill which is 0.15mm longer than the center hole. A side hole will be drill in order to make sure that the air can flow through the two holes. A plug is inserted to avoid the air leakage from the side hole. The last step is to insert the tubes. One of the pressure ports of the tube is through the whole base, the other one is put into a small hole which is next to the center hole. It should keep the tube about 1.7mm above the pressure port on the top of the base.



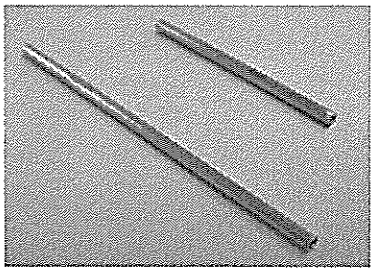
(a) Final probe

Figure 10(left): Diagram of Irwin Probe plan

Source: A.S.C.E, 2003, ***Outdoor human comfort and its assessment****, published by the American Society of Civil Engineers, US, pp20-23*

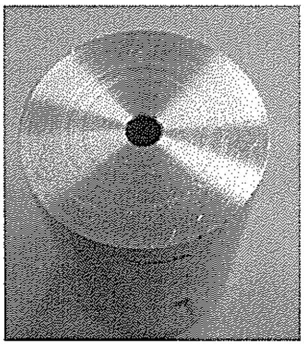
Materials:

(b) Collect materials: 250mm base

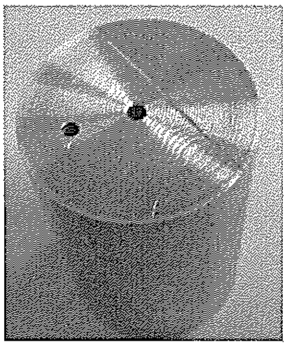


(c) Collect materials: 0.16mm brass tube

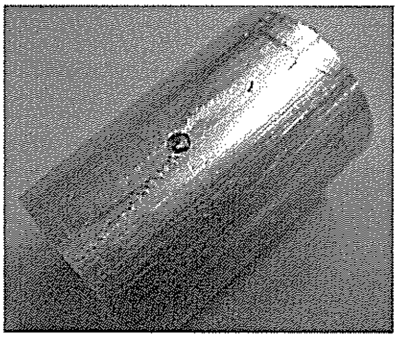
Drill holes:



(d) Drill a larger hole

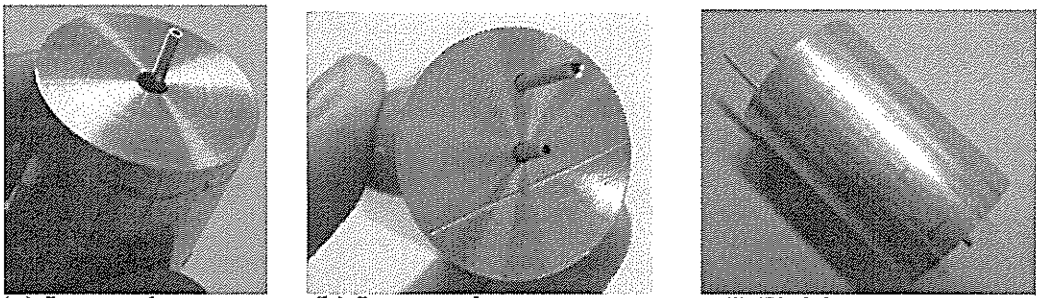


(e) Drill two same smaller holes



(f) Insert a plug

Insert tubes:



(g) Insert a longer tube through the center hole

(h) Insert a shorter tube through the side hole

(i) Finish

Figure 11(a-i): Process of conduct an Irwin Probe

Pitot Tube

A Pitot Tube is a pressure measuring instrument. It consists of a simple metal tube bent at right angles. The tube must be directed to the wind direction, and is measuring the difference between the pressure sensed by the tube and the pressure of the surrounding air flow. A stagnation point is where the velocity near the front port is zero [43]. The approaching air is deflected away from the stagnation point. The pressure different is the difference between the pressure at the stagnation point and the static ports. Lawson 1980 [44] states that the difference between total pressure and static pressure, the total pressure port is used when measure the wind speeds around a model, whereas the static pressure is used when assuming the pressure is equal to the mean ground level pressure.

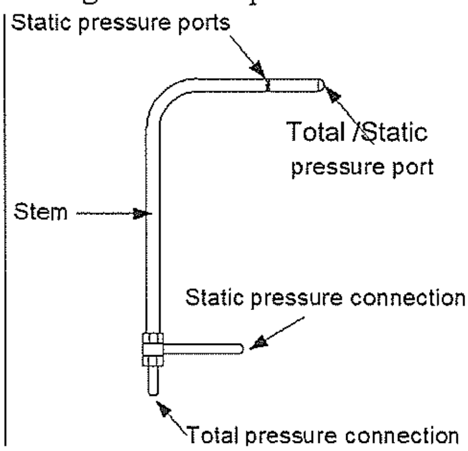
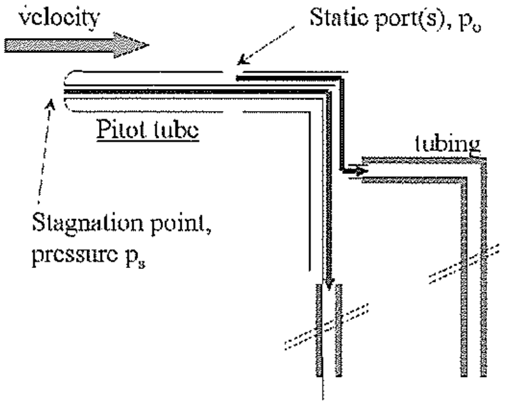


Figure 12: Diagram of a typical pitot tube

Source: www.flowkinetics.com/measurement.htm

It regarded as the most accurate method for measuring flow velocity on a routine basis. The accuracy can be kept around 1% [45]. It is simple to find the velocity by applying the Bernoulli's equation. The Bernoulli's equation describes the relationship between the velocity and pressure [46]. By using the formula which converts pressure to velocity, the wind velocity at the top of the tube can be calculated. The variables in the equation are the pressure difference, the density of the air p=1.225kgm-3(at normal temperature and pressure).



$$\frac{V^2}{2g} + z + \frac{P}{\rho g} = C$$

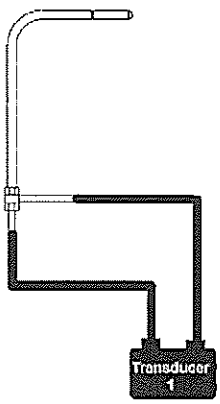
$$v = \sqrt{\frac{2\left(p_{\text{stagnation}} - p_{\text{static}}\right)}{\rho}}$$

Figure 13(left): Digram of a Pitot Tube
Source:[*www.faculty.eas.ualberta.ca/.../eas327wind.html*]

Figure 14(right): The Bernoulli's equation
Source: [*www.efunda.com/.../pitot_tubes_theory.cfm*]

Pressure transducer

Both of the Irwin Probe and Pitot tube are used to determine the wind speed by measuring the pressure difference. In order to get the pressure difference data from each system, a pressure transducer interprets the data and provides a linear D.C voltage output. Setra differential pressure sensor is a useful instrument which measures the difference between two pressures. When sensor connected to a supply voltage, it produces an output voltage which is proportional to the pressure. There are two pressure ports on each of the transducer, and both of the ports connected with the tube. One transducer is connected with the Irwin Probe and the other transducer is connected with the Pitot Tube, therefore the pressure difference data from the Irwin Probe and Pitot Tube transfer to the transducers, and the transducers interpret the output by connecting the LabJack into the computer.



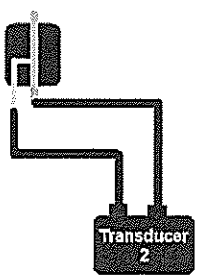


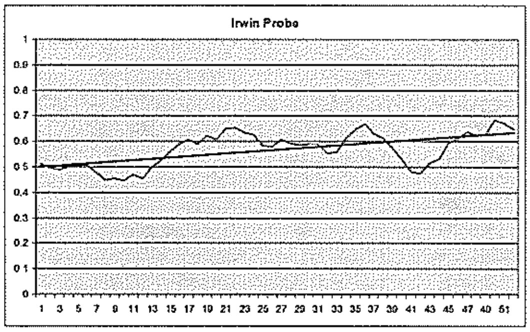
Figure 15(left): Pitot Tube connects with a transducer

Figure 16(right): Irwin Probe connects with a transducer

Calculate wind speed in the wind tunnel test

Both of the systems are used to calculate the pressure differences. In order to compare both of the data, we test them individual at the same height and with same speed in the wind tunnel. Four of us adjusted the Irwin Probe about 50mm above the wind tunnel in a certain period of time. The results of that time shows the voltage is about

0.56Pa. Secondly the Pitot Tube is being tested and aligned with wind flow. The wind direction is not considered in the Irwin Probe, therefore no alignment of the sensor is required. After testing with the Pitot probe using the same method, the result shows the voltage is about 0.68Pa which is close to the output from the Irwin Probe. The accuracy of the Irwin Probe may cause the difference between the two systems.



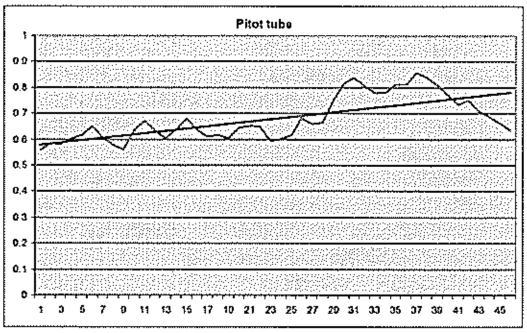


Figure 17(left): data from transducer for Irwin Probe
Figure 18(right): data from transducer for Pitot Tube

Conversion factor

The output data is the voltage induced from the pressure difference between the two tubes. The voltage generated from the sensor used to convert to a pressure value. A conversion factor is essential because all voltage has to be converted and the fraction of full scale voltage is the fraction of full scale pressure. As we know from the Bernoulli's equation, the pressure can be converted into velocity readings when using a Pitot Tube. By testing pressure with the hose connecting both taps, the wind speed is 2.1m/s at 30 Hz and the average of the voltage for Pitot Tube is 0.68Pa. (p=1.225) From the equation by working backward, the pressure difference is 2.7Pa.

$$v = \sqrt{\frac{2\left(p_{\text{stagnation}} - p_{\text{static}}\right)}{\rho}}$$

$$2.1 = \sqrt{\frac{2\text{x}\, p}{1.225}}$$

$$p = 2.7Pa$$

Figure 19: Find out the pressure difference by using the Bernoulli's equation

Therefore the conversion factor for voltage to pressure is:
Conversion Factor for Pitot Tube =the pressure difference/induced voltage =2.7/0.68=3.97. For the Pitot Tube, by using the conversion factor the voltage converted to the average of pressure 2.7Pa (0.68x 3.97). Now we have the data of pressure difference, if the velocity is unknown, from the Bernoulli's equation the average velocity can be calculate.

For the Irwin Probe, the average of the voltage is 0.56Pa, because both of the systems are used to measure the wind speed in terms of pressure difference. To find out the conversion factor for Irwin Probe, I use the velocity calculated for Pitot Tube, then

divide by the average of the voltage. Therefore conversion factor is = average velocity/induced average voltage= 2.1/ 0.56=3.8. In Order to calculate the average velocity, firstly we use the conversion factor of 3.8 by converting the voltage into pressure, and then apply the Bernoulli's equation. Therefore the average velocity for Irwin Probe is 1.88m/s. Refer to Appendix 1
{Average velocity for Pitot Tube = $(2x\ 2.7/1.225)^{1/2}$=2.1m/s}
{Average velocity for Irwin Probe = $(2x\ 0.56x\ 3.8/1.225)^{1/2}$=1.876m/s}

We able to use the conversion factor predict the pressure difference for any data of voltage from the transducer. Any voltage times the factor is in the unit of pressure. Let us assume that with a ½ full scale, the output of the voltage is 1, by using the conversion factor, the voltage convert to pressure is 1x3.8=3.8 Pa. If we double the pressure, the output of pressure will be 7.6Pa which is 2x 3.8Pa.

3. How to related speed in wind tunnel to speed for real

Both measurements in Wind Tunnel test

It is easy to predict wind speed around the building in the city such as pedestrian height in relation to the wind speed above the city, such as 150m. By comparing the output from both systems, the ratio between the heights of the measurement can be determined. If we find the ratio between 150m above the city and 1.5m at the pedestrian height is 2, the wind speed at 150m above the city is twice the speed measured at the pedestrian level. The output of the pressure difference also can be calculated and converted to the wind speed by using the equation from the Pitot Tube, which is

$$v = \sqrt{\frac{2\left(p_{\text{stagnation}} - p_{\text{static}}\right)}{\rho}} \quad [46]$$

To carry out the test, the Pitot tube must be aligned with the wind flow. The wind direction is not considered in the Irwin Probe, no alignment of the sensor is required, but it must adjust both of the system at the same vertical position. The Pitot Tube is 150m above the ground level and the Irwin Probe is below the Pitot Tube and 1.5m above the ground. The measurement is taken at the same time, the data transfer to both of the transducers and record into the computer.

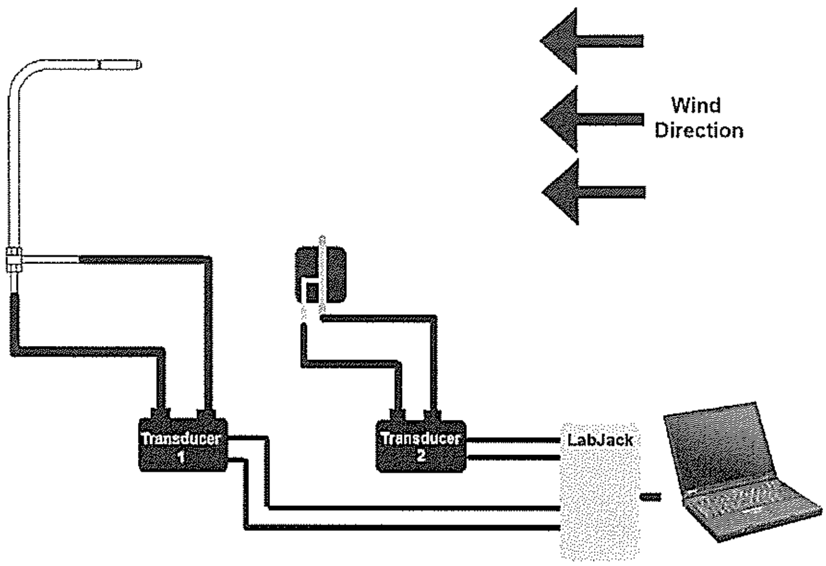
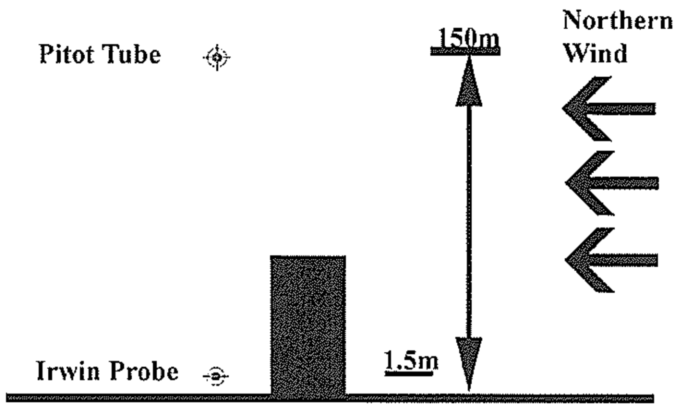


Figure 20: Both systems connect together and take the measurement at the same time

For example, if we locate the Irwin Probe at a pedestrian height in front of the a single model, and measure the pressure difference for both Irwin Probe and Pitot Tube at the same time for a period of time, the LabJack will interpret the data into the computer. By comparing the two data, we find out the average value for each measurement, then calculate the ratio between these two, say the ratio is 4 for northern wind. To calculate the wind speed measured at 150m above the ground, the equation for the Pitot Tube can be used. If the Pitot Tube measured the pressure difference is 10, therefore the velocity is 4m/s at 150m above the ground and the wind speed in front of the single model at the pedestrian height is 1m/s (by dividing by the ratio of 4). The result shows the wind speed is acceptable at the pedestrian height. If we measure the southern wind, the Irwin sensor is exposed to the wind as well as the Pitot Tube, therefore the ratio between the two measurements is lower than the northern wind, say the ratio is 1.5. The wind speed at the pedestrian height for the southern wind is 2.7m/s.



$$v = \sqrt{\frac{2(p_{stagnation} - p_{static})}{\rho}}$$

$$V_{150m} = \sqrt{\frac{2x\,10}{1.225}} = 4m/s$$

$$V_{1.5m,\,north} = 4/4 = 1m/s$$

$$V_{1.5m,\,south} = 4/1.5 = 2.7m/s$$

Figure 21: calculation of use the Bernoulli's equation by converting the pressure into wind speed

How to relate to comfort?

There are many methods of wind tunnel measurement available for different requirements. The main goal of using wind tunnel test is to determine comfort. In order to avoid any dangerous accident from happening, a wind tunnel test for a particular area is essential. To find out where is the worst situation, sensors have to be located at each area, and measure the wind speeds at a particular sensor area. Bachlin et al. [47] concluded the comparison of field and wind tunnel data indicated excellent agreement, the wind tunnel measurement of the built up area and complex building structures are representative of natural conditions. The accuracy of the wind tunnel test depends on the model as well as the instrument. A model with more details will represent the data more accurately. For example of Irwin Probe, if the size of the probe constructed precisely then the output of the wind pressure at a particular sensor location will be more accurate. Therefore the pedestrian comfort level can be analyzed based on the data.

The main components that influence the pedestrian comfort are: activity, location, time and speed. Different areas are greatly affected by the local microclimate. In situation like Wellington which is known to be windy and where the resident are accustomed to wind, Lawson 1980 [48] suggests that either the percentage time or the ranges of the Beaufort scale used would be increased. The criteria for assessing comfort level vary depending on the different activities involved in a particular area. The requirement for each activity based on wind speed under the probability of occurrence. By modelling and testing an area in the wind tunnel test, the results will show whether the area is comfortable or not.

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Appendix 1

31/05/2007
3:54 p.m. **Pitot Tube**

Seconds	Voltage	Pressure= voltagex 3.97	Velocity= (2x pressure difference/1.225)1/2
1	0.556608	2.209734	1.899402
2	0.583933	2.318214	1.945466
3	0.581833	2.309877	1.941965
4	0.601788	2.389098	1.974986
5	0.617112	2.449935	1.999973
6	0.648963	2.576383	2.050936
7	0.608272	2.41484	1.985597
8	0.578916	2.298297	1.937091
9	0.559508	2.221247	1.904344
10	0.635621	2.523415	2.029744
11	0.670572	2.662171	2.084802
12	0.633219	2.513879	2.025905
13	0.605291	2.403005	1.980726
14	0.637526	2.530978	2.032784
15	0.679995	2.69958	2.099399
16	0.634458	2.518798	2.027887
17	0.611976	2.429545	1.991633
18	0.617226	2.450387	2.000158
19	0.605669	2.404506	1.981344
20	0.643677	2.555398	2.042566
21	0.65333	2.59372	2.057825
22	0.649321	2.577804	2.051502
23	0.593679	2.356906	1.961634
24	0.601631	2.388475	1.974728
25	0.615632	2.444059	1.997574
26	0.681771	2.706631	2.102139
27	0.659635	2.618751	2.067731
28	0.664189	2.63683	2.074856
29	0.752864	2.98887	2.209024
30	0.814602	3.23397	2.297814
31	0.837445	3.324657	2.329809
32	0.806157	3.200443	2.285873
33	0.77763	3.087191	2.245064
34	0.781657	3.103178	2.25087
35	0.809938	3.215454	2.291227
36	0.811663	3.222302	2.293665
37	0.857281	3.403406	2.35724
38	0.837773	3.325959	2.330265
39	0.807018	3.203861	2.287093
40	0.768386	3.050492	2.23168
41	0.733897	2.913571	2.181021
42	0.752563	2.987675	2.208583
43	0.705788	2.801978	2.138845
44	0.688752	2.734345	2.112874
45	0.66128	2.625282	2.070308
46	0.633877	2.516492	2.026958
Average	**0.679781**	**2.69873**	**2.095063**

3:47 p.m. **Irwin Probe**

Seconds	Voltage	Pressure= voltagex 3.8	Velocity= (2x pressure difference/1.225)1/2
1	0.51112	1.942256	1.780739
2	0.495228	1.881866	1.752836
3	0.488744	1.857227	1.741324
4	0.498747	1.895239	1.759053
5	0.502441	1.909276	1.765555
6	0.506293	1.923913	1.77231
7	0.478183	1.817095	1.722407
8	0.447356	1.699953	1.665963
9	0.455508	1.73093	1.681074
10	0.445279	1.69206	1.662091
11	0.470238	1.786904	1.708038
12	0.454714	1.727913	1.679608
13	0.499732	1.898982	1.760789
14	0.524387	1.992671	1.803702
15	0.56242	2.137196	1.867967
16	0.58958	2.240404	1.912538
17	0.606354	2.304145	1.939554
18	0.587432	2.232242	1.909051
19	0.621643	2.362243	1.963854
20	0.608224	2.311251	1.942542
21	0.649981	2.469928	2.008117
22	0.651664	2.476323	2.010715
23	0.63361	2.407718	1.982667
24	0.625171	2.37565	1.969419
25	0.581234	2.208689	1.898953
26	0.580154	2.204585	1.897188
27	0.605521	2.30098	1.938221
28	0.591299	2.246936	1.915324
29	0.583929	2.21893	1.903351
30	0.586922	2.230304	1.908222
31	0.588885	2.237763	1.911411
32	0.552266	2.098611	1.851028
33	0.557628	2.118986	1.859992
34	0.611347	2.323119	1.947523
35	0.64713	2.459094	2.003708
36	0.667183	2.535295	2.034517
37	0.631669	2.400342	1.979628
38	0.611856	2.325053	1.948334
39	0.57272	2.176336	1.884994
40	0.528978	2.010116	1.81158
41	0.480574	1.826181	1.726708
42	0.47219	1.794322	1.71158
43	0.516501	1.962704	1.790088
44	0.530825	2.017135	1.81474
45	0.595091	2.261346	1.921456
46	0.608884	2.313759	1.943596
47	0.636576	2.418989	1.987302
48	0.623943	2.370983	1.967484
49	0.625319	2.376212	1.969652
50	0.683997	2.599189	2.059994
51	0.670463	2.547759	2.039512
52	0.645087	2.451331	2.000543
Average	**0.56735**	**2.155931**	**1.876136**