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Performance evaluation of misting fans in hot and humid climate

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ABSTRACT

Singapore experiences a hot and humid climate throughout the year. This in turn results in heavy reliance on mechanical systems especially air-conditioning to achieve thermal comfort. An alternative would be the use of evaporative cooling which is less energy intensive. Objective and subjective measurements were conducted at an experimental setup at the National University of Singapore (NUS) to evaluate the thermal conditions and thermal sensations brought about by misting fans. Field measurements were also conducted at food centres in Singapore to determine if they are coherent with the objective and subjective measurements conducted. Analysis of objective and subjective data showed that the misting fan was able to significantly reduce the dry-bulb temperature and thermal sensation votes. This is consistent with field measurements taken, where regression analysis showed that with the misting fan, thermal neutrality can be obtained at a higher outdoor effective temperature (ET*). However, the reduction in temperature comes at the expense of higher relative humidity which results in consistently greater biological (bacterial and fungal) pollutants being enumerated from samples collected under the misting fan system. In some samples, the bacteria count is very much greater than samples collected under the non-misting fan, illustrating the potential for a substantial increase in biological pollutants due to the generation of mists.

1. Introduction

Singapore being situated 1°21′N of the equator is characterised by uniformly high temperatures, high humidity and abundant rainfall throughout the year. This in turn results in heavy reliance on mechanical systems especially air-conditioning to achieve thermal comfort. An alternative would be the use of evaporative cooling. The advantage of evaporative cooling comes from its relatively low energy consumption and absence of environmentally aggressive refrigerants. In addition, the use of evaporative coolers will certainly result in lower operating and initial costs as compared to a comparable mechanical system [1].

The main objectives of this study are as follows:

1. Determine the thermal comfort level for semi-outdoor dining areas with misting fans
2. Determine the possible factors contributing to its effectiveness or ineffectiveness in a hot and humid climate
3. Determine if the generation of mist increases the potential for the harbouring of bacteria and yeast in the ambient air

The use of evaporative-cooling systems are however dependent on climatic conditions and hence the successful use of an evaporative cooler achieved at one particular climatic condition cannot be guaranteed at another location with a different climatic condition. As a result, the feasibility of evaporative cooling should be determined specifically for each individual location and climatic condition. Performance of direct evaporative cooling in hot arid climates have however been widely studied, particularly for glasshouses. A study which applies water droplets through spray mists to the roofs of a glasshouse have shown that roof temperature of glasshouses with plants growing inside was reduced by nearly 8 °C as a result of direct evaporative cooling [2]. This study goes on to conclude that much larger reductions in roof temperature were obtained when water vapour deficit in the ambient air was high as compared to under low water deficit conditions where evaporative cooling reduced air temperature by less than 1 °C. Similarly, theoretical analysis into the effectiveness of direct evaporative cooling of glasshouses at areas characterised by high solar radiation intensities and low humidity by Landsberg et al. [3] indicates that single stage direct evaporative cooling can reduce air temperature in the glasshouse by 8–12 °C. Apart from studies on glasshouses, an experiment by Aimiuwu [4] recorded that the evaporation of water placed in hot arid regions was able to achieve a drop of 10.4 °C below ambient temperature in still air, while the temperature fell

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by 15.0 °C under forced convection. One type of evaporative-cooling system that has been increasingly used in dinning locations around Singapore is the misting fan system which utilises atomisation nozzles to produce a cloud of very fine water droplets. The misting fan system is essentially a direct evaporative system. ASHRAE [5] defines direct evaporative equipment as one which cools air by direct contact with water, either by an extended wetted-surface material or with a series of sprays. These droplets come into direct contact with the airstream, removing its latent heat of vaporisation and thus cooling it in the process.

Under the misting fan system, a cloud of very fine water droplets is produced using atomization nozzles, inducing mixing between the airstream and water, thus allowing the ambient air, to cool from its dry-bulb temperature to its wet bulb temperature if the droplets are fully vaporised [6].

Although evaporative cooling is expected to be more effective in a hot and dry climate, a simulation carried out by Yu and Chan [7] concluded that evaporative pre-coolers can function properly even under hot and humid climate. Although the use of evaporative cooling is able to reap benefits in terms of energy savings due to its lower energy consumption and absence of environmentally aggressive refrigerants as compared to mechanical system, there is a lack of research into the effectiveness of evaporative coolers particularly in hot and humid climates [1].

In addition, the use of misting fans is limited by the plausible increase in biological pollutants due to belief that mist generated would provide a more conducive environment for the harbouring of bacteria and yeast [8]. High moisture and relative humidity has long been hypothesised to be required for optimal growth [9]. In addition, of greater relevance was a study on cold-mist vaporizers in which the level of fungal particles increased sharply during the use of the vaporizers [8]. However, there is a lack of research into the bacterial and fungal aerosols arising from misting fans. In view of the potential benefits as well as the increase in use of misting fans in Singapore there is a need to look into the viability of evaporative-cooling systems in hot and humid climate.

2. Methodology

2.1. Overview

To study and determine the effectiveness of misting fans, both objective and subjective measurements were carried out for a semi-outdoor experimental layout at NUS to allow for direct comparison between misting and non-misting fans under the same ambient conditions. To supplement the experimental data, field measurements which includes both objective and subjective measurements would also be conducted at 2 food centres and 1 coffee outlet during different time periods to obtain a wide data range for the environmental parameters measured.

2.2. Experimental procedure at NUS

In an attempt to determine the effectiveness of misting fans, two similar layouts have been setup 10 m apart as shown in Fig. 1 at the NUS, with one layout being provided with misting fans and other with similar fans but without the mist generating system. The experimental setup would be at a semi-outdoor location to ensure consistency with field measurements that were obtained from semi-outdoor dining areas.

The experiment was carried out on the 21st, 22nd, 23rd and the 24th of September 2009. 80 (40males and 40 females) college-age persons were used throughout the entire experiment. On each day, 20 participants (10 under each setup) would be randomly allocated to be under either the misting fan setup or the non-misting fan setup. During the allocation of participants, it was ensured that there would be an equal proportion of males and females under each setup. During each day, each participant would be limited to sedentary activities under their allocated setup during the time period of 9.30–11am (morning), 12.30–2pm (afternoon) and 3.30–5pm (late afternoon). For each time period, each participant would be required to complete a thermal comfort questionnaire every subsequent half-hour period after the participants have settled in for at least 30 min. Throughout the experiment, a Babuc A data logger would be used to record each of the four environmental parameters at 15 min intervals from 9am to 5pm. This is to allow correlation to be established between the comfort levels and the corresponding ambient conditions that has been recorded.

Objective measurements would be taken at a height of 1.0 m above the floor level which represents the respondent's head level when seated.

2.3. Field measurements

The 2 semi-outdoor food centres, food centre A and food centre B were selected because they have similar orientation, with food centre A using the misting fan system (Fig. 2) and food centre B using non-misting fans. Data for food centre A was collected on 22nd August 2009 and 20th September 2009, and data for food centre B was collected on 29th August 2009 and 27th September 2009. The semi-outdoor coffee outlet was selected because it utilises the misting line system (Fig. 3) in which mist is generated at a lower velocity only at the perimeter of the outlet. For the coffee outlet, measurements were taken at different time periods when the misting line system was operational and non-operational since permission was granted to turn the misting system off. In this case, comparison can be made between the data collected during the different time periods (operational and non-operational) to determine the effectiveness of the misting line system. Data for the coffee outlet (without mist line) was collected on 30th August 2009 and 5th September 2009, and data for coffee outlet (with mist line) was collected on 23rd August 2009 and 13th September 2009.

Both objective and subjective measurements were carried out concurrently in this study and in the occupied zones of the dining area. In addition, respondents were chosen only where they have a residency of more than 15 min in the space [10].

2.3.1. Objective measurements

Spot measurements of the four environmental parameters which include air temperature (T_a), globe temperature (T_g), relative humidity (RH) and air speed (v) were taken within the dining areas using the Testo 445. At each sampling point, the Testo 445 was left to run for 3 min to obtain a timed-average value for the four environmental parameters. All objective measurements are taken at a height of 1.0 m above floor level which represents the height of the respondent when seated. The mean radiant temperature is approximated using the equation $T_{mrt} = T_g + 2.44\sqrt{v}(T_g - T_a)$ for a standard globe of 150 mm diameter [11].

Outside each dining area, the HOBO weather station would be setup in an open space without shading to measure the outdoor environmental parameters which include air temperature, relative humidity and wind speed.

Besides environmental parameters, physical factors which include clo values and metabolic rates were also estimated in accordance with ASHRAE standard 55-2004 [10]. Metabolic rates were taken to be 1.0 met or 60 W/m^2 which is the value for sedentary activities. The clo value was computed by taking the sum of individual clo values for each garment which is obtained

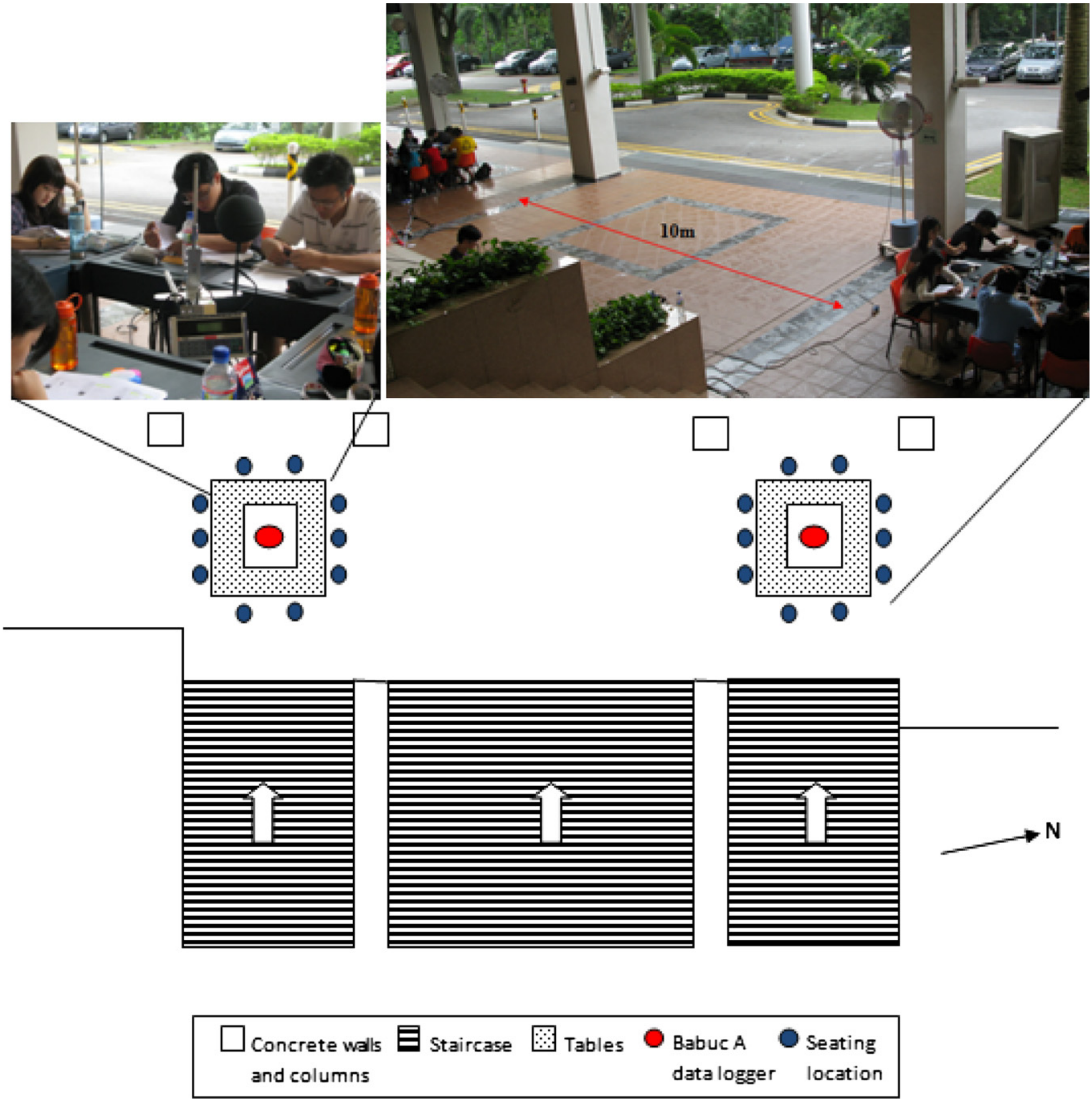

Fig. 1. Experimental setup at NUS.

from chapter 8 of the 2001 ASHRAE Handbook – Fundamentals [12].

These semi-outdoor and outdoor climatic measurements are also used as inputs to allow heat-balance indices which include the outdoor ET*, semi-outdoor PET and SET to be computed for each respondent. Both the semi-outdoor PET and SET were computed using RayMan version 1.2. Inputs include T_a, T_{mrt}, RH, v, location, time, date, clo value, activity and personal data (height, weight, age and sex). The model 'RayMan' in generating thermal indices such as PET and SET takes into account complex urban structures and hence is suitable for urban areas such as Singapore [13]. Outdoor ET* on the other hand was computed using the UC Berkeley Thermal Comfort Program Version 1.03 [14]. The measured outdoor environmental conditions (T_a, T_{mrt}, RH and v) together with clo values and the respondent's activity are used as inputs to the model on the left hand side of the screen which generates the ET* with no time delay on the right hand side of the screen.

2.3.2. Subjective measurements

Thermal comfort questionnaires developed based on the sample questionnaire provided in ASHRAE standard 55-2004 would be completed by respondents concurrently as objective measurements are being conducted [10]. The same thermal comfort questionnaire would be utilised during both field measurements and for the experiment at the NUS. Analysis of the comfort condition would be based on the respondent's vote on the ASHRAE scale (thermal sensation) and Bedford scale (comfort sensation). It also includes an analysis of the respondent's votes on humidity (humidity sensation and preference) and air movement (airflow sensation and preference).

Fig. 2. Misting fan system.

2.4. Biological sampling

Air samples were collected using single stage N6 Andersen samplers before and during the operation of mist generating system at different locations within each dining area. The Andersen sampler is designed as a substitute of the respiratory tract as a collector of viable airborne particles and hence should reproduce to a reasonable degree the lung penetration by these particles. The single stage is a plate perforated with 400 orifices through which the sample of air is drawn and is placed over the uncovered agar plate. The devise is pressure sealed with gaskets and three adjustable spring fasteners. Each sampler was connected to a pump to draw samples at a rate of 28.3 L min^{-1}. When the velocity imparted to a particle is sufficiently great, its inertia will over-come the aerodynamic drag and the particle will leave the turning stream of air and be impinged on the surface of the agar plat [15]. Collection was made over a period of 4 min at the occupant's breathing level (1.2 m) using either the Tryptic Soya Agar (TSA) plates for bacteria or Potato Dextrose Agar (PDA) plate for yeast and moulds. After collection, the samples were transported to the Indoor Air Quality Laboratory at NUS for incubation. The TSA plates were incubated for 48 h at 37 °C while the PDA plates were incubated for 120 h at approximately 25 °C. After incubation, the number of colonies on each plate were enumerated and summed.

Collection was made at two semi-outdoor dining areas (food centre A and another food centre C which utilises misting fans so as to obtain a better representation for bacteria and yeast counts under misting fans) and at an experimental setup at NUS. Food centre C is a shop selling desert along Temple Street located in Chinatown. Fig. 4 shows the location of the misting fans and the sampling points in dining area C. Fig. 5 shows the location of the misting fans and the sampling points in food centre A.

The collection of samples was done before food centres A and C open for business so as not to hinder the operating of the dining areas. This also means lower human activities during the collection period. The sampling points were selected based on the location of the misting fans as well as the seating locations.

At NUS, collection was done concurrently, with one air sampler located under a misting fan and another under a similar fan without the mist generating system. The two air samplers were located such that they are far enough not to be affecting one another. A total of 3 samples with each sample being collected consecutively at the same sampling point under both misting and non-misting fans were conducted. This is to ensure that any difference in bacterial and fungal count is due to the higher relative humidity under the misting fan and not due to variations that may result from the use of an Andersen sampler [9].

3. Results and analysis

3.1. Effectiveness in reduction of dry-bulb temperature

Fig. 6 shows the dry-bulb temperature recorded from the NUS experiment under the mist and non-mist setup respectively throughout the four days (21st–24th September 2009) between 10am and 5pm with readings being taken at 15 min time intervals. From Fig. 6 it is obvious that the misting fan is able to lower the ambient temperature further, with lower temperatures being recorded under the mist fan setup throughout the four days of experiment, with the difference between temperatures recorded under the two setups being statistically significant ($Z = 6.82$, $p = 0.00$).

In addition, the 95% confidence interval for the reduction in dry-bulb temperature is $1.5 \pm 0.1 = (1.4$ °C, 1.6 °C), where 1.5 °C is the mean reduction in dry-bulb temperature recorded over the four days. Hence it is predicted with 95% confidence level that the misting fan is able to lower the dry-bulb temperature to somewhere between 1.4 °C and 1.6 °C as compared to the non-mist setup.

However, it is important to note that there were instances during which the dry-bulb temperature was higher under misting conditions as compared to non-misting conditions. From Fig. 6, it can be seen that these instances occurred during the 21st and 23rd September of the experiment after 4pm. This is due to the effect of

Fig. 3. Misting line system.

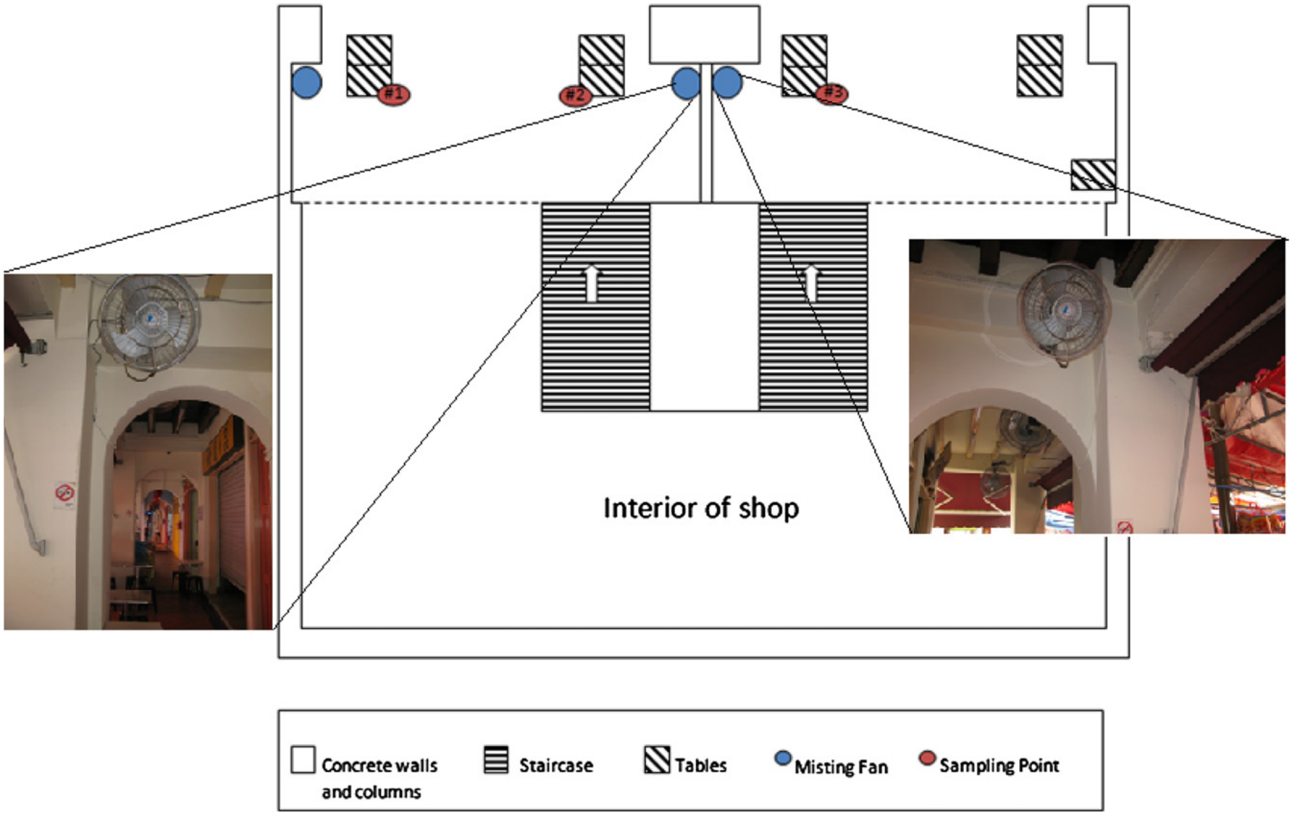

Fig. 4. Location of sampling points at food centre C.

evening low angle solar radiation falling only on the misting fan setup. These instances were however not consistent after 4pm. This is due to the extensive cloud cover in Singapore that varies from time to time. Such instances of higher dry-bulb temperatures under misting conditions were however not present on the 22nd and 24th September of the experiment due to overcast skies during these two days.

3.2. Effect on relative humidity

Fig. 7 shows the relative humidity recorded from the NUS experiment under the mist and non-mist setup respectively throughout the four days (21st–24th September 2009) between 10am and 5pm with readings being taken at 15 min time intervals. From Fig. 7 it is obvious that the relative humidity recorded under

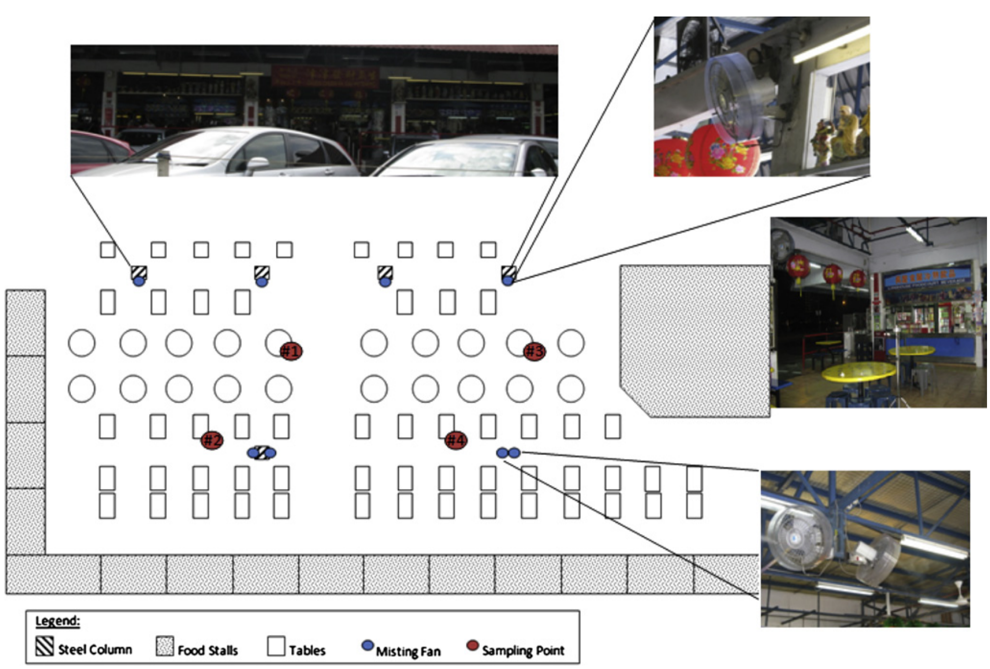

Fig. 5. Location of sampling points at food centre A.

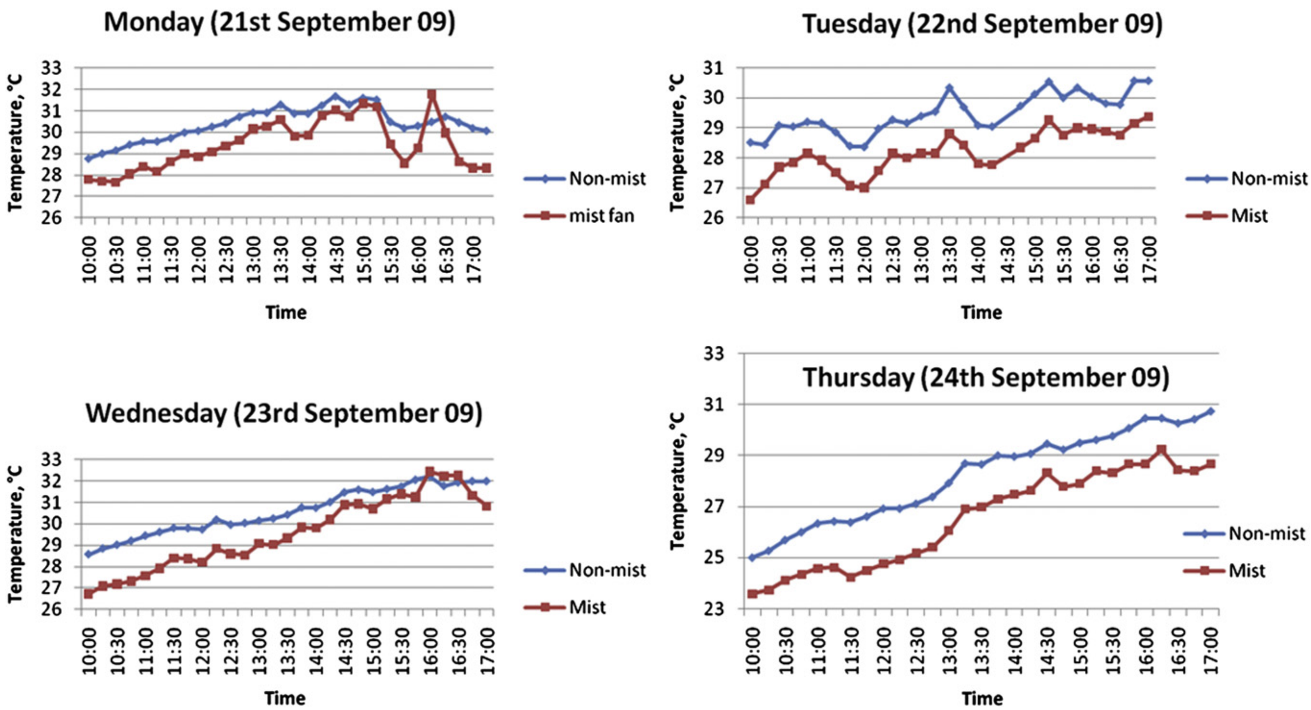

Fig. 6. Comparison of dry-bulb temperature recorded on 21st–24th September 2009 for the experiment at NUS.

the misting fan setup is constantly higher than that recorded under the non-misting fan setup, with this difference being statistically significant ($Z = 9.39$, $p = 0.00$).

Furthermore, the 95% confidence interval for the increase in relative humidity is $9.497 \pm 0.882 = (8.61\%, 10.38\%)$, where 9.497 is the mean increase in relative humidity recorded over the four days. Hence, it is predicted with 95% confidence level that the misting fan increases relative humidity to somewhere between 8.61% and 10.38% as compared to under the non-mist setup.

3.3. Effect of air velocity and clothing values

Table 1 shows the average air velocity recorded from the NUS experiment for each of the four days as well as the sum average for all four days. Table 2 shows the average clo value for all participants under each setup for each day as well as the average value for all four days. From Table 1, it can be seen that there is no obvious difference in air velocity between the misting and non-misting setup. In addition, solving for the p-value ($Z = 1.26$, $p = 0.21$) for

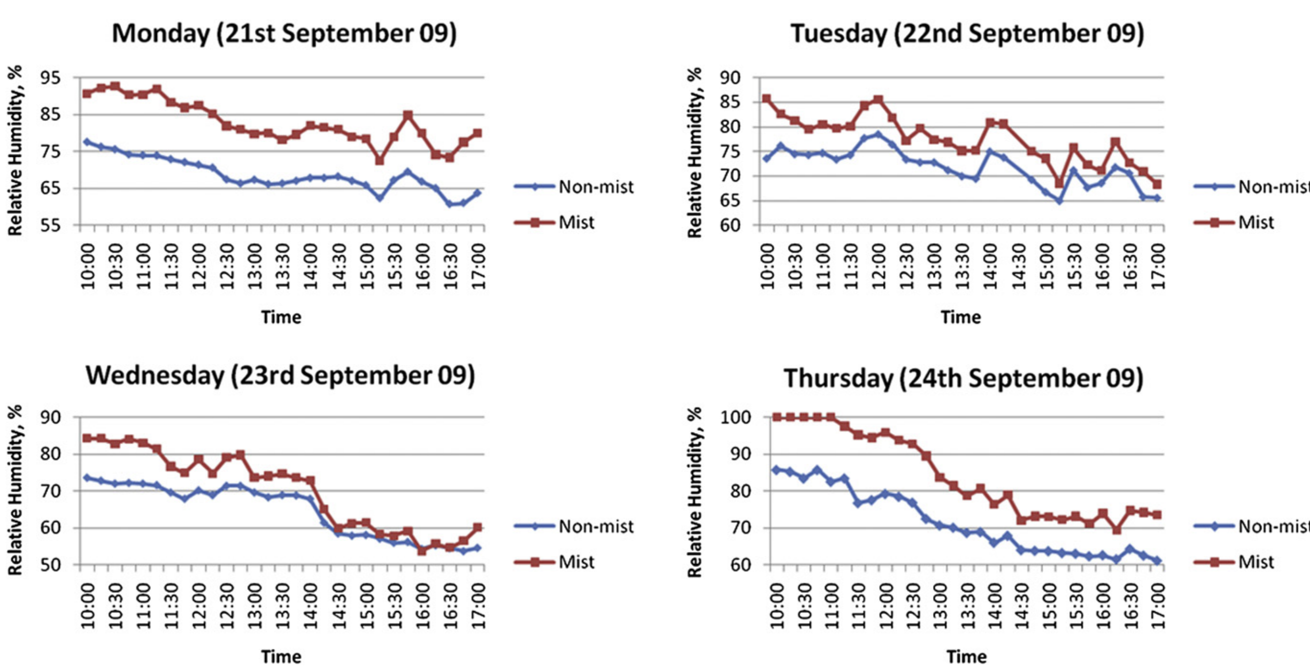

Fig. 7. Comparison of relative humidity recorded on 21st–24th September 2009 for the experiment at NUS.

Table 1
Average air velocity for each day and the summed average for all 4 days.

Average daily Air Velocity (m/s)		
	Non-Mist	Mist
Monday	0.80	0.72
Tuesday	0.62	0.81
Wednesday	0.82	0.50
Thursday	0.51	0.55
Average for all four days	0.68	0.64

each of the data recorded showed that the difference between the air velocity recorded under the two setup is not statistically significant. This tells us that any reduction in dry-bulb temperature under the misting fan setup would not be due to an increase in air velocity. In fact, the average air velocity over all four days is slightly greater under the non-misting fan setup at 0.68 m/s as compared to 0.64 m/s under the misting fan setup.

However, the difference in clothing level is statistically significant ($Z = 2.89$, $p = 0.0038$). The average clo value is however greater for participants under the misting fan setup as compared to those under the non-misting fan setup as seen from Table 2 which means that even if the difference in clo values had an effect on the participant's comfort levels, it would be in favour of the non-misting fan setup. On the contrary, votes on thermal comfort and thermal sensation appears to be lower under the misting fan setup as would be illustrated in the next section.

3.4. Thermal sensation vote (ASHRAE scale) and thermal comfort vote (Bedford scale)

Fig. 8 shows the distribution of thermal sensation votes (ASHRAE scale) and thermal comfort votes (Bedford scale) of the participants recorded from the NUS experiment under both the misting fan and non-misting fan setup. From the distribution of votes under the ASHRAE scale, it can be seen that most participants (28%) under the influence of the misting fan felt slightly cool as compared to under the non-misting fan setup where a majority (32%) felt neutral. In addition, the thermal sensation votes cast by participants placed under the misting fan setup centred around −2 (cool), −1(slightly cool) and 0 (neutral) whereas those cast by participants under the non-misting fan setup centred around −1 (slightly cool), 0(neutral) and 1(slightly warm). From these observations, it would seem that the misting fan is capable of reducing thermal sensation by 1 step on the ASHRAE Scale. This is consistent with thermal comfort votes on the Bedford scale where majority (69%) of the participants under the misting fan setup voted −1 (comfortably cool) and 0(comfortable) on the Bedford scale as compared to 69% of those under the non-misting fan setup who voted 0(comfortable) and 1(comfortably warm).

3.5. Humidity sensation and preference

Fig. 9 shows the distribution of humidity sensation votes of the participants recorded from the NUS experiment both under the misting fan and non-misting fan setup while Fig. 10 illustrates their humidity preference. From Fig. 9 it can be observed that there is only a slight difference in the humidity sensation of participants between the two setups, with a majority (48%) of the participants under the misting fan setup voting 0 (just right) followed by 35% voting 1 (slightly humid). This is similar with a majority (60%) of the participants under the non-misting fan setup voting 0 (just right) followed by 21% voting 1 (slightly humid). In addition, from Fig. 10 it can be seen that most of the participants under the misting fan (63%) and non-misting fan (66%) would like no change in humidity levels in the environment. This seems to suggest that the increase in relative humidity by the misting fan does not have significant impact on the respondent's vote of humidity sensation and preference.

Table 2
Average clo value for each day and the summed average for all 4 days.

Average Clo Value		
	Non-Mist	Mist
Monday	0.36	0.27
Tuesday	0.31	0.34
Wednesday	0.24	0.37
Thursday	0.33	0.40
Average for all four days	0.31	0.34

3.6. Physiological equivalent temperature, standard effective temperature and outdoor effective temperature

3.6.1. Misting fan system

Fig. 11 shows the regression models when standard effective temperature (SET) and physiological equivalent temperature (PET) is plotted against the outdoor effective temperature (ET*). From the regression model of SET against outdoor ET*, it can be observed that the food centre using the misting fan system constantly recorded a lower SET for the same outdoor ET* with statistically significant correlations for data collected at the 2 food centres ($r = 0.78$ for food centre using non-misting fan and $r = 0.91$ for food centre using misting fans). Similarly, the regression model of PET against outdoor ET* also illustrates that lower PET was recorded with statistically significant correlations, for the food centre using the misting fan system ($r = 0.95$) as compared to the food centre using non-misting fans ($r = 0.84$) for the same outdoor ET*. It can also be observed in Fig. 11 that the gradient of the regression model for food centre A is steeper than that for food centre B and that as outdoor ET* increases, the misting fan seems to be less effective in reducing the PET and SET. From the data collected, the high outdoor ET* is usually characterised by high dry-bulb temperatures and low RH. Hence one possible cause of such a trend is that the increase in humidity may offset the reduction in dry-bulb temperature. This in turn may result in a lower decrease in PET and SET since with a lower ambient RH, RH may increase to a greater extend under the influence of misting fans as compared to where ambient RH is high. This is because both PET and SET is based on Gagge two-node model [16,17]. Hence the greater increase in RH may in turn cause an increase in skin temperature which increases both PET and SET since greater RH means less evaporative regulation is possible [11]. Further studies however need to be conducted to affirm the cause behind such a trend.

3.6.2. Misting line system

Similarly, Fig. 12 shows the regression models when SET and PET is plotted against the outdoor ET* and is computed from data collected at the coffee outlet when the misting line system is operational and non-operational. Both models are statistically significant with correlations of 0.91 (without mist line) and 0.68 (with mist line) for regression of SET against outdoor ET* and 0.96 (without mist line) and 0.79 (with mist line) for regression of PET against outdoor ET*.

From Fig. 12, it can be seen that for lower outdoor ET*, SET and PET is approximately the same with and without the operation of the misting line system. However at higher outdoor ET*, lower SET and PET can be observed when the misting line system is operational, suggesting that the misting line system is only effective at higher outdoor ET*.

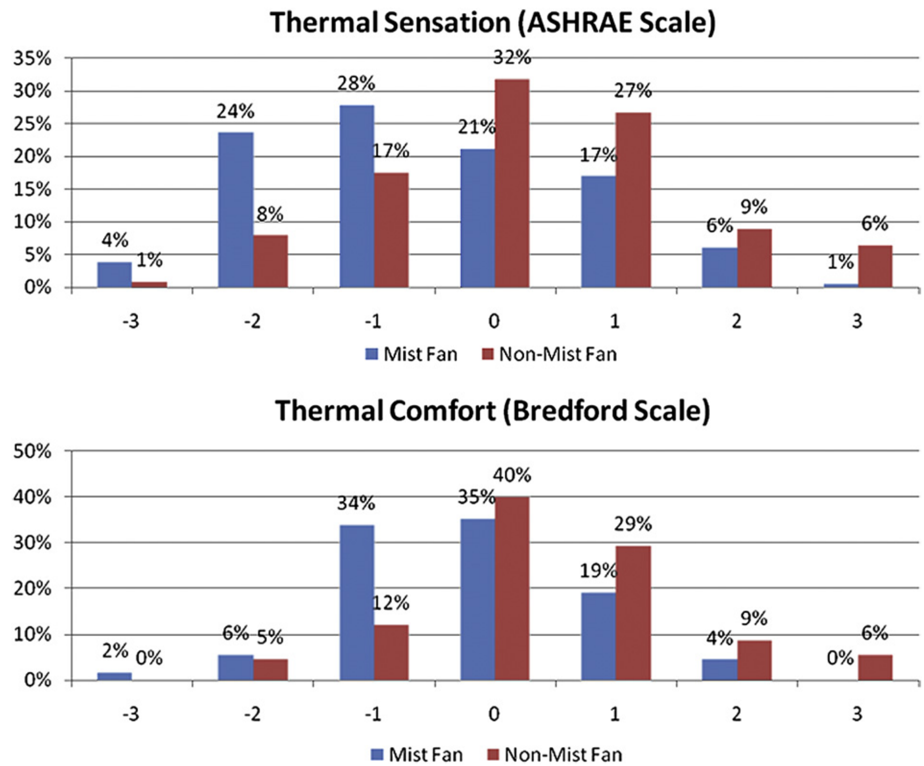

Fig. 8. Distribution of thermal sensation votes and Distribution of thermal comfort votes of participants in experiment at the NUS.

3.7. *Thermal sensation and neutrality*

3.7.1. *Misting fan system*

Fig. 13 shows the regression of thermal sensation vote of respondents against the outdoor ET* recorded at the time when the survey was conducted at the food centre using mist fans and non-mist fans respectively. From the regression model, correlations of $r = 0.54$ for food centre A with misting fans and $r = 0.48$ (for food centre B using non-misting fans were obtained). This is statistically significant considering the subjectivity of thermal sensation on the ASHRAE scale and also due to the fact that it is an absolute scale which does not provide for thermal sensations that may fall between the absolute numbers provided under the ASHRAE scale. Solving each of the regression model for zero defines the thermal neutrality for outdoor ET* at each of the 2 food centres.

From Fig. 13, thermal neutrality is at 31.8 °C (mist fan) and 31.0 °C (non-mist fan) respectively. This provides evidence that thermal neutrality could be obtained with a higher outdoor ET* for the food centre with the misting fan system. It can also be observed that the same thermal sensation vote can be achieved at a higher outdoor ET* with the food centre using the misting fan system, implying that the mist generating system is more effective in lowering outdoor ET*. This seems to suggest that given the same outdoor ET*, the misting fan system would provide a lower thermal sensation vote as compared to fans that do not utilise the mist generating system.

3.7.2. *Misting line system*

Fig. 14 shows the regression of thermal sensation vote of respondents against the outdoor ET* recorded at the time when the survey was conducted at the coffee outlet when misting line system is operational and non-operational. In both cases, the regression model is statistically significant with correlations $r = 0.41$ when the misting line is operational and $r = 0.50$ when the misting line is non-operational. From Fig. 14, thermal neutrality is approximately the same at 28.9 °C (with mist line) and 28.6 °C (without mist line), suggesting that the misting line system is not significantly more effective in lowering outdoor ET*.

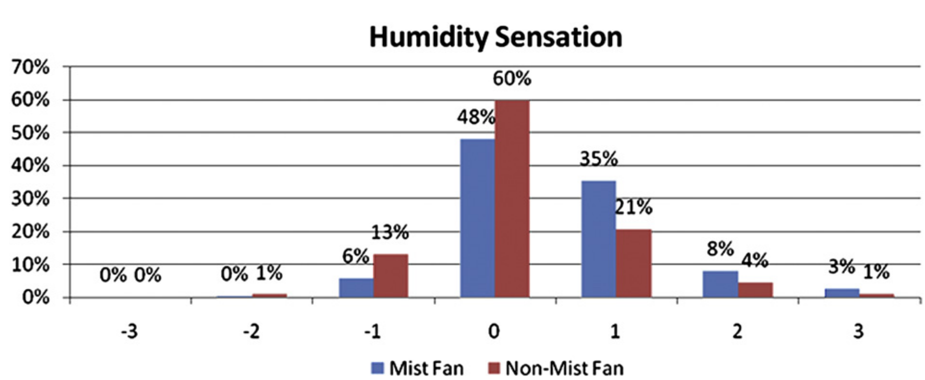

Fig. 9. Distribution of humidity sensation votes.

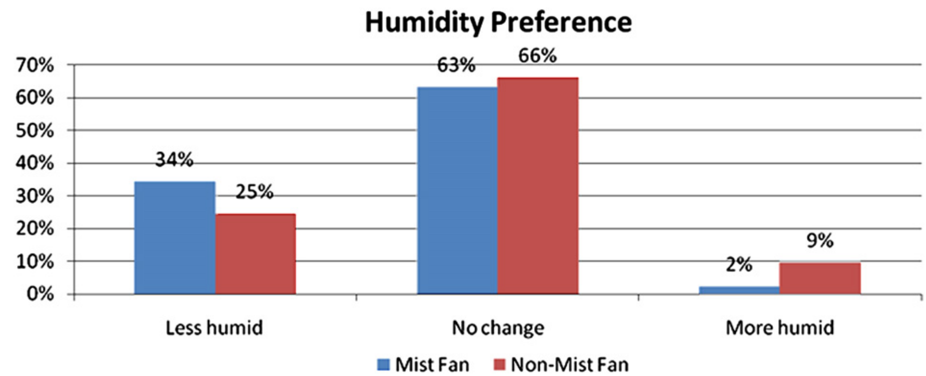

Fig. 10. Distribution of humidity preference votes.

3.8. Biological samples

Tables 3, 4 and 5 shows the bacterial and fungal count for samples collected at the various sampling points at food centre A, food centre C and NUS respectively. These three tables show that both bacterial and fungal count collected at all the sampling points were greater under the misting fan system with the exception of sampling point #4 at food centre A and #3 at food centre C where slightly greater biological particles are observed under the non-misting fan as compared to under the misting fan. This discrepancy may be due to huge variations (up to 1000 fold) that may result from the use of an Andersen sampler when measuring biological particles which is why analysis is done based on the average and range of biological particles collected [9].

At food centre C, the bacteria count enumerated from samples collected under the misting fan is much greater than the bacteria count for samples collected when the mist generating system is turned off. Samples collected from sampling points 1–3 averaged at a value of 674 CFU m^{-3} and ranged from 477 to 795 CFU m^{-3} as compared to the significantly lower 400 CFU m^{-3} with a range of 300–459 CFU m^{-3} when the mist generating system is turned off.

A similar trend is observed, although less significant for yeast and moulds, with fungal count averaging at 271 CFU m^{-3} for samples collected under the misting fan and a slightly lower average of 233 CFU m^{-3} when the mist generating system is turned off.

At food centre A, a slightly higher bacterial and fungal count is observed from samples collected under the misting fan. Bacteria

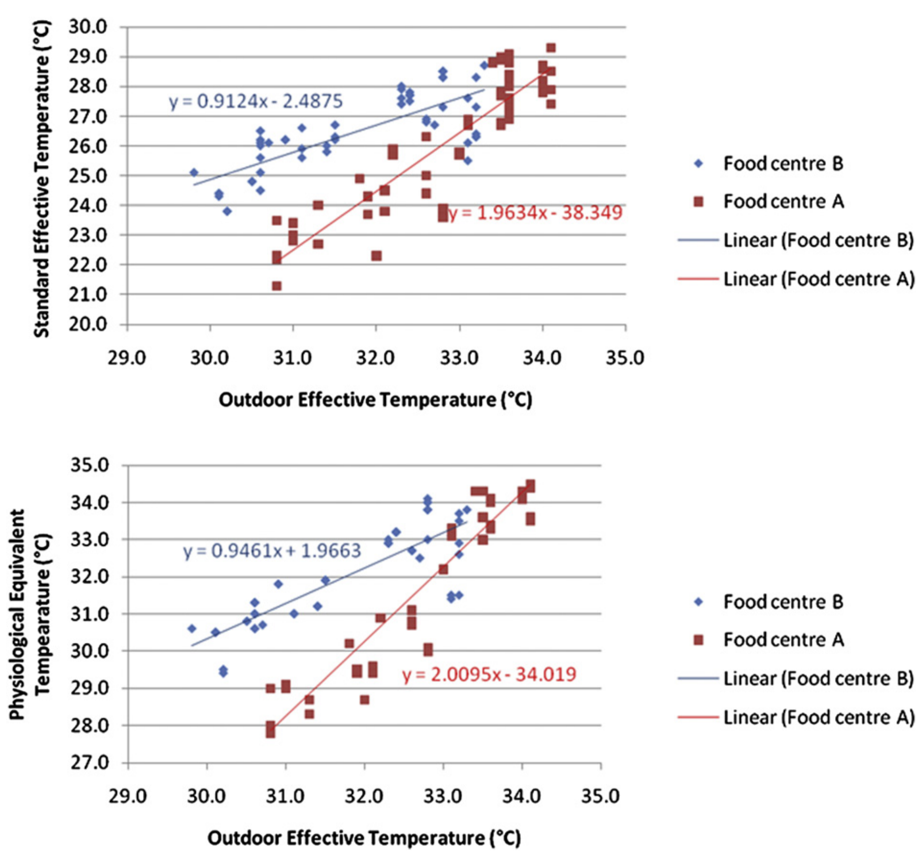

Fig. 11. Regression of standard effective temperature and physiological equivalent temperature against outdoor effective temperature for the 2 food centres.

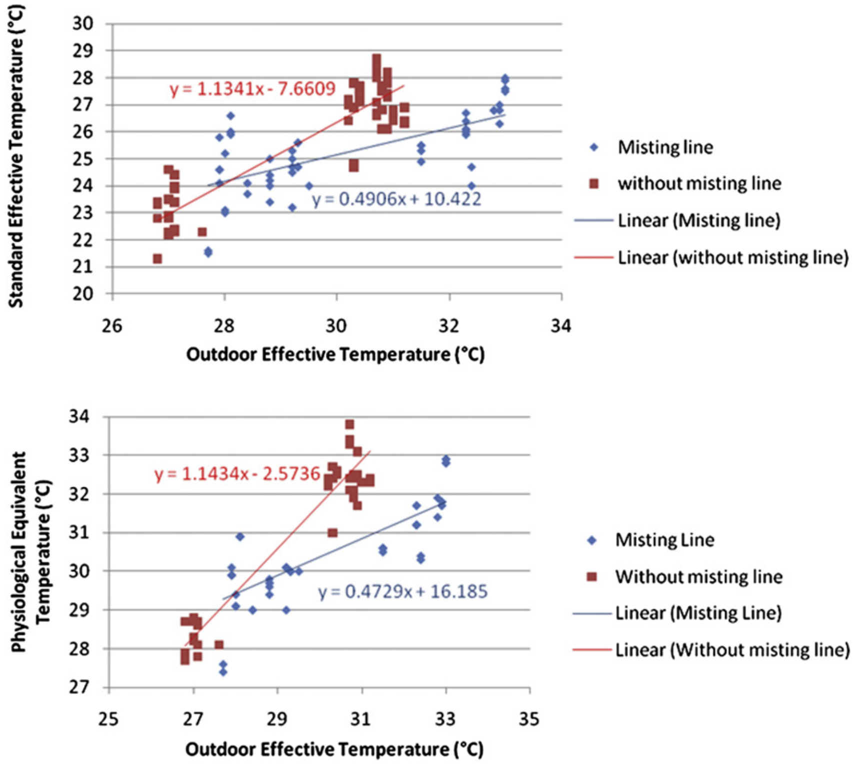

Fig. 12. Regression of standard effective temperature and physiological equivalent temperature against outdoor effective temperature for coffee outlet with and without the operation of the misting line system.

count averaged at a value of 110 CFU m^{-3} under the misting fan as compared to 71 CFU m^{-3} when the mist generating system is turned off. Fungal count averaged at 598 CFU m^{-3} under the misting fan as compared to 550 CFU m^{-3} when the mist generating system is turned off.

For the samples collected at NUS, the bacteria count collected under the misting fan is much greater with an average value of 1060 CFU m^{-3} as compared to a much lower average value of 150 CFU m^{-3} from samples collected under the non-misting fan. It is important to note that the bacteria count enumerated from sample #1 is at an extremely high value of 2111 CFU m^{-3} which is approximately 10 times larger than the greatest bacteria count enumerated from samples collected under the non-misting fan. This may also explain the much higher average value of 1060 CFU m^{-3}.

A similar trend is also observed for moulds and yeast, although less significant, with an average fungal count of 277 CFU m^{-3} under the misting fan and an average of 206 CFU m^{-3} under the non-misting fan. Hence it can be seen that although the increase in bacterial and fungal count under the misting fan may vary considerably, consistently higher bacterial and fungal count can be observed from samples under the misting fan as compared to those collected under the non-misting fan.

4. Discussion

4.1. Effectiveness of misting fans

Based on the analysis of Fig. 6, it appears that the misting fan system is effective in reducing the dry-bulb temperature. This is reinforced by field measurements of food centres using the same misting fan system in which constantly lower SET and PET were recorded over a wide range of outdoor ET*(Fig. 11) when compared

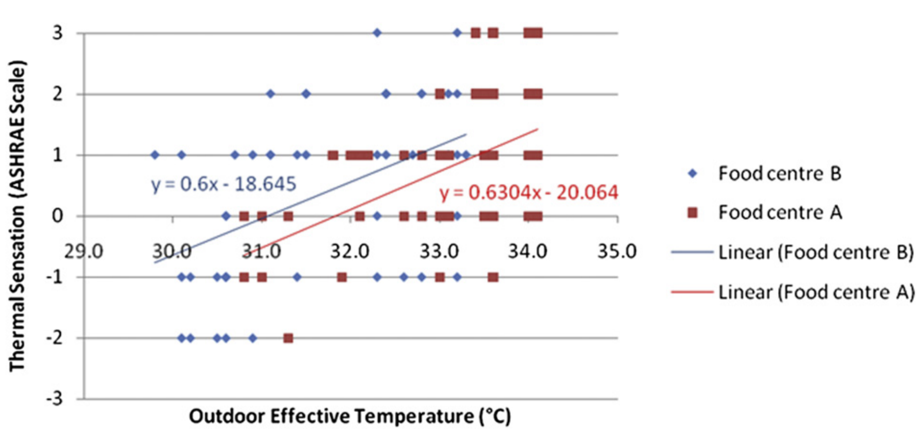

Fig. 13. Neutrality and outdoor effective temperature at the 2 food centres.

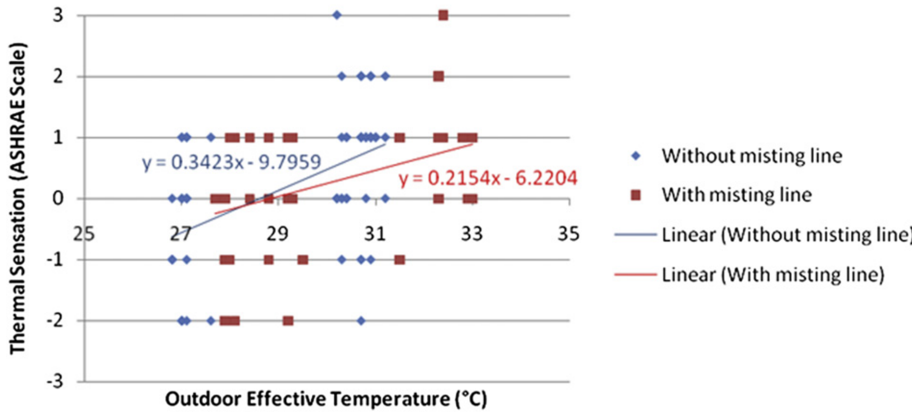

Fig. 14. Neutrality and outdoor effective temperature at coffee outlet with and without operation of the misting line system.

Table 3
Biological counts from samples collected at food centre A.

Location	Mist		Non-mist	
	Bacteria Count/ CFU m^{-3}	Fungal Count/ CFU m^{-3}	Bacteria Count/ CFU m^{-3}	Fungal Count/ CFU m^{-3}
#1	141	548	53	442
#2	141	663	71	689
#3	71	627	62	486
#4	88	557	97	583
Average	110	598	71	550

to another food centre within the same district of similar orientation but using non-misting fans instead. Evidence of the effectiveness of misting fans is further strengthened by Fig. 8 where lower thermal sensation and thermal comfort votes were obtained from respondents under the misting fan system.

Fig. 15 shows the regression model of the observed thermal sensation votes against the relevant dry-bulb temperature recorded for the semi-outdoor experiment conducted at the NUS between 21st and 24th September 2009. The model is statistically significant with correlation $r = 0.64$. Solving the regression model for thermal neutrality yields a dry-bulb temperature of 29.2 °C. This is consistent with the adaptive theory which proposes that people living in warmer climates may be more adapted to higher temperatures and hence their corresponding temperature for thermal neutrality should be higher [18]. Earlier observations propose that the misting fan is capable of lowering thermal sensation votes, indicating that the misting fans should only be turned on when temperature is found to be above this neutral temperature (29.2 °C) and turned off when temperature falls below the neutral temperature. This would optimise the ability of the misting fan to lower ambient temperature and hence thermal sensation votes to achieve a greater proportion of thermal satisfaction amongst occupants.

However, the process of evaporative cooling also results in substantial increase in relative humidity (Fig. 7). The increase in relative humidity however, does not seem to have much effect on thermal sensation since lower thermal sensation and thermal comfort votes were observed from respondents under the misting fan system despite the higher relative humidity. This may be because the decrease in temperature may have a greater effect on thermal sensation than the increase in relative humidity, due to the relatively high air velocity (Table 1), low clo level (Table 2) and low metabolic rates since respondents are sedentary [19]. In addition, the discomfort caused by high humidity is mainly due to the inhibition of sweat evaporation [11]. Since the respondents are undertaking sedentary activities and hence not sweating, they may find the high relative humidity less oppressive than it would be if they were to undertake higher activity levels which cause them to sweat.

4.2. Effectiveness of misting line system

Judging from the analysis of Fig. 12, the misting line system unlike misting fans did not seem to be consistently effective in further reducing the ambient temperature. This is further reinforced by Fig. 14 where the neutral temperature is approximately the same (28.6 °C and 28.96 °C) for the same outdoor ET*. This could be due to the fact that the misting line system generates mists only at the perimeter of the coffee outlet and at a lower velocity unlike the misting fan system in which the generated mist is sprayed directly at higher velocity onto the respondent. It also appears that the misting fan system is more effective than the misting line system; lending support to the hypothesis that mist generating system only provides localised cooling and may require high air velocity in order for evaporative cooling to be more effective.

4.3. Biological pollutants

Based on the analysis of Tables 3, 4 and 5, it appears that mist generating system provides a more conducive environment for

Table 4
Biological counts from samples collected at food centre C.

Location	Mist		Non-mist	
	Bacteria Count/ CFU m^{-3}	Fungal Count/ CFU m^{-3}	Bacteria Count/ CFU m^{-3}	Fungal Count/ CFU m^{-3}
#1	795	371	459	265
#2	477	274	442	230
#3	751	168	300	203
Average	674	271	400	233

Table 5
Biological counts from samples collected at NUS.

Sample	Mist		Non-mist	
	Bacteria Count/ CFU m^{-3}	Fungal Count/ CFU m^{-3}	Bacteria Count/ CFU m^{-3}	Fungal Count/ CFU m^{-3}
#1	2111	256	159	186
#2	618	256	88	212
#3	451	318	203	221
Average	1060	277	150	206

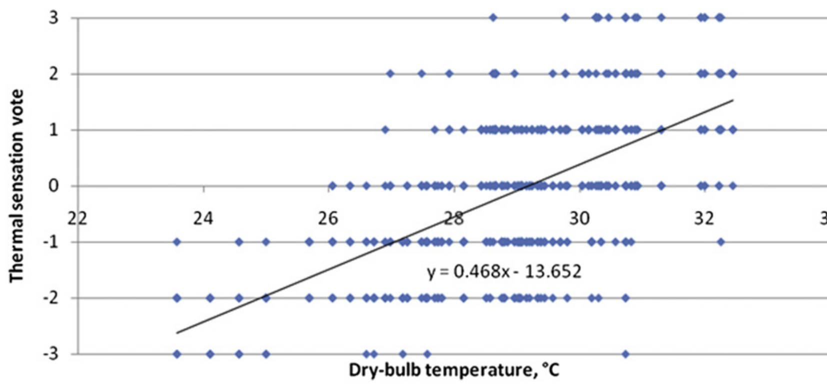

Fig. 15. Regression of observed thermal sensation votes and dry-bulb.

bacterial and fungal growth. This can be attributed to the higher relative humidity which has been shown to be required for sustained growth rather than the mere germination of spores [20]. This increase in relative humidity is supported by objective measurements recorded (Fig. 7). Based on these measurements, it is predicted with 95% confidence level that the mist generating system is able to significantly increase relative humidity from between 8.61% and 10.38%. All these point to the fact that although the mist generating system may effectively reduce the dry-bulb temperature, it is at the expense of greater relative humidity which in turns provides a more conducive environment for bacterial and fungal growth.

In addition, it is also important to note that although the increase in biological pollutants may vary considerably (Tables 3–5), there is potential for biological pollutants to increase greatly as seen from samples #1 and #2 collected from NUS and samples #1 and #3 from food centre C, where a much higher bacteria count is observed.

5. Conclusion

This research project estimated the difference in thermal comfort levels provided by the misting fan system as well as the possible increase in biological pollutants due to the increase in relative humidity brought about by the generation of mists.

Results from objective measurements recorded from the experimental procedure at NUS showed that the misting fan is able to effectively reduce the dry-bulb temperature by approximately 1.38–1.57 °C at a 95% confidence interval with the difference being statistically significant ($Z = 6.82$, $p = 0.00$). Subjective measurements from this experiment also showed that lower thermal sensation votes were obtained under the misting fan setup as compared to under the non-misting fan setup.

From regression analysis of field measurements conducted at the 2 food centres and the coffee outlet, it appears that with the misting fan system, thermal neutrality can be obtained at a higher outdoor ET*, implying that for the same outdoor ET*, lower votes of thermal sensation is obtained under the misting fan system. On the contrary, no significant difference is observed for the misting line system, suggesting that the mist generating system only provides localised cooling and may require high air velocity in order for evaporative cooling to be more effective.

In addition to the evaluation of thermal comfort, biological (bacteria and yeast) samples were also collected from 2 dining areas and from an experiment setup at NUS. The samples showed that consistently higher bacterial and fungal counts were observed for samples collected under the misting fan. This may be attributed to the higher relative humidity brought about by the mist generating system as seen from the experimental procedure at NUS in which the objective data showed that the misting fan is able to increase relative humidity by 8.61%–10.38% at the 95% confidence interval with this difference being statistically significant ($Z = 9.39$, $p = 0.00$). From the biological samples collected, it can also be observed that there is a possibility that biological pollutants may reach much higher levels under the influence of the mist generating system.

Hence, to cope with the biological pollutants, a possible alternative would be a two-stage indirect/direct evaporative cooling system. Such a system consists of two air streams, ambient air in the dry channel and secondary air in the wet channel. Intake air passes through the dry channel and is cooled by the wet channel in which secondary air is cooled through direct contact with water. As a result, the output air through the dry channel which is supplied to the space would be at a lower temperature without any increase in humidity since only sensible cooling occurs in the dry channel. Some of the output air is also directed to the wet channel to further increase sensible heat loss in the dry channel. Studies have shown such a system to be more effective than direct systems particularly in hot and humid climates where adiabatic cooling is limited by the amount of moisture in the air [21,22]. Further studies however need to be conducted on the viability of such a system in a semi-outdoor area. In addition, the incorporation of a dehumidifier unit should also be studied to further reduce air humidity not only to improve comfort conditions but also to address the issue of biological pollutants which is especially important at dining areas.

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