

Exploring the Dynamic Aspect of Natural Air flow on Occupants Thermal Perception and Comfort

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Abstract

The main purpose of this paper is to review the effect of the dynamic aspect of natural air movement on occupants' thermal comfort. Recent advanced investigations addressed the dynamic aspect of air movement in terms of turbulence intensity, probability distribution and power spectrum. This paper is not only about providing a thorough description and discussion on the underlying physical mechanisms of these factors, it is also about reviewing the effect of these parameters on occupants' thermal sensation, perception and comfort under different thermal conditions. Understanding the theoretical aspect of the fluctuating air movement and how it affects occupant thermal comfort specifically under hot-humid climatic conditions may yield to potential long-term savings and may reduce our demands for fossil fuels.

Keywords: Review, thermal comfort, fluctuating air movement, turbulence intensity

Several researches have been carried out on reducing energy consumption in air-conditioned spaces, but most of the investigations did not bring practical sustainable solutions. Additionally, many negative effects were reported when using air-conditioning such as "Non-adaptability of air conditioning", "Sick building syndrome" (Zhao et al., 2004). It has also been reported that the lack of stimulation due to a constant air flow such in air-conditioned spaces may induce the workers to become mentally disorientated and thereby decreasing their performance. Can some negative effects be avoided? This question has been raised by some investigators in building sector. Hara *et al.* (1997) stated that occupants do not usually feel well as they feel when exposed to natural breeze. This is because the sudden enhancement of heat flux movement from the human body causes a state of over-sense in thermal sensation and relaxes the discomfort (EL-Bezri, 2011). Kang *et al.* (2013) elaborates on this, fluctuating airflow brings more cooling effect to the human bodies, especially the fluctuating airflow with a frequency similar to that of natural wind. This will definitively helps in reducing energy consumption in air-conditioned buildings. In short, this also should lead to better adaptability toward air-conditioning. This is crucial in the humid tropics and in any location subjected to higher indoor air temperatures. This is even more important when we just consider the effect of the fluctuating air movement for passive cooling.

Several parameters were suggested and used to characterize natural and mechanical air flow. The parameters that are widely recognised include the turbulence intensity, probability distribution of air flow, in addition to spectral characteristics (Fanger *et al.*, 1998, Zhao et al., 2004; Hara *et al.*, 1997; Arens *et al.* 1998; Kang *et al.*, 2013) and many others. However, little is known about how natural air movement affects

occupants' thermal perception. Till today we still do not know the true nature of natural air movement, and this precisely why several investigations over the world were conducted in the first place and still carried out today. What are the most crucial parameters that affect human desirability toward a specific natural air movement compared to another natural air movement when most of the parameters hold constants?

1 The Nature of the wind

In a macro-scale level, wind is the flow of a large body of air masses from the higher to the lower pressure area due to a difference in atmospheric pressure. It is mainly originated by temperature differences. The atmosphere has two distinct states of motion: laminar (Flow in a parallel direction) and turbulent (No specific dominant direction). Mixing occurs only in turbulent flow by dynamic mixing called turbulent eddies. Figure 1 shows a drawing of turbulence flow by Leonardo da Vinci. Note that part of the drawing has been removed for clarity.



Figure 1. Turbulent flow by Leonardo da Vinci (Storm)

On the surface of the Earth, the bulk movement of the air generates various winds speeds which change frequently in direction (Youm et al., 2005). It can be spatially and temporally described. Temporally, wind is characterized by long term and short term fluctuations. Long term fluctuations include hourly, daily, seasonal, annual and diurnal records. This will be discussed in section 4. Spatially, it is characterized by a three dimensional vectors (Gavriluta et al., 2012). Two-dimensional vectors are for describing the surface horizontal wind (i.e., East, West, North and South) and the vertical component for a complete three dimensional perspective. Figure 2 shows wind azimuth and elevation records on 6 April 2012. The raw data used for this analysis are available for download from Google. The files may be obtained by visiting: <http://code.google.com/p/google-rec-csp/downloads/list>. The data are freely provided by Google to anyone who may be interested. Approximately one sample was recorded every 0.13 seconds. The instrument used for data collection is RM Young 81000V, 3-axis ultrasonic anemometers. Figure 2 illustrates the variation of wind speed, azimuth and wind direction. It must be emphasised that the observed variation may not always occur in similar manner.

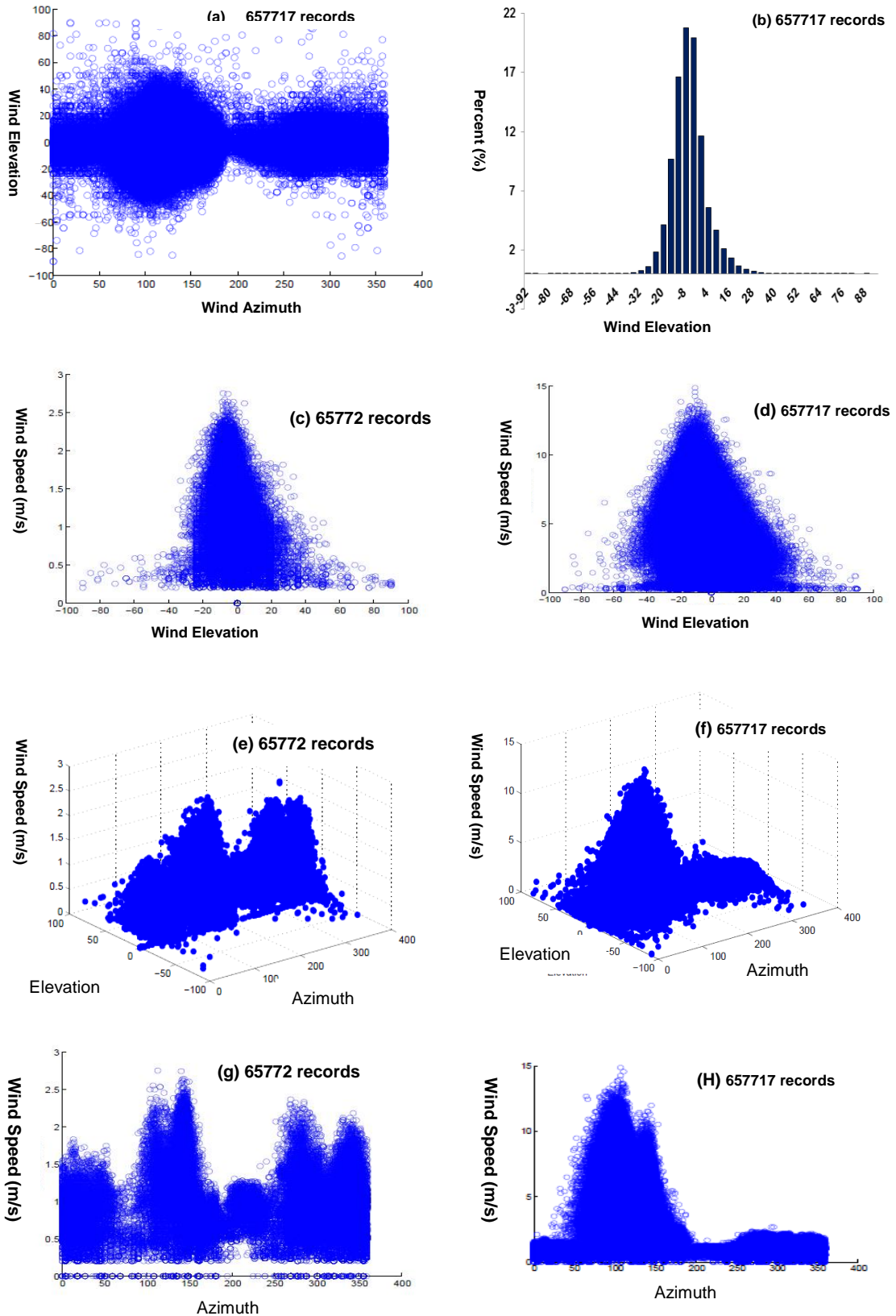


Figure 2. Variation of wind speed, azimuth and elevation
 Sampling Interval is about 0.13s.

The most striking feature of the observed variation in Figure 2 is the emerged patterns. A close look at Figure 2(a) reveals a specific symmetrical shape. Figure 2(b) provides further insight about the wind elevation. The variation of wind elevation was within a narrow range. The highest probability record was observed for the wind elevation of -12 degree. Data analysis revealed that the wind elevation was not normally distributed. About 439 low and 2095 high outliers were found. This might be occurred due to the presence of temporary objects which could distribute the wind pattern or for other factors. When the wind elevation was plotted versus wind speed in Figures (2c) and (2d), the obvious similarities between the two triangular shapes related to the first 10 minutes and the 60 minutes records were observed. This occurred despite the considerable differences in wind speed. For instance, the wind speed records in the first ten minutes were far below 3m/s, whereas for the 60 minutes records, the wind speed reached above 14m/s. Differences were also observed for the wind elevation. The higher is the wind speed, the more is close to the horizontal direction.

Fractals and chaos might provide a better interpretation of the results. Figure 2 (e) reveals the similarities of the 3D scatter plot between azimuth, elevation and wind speed. It is apparent that there are two grouped data which might exhibit similar patterns. This was noted for the short record of the first 10 minutes, whereas the situation is not the same for the one hour records. The same holds for Figures 2 (g) and (h).

The effect of the wind speed; direction and elevation on humans' thermal comfort may need further investigations for better understanding of the effect of the dynamic aspect of natural air movement on thermal comfort. This might be supported by Fanger et al. (1988) statement:

“As in the studies by Fanger and Christensen a **flow direction** from behind the subject was provided. This **seems** to be the direction at which **humans are most sensitive...**”

This also means that air movement may be perceived differently according to the wind direction. Earlier, Fanger et al. (1974) found no influence of the direction of air flow on creating thermal comfort. However, they found that the heat loss measured by the thermal manikin was higher when the air motion was from front (Simone and Olesen, 2013). One should be very careful for the conclusions made from experiments carried out in a controlled environment. This is because; it might not be similar to the field observation. In a nutshell external validation from field investigation is required.

Air movement as shown in Figure 2, can have several directions. It can be horizontal or from bottom to top, or top to bottom. According to a literature related to leave response to air movement in a controlled environment, it has been found that top to bottom air in controlled-environment rooms will more closely mimic humidity and temperature profiles found under field conditions (Robert et al., 1997).

It seems to be more interesting in thermal comfort research studies to mimic all the known climatic parameters that may provide pleasant thermal sensation in a controlled environment. This is because human being did not perceive air movement separate from other climatic parameters. For instance wind might be perceived draught in a cold environment but pleasant under hot environment. Figure 3 shows the fast variation of wind direction for the selected short record.

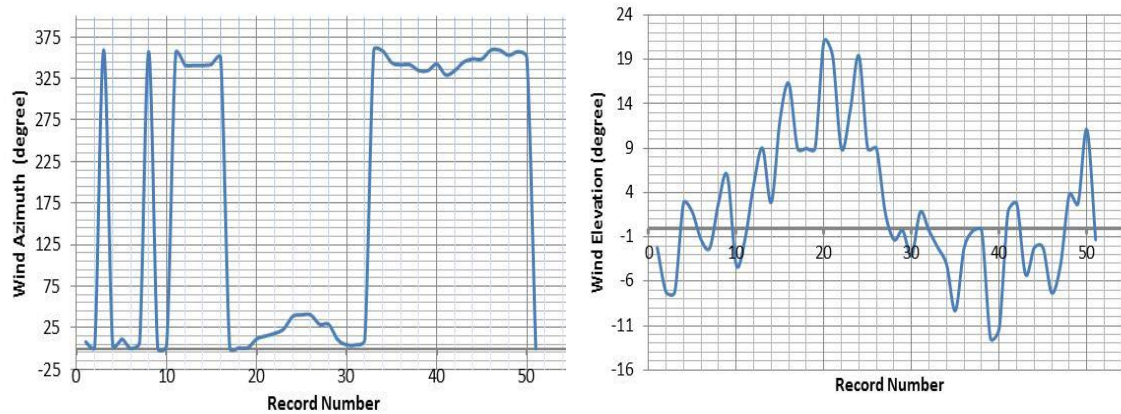


Figure 3. Variation of wind direction (Wind azimuth and elevation)
Air temperature was constant of about 58.4F (14.67C) (Sampling Interval is about 0.13 s)

2 The Characteristics of natural wind

Air flow is usually assessed in two ways, either as a time domain analysis or in the frequency domain as a power spectral density analysis. Time domain measures are the simplest to calculate. The main advantages of power spectral density analysis over the time domain measures is that it provides information on how the power (The variance) is distributed as a function of the frequency.

Since 1997 or even earlier, the Japanese investigators observed that natural wind has the feature of $1/f$ fluctuations (Hara et al., 1997). This is currently quite commonly known fact. $1/f$ fluctuations have also been found in biological systems. This type of fluctuation plays an essential role in preserving life in biological body (Musha and Yamamoto, 1997). The following is an interesting statement quoted from the same reference:

*“ ...It seems that the biological rhythm is basically subjected to $1/f$ fluctuations from cellular to behavioural levels....As regards biological phenomena, we often ask “How?” and “Why?”. The question of “why?” is still unsolved. “ $1/f$ fluctuations” was first found in **electric devices**, and now it is ubiquitous in nature. The physical “Why?” is still unsolved, but this phenomenon is **very basic in physics as well as in biology**”*

The acceptability of human to wind is connected closely to the stimulus of airflow on the surface of skin (Quyang et al., 2006). The human sensation toward air temperature and air movement may be explained by that, the hypothalamus receives information about skin temperature coded as **frequency** of nerve action. Huang et al. (2012) reviewed the effect of the frequency on human perception in more detail. They found that the airflows of 0.2 - 1.00 Hz had the stronger cooling effect on subjects (Huang et al., 2012). It must be emphasised that most of the investigations about the effect of frequency on thermal comfort were carried out in a controlled indoor climate for a limited indoor climatic range. Turning to thermal sensation, humans may sense air temperature and air movement according to their thermal and mechanical sensibility. For the thermal sensibility, the cold environment seems to be perceived stronger and faster than the hot environment. This is because there are more sensitive points at the skin level to cold than to hot (de Dear, 2010). The distribution density of cold sensors as reported by (Zhoo et al., 2004) is of 6-10 times than warm sensors and it is

unevenly distributed throughout the skin (Schacher et al., 2011). According to Schacher et al. (2011), mechanical sensibility depends on numerous parameters such as shape, surface, duration and intensity of the stimulus. Mechanical sensibility toward air movement might correspond to the human response to pressure (Wind speed), touch (might be related to our perception toward the fluctuating air movement) and as well as to vibration solicitations (might be connected to frequency).

Natural phenomena as described by Francesc (2010) usually have variability that is frequency dependent. The analysis of spectrum provides insight about the physical mechanisms that are behind (Francesc, 2010). Power spectral analysis is widely used in understanding the dynamic characteristics of airflow (Hara et al., 1997). It is inversely proportional to the frequency. In fact, Kang et al. (2013) added further insight about the term “1/f fluctuation”. It seems that (1/f) is also widely used to describe the mechanical air flow. They explained that

“Within the scientific literature, the term “1/f fluctuation” is sometimes used more loosely to refer to any fluctuation with a power spectral density of the form $E(f) \propto 1/f^\beta$, where f is the frequency and $0 < \beta < 2$, with β usually close to one”

Wind spectrum breaks sample variance of time series up into pieces, each of which is associated with a particular frequency. The function that describes turbulence as a function of frequency is known as a “spectral density function”. It is defined as the Fourier Transform of the autocorrelation sequence of the time series (Latawa, 2010). Fast Fourier Transform is quite known method but might not be necessary the most accurate (Latawa, 2010). Figure 4 exhibits a typical graph of the power spectral density of the wind speed. Usually the slope of the power spectral density of the wind speed is the most widely used to characterize natural wind from mechanical Wind. Fast Fourier Transform was used for the prediction.

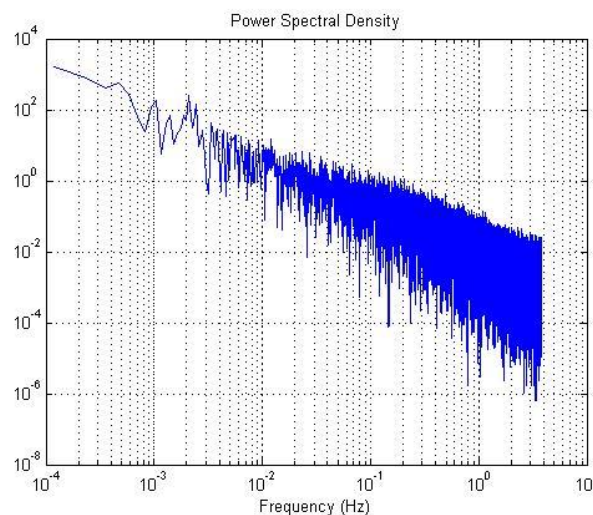


Figure 4. Power Spectral Density (Wind Speed, azimuth and elevation)
Sampling Interval is about 0.13 s.

It must be emphasised that several approaches have been developed to estimate the spectrum from an observed time series, Periodogram, Burg, Covariance, Modified Covariance, Thomson Multitaper method, Welch, Blackman-Tukey and many other methods (Latawa, 2010; Apt, 2007; Chatfield, 2004; Bloomfield, 1976). However, little is known about the spectral analysis algorithms used by many investigators in

characterising air movement. Therefore, it is hoped that this observation will be considered so that comparison among studies will be meaningful. A clear systematic accurate approach will certainly help to concentrate in solving other issues and therefore advancing faster and better in thermal comfort science.

Returning back to the discussion about the differences and similarities between natural and mechanical wind in built environment; Quayang et al. (2006) found that the slope of the curves for natural wind was steeper than that of mechanical wind. Further, Kang et al. (2013) also observed from their field investigation in a mountain subjected to a hot and humid environment that comfortable wind has a steeper slope compared to uncomfortable natural wind or mechanical wind ($\beta_{\text{comfortable}} > \beta_{\text{uncomfortable}}$). Thus we may assume that under hot humid conditions, the steeper is the slope of the curve of the logarithmic power spectrum of the wind, the more is desirable. It is necessary to highlight that the present assumption should not be generalised for lack of validation. Quayang et al. (2006) observed that the slope of the power spectral density (β value) of the wind speed increased with the elevation of the mean velocity. This is for the seashore case study only, but the two parameters were not correlated for the following cases: outdoor open area, on the roof of the building, around the building and indoors. The reasons of discrepancies were not reported and seem to be unknown. Additionally, wind speed records for the investigation carried out by Kang et al. (2013) were not normally distributed. Here, we may raise an interesting question: How far such deviation from normality might affect the estimated mean and therefore the conclusions made by the investigators?

Before passing to the next section, it must be emphasised that fractals, wavelet transformations, phase reconstruction map and other complex methods for the characterisation of the wind speed have been used by some investigators (Dear et al. 2013). However, due to the limitation of the space and the availability of the time such complex methods will be reviewed in the future mostly from the available English publications.

3 Mean Wind Speed versus Fluctuating Wind Speed

The wind speed at a fixed point can be divided in two components: the mean speed and the fluctuating wind speed. The mean velocity is insufficient to describe accurately humans' thermal perceptions, specifically when subjected to a fluctuating air movement. Earlier in 1973, Fanger stated the following:

*“The **mean air velocity** and the air temperature are, of course, of **importance** for convective heat transfer and they should be balanced according to the comfort equation. But the **mean velocity is not sufficient** to explain the draught phenomenon. Man can be comfortable at quite substantial air velocities (i.e., **1m/s**) provided that the ambient temperature is adjusted to a suitable level.... Other **aerodynamic magnitudes might be important**....”*

We may add the mean velocity is not also sufficient to explain the desirability toward fluctuating air movement. Figure 5(a) shows the high variation of the mean wind speed records for the selected sampling interval of one second. The selected duration is one minute. Figure 5(b) depicts the smooth variation of the mean wind speed for the selected sampling interval of ten minutes. The graph portrays the wind variation during one hour.

The variation of the wind when considering the extreme lowest and highest values (The height of the wave) reached up to 0.5 m/s within an interval of 40 seconds. This

was only one single observation and therefore it might be even higher in other cases. This reflects the complexity in predicting the effect of air movement on human thermal comfort. But what are the consequences of this observation? The answer seems to be difficult. In fact there are others questions need to be addressed. For instance, does the effect of air movement perceived by the subject prior filling in the questionnaire affects subject decision? Taking as an example the situation faced by the psychologist related to human perceptions and adaptations, we found the following (Zimbardo et al., 2003)

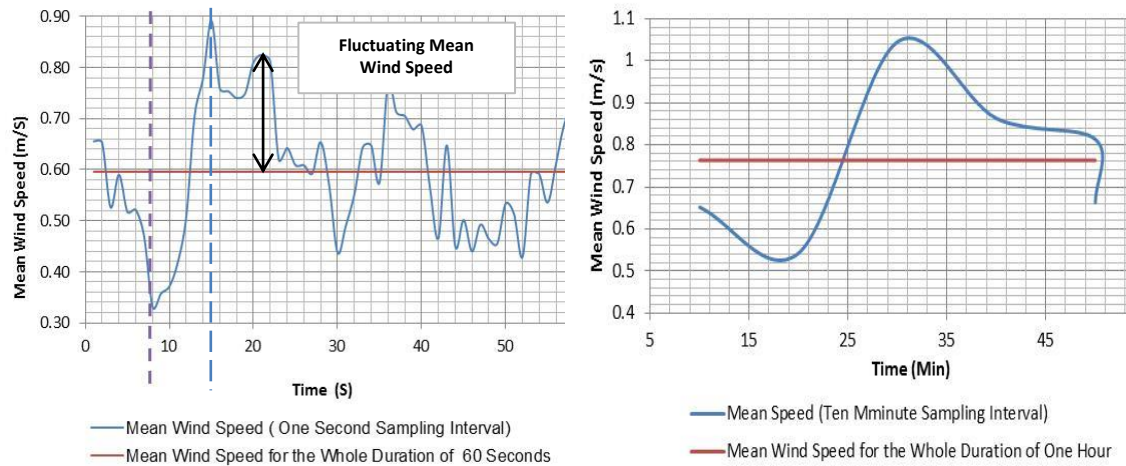


Figure 5. Variation of wind speed over time

*“Signal theory recognizes that the **observer, whose physical and mental status is always in flux, must compare a sensory experience with ever-changing expectations and biological conditions.** This contradicts the classical psychophysics which states that if the signal were intense enough to exceed one’s absolute threshold, it would be sensed; if below threshold, it would be missed...Sensation is not a simple present/absent, “yes/no” experience”*

Human adaptation seems to be a continuous dynamic process and our perceptions toward thermal environment parameters will be always based on what we experienced in the past. This means that humans might not have similar desirability toward natural air movement all the time. This adds more complexity to the raised issue. It must be emphasised that no thermal comfort data have been presented to provide evidence related to this assumption. However, it might be possible with the current available technology to address the issue in a systematic simple way. In our opinion for more accurate prediction, an online questionnaire may provide the precise time records of subject’s response during a conducted survey. The subjects should be informed to provide an instantaneous answer. The automatic records have a double advantage in reducing other possible errors that may be induced due to the manual records. Additionally, 3D ultrasonic anemometer or other accurate instruments which records wind speed, direction and elevation with high accuracy and fast response may provide better measurements and further insight. According to Schacher et al., (2011), the human sensory response is generated after 0.1 to 0.2 second after the simulation. The response to a sensory stimulation could be physiological, behavioural, verbal, or psychological. Therefore, continuous records of air movement for about 15 to 30 minute prior and during the time of filling in the questionnaire by the subject is necessary for an accurate interpretation of the results.

Many anemometers are also available for instantaneous air movement measurements. However the main limitation of **most** of them is that they do not necessary records air movement accurately from all directions. The measurement error can reach up to **50% according to the orientation of the hot-wire** (Robert et al.,1997). The instrument may interface with air movement which will affect the records.

Several crucial recommendations were provided in the reference by Robert et al., (1997) for the selection of the anemometers and therefore we will not repeat most of the recommendations here. However, the calibration when using wind tunnels must be addressed. It is widely accepted in thermal comfort investigations that wind tunnel provide better calibration. Unfortunately, this is not always true. According to the same reference, **most** wind tunnels operate poorly below 1 ms^{-1} . The reader may refer to the authors' publication (Open Access) for further insight about the why and also for the selection of the most appropriate method for the calibration. A laser Doppler anemometer can also be used to measure the velocity at a point in a flow using light beams which does not disturb the flow being measured. This instrument provides accurate measurements. Ultrasonic anemometer is also widely used device to evaluate turbulent parameters such as mean air velocity, turbulence intensity and integral length scale (López et al., 2011). The advantage of using an ultrasonic anemometer is that, it can also test both the mean wind speed and the fluctuating component (Yin et al., 2013). It allows also the measurement of very low air velocities as well.

3.1 Mean wind speed

The arithmetic mean value of wind speed has been widely used for investigating the effect of air movement on occupants' thermal comfort. In fact turbulence intensity requires knowledge of the mean value for the selected period. However, a mean value may not be the prevalent air movement. In addition, air movement in many cases is not normally distributed. It is mostly skewed and therefore the predominant wind speed might be lower than the mean value. The median estimate is preferred for non-symmetrical distributions. However, transformation of the data might help in correcting the degree of skewers prior estimation of the mean. The Weibull distribution is well accepted and widely used for wind data analysis. Robin Roche (2013) developed a Matlab script to compute the Weibull distribution parameters from a wind speed time series. Some important recommendations and references can also be found in the script. Therefore a preliminary data analysis might help to get better information about the collected data prior analysis. Figure 6 illustrates the probability density and the linearized curve and fitted comparison of the wind speed for the first 65772 records using Robin Roche (2013) script. The histogram shown in the same figure was generated using Matlab. From the figure, it is apparent that the wind is skewed to the right.

Other distributions may provide even better predictions for the description of the collected data. The reader may refer to the Easy-fit 5.5 professional software (free trial) or any other reliable references. It must be emphasised that the final selection of the wind distribution should be based on the goodness of fit tests. This can also be found in the software. Unfortunately, the analysis for the free trial is limited to 500 records only. Therefore, the software was not used for illustration. Among the available tests provided in the software are; Kolmogorov-Smimov, Anderson-Darling and Chi-Squared Tests. These can be used to test how well a theoretical probability distribution fits the collected data. It is necessary to mention that it has been reported that Weibull distribution did not take into consideration the dependence structure of wind observations. The weibull distribution assumes the randomness of the data.

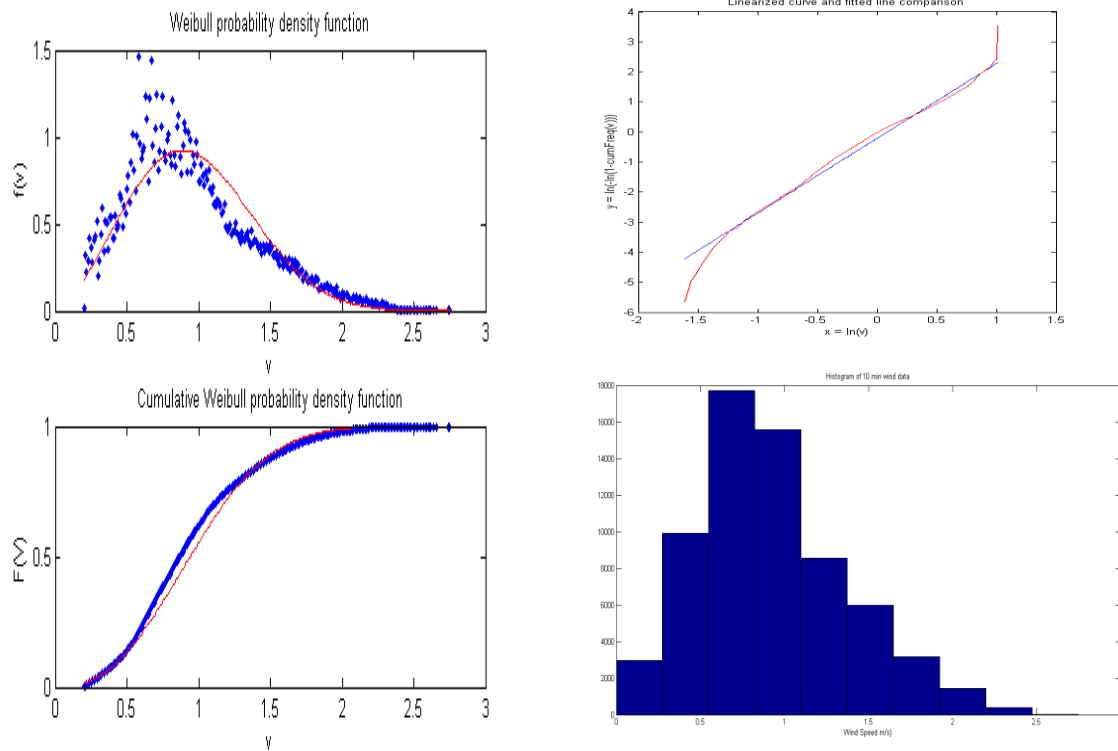


Figure 6 Probability density and Histogram of Wind Speed.
About 65772 records were considered for this plot

Hara et al. (1997) in their interesting investigation reported that the fluctuation of natural wind has some chaotic properties. According to Fei et al. (2013):

Natural wind is random and irregular macroscopically while it contains different scales swirls with self-similar structure microscopically, reflecting Chaos feature of turbulence....it means that a seemingly chaotic and disorganised graph has a fine structure, which is called the self-similar structure, mainly expressing an intrinsic geometric regularity, that is, the self-similarity of proportion”

To sum up, a careful analysis of the prevailing wind speed is necessary prior investigating the effect of the wind speed on occupants’ thermal perception and comfort.

Finally, comparison of one hour wind speed averages (black) with data samples for wind speed at 7.6 Hz (green) is illustrated in Figure 7. This figure provides evidence of the importance for tracking actual wind speed data instead of relying on averages as exactly stated in reference (<https://code.google.com/p/google-rec-csp/downloads/list>). It is apparent from the figure that the instantaneous wind speeds have a clear band around the means. This may help in investigating subjects’ perception toward air movement according to the band (range) as well. The wind pattern inside a room may not be similar to the outdoor environment. However, this observation is useful when mimicking the natural air movement in a controlled environment or for outdoor thermal comfort investigations.

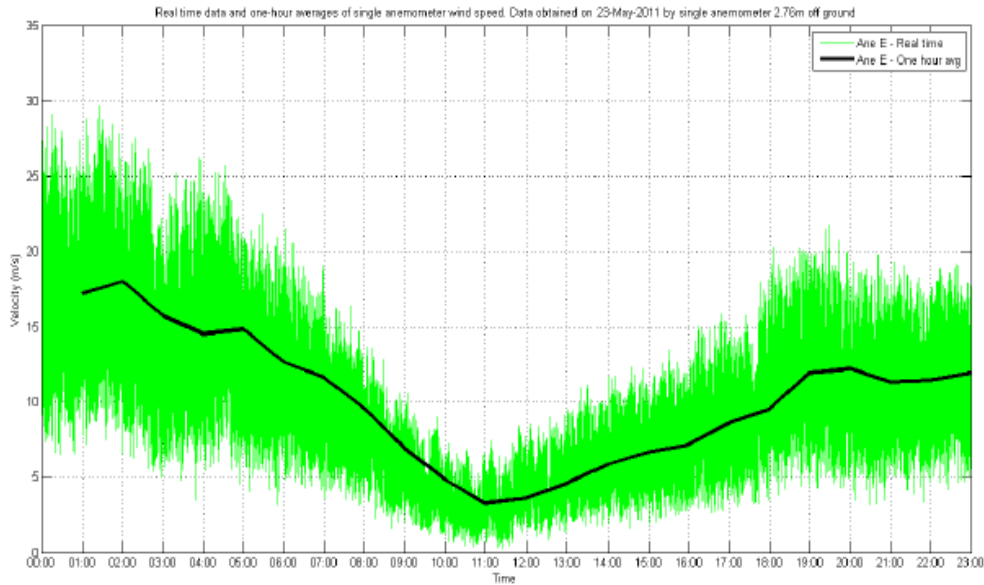


Figure 7 Sampled wind data at 7.6 hz (Green) vs 1-hour averages
 (Source of this plot: <https://code.google.com/p/google-rec-csp/downloads/list>)

3.2 Turbulence intensity

Mean speed is often referred to as quasi-steady mean speed. Short term fluctuation is mostly used for the description of the turbulence and wind gust over a short period of time. It is typically less than 10 minutes (Francesc, 2010). Gust factor is referred to a rapid increase in the strength of the wind relative to the mean strength at the time. It is defined as the ratio between a peak wind gust and mean wind speed over a period of time (Paulsen and Schroeder, 2005) which depends on gust duration. The longer is the duration, the smaller will be the gust coefficient (Yin et al., 2013). It has been reported that greater turbulence intensity is associated with the larger gust factor. It is considered an important factor in addition to other statistical wind parameters to describe the structure of the wind. Gust is highly reliant on the terrain characteristics (Paulsen, Schroeder, 2005). However, it is the least considered in describing the dynamic aspect of air flow in thermal comfort studies. The gust speed and direction are defined by the maximum three second average wind speed occurring in any period (NMLA, 2013). It is sampled at high frequency (0.25sec) to catch the intensity of gusts which are described as short-lived peaks in speed. These cause greatest damage in storm. Wind direction, speed and gustiness are generally determined instrumentally. According to U.S. weather observing practice, gusts are reported when the peak wind speed reaches at least 16 knots (8.2 m/s) and the variation in wind speed between the peaks and lulls (lulls means calm: a period without waves or wind) is at least 9 knots (4.6 m/s). The duration of a gust is usually less than 20 seconds according to the same source. However, such wind intensity is of no interest in thermal comfort field investigations.

A turbulence flow is mostly defined as a continuous three dimensional flow of many dynamic moving eddies (vortices) of different sizes and strengths reflecting chaos feature of turbulence (Yin et al., 2013). Turbulence occurs due to wind shear which arises in the boundary between air volumes with different velocity. Turbulence may also occur due to mechanical forces between the moving air and an obstacle (i.e. friction with the ground surface, barrier such building and forest, topography of the

site, water). This results in deflection of the flow of the air (Nicole, 2011). Convection affects the turbulence of air flow (Hoven, 1957) due to the thermal effects that causes air to move vertically. The fluctuations occur in all the three directions (Francesc, 2010).

Turbulence intensity is also defined as the ratio of the standard deviation of velocity to the mean velocity for a given time history of air velocity (Aynsley 2008). It is often multiplied by 100 to give a percentage expression (Marcel, 1998). An idealized flow of air with absolutely no fluctuations in air speed or direction would have a Turbulence Intensity value of 0%. Because the turbulent motions associated with eddies are approximately random, we can characterize them using statistical concepts. Statistically, the turbulence intensity is defined as the standard deviation by the mean velocity (Fanger et al., 1988)

$$x = \frac{\sqrt{v'^2}}{\bar{v}} = \frac{\sigma}{\bar{v}} \quad (1)$$

Where

σ is the standard deviation.
 v' is the instantaneous air velocity
 \bar{v} is the mean wind speed

Looking at this equation, it can be seen that the larger the mean air movement is, the larger the denominator will be and therefore the turbulence intensity will be smaller. So what sample size would be recommended in thermal comfort field investigations? So, it depends on the effect that is being investigated, however ten minutes are widely used in estimating turbulence intensity. Hara et al. (1997) made an important conclusion from their research investigation which was that the rapid increasing wind velocity was found to be more comfortable than slowly increasing one. Of course, this seems to be in agreement with common sense as well. One may need just to drive a car in a windy hot day to understand how rapid increase in air movement provides a desirable sensation. The sudden or rapid variation in air movement (from extreme minimum to extreme maximum in a very short period of time) probably might not be well described by turbulence intensity. This is because the standard deviation provides an average fluctuation above or below the mean. Further investigation in that direction is worth pursuing in a more focussed study

4. Conclusions

Many observational studies have been conducted for exploring the characteristics of air flow based on short and long term observations. Exploring the characteristics of air flow on human thermal perception is of interest of thermal comfort field investigations and was the main objective of this review. The following are the main conclusions:

- (1) The mean velocity is not sufficient to explain the desirability of subjects' thermal perceptions toward natural air movement.
- (2) The arithmetic mean value of wind speed has been widely in thermal comfort studies. Air movement might not be normally distributed. The knowledge of the distribution of the data is important before data analysis.
- (3) Wind direction and elevation were very seldom considered in thermal comfort field investigations. Those parameters require further investigation.

- (4) Turbulence intensity may not describe fully the sudden increase of the fluctuating air movement on humans' thermal perceptions. Further investigation in that direction is worth pursuing in a more focussed study.

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