Investigation on the Dynamic Characteristics of Natural Wind for Thermal Comfort Studies

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Investigation on the Dynamic Characteristics of Natural Wind for Thermal Comfort Studies

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Abstract
The main purpose of this article is to investigate the dynamic characteristics of natural wind for thermal comfort studies. A primary and secondary data were used. For the primary data, field study was conducted at the Universiti Malaysia Sabah, East Malaysia. The measurements were made under a tree. The site location of the collected secondary data is at Tracy. The site is flat and windy. Wind data of both case studies were recorded using ultrasonic anemometers. The wind speed data were analysed by using descriptive statistics, Weibull distribution and the power spectral analysis. Turbulence intensity was also included. The assessment of rapid increasing wind speed was also addressed in this study. A new method was developed to assess the rapid increasing wind speed for thermal comfort research studies. A comparison was made between both case studies.

Keywords: Natural wind; Natural Air Speed; Thermal comfort; Humid tropics, Malaysia, Tracy.

INTRODUCTION

Air velocity is described by speed (magnitude), and direction. In thermal comfort studies, air speed is usually related to the cooling effect of the air flow on the skin. The acceptability of human to wind is connected closely to the stimulus of airflow on the surface of skin [1]. Wind speed is formed by air displacing from high pressure to low pressure, generally due to modifications in temperature.

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. Humans may sense air temperature and air movement according to their thermal and mechanical sensibility. For the thermal sensibility, the cold environment is probably 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 [2]. The distribution density of cold sensors as reported by Zhoo *et al.* [3] is of 6-10 times than warm sensors and it is unevenly distributed throughout the skin [4]. According to Schacher *et. al*. [4], 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 to vibration solicitations (might be connected to 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 [5]. Usually the slope of the power spectral density of the wind speed is widely used to characterize natural wind.

The main purpose of this article is to investigate the dynamic characteristics of natural air movement for thermal comfort. Wind speed measurements were recorded in Kota Kinabalu city in Malaysia. This is because; there is no study on the dynamic characteristics of wind speed for thermal comfort in Malaysia. A proper analysis of wind data is a very important step when investigating human thermal perceptions and comfort toward natural wind speed. Additionally, the dynamic characteristics of natural wind at Tracy, California were also made. A comparison was done between both case studies.

METHODOLOGY

Field study was conducted to characterize the natural wind in the humid tropics of Malaysia. The site is shown in Figure 1. The main ultrasonic anemometer and secondary instruments used in this study are listed in Table 1. The ultrasonic anemometer for wind measurements is also shown in the same figure. The measured secondary parameters are air temperature, relative humidity, and solar radiation. These parameters were measured at the beginning and the end of the experiment only. A rechargeable battery was supplied to overcome any unpredictable issue with the power supply. The selected spot for the measurements was under a tree. It is necessary to mention that little information is available about the characteristics of natural wind under a tree. A gentlebreeze is usually desired in the equatorial humid tropics. This is because the temperature is mostly warm to hot all year round [6].

Figure 1: Wind Records under the Three

Table 1: Specifications of Instruments used in the Present Article

Instrument	Company	Measurement	Specifications	
Datalogging RH/Temp pen 800013	Sper Scientific	Air Temp	Resolution	0.1^0C
			Range	-40-85^0C
			Accuracy	±1.2^0C
		Relative Humidity	Resolution	0.1%
			Range	0.1-99.9%
			Accuracy	±3% (@250C & 10 ~99%RH) otherwise ±5%
Solar Power Meter TM-207		Solar Radiation	Resolution	N.A. Sampling time 0.25 second
			Range	2000 W/m2,
			Accuracy	Typically within ± 10W/m2 or +/-5% whichever is greater in sunlight; Additional temperature included error ± 0.38 W/m2 / º C /Angular accuracy: Cosine corrected <5% for angles <60º
Ultrasonic Anemometer Model 81000	Young	Wind Velocity	Resolution	0.01m/s
			Range	0:40m/s
			Accuracy	±1%m/s (0-30 m/s) ±3%m/s (30-40 m/s)

The selected wind measurement point was at a height of 1.3 m from the ground. The ultrasonic anemometer was fixed above a small table. The level of the table was adjusted to be horizontal by using waterproof Torpedo Digital Level (model: DWL-280Pro). The level of the table was slightly inclined by about 1^0after adjustment. A basic compass was used for the ultrasonic orientation adjustment. The accurate orientation adjustment was estimated about $\pm10^0$. In this article, the analysis was made mainly for wind speed. The transmission of wind records from the instrument to a laptop was made via USB to RS232 to PC Hyper Terminal.

Figure 2: Instruments Used in This Study

The wind speed was measured eight times in a second for the duration of 30 minutes. There were 14400 records. In this study, descriptive statistics, spectral analysis, and other statistical methods were used to investigate the dynamic characteristics of natural wind. In accordance with previous researches, power spectral analysis of the collected data was made within the frequency range of 0.01– 1.0 Hz [7]. For the purpose of a meaningful comparison and better understanding about the dynamic characteristics' of natural wind, raw data fromgoogle.org [8]were collected and analysed in this study. The instrument used for the secondary data is RM Young 81000V, 3-axis ultrasonic anemometers (Figure 3). The site location was at Tracy (USA, California). Approximately one sample was recorded every 0.13 seconds. It is important to mention that only 14400 raw data was extracted or used in this study. The selected raw data was from Anemometer (E). The data was recorded on 05/25/2011. The site location is relatively flat and windy.

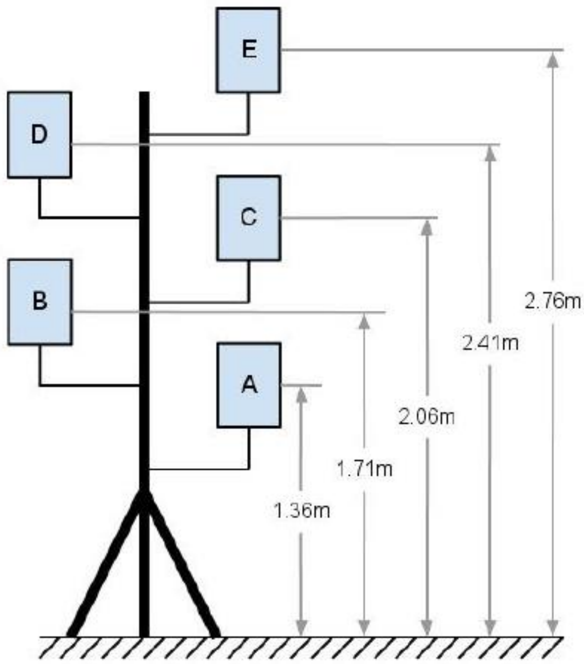

Figure 3: Physical Setup of Anemometer Array

RESULTS AND DISCUSSION

Wind speed data from both locations were firstly analysed by using descriptive statistics. The average recorded air temperature and relative humidity of primary data were about 33.02 ^{0}C and 65%. The measured solar radiation was about 1189 w/m^2. It is important to mention that the measured solar radiation may not be accurate. This is because the operator faced some issues with the instrument. Additionally, it was observed that the solar radiation was subjected to many changes during the initial testing. It was not possible to disturb the wind pattern for further measurements of the secondary parameters.

The natural wind records under the tree were initially plotted for general observation of the data. The averaged results are illustrated in Figure 4.It represents time series plot of one minute mean wind speeds and their corresponding standard deviation values. The mean speed for the entire duration of 30minutes is also plotted in the same figure. Scatterplot of wind elevation versus wind azimuth is shown in Figure 5. No obvious pattern emerged from the plot.

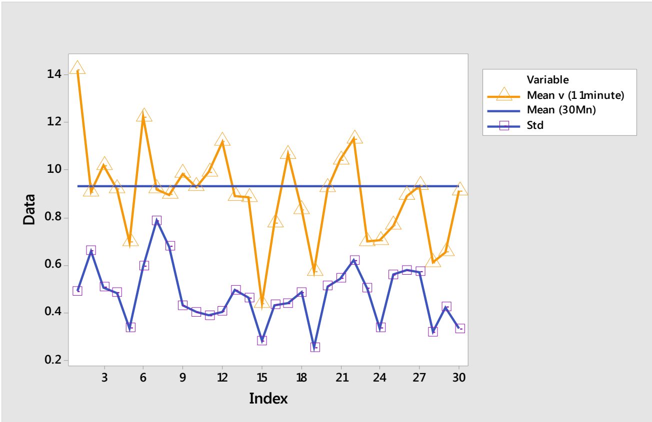

Figure 4: Time Series Plot of Mean wind speed

It is necessary to mention that prior starting the experiment, a sheet of paper was prepared for recording the additional environmental parameters. However, due to a sudden increase in wind speed, the paper was flaying away.

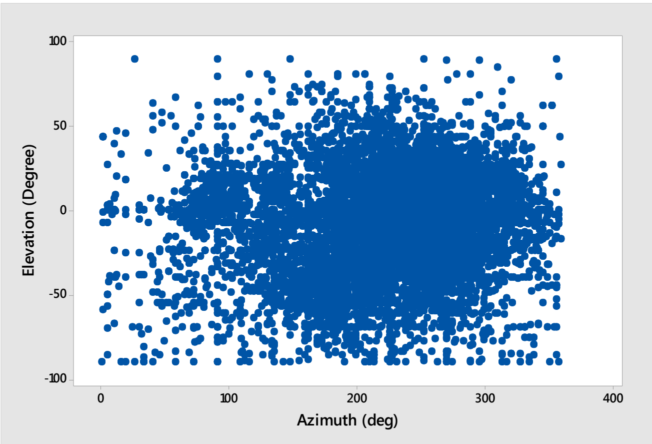

Figure 5: Scatterplot of Elevation vs Azimuth

WEIBULL DISTRIBUTION

The Weibull distribution is the most widely accepted distribution for wind speed [9]. The purpose of the Weibull distribution is to determine the shape factor and the scale parameter. The shape factor in Weibull distribution describes the skewness of the plot. The scale parameter indicates the average mean speed. The Weibull distribution of the collected data is plotted in Figures 6 and 7. It is apparent that the distribution is right skewed. It may be explained by that the wind was mostly close to the mean towards low values. The scale parameter representing the mean wind speed was slightly different from the median and the mean wind speed. This inconsistency may be due to the assumption of the randomness of the data. The generated dimensionless shape and scale parameters in this investigation are 1.94 and 1.05 m/s respectively. It is necessary to mention that Weibull distribution did not take into account the dependence structure of wind observation. It assumes the randomness of the data [10].

Table 2: Descriptive Statistics of the Natural Wind Speed

Data	Mean	SEMean	StDev	Median	Min	Max	Skewness	Kurtosis
Primary	0.8906	0.0044	0.5286	0.8100	0.0000	3.9700	0.90	1.39
Secondary	6.7686	0.0088	1.057	6.800	2.4200	10.8100	-0.10	-0.19

Therefore, the characterisation and the identification of natural wind for thermal comfort studies should not only consider the mean speed but also the maximum instantaneous wind speed. This is specifically important in office buildings or classrooms. The situation may be different in residential buildings. The characterisation of natural wind for thermal comfort studies requires knowledge of the effect of several wind parameters on thermal comfort.

Descriptive statistics was further made to describe the primary and the secondary wind data. The results are summarised in Table 2. Overall, the measured mean speed is 0.93m/s, the median is 0.84m/s. The plot of the frequency distribution was also generated via Minitab. However, it is not shown in the article. Overall, the dominant wind speed is 0.75m/s. The maximum wind speed in this study is 3.97m/s. The data is skewed to the right. The descriptive statistics showed that the mean speed in the present case study is lower compared with the second case study (secondary data). This probably occurred because of the elevation of the point measurement of the selected data. It might be also due to the site location.

For the secondary data, the generated dimensionless shape and scale parameters are 7.10 and7.22 m/s respectively. It is apparent from Figure 7that the distribution is left skewed. This means that the wind speed was mostly average to high.

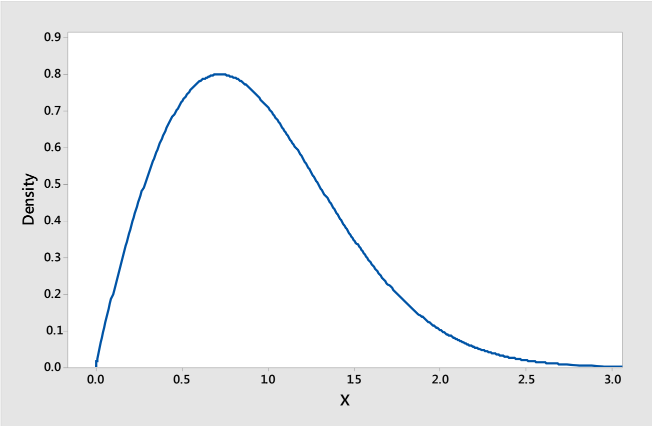

Figure 6: Weibull Distribution Plot of Natural Wind (Kota Kinabalu)

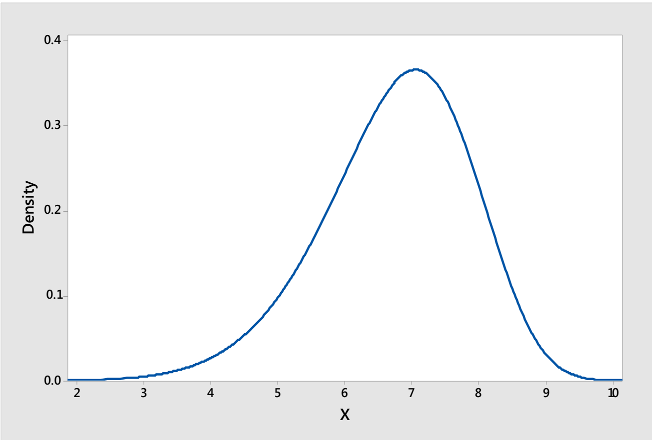

Figure 7: Weibull Distribution Plot of Natural Wind (Tracy)

SPECTRAL ANALYSIS OF NATURAL WIND

Power spectral analysis is widely used in investigating the dynamic characteristics of airflow [11].Several thermal comfort investigators used power spectral to analyse the fluctuating characteristics of natural wind [1, 7]. In this study, Fast Fourier Transform (FTT) was applied to identify the power spectral slope of the wind. Figure8 and Figure 9show the logarithmic power spectrum curve of natural wind from this investigation. The estimated slope (β-value) was 1.6 for the frequency range of 0.01 to 1Hz. For the second case study, the estimated slope (β-value) was 1.03 for the same frequency range. This shows that the β-value for the mean wind speed of 0.9m/s is higher than the β-value for the mean wind speed of 6.8m/s for the second case study.

Kang *et.al*. [7] investigated people thermal comfort when exposed to natural wind in a mountain environment during the summer. The location was subjected to a hot and humid environment. They found that the β-value becomes smaller when the average wind velocity increases. This is in agreement with the obtained results. They also observed that the power spectrum exponent (β-value) for people feeling comfortable has a median value of 1.61. However for people feeling uncomfortable, the power spectrum exponent (β-value) has a median value of 1.10.

In an earlier study for the dynamic characterisation of natural and mechanical wind; Ouyang *et al.*[1] found that the power spectrum exponents (β-value) of natural wind were between 1.1 and 2.0. They also observed that with the elevation of mean velocity, there was a decrease of power spectrum exponent. This suggests that the power spectral slope (β-value) of the present study is close to the obtained comfortable wind when compared with both studies. The situation may not be the same for the second case study.

In addition to the earlier observation and discussion, it is important to mention that people thermal perception does not depend on the slope (β-value) only. There are other environmental parameters that affect subjects' thermal comfort such air temperature, solar radiation and others. Therefore, there might not bespecific characteristics of natural wind that satisfy subjects' thermal comfort under all conditions. However, understanding the characteristics' of natural wind will certainly provide better understanding on the desired natural wind for thermal comfort in the future. This will also help in providing more satisfying indoor environment in mechanically ventilated buildings.

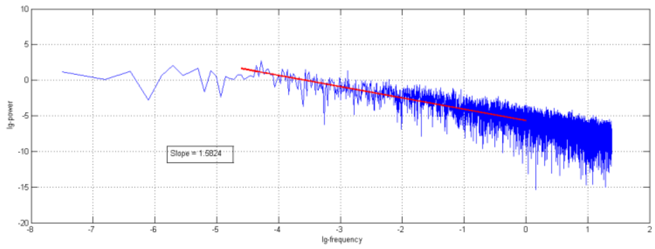

Figure 8: Power Spectrum Slope (Kota Kinabalu)

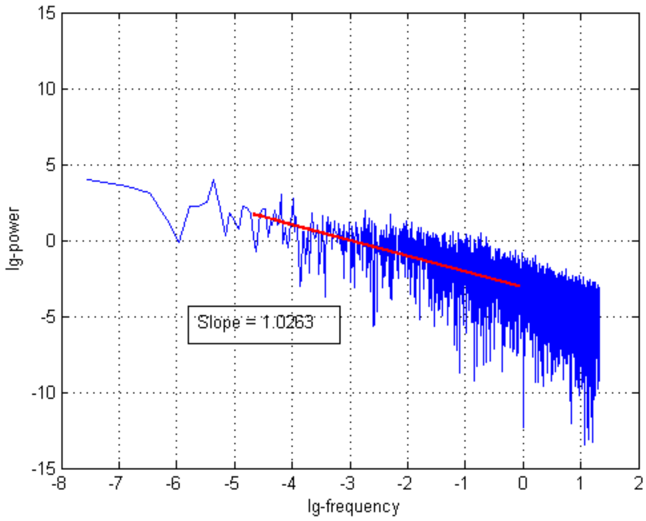

Figure 9: Power Spectrum Slope (Tracy)

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 [12].Turbulence intensity is widely used to investigate the comfortable wind speed in air-conditioned buildings. Turbulence intensity is the ratio of the standard deviation of wind speed to the mean wind speed for a given mean of wind speed [13, 14].Turbulence intensity is often expressed in percentage. Several investigations were made by Fanger *et al.* on the effect of air movement on thermal comfort [14, 15] for the establishment of the method. However, little is available about the characteristics of turbulence intensity of natural wind for thermal comfort studies. In this article, turbulence intensity was estimated for one minute and three seconds period of time. Three seconds period of time was selected to represent turbulence intensity in the shortest possible records. This is because within three seconds, the number of the collected values for the first case study is 24 records. The obtained results are plotted in Figures 10 and 11.

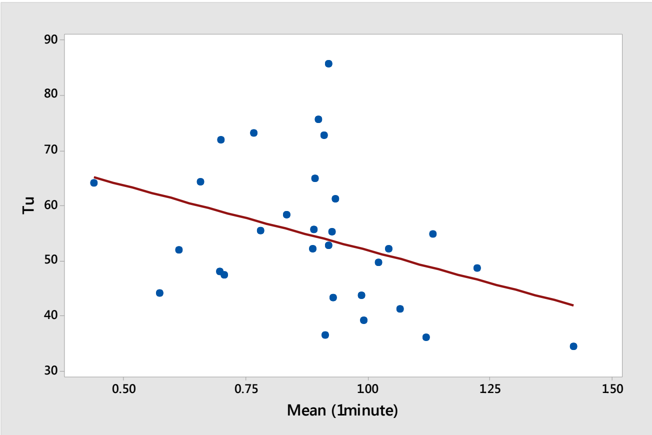

Figure 10: Turbulence Intensity versus Mean wind speed (1minute)-Kota Kinabalu

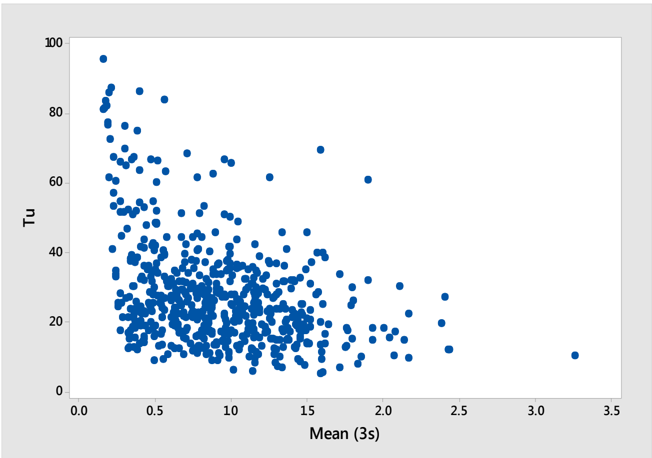

Figure 11: Turbulence Intensity versus Mean wind speed (3seconds)-Kota Kinabalu

A close observation in Figure 10 showed that the correlation between the mean wind speed and turbulence intensity is weak. The coefficient of determination and the adjusted coefficient of determination are R-Sq = 13.7% R-Sq(adj) = 10.7% respectively. The *P*-value is 0.044.

The procedure was repeated for three second period of time. The *P*-value is 0.000. The coefficient of determination and the adjusted coefficient of determination are R-Sq = 14.0% R-Sq(adj) = 13.9% respectively.

It is apparent from Figure 11 that the correlation between mean wind speed and turbulence intensity is stronger than with one minute time period. This was attributed to the pattern of the turbulence intensity and mean wind speed. Further, there were more data when considering three seconds time interval. The procedure was not repeated for the case study.

RIW-RATIO OF INCREASING WIND VARIATION

Hara *et al.* [11] observed from their research study that the rapid increasing wind speed was more comfortable than slowly increasing one. The sudden or rapid variation of the wind (from extreme minimum to extreme maximum in a very short period of time) might not be well described by turbulence intensity. This is because the standard deviation provides an average fluctuation above or below the mean [10]. In this investigation, a new procedure was developed for addressing the increasing wind of both case studies. Matlab code was written to investigate the rapid increasing wind speed. In the first step, the maximum and minimum wind speeds were determined for the entire duration. The selected interval is every 24 records. The maximum records were subtracted from minimum records. Only positive results of increasing speed were retained. If the wind speed in any three seconds interval (more precisely every 24 records for both case studies) decreased from a maximum value to a minimum value, it was ignored. The time durations for the wind to shift from maximum to the minimum were also calculated based on the selected interval. The increasing wind variation was named RIW-ratio. It represents the difference of maximum wind and minimum wind speeds over their time difference. Thus if the difference of the maximum wind speed to the minimum wind speed is high and the duration of the shift is small, then the wind was assumed to be subjected to rapid increasing wind. In this study, the RIW-ratio was expressed in Percentage. The higher the RIW-Ratio, the higher is the rapid increasing wind. The obtained results of both case studies are summarised in Table 3.

Table 3: Descriptive Statistics of RIW-Ratio (%)

Variable	NR	Mean	SEMean	StDev	Median	Max
Primary data	291	8.501	0.458	7.816	6.333	70.000
Secondary data	295	37.75	1.77	30.33	28.71	255.00

NR: represents the number of times the wind shifted from minimum to maximum wind speed in every three seconds time interval

For primary and secondary data, the obtained mean RIW-ratios are 8.5% and 37.75 % respectively. It is apparent that the wind speed of the first case study was less subjected to increasing wind speed compared to the second case study. The histograms of the RIV-ratios in percentage are plotted in Figure 12 and Figure 13. The dominant RIW-ratio for the first case study is 5. For the second case study, the dominant R-ratio is 20.

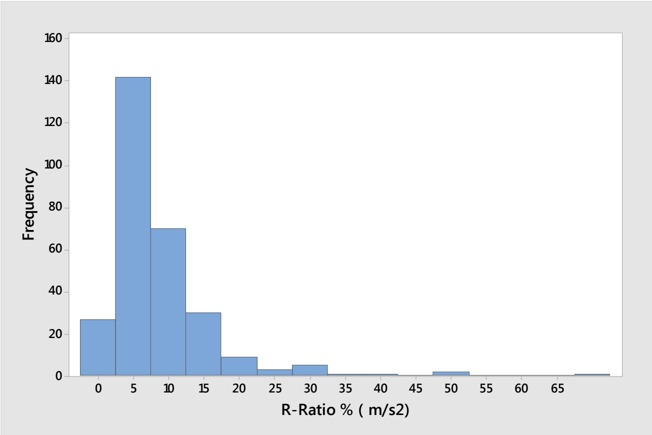

Figure 12: Histogram of R-Ratio in % (Kota Kinabalu)

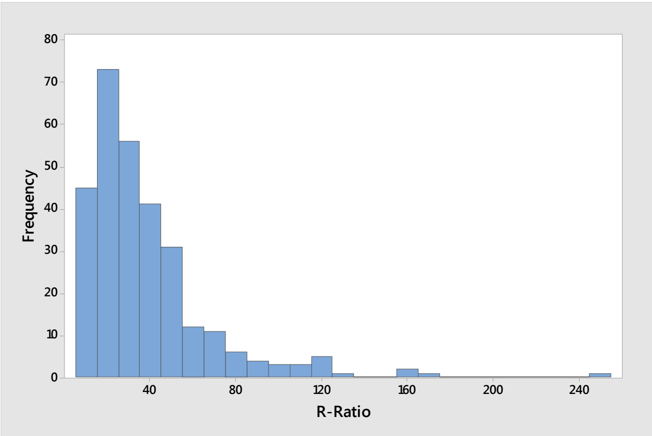

Figure 13: Histogram of R-Ratio in % (Tracy)

Finally, the mean time sift of wind speed from a minimum to a maximum was calculated for the selected cycle of 24 records. The obtained mean values for the first and second case study respectively are 11.7 and 11.91. It is important to mention that the method has some limitations and requires further improvement.

CONCLUSIONS

Measurements of natural wind speed were made in the faculty of engineering at UMS, Malaysia. The conclusions made from this study are:

- The characterisation of natural wind for thermal comfort studies should not only consider the mean but also the maximum wind speed.
- The generated dimensionless shape and scale parameters of the first case study are 1.94 and 1.05m/s m/s respectively. The Weibull distribution showed that the wind was mostly circulating average to low speed. Weibull distribution did not take into account the dependence structure of wind observation. This is the main limitation of Weibull distribution.
- In this study, Fast Fourier Transform (FTT) was applied to identify the power spectral slope of the wind. The estimated slope (β-value) for the first case study was 1.6 for the frequency range of 0.01 to 1Hz. The power spectral slope (β-value) of the present study is close to the obtained comfortable wind when compared with two independent studies
- The correlation between mean wind speed and turbulence intensity was strong when considering three seconds as a unit for the calculation. The situation is different when the unit of the calculation was one minute period of time
- A procedure was developed to assess the rapid variation of wind speed and comparison was made with the first case study. Further improvement of the method was recommended.

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