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Accettabilitá di elevate velocitá dell´aria per il raffrescamento in ambienti caldi

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"Acceptance of increased air velocity for cooling effect in warm environment"

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Sommario

E' esperienza comune come l'utilizzo di elevate velocità dell'aria aiuti a ridurre la sensazione di calore dovuta alle alte temperature dell'ambiente in cui ci si trova. L'apertura di finestre e l'utilizzo di ventilatori sono i sistemi più utilizzati per generare flussi d'aria al fine di compensare l'incremento di temperatura.
Diversi studi sono stati realizzati per quantificare la possibilità di utilizzare ventilatori per mantenere condizioni di comfort, ottenendo un consumo energetico relativamente basso.
In particolare, l'energy saving può essere realizzato aumentando la temperatura di set point del sistema di climatizzazione, compensando tale incremento con flussi d'aria.

Nel nostro studio sono stati investigati gli effetti sulla percezione dell'individuo di flussi d'aria generati da un prototipo di ventilatore cinese. Questi ventilatori sono in grado di produrre differenti modelli di flusso: costante, sinusoidale, simulazione del vento naturale.
27 soggetti scandinavi, all'oscuro dello scopo dell'esperimento condotto, sono stati esposti a differenti condizioni termiche in una camera climatica che riproduceva un classico ufficio.
Le sessioni sperimentali sono state suddivise in due parti. Nella prima sono state studiate condizioni ambientali con temperature crescenti da 26°C a 34°C e umidità assoluta di 12.2 g/kg.
Durante questa sessione è stato valutato l'effetto di raffrescamento fornito da flussi d'aria locali e costanti a diverse velocità.
Nella seconda sessione gli stessi soggetti hanno espresso valutazioni di ambienti termici dove le velocità dell'aria costanti preferite, scelte nella sessione precedente, sono state comparate con la simulazione di vento naturale avente la stessa velocità dell'aria media. Le condizioni analizzate sono state temperature della stanza di 28°C e 30°C e umidità assoluta costante.
Infine, tramite cosiddetti manichini termici sono state realizzate riproduzioni delle reali esposizioni dei soggetti: l'analisi ha riguardato flusso termico e temperatura equivalente per ogni parte del corpo.

I risultati mostrano come sia effettivamente possibile compensare la sensazione di calore entro un range di condizioni climatiche per gli ambienti interni utilizzando elevate velocità dell'aria.
Il modello di simulazione del vento naturale presenta più elevata sensazione di raffrescamento per gli occupanti, sebbene sia percepito come meno piacevole rispetto al flusso costante.
Le misurazioni effettuate con i manichini invece dimostrano l'assenza di differenze tra i due tipi di flussi d'aria nei parametri fisici registrati.
Il paragone realizzato con i risultati di precedenti esperimenti condotti in Cina porta a concludere che soggetti abituati a climi più caldi possono accettare maggiori velocità dell'aria e valutare come meno scomfortevoli condizioni ad elevate temperature.

Per quanto concerne la struttura di questo lavoro, il primo capitolo riporta una breve rivisitazione della letteratura in termini di standard e articoli che riguardano il tema del thermal comfort e l'accettazione di elevate velocità dell'aria. L'argomento dell'adattamento termico è successivamente introdotto, assieme a rapide considerazioni su potenziali risparmi energetici.

Nel secondo capitolo si introduce la descrizione di tutta la strumentazione utilizzata, camera climatica e procedure adottate durante gli esperimenti.

Il capitolo seguente presenta i risultati dalle nostre misurazioni e dai questionari forniti ai soggetti per le valutazioni dell'ambiente termico. In particolare vengono analizzati: misurazioni di velocità dell'aria dai ventilatori, flussi di calore e temperature equivalenti delle parti del corpo in cui sono suddivisi i manichini, misurazioni dei parametri fisici delle condizioni della stanza, valutazioni soggettive delle condizioni termiche, temperature della pelle dei soggetti.

Successivamente è presentato un capitolo dove vengono riportate analisi più approfondite sulle valutazioni tramite questionari e discussione sulla base di risultati dalla letteratura. In particolare, si realizza una comparazione coi risultati dei simili precedenti esperimenti condotti in Cina.

Infine si riporta un paragrafo dove si sintetizzano le conclusioni ottenute dalle nostre analisi e si riportano alcuni suggerimenti per futuri test.

Summary

It is a common experience how increased air velocity helps to offset warm sensation due to high air temperature of the environment. Opening windows and turning on fans are the most common systems to generate airflows to compensate for increasing temperature.
Many studies were performed to quantify the possibility of using fans to keep comfortable conditions for occupants, using relatively low energy consumption.
Particularly, energy savings can be realized increasing the set-point temperature of the air conditioning system and compensating it using airflows produced by fans.

In our study, the effects on human perceptions of airflows generated by a prototype Chinese fan were investigated. Particularly, these fans can generate different airflow patterns: constant, sinusoidal and natural wind simulation.
27 Scandinavian subjects, blind of the purpose of the conducted experiment, were exposed to different thermal conditions in an office-look climatic chamber. The studied experimental exposures have been divided in two parts. In the first session environment with temperatures rising from 26°C to 34°C and constant absolute humidity of 12.2 g/kg were investigated. During this session the cooling effects provided by the local constant airflows at different air velocities were assessed.
In the second session the same occupants were assessing the thermal environment where the preferred constant air velocities, earlier chosen, were compared with the simulated natural wind that had equal average air velocity at room temperatures of 28°C and 30°C and constant absolute humidity.
Reproductions of subjects' exposures were also realized by using two thermal manikins. The produced heat fluxes and equivalent temperatures for each body segment were recorded.

Results show how it is actually possible to offset warm sensation within a range of indoor conditions using increase of air velocity.
Natural wind pattern presented higher cooling sensation for the occupants, however it was perceived as less pleasant than the constant air flow. Manikins' measurements instead demonstrated that no differences in physical values are present between the two types of airflows.
Comparison with previous Chinese findings reported how subjects used to warmer climate could accept higher air velocities and state less uncomfortable warm conditions.

The first chapter of the present work reports a brief literature review of standards and articles regarding the topic of thermal comfort and experiments on acceptance of increased air velocities. The theme of thermal adaptation is introduced as well as short considerations on potential energy saving are reported.

In the second chapter, description of all used instruments, climatic chamber, and adopted procedures during the experiments are introduced.

Results from physical measurements and from questionnaires given to the subjects for the assessments of the thermal environment are presented in the third chapter. In particular, air velocities measurements from fans, heat flux and equivalent temperature of manikins' body parts, physical measurements of room conditions, subjective evaluations of the room thermal conditions, skin temperatures of occupants have been analyzed.

Additional results and discussions are reported in the fourth chapter. More deeply analyses on the assessments by questionnaires and discussions based on literature findings are presented. Moreover, comparison with the results of previous similar experiments, performed in China, is discussed.

Finally, in a conclusive chapter, the findings of our experiment are synthetically summarized and some suggestions for further analysis and continuation of the present study are given.

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I am really grateful to all the students I met in the office of the International Centre. Particularly I want to thank Pavel, Natalia, Kaska, Lorenzo and Anna. They have been much more than people who I shared a space with.

It is hard then to report here the names of all the persons I spent even only a short time with but I am very glad I met. Not wanting to hurt anybody, I will simply say thanks to all of them, for all the great moments I had and for supporting me during my work.

Finally, I must quote my parents and my sister, to be the closest people I had and have, without them it would not have been possible to finish my studies.

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1.1 - Thermal comfort

1.1.1 - Energy balance of human being

A short review about human body systems for temperature control is necessary before introducing the definition of thermal comfort.
Our physiology provides separated heat and cold sensors and these receptors are placed on the skin, while the impulses coming from them are processed by the hypothalamus, located in our brain.
When the temperature detected exceeds 37°C, two cooling mechanisms start: increasing of blood flow over skin to enhance heat loss, sweating. When thermo-receptors record a temperature below 34°C, reducing of blood flow over skin to decrease heat loss and shivering (metabolism increase by muscles activity) are triggered.
All these systems take part in the heat balance of the whole body that is represented in Figure 1 and described by the "Heat Balance Equation":

$$S = M \pm W \pm R \pm C \pm K - E - RES$$

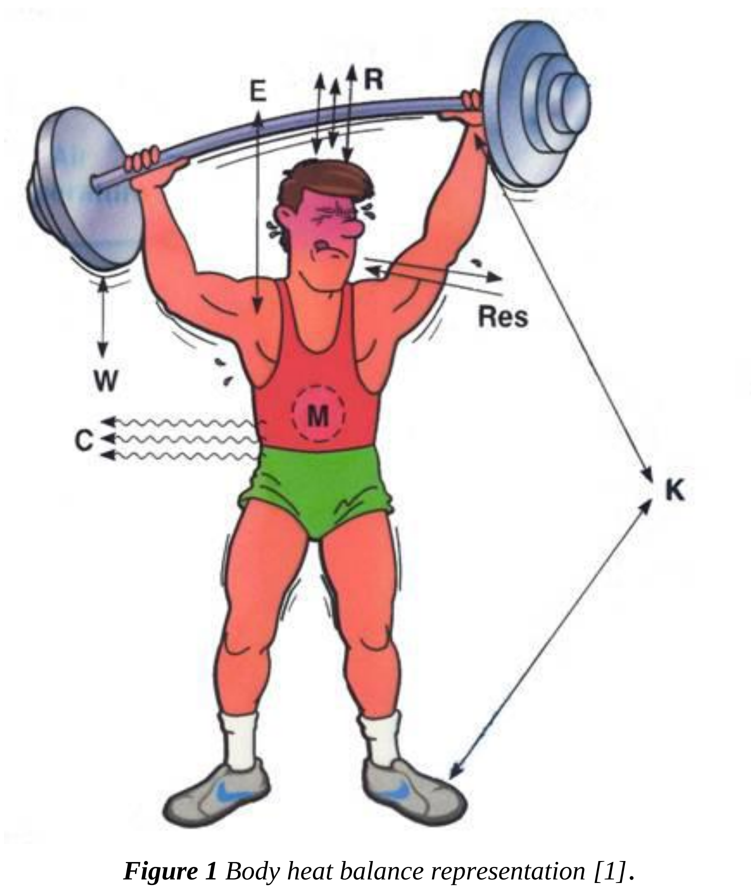


Figure 1 *Body heat balance representation [1].*

where:
S - rate of heat storage
M - rate of metabolic heat production
W - rate of mechanical work accomplished
R - rate of heat exchange by radiation
C - rate of heat exchange by convection
K - rate of heat exchange by conduction
E - rate of heat exchange by evaporation
RES - rate of heat exchange by respiration

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" [2]. In order to obtain this, S should be equal to zero, meaning that the heat produced by metabolism equals the heat lost from body.

1.1.2 - Prediction of thermal comfort

Satisfaction with thermal environment, when considering the whole body, is affected by six main parameters: air temperature, mean radiant temperature, air velocity and air humidity as environmental parameters; physical activity and clothing as "subjective" parameters.
When all these values are known, it is possible to predict the thermal sensation of the occupants of that environment through the calculation of PMV (Predicted Mean Vote), using a complex equation. This is an index that expresses the mean value of votes from a large group of persons through a 7-point scale of thermal sensation, as reported in the following table.
The model is applied on steady-state conditions, however it is also possible to use with good approximation during minor fluctuations of one or more variables.

Table 1 *Seven point thermal sensation scale[2].*

+ 3	Hot
+ 2	Warm
+ 1	Slightly warm
0	Neutral
– 1	Slightly cool
–2	Cool
– 3	Cold

Next to PMV, it is possible to calculate PPD (Predicted Percentage Dissatisfied), a value derived from PMV that expresses the percentage of thermally dissatisfied people that are who asses hot, warm, cool or cold the environment. The figure below shows the correlation between the two indexes.

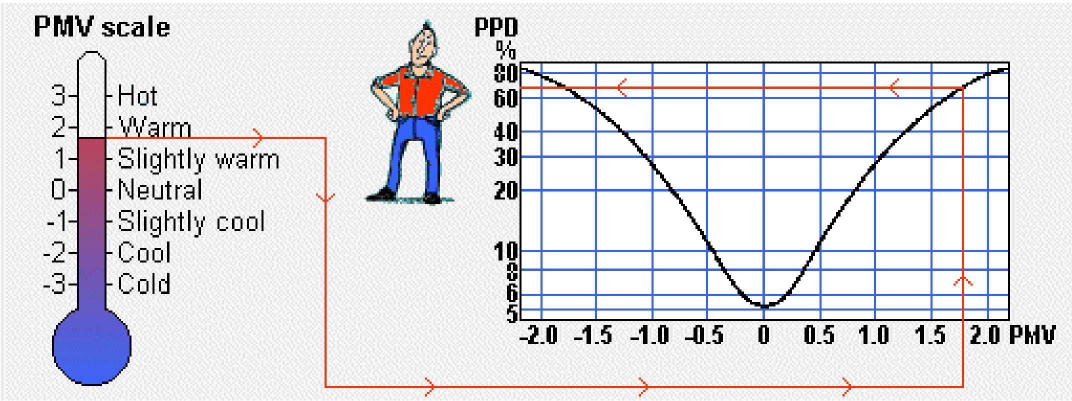


Figure 2 *PPD as a function of PMV [1].*

Standard ISO 7730:2005 [2] and ASHRAE 55-2010 [3] present tables that can help in computation of the two values, since using directly the equations needs long time. It's also possible to exploit software for this purpose.
Also simplified table to find out metabolic rates and insulation of clothing are reported in the mentioned standards.

1.1.3 - Local thermal discomfort

PMV and PPD concern the so-called global thermal comfort, since these indices do not consider local causes of dissatisfaction. While the body, considered as a whole, could be in a comfort state according to PMV, the person could be dissatisfied because of local thermal discomforts. The most common cause is draught, but also radiant asymmetry, vertical air temperature differences and floor temperature can affect human thermal sensation assessment.
It is fair to say that people at light activity are more sensitive to local discomfort. Increasing activity level results in a lower thermal sensitivity.

1.1.4 - Draught

This phenomenon is defined as an unwanted local cooling of the body caused by air movement. The most sensitive areas of the body as regard draught are neck and ankles, especially if they are not covered with any clothes. The sensation depends on air velocity, air temperature, activity and clothing of course.
It is possible to calculate an index, DR (draught rate), that expresses the percentage of people predicted to be bother by this phenomenon, considering also the local turbulence intensity [2]. The formula is following reported:

$$DR = (34 - t_{a,l})(v_{a,l} - 0.05)^{0.62}(0.37 v_{a,l} T_u + 3.14)$$

where:
$t_{a,l}$ is the local air temperature, in degree Celsius, 20°C to 26°C
$v_{a,l}$ is the local mean air velocity, in meters per second, < 0.5 m/s
Tu is local turbulence intensity, in percent, 10% to 60%.
It is fair to say that the model applies to people at light activity, with a thermal sensation for the whole body close neutral.

The standard [2] presents tree different categories of thermal environment for indoor spaces, A, B and C. These have different allowed values for PMV, PPD etc. As regard draught risk, the maximum allowable mean air velocity as function of local air temperature and turbulence intensity is reported, depending on the category of the environment, as shown in Figure 3.

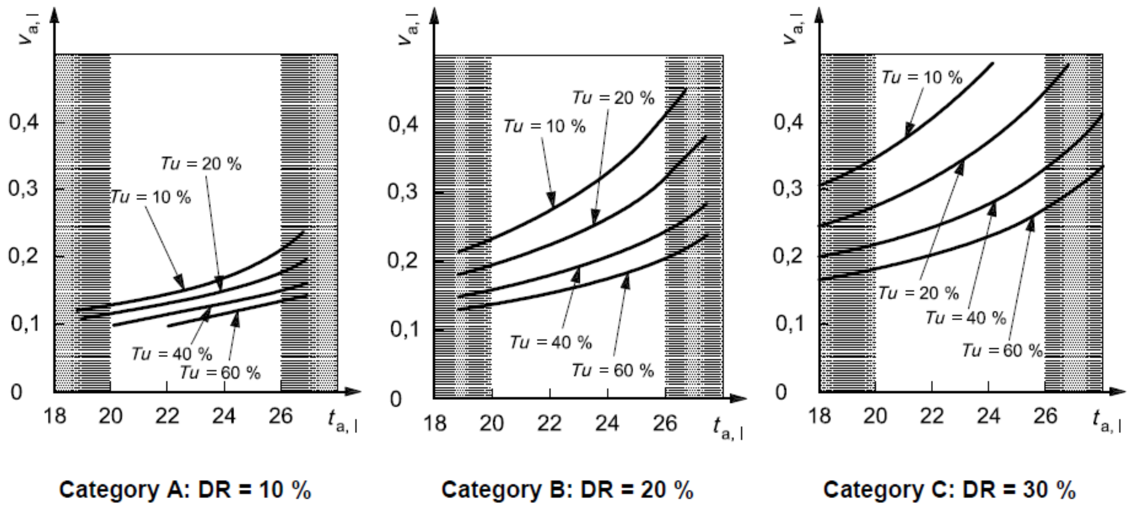


Figure 3 *Maximum allowable mean air velocity function of air temperature and turbulence for each building category [2].*

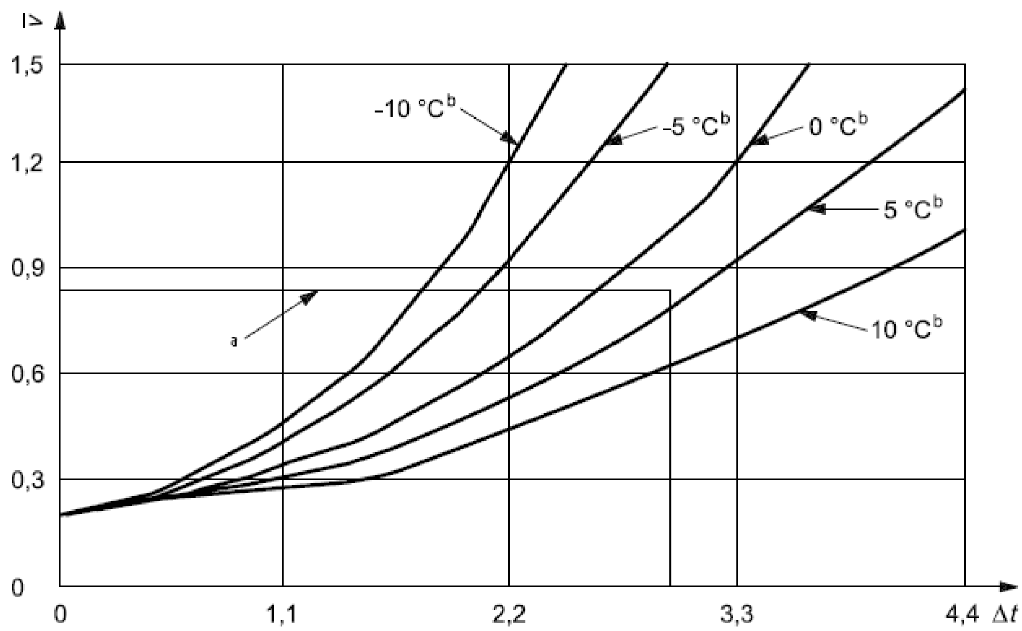
Moving from the best category (A) to (C), higher air velocity and turbulence intensity are allowed keeping the same temperature, since the draught risk permitted increases.

1.2 - Effect of air velocity

Air velocity is one of the six parameters influencing thermal comfort. Particularly, airflow affects the convective heat exchange between human body and the environment. It is a common experience that is possible to offset warm thermal sensations increasing airflow, for example opening windows or using fans.

In this way it is possible to keep thermal comfort for occupants in higher temperature conditions increasing air velocity. This finding is very interesting since in air conditioning environments it could be possible to set the thermostat to higher temperature, decreasing energy consumption while keeping comfort conditions. It is clear that is necessary to calculate the energy cost of the system to increase airflow (usually fans) in order to obtain the real saving.

Standards ([2] and [3]) present a correlation between increase of air temperature and increase of air velocity necessary to keep comfort condition, plotted in Figure 4.



For light primarily sedentary activity, Δt should be < 3 °C and $\bar{v}$ < 0,82 m/s.

Key

Δt temperature rise above 26 °C

$\bar{v}$ mean air velocity, m/s

a Limits for light, primarily sedentary, activity.

b ($\bar{t}_r - t_a$), °C (t_a, air temperature, °C; $\bar{t}_r$, mean radiant temperature, °C).

Figure 4 *Correlation between increase in temperature and air velocity to keep comfort condition[2].*

The lines presented in the figure result in the same total heat transfer from the skin. They are function of the difference between mean radiant temperature and air temperature. It is shown that when mean radiant temperature is low and air temperature high, air velocity is less effective in offset the increase of temperature, and vice versa.
The reference point in this graph is 26 °C and 0.20 m/s of air velocity. It must be considered also clothing, activity and difference between surface temperature of clothing/skin and air temperature in order to assess the benefit that is possible to obtain by increasing airflow. In this graph summer clothing (0.5 clo) and sedentary activity (1.2 met) is considered.
It must be considered draught risk as well, since increasing air velocity could lead to the local discomfort.

Many studies were conducted about airflow types and their effects on human body, both from a psychological and a physiological point of view. Today it is possible to generate different kinds of airflows, from a constant with different velocities, to a simulation of natural wind. Since one of the aim of this work is finding which could be the best solution to keep thermal comfort using fans, it is interesting to make a quick overview of some previous experiment performed on the same matter and their results.

Natural wind seems to be the best solution to cool people with airflow, since in natural ventilated buildings was found that the acceptable air temperature is higher than in air-conditioned rooms. For this reason many studies were realized about responses of people to an airflow generated by fans that simulate natural wind, even if differences in turbulence intensity and power spectrum slope were found between mechanical and actual natural wind.
Zhou (et al. [4]) performed a study about human thermal response to different airflow fluctuations. Constant, sinusoidal and natural wind simulation airflows were used in 2 different thermal environments, neutral warm (30°C) and cool-neutral (26°C).
The following graphs show a qualitative trend for each type of airflow, reporting how the air velocity changes during time:

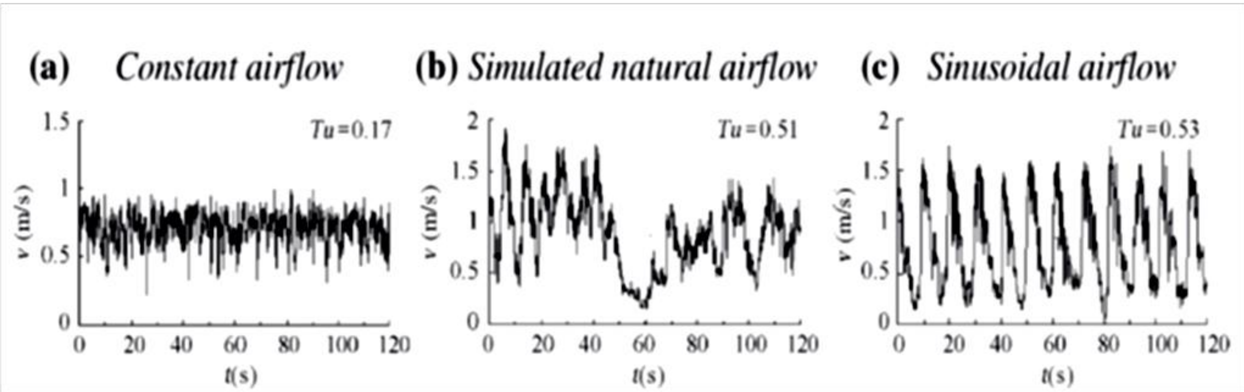


Figure 5 *Airflow patterns provided by fans used in the experiment[4].*

A first result shows that natural simulated wind creates the highest perception of airflow intensity, even if the mean air velocity was equal to constant and sinusoidal flows, in both the condition. Figure 6 reports these findings.

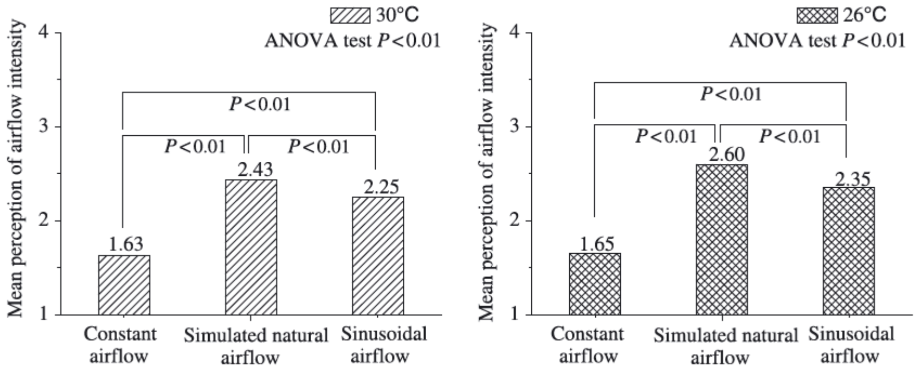


***Figure 6** Perception of airflow intensity with different airflow patterns [4].*

This has been found to be probably due to the higher Tu (turbulence intensity) of this type of flow. About draught sensation, it is very interesting to note that natural wind simulation airflow gets the lowest dissatisfaction at 30°C, while it becomes similar to the others two types of air flow at 26°C, as clearly shown in the figure below.

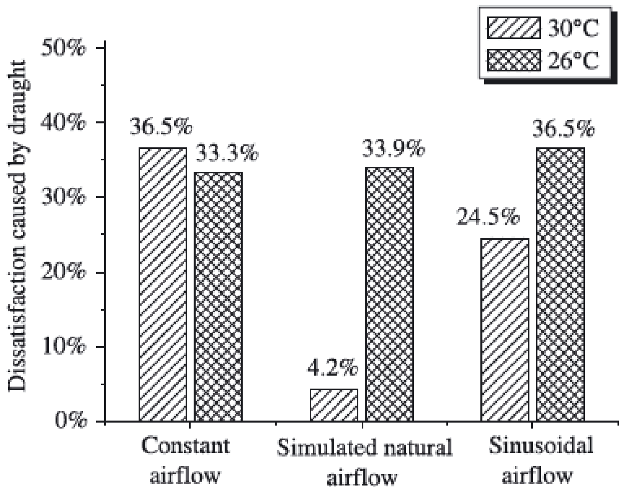


***Figure 7** Dissatisfaction caused by draught with different airflow patterns [4].*

TSV (thermal sensation vote) in both 26°C and 30°C conditions is lower for natural wind and sinusoidal, therefore dynamic airflows have a stronger cooling effect on human body.

TCV (thermal comfort vote) is higher at 30°C for dynamic airflow, instead at 26°C is lower; thus dynamic, and in particular natural simulated, airflows are the most comfortable only with warm environment.

In conclusion it was found that the preferred airflow at 26°C was the constant, and at 30°C simulation of natural wind.

Fanger (et al. [5]) investigated if it is possible to keep comfortable a person at a given air velocity over the entire body adjusting the temperature of the environment. This study is concerned with different air flow direction, since the previous studies analyzed only air flow from above and in front; particularly, if the temperature to be in thermal comfort depends from the direction of the airflow. It was chosen only one air velocity (0.8 m/s). As regard other conditions, it was decided sedentary activity for the subjects, 0.6 clo of clothes insulation, mean radiant temperature equal to air temperature, relative humidity 50%. During the experiments the temperature of the chamber was continuously changed depending on subjects requests.

Results showed that there are slight differences in the preferred air temperature, evaporative weight loss, rectal temperature and skin temperature for the various flow directions.

Subjects prefer on average 2.3 °C higher room temperature with 0.8 m/s air velocity then in still air, but no significant differences for skin temp and other parameters were observed.

On average the subjects prefer 0.7 °C higher temperature at high turbulence intensity, therefore not only mean velocity but also fluctuation of the airflow influences heat balance of the person and thus comfort.

In conclusion it was found that the direction of the airflow is not significant to obtain thermal comfort. Skin temperature and evaporative weight loss are independent from air velocity and direction.

Draught is one of the most common causes of complaint in ventilated or air-conditioned environments. Increase air movement by fans obviously could lead to this problem.

In another study Fanger (et al. [6]) carried out an analysis about the impact of turbulence intensity on sensation of draught. Subjects were exposed to different air velocities with different levels of turbulence intensity. The experiment led to some results: increase in air velocity and/or turbulence creates an increase in the percentage of dissatisfied people. As expected, it was found that the regions with most complaints were head, arms and feet. For a given percentage of people feeling draught, a quite higher mean velocity can be used when the air flow has low turbulence intensity.

It was also confirmed the result of previous studies: people feel more comfortable a constant flow than a fluctuating velocity, typical of high turbulence flow. High turbulence is felt uncomfortable because convective heat transfer grows with turbulence itself. Another reason proposed is fluctuation of skin temperature that is read as a warning sign from the brain and leads to an uncomfortable sensation.

Two kinds of thermo-receptors were considered in this study to find a correlation with thermal environment assessments of subjects, static and dynamic: static receptors act depending on the level of skin temperature, dynamic on the rate of change of skin temperature.

A model for the prediction of dissatisfied people percentage (PD) due to draught as a function of air temperature, mean velocity and turbulence intensity, based on these patterns of responses, is presented as well. Figure 8 in the next page shows a 3D representation of the model.

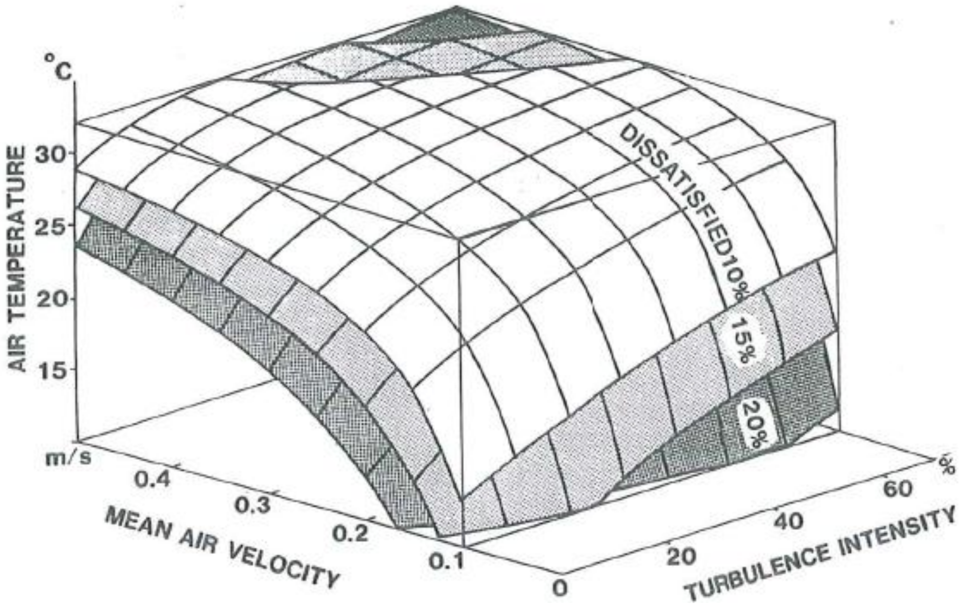


Figure 8 *PD due to draught as function of air velocity, temperature and turbulence intensity [6].*

It is possible to verify how the highest percentage of dissatisfied people is for high turbulence intensity, high mean air velocity, and low air temperature.

Subjects' evaluations of different indoor environment conditions and airflows were also investigated by Hiroko (et al [7]). Changing temperature and humidity, preferred air velocity were found in each analyzed condition. For example with 26 °C and 50% RH it was found that the preferred air velocity was 0.53 m/s, while with 30 °C and 80% RH was 1.27 m/s.
An interesting result about thermal sensation vote is presented: when subjects were exposed to preferred air velocity, they mostly reported themselves slightly cool in the case of all air temperatures and humidity. Thermal comfort vote instead has been always comfortable.
One of the aim of this research was finding limits in air temperature at which thermal comfort can be obtained with the preferred air velocity, considering age and sex. No significant differences were found between male and female subjects, instead it was found between young and old. For young subjects the study revealed that the lower temperature able to provide thermal comfort is 26 °C, 30 °C the upper, when the subjects wear a 0.3 clo clothes. For old people, the authors suggest to use an air velocity at values about 0.2 m/s lower than the young at the same temperature.

1.3 - Thermal adaptation

A comparison between thermal comfort assessments of people from China and people from Scandinavian countries is part of the present work. The aim is making an evaluation of possible differences in perception of the same warm environment between people used to quite different climates. While Chinese subjects from previous experiments were used to warm and humid condition, Danish people live in a cooler region.
The process of adaptation could take part in providing different responses regarding the same thermal environment, but there are various mechanisms that go under this concept.

Standard ISO 7730 [2] considers the topic of adaptation in general, reporting that "in warm or cold environments, there can often be an influence due to adaptation. Apart from clothing, other forms of adaptation, such as body posture and decreased activity, which are difficult to quantify, can result in the acceptance of higher indoor temperatures. People used to work in warm climates can more easily accept and maintain a higher work performance in hot environments than those living in colder climates".

A comprehensive review about the theme of thermal adaptation is presented by Gail S. Brager (et al. [8]), where basically is reported how people's thermal perception is influenced by past "thermal history" and cultural and technical practices, leading from the classic heat balance model to the new concept of adaptive one.
The old approach considers the person only as a passive actor, since the thermal exchange with a given environment depends exclusively by physical processes between body and environment itself. Starting from this concept, many experiments in climate chambers were performed, where each parameter of the environment was set by the experimenters, from temperature and humidity to clothes and possibility of using cooling systems like fans.
The new approach sees people playing a primary role in building a desired thermal condition, interacting with the environment, modifying the behavior and adapting their expectations.

Widely defined as gradual diminution of organism's response to repeated environmental stimulations, adaptation could be divided in three main processes:

1. Behavioral adjustments: modifications that a person could make to alter the heat exchange with the environment. It is possible to define: personal adjustments, like changing clothes, postures, drinking cold/hot beverages; technological and environmental adjustments, like opening/closing windows, turning on fans or heating; cultural adjustments, that means scheduling activities.
2. Physiological feedback, acclimatization: it derives from changes in body responses due to long exposure to thermal factors, leading to less strain from the environment. This kind of adaptation can be divided in 2 categories: genetic adaptation, coming from genetic heritage of an individual group of people, and acclimatization so-called, consisting in changes in the setting of the thermoregulation system over a period of days or weeks.

   Being this aspect of adaptation close to our investigation, it is worth to say something more about. While adaptation to cold environments is mainly found to be behavioral, for heat exposure physiological mechanisms are involved.

Especially in hot-dry climates the first system triggered is an increase in sweating capacity for a given heat load. Other changes related to thermoregulatory sweating are a fall in set-point body temperature at which sweating started and a better distribution of sweat on the skin, but different mechanisms, such as reduction of heart rate, are also present.

All this human body responses depend on the type of environment considered; for hot and humid climates indeed the elevated capacity of sweating seems to be less important. In this situation, increasing in heat loss is obtained by a rise in peripheral blood flow and elevated skin temperature that means increase in dry heat exchange.

3. Psychological feedback: habituation and expectation modify persons' perception and reaction to sensory stimuli. Repeated or chronic exposure to an environmental stress brings to a less sensation intensity after a certain period.

   This adaptation mechanism likely covers the most important reason that lead to differences in observed and predicted thermal sensation. Even if the most difficult to analyze and the least studied, its importance is acknowledged in recent study as McIntyre [9] one, who says "a person's reaction to a temperature which is less than perfect will depend very much on his expectations, personality and what else he is doing at the time".

Various studies in climate chambers were performed to analyze the whole process of adaptation, but it should be take into account the lack of realism of these particular experiments. However, it is useful to have the high degree of control and reproducibility typical of laboratory's experiments.

Results from these works, where people used to different thermal environment were compared, showed that the process of physiological acclimatization seems not to influence subjective discomfort and thermal acceptability under the most typical conditions in residences and office buildings.

Particularly, Fanger (et al. [10], [11]) using a climate chamber compared the temperature preferences of three group of Danish subjects, college students, winter swimmers, meat packers from a refrigerated storeroom. The results showed that there were no significant differences in the preferred temperature that was found to be about 25.5 °C.

Different findings come from field analysis instead, where is found how indoor temperatures and occupant thermal expectations are dependent on outdoor temperature.

Humphreys [12] presented a work where is reported the relation between mean monthly outdoor temperature and so-called indoor neutrality, that is the temperature at which subjects stated comfortable the thermal environment. Data from "climate controlled buildings" (with centralized HVAC) and "free running buildings" (without centralized heating and cooling) are graphed in Figure 9, where for this second type the influence of the external climate appears stronger.

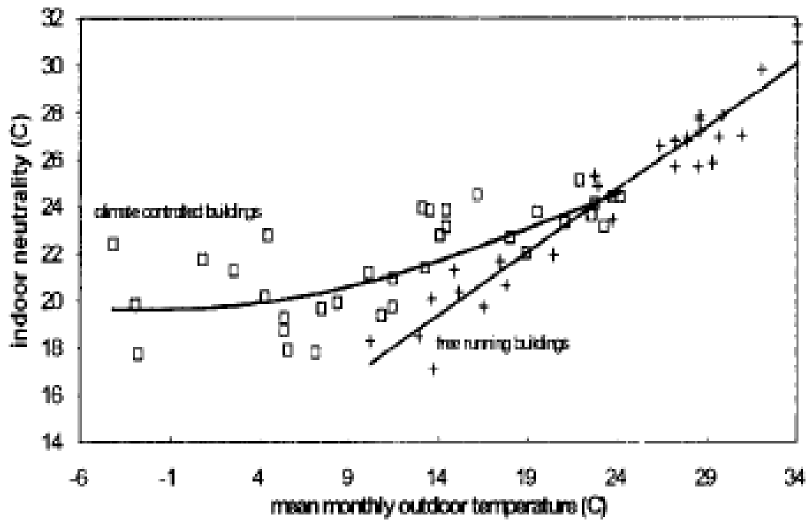


Figure 9 *Indoor neutrality as function of mean monthly outdoor temperature [13].*

It is therefore found that acclimatization is an occurring phenomenon, since acceptable temperature of indoor environments grows with the outdoor temperature during the year.

Also psychological topic has been investigated by numerous studies. The main aspect influencing this side of adaptation seems to be the perceived degree of control on thermal environment that occupants can experience. More control of indoor climate means higher levels of satisfaction, even if the thermal conditions are exactly the same of a less personal-controlled environment.

It is fair to report how responses of air-conditioned buildings' occupants are quite different from naturally ventilated buildings' ones. Expectation (considered as part of the psychological feedback) plays the most important role, since past thermal experiences in a particular environment create a reference for the future. In air-conditioned buildings, occupants expect a particular thermal environment, characterized by cool, constant, uniform conditions: essentially, they base the evaluations on the benchmark of their own preconceptions of what air-conditioning should achieve.
On the other hand, occupants of naturally ventilated buildings recognize how the indoor environment follows the diurnal and seasonal variations. In this way subjects' expectations of thermal comfort are not so strict, both regarding indoor temperature mean value and fluctuation intensity.

Buildings with indoor climate closer to outside conditions and higher control degree of thermal comfort parameters could lead to a new concept of indoor environment, with different advantages, especially improvements in comfort and potential energy savings.
As reported by Christhina Candido [14] "it is possible to physiologically acclimatize such air-conditioning addicts to warmer indoor environment without, however, compromising their thermal acceptability. These results reinforce the opportunities to higher set points in air conditioning buildings, contributing to significant energy consumption cut-offs within the built environment".

Therefore, adaptation brings occupants to feel in every case comfortable also with rising in set point temperature (in warm environment case), and personal control of thermal variables improves psychological condition.

Using fans to cool people in warm climates goes in this ideal direction, since increasing in rooms' temperature is allowed by the compensation of airflow effect: it is possible to follow more closely outdoor trend of temperatures and humidity, also reducing energy consumption for the HVAC systems. On the other hand, personal control of fans' air velocity leads to an improvement in psychological disposition, and in conclusion could bring to an higher thermal comfort sensation perceived.

1.4 - Energy implications

Using fans to provide subjects' thermal comfort in warm environments has different implications. It is clear that a fan is a simple machine compared to an air conditioning system; fans are a cheaper and less problematic system. No pipes, refrigerant fluids, compressors, heat exchangers etc. implies lower cost of purchase, easier installation, absence of maintenance, less environmental problems.

From another point of view, it is possible to combine fans and air conditioning (AC) to obtain energy savings. The main idea is to keep higher the temperature of the environment, reducing energy consumption of the AC system, and to compensate it by using airflows generated by fans.

In the Environment Design Guide Richard Aynsley [15] reports a review of a research by the US utility company Reliant Energy, which indicates that for each Celsius degree raised in the temperature set above 25°C in summer, a cooling energy saving between 9% and 12% with the air conditioning system can be achieved. The energy consumption of circulating fans running at high speed for summer cooling is approximately 2% of the air conditioning savings, leaving net savings from between 7% to 10% for every degree of thermostat rise.

Different and more complete results were reported by Schiavon and Melikov [16]. A simulation of energy consumption in different cities and for different categories of building was performed. It was consider an HVAC system and the use of fans to increase the set temperature in the indoor environment, keeping occupants' comfort conditions.

In every case it was calculated the so-called net electrical energy saved [kWh/(m^2y)], difference between the saved (in the chiller) and the consumed (by the fans) energy.

It is clear that different parameters take part in this computation, such as air velocity used with fans, COP of the chiller and electrical input power of the fan, being found this last one the critical factor.

The results of these analysis report that is never possible to reach a net energy saving with a fan input power higher than 60 W, while on the other side is always possible to obtain energy saving when the input power is lower than 15 W.

Moreover, in case of best values for COP (about 4), energy saving will not be achieved with fans using more than 20 W of power input.

However it is possible to say that high performances for the HAVC system should be considered in case of new buildings; an elevated COP value is indeed achievable with the current technology. In case of evaluation with an existing air conditioning system, less restrictive limits could be used.
Less than 20 W electrical power input is typical for small desk fans, while ceiling fans and standing fans basically cannot be used for saving energy since they need respectively about 70 W and 50 W.
In Figure 10, some graphs show how much energy can be saved as a function of the fan input power.

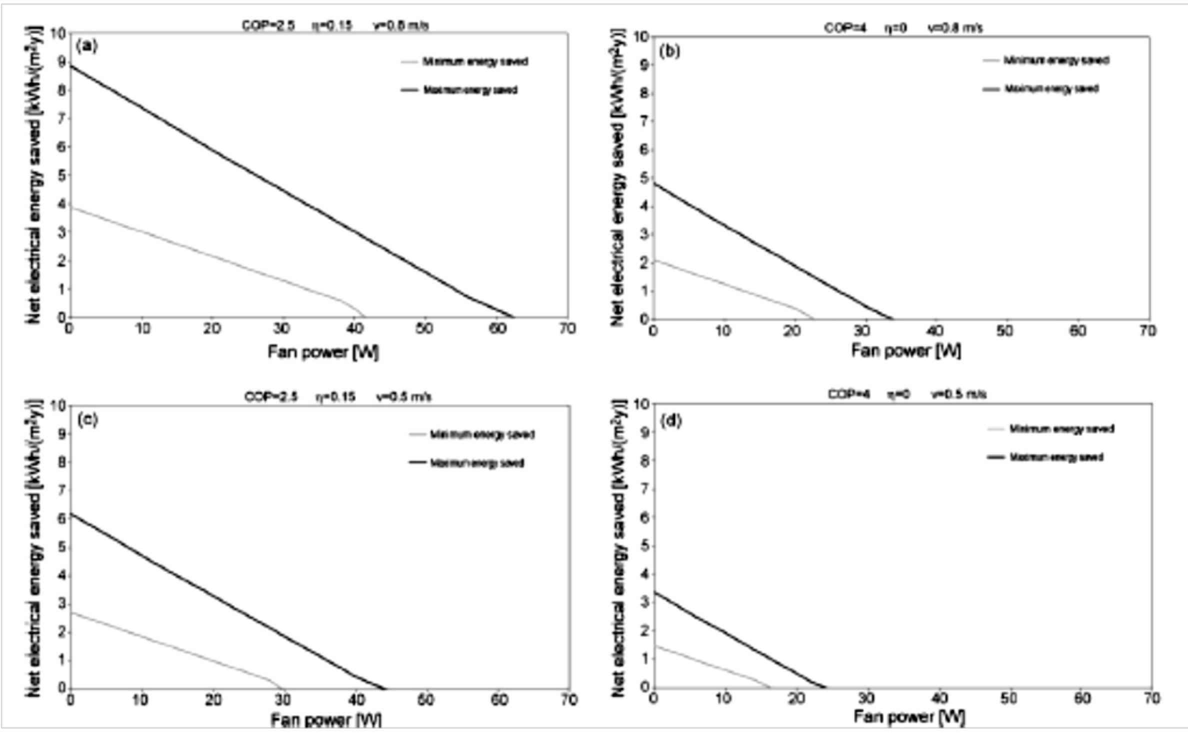


Figure 10 *Energy saving as function of fan power and performance of the chiller [16].*

Extreme cases of HVAC performances are reported, in order to show which is the maximum and the minimum saving possible to obtain. The two lines represent the band of energy saving values expected for those conditions.
Two air velocities are considered, 0.5 m/s and 0.8 m/s; higher air velocity allows higher energy savings.

1.5 - Objectives

This brief literature review shows what standards and studies related to the planned study already report. The purpose of the present work is to:

- See if an increase in air velocity can actually compensate for an increase in air temperature, keeping comfort condition for the occupants. Particular attention is paid to the use of mechanical simulation of natural wind and the capacity to create a higher cooling effect on people compare to the constant airflow.
- Find if people exposed to simulated natural wind can accept warmer environmental condition and higher mean air velocities than when exposed to constant airflow.
- Analyze if Danish subjects state as acceptable the same warm environmental conditions as Chinese subjects, and particularly if there is a difference in the acceptability of high air velocity. The theme of adaptation plays an important role in these aspects.

Chapter 2 - METHODS

Experiments with subjects in a particular chamber simulating an office were performed. Different velocities provided by fans were used while different room temperatures set. Assessments of occupants and measurements of physical parameters as air temperatures and air velocities were collected during each exposures.

2.1 - Experimental Chamber

The experiments, including also the humans' subjects experiment, were performed in a particular climatic chamber at the International Centre for Indoor Environment and Energy of the Technical University of Denmark.

The dimensions of the room are 5.9*5.8*3.2 m.

A mixing ventilation system for providing the desired temperature and fresh air flow is installed. The supply air terminal devices are located at 2.5 m of height, and consist of two outlets, with nozzles directed in the center of the room in order to create the most uniform airflow possible that generates an optimum mixing without annoying subjects. Evidences of the trend of the airflow were carried out by a smoke machine; it was possible to see how the air is first directed towards the chamber's centre, then goes down reaching the floor and moving to the wall with the external windows, and finally comes to subjects' location, when by now the velocity is very low and cannot provoke any bothering for draught.

Figure 11 *Supply air terminal device and airflow evidence provided by smoke machine.*

The exhausted air terminal is located at the floor level, and presents a silencer to reduce the background noise caused by the ventilation system.

Room temperature is controlled by a transducer, placed in the room's centre at 1.1 m height above the floor. The signal is then elaborated by a pc software control system, and in this way air heating or cooling activated.

This sensor can also record the value of relative humidity, but the system cannot provide any control of this parameter. Therefore, seven ultrasonic humidifiers were put in the room at 2.5 m of high in two corners, and activated manually when necessary by the experimenter, who was informed in real time about the value of this variable.

Figure 12 *Ultrasonic humidifier.*

Beyond thermal parameter's control systems, the room was furnished with 8 desks and chairs that subjects used to take place. Another desk and chair were put in a corner for the experimenter. Other furnishing elements were desk lamps and fake plants, in order to reproduce as similar as possible a real office environment. Laptops, with allowed internet connection, were also provided to the subjects, and of course a personal fan, the most important element for our experiment.

One wall of the room presented windows with a view on the outdoor, and blinds to shading direct sunlight were present on.

For interior lighting twelve ceiling lamps were switched on if necessary.

The layout of the chamber was almost symmetrical, with four desks for each side. In the middle a partition was placed, to avoid that the airflow coming from fans in one side of the room affected the responses of the subjects sitting in the other side. A scheme is reported in Figure 13.

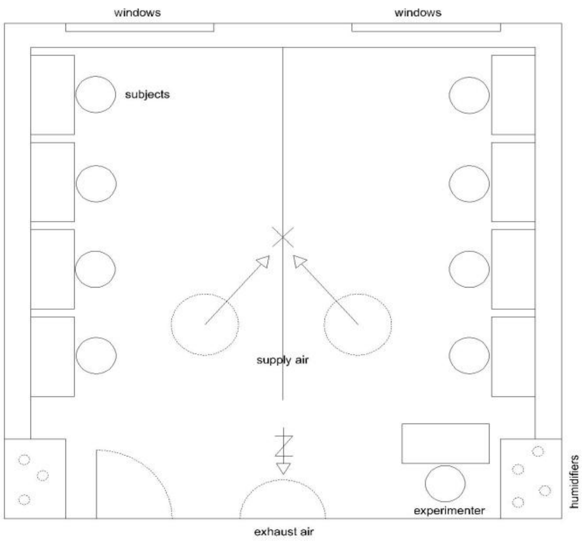


Figure 13 *Plan of the experimental chamber.*

It is worth to report some consideration about the thermal behavior of the chamber used in this experiment. All the objects present inside the room (chairs, desks...) created a kind of thermal inertia; therefore changing the temperature to different values sometimes was difficult, since it was necessary to overheat/overcool the air in the chamber itself, waiting for all the furniture to reach the set temperature.

Another aspect regarded the position of the room that was with ceiling and a wall directly outwards, and the presence of a lot of glass surfaces due to the windows. While the typical climate chamber is located entirely inside a building and thus extremely controllable, keeping stable condition in our case was sometimes difficult. Outwards walls meant more thermal dispersions, instead windows lead not only to bigger dispersion, but also to problems including radiant asymmetry. From one side this can be seen as a disadvantage, since reproducibility is partly compromised; but from another, subjects were in an indoor situation closer to a real office location, so it is possible to say that personal assessments of the thermal environment were affected by less lack of realism, problem typical for traditional climate chamber.

Lastly, also the position of the humidifiers was relevant: placing them in two corners brought the moisture generated to concentrate in one area, which it could un-likely provoke a higher perception of air humidity for those subjects sitting near these zones.

2.2 - Air and Globe Temperature sensors

Calculation of thermal comfort requires to know air and operative temperature. To obtain these values, air temperature and globe temperature sensors were put in different places in our chamber.

Differences characterize these instruments:

- air temperature sensor records air temperature itself, since it presents a protection for thermal radiation surrounding the sensitive element;
- globe temperature sensor records operative temperature, defined as the temperature of an imaginary enclosure with the same dry heat exchange by radiation and convection as in the actual environment. The sensor is built as a sphere with the sensitive element inside; in this way it can record the temperature deriving from the air surrounding it and from the radiation heat flow coming from all the surfaces of the environment in which is placed.

The exit of these instruments is voltage, and was recorded in portable HOBO data loggers. To obtain temperature's values a calibration equation is necessary. Calibration was carried out in a particular chamber where room's temperature was easy and fast to control. The temperature range used was from 37.7 °C to 15 °C, and as reference a thermometer with ±0.1°C accuracy was used. The accuracy of the air and globe temperature sensors resulted to be within ±0.3°C.

Values of relative humidity were also recorded during the experiments by the integrated sensor in the HOBO, with an accuracy of ±5% in the range 0÷90%.

The sampling rate of the data logger was set to 30 seconds.

Figure 14 *Globe and air temperature sensors mounted on a stand.*

2.3 - Air velocity sensors

Sensoanemo Anemometer

Anemometers consisting of a 2 mm omnidirectional spherical sensor were used to take air speed measurements during all the experiments and to check the air velocity that was possible to obtain from the fans. Characteristics of these instruments are: range of speed from 0.05 to 5 m/s; accuracy ±0.02 m/s ±1% of the reading.

Figure 15 *Close view of the anemometer Sensoanemo.*

During the experiments four of these sensors were placed on a stand at the reference heights of 0.1, 0.6, 1.1, 1.7 m, and were connected to a wireless transmitter. This transmitter communicated with a USB receiver connected to a computer, where a software recorded air temperature and air velocity with average and standard deviation.
The stand was usually placed in front of a desk, simulating a subject. When all the desks were occupied by subjects, it was put behind one of them.
Anemometers were also used to check the different air velocities generated by the desk fans, changing the distance between sensor and fan itself.
Since the probe of these instruments is very delicate, a protection is provided. Though this protection should not influence the air flow, and what is recorded by the sensor, differences were found using the probe with/without it. Particularly, a lower value of air velocity was found using the protection.

Swema 3000 Anemometer

To check the air velocities provided by the fan a Swema 3000 anemometer was used as well.
Also the sensor of this instrument is omnidirectional. Characteristics are: range of speed 0.1 - 10 m/s; accuracy ±0.04 m/s ±4.5% of the read value.

Figure 16 *Swema 3000 anemometer.*

2.4 - Experimental setup

Sensors for air temperature, globe temperature, relative humidity and air velocity were placed at different height in the positions shown in Table 2 and Figure 17.

Table 2 *List of recorded parameter during the exposures.*

Position	Height [m]	T air	T globe	RH	V air
A	1.1	X	X	X	
	0.6	X	X	X	
B	0.6	X	X	X	
C	0.6	X	X	X	
D	1.7	X	X		X
	1.1	X	X	X	X
	0.6	X	X	X	X
	0.1	X	X	X	X

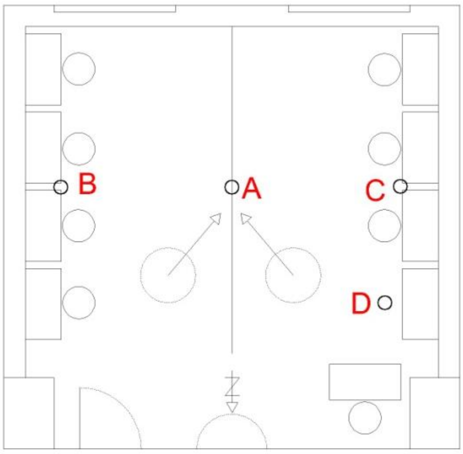


Figure 17 *Position of sensors in the room.*

2.5 - Skin temperature sensors

The skin temperature of four body area of subjects was continuously recorded during the experiments: forehead, right scapula, left hand, right shin. In this way it has been possible to calculate an average value of the skin temperature and check its trend during the different conditions subjects were exposed to.

iButtons sensors were used, consisting in small instrument similar to a button, without wires, with dimensions of 17 mm of diameter and 6 mm of height.

They can operate in a range of +15 ÷ +46 ±1°C and can store up to 2048 temperature values in a built-in data logger. The sampling rate was set of 2 seconds.

These sensors were applied directly on subjects' skin using medical tape, after cleaning skin surface with medical alcohol in order to remove eventual skin grease, make-up or else.

iButtons were calibrated as well as air and globe sensors.

Figure 18 *Skin temperature sensor.*

2.6 - Noise measurements

Noise level measurements were performed during each experiment. It was used a noise level meter with range 35 to 100 dB and accuracy of 2 dB.
Spot measurements were repeatedly taken in different locations of the chamber, especially in the room centre and near the subjects.
One of the main goal was to record the maximum noise level achievable during the whole experiment; fans operating in natural wind simulation presented peaks of velocity that involve elevated noise level, likely leading to annoyance for the occupants.

Figure 19 *Noise level meter.*

2.7 - Heart rate measurements

In order to calculate the metabolic activity level, Suunto heart rate memory belt were used. This instrument can record data on an integrated memory chip for downloading and analyzing at a later time, using a docking station. It is fair to say that the belt is realized for monitoring athletic activity, while in our case subjects were performing sedentary tasks, and this could lead to an higher error in the beat rate recording.

Figure 20 *Heart rate belt.*

2.8 - Fans

All the different patterns of airflow used in our experiments were generated by the same type of fan. It consists in a stand box fan with 28 cm of diameter, equipped with an external control unit programmed at Tsinghua University, Beijing, China [17].

Figure 21 *Fans used during the experiments.*

The control unit allows to create basically three different types of airflow: constant, sinusoidal, natural wind simulation. For each of these it is possible to choose different air velocities.
While constant airflow does not need particular insights, sinusoidal trend and natural wind simulation present particular features.
Sinusoidal airflow pattern reproduces a sinusoidal wave, where the two main parameters are air velocity and frequency. Both can be controlled by the electronics the fan is equipped with. Many experiments were performed in order to analyze the effects of this model, finding as increasing frequency leads to a higher perception of cooling by the subjects, keeping constant the air velocity.
On the other hand, draught risk is increased as well.
As regard wind simulation, the aim of the manufacturers is to reproduce exactly the trend of airflow it is possible to find in outside; however some studies demonstrated that natural and mechanical wind present differences in power spectrum and turbulence intensity. Anyway these fans can reproduce a random progress, with peaks of velocity typical of the wind gusts, presenting therefore a completely different effect on human air intensity perception. In our case, the fans developed all the pattern trend in one hour, after which the air flow model started again. For this reason, measurements and subjects' exposure to natural wind simulation lasted one hour. The only parameter possible to control with this setting is choosing three different air velocities, that mean the same curve of trend is reproduced with higher or lower air flow intensity.

In our experiments constant and natural wind simulation were used. Especially, one of the aim was a comparison between the different effects these airflow patterns can create on human body's thermal sensation, and which one could be considered as preferable.
The settings we decided to use will be further explained in the experimental procedure chapter.

Fans were placed in a raised position in front of the desk, slightly inclined, in order not to hinder the airflow with the laptop screens. Though in other previous experiment performed the position was different, for example on one side of the desk, it is documented as changing the direction of the airflow lead to negligible differences in human perception and in heat loss achieved [5].

Figure 22 *Subjects during an experimental session.*

2.9 - Thermal manikins tests

Two thermal manikins were used to obtain a measure of the local dry heat loss of the human body in most of the environmental conditions we realized in our experiment.
The body of these "instruments" is realized in glass fibre and presents a nickel wire imbedded inside, in order to provide the heat flux. It is divided in many thermal sections, whose regulation is independent. External equipment consists of a small power supply and a laptop to control the manikin itself. The pc software presents four control modes to run the manikins: only measuring, no heat; heating to keep constant surface temperature; heating with fixed heat loss; comfort equation.
The last one was used during our measurements, since it allows to simulate human thermal behavior and therefore to make a comparison with occupants' assessments.
Manikins were dressed with a clothing insulation of about 0.5 clo, the same subjects had in the experiments, and placed at two different workplaces.
Some exposures of our experiments were repeated with the two manikins inside the chamber, while surface temperatures and power consumption were recorded.
From power consumption P [W/m^2] is possible to obtain directly the dry heat loss, while is possible to calculate the equivalent temperature T_{eq} [°C] from surface temperature T [°C], power consumption P [W/m^2] and heat transfer coefficient h [$W/(m^2$°C)], for each part of the body [18]:

$$T_{eq} = \mathrm{T} - \frac{\mathrm{P}}{h}$$

Equivalent temperature is defined as "the uniform temperature of the imaginary enclosure with air velocity equal to zero in which a person will exchange the same dry heat by radiation and convection as in the actual non-uniform environment". In our case, having the values for each part of the body, we calculated the so-called local equivalent temperature that is a useful value to understand how the body is reacting to a given thermal environment.
While heat loss and skin temperature derive directly from data recorded during the experiments, heat transfer coefficients come from a calibration carried out before the experiments.

Figure 23 *Thermal manikins during previous tests.*

2.10 - Questionnaires

A background questionnaire before the first experiment was given to each subject, which included assessments about: hours per day at the desk; self-assessed preference of thermal environment comparing to other people; self-assessed sensitivity to draught comparing to other people; occurrence of certain body parts warmer or colder than the rest of the body; use of optical devices; self-assessed health state; occurrence on daily bothering by draught; occurrence of mucous or skin irritation.

During each exposure different questionnaires were given to the subjects; the schedule is reported in the experimental procedure chapter.
Questions regarded:
1) thermal environment, namely thermal comfort, thermal acceptability, air movement preference, local air movement sensation, local comfort sensation;
2) air quality, namely acceptability of air quality, perception of air humidity, preference on air humidity;
3) satisfaction with light and noise level;
4) experience of symptoms such as headache, dry eyes, irritated throat, nose irritation;
5) preference in using fan or air conditioning in the given environment and assessments about current value of air velocity.

The questionnaires consisted mainly of continuous-scale evaluations. The acceptability scale for thermal environment, air movement, noise level, light level and indoor air quality were divided in two parts, to get the subjects making a clear choice. Space for other personal comments about exposure experience was available in each questionnaire.

Subjects voted their thermal sensation using the continuous scale reported below (Figure 24).
The question was "Right now, how do you feel?":

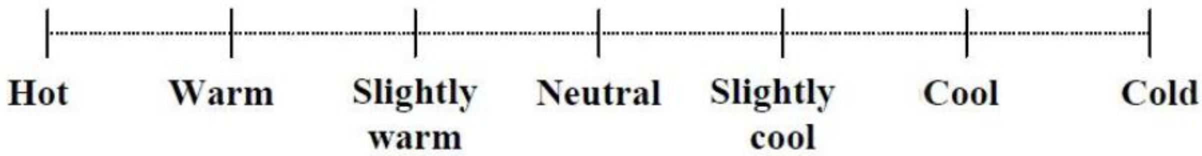


Figure 24 *Continuous scale for the Thermal Sensation Vote.*

Comparison between Thermal Sensation Vote, coming out from this assessment, and PMV, calculated on the basis of thermal environment parameters, was carried out.

2.11 - Experimental procedure

Basically two types of experiments were performed. During each experiment there were from one to eight subjects; it would have been preferable to have a constant number of occupants during every experiment, to obtain more constant conditions between the exposures, but problems regarding organization and availability of subjects occurred.

Before each session, six dummies were placed inside the chamber, in order to simulate the heat load of the subjects and thus keeping the chamber as close as possible to its steady state after the entrance of the occupants in the room.

All the sessions were performed between September the 17th and October the 8th; experiments from 9:00 to 11:00 and from 14:00 to 16:00 were scheduled.

During each experiment it was not possible to smoke or consume own food and beverages, only mineral water was provided by the experimental staff.

2.11.1 - First type experiment

Five conditions were investigated in these exposures. The following table reports all of them:

Table 3 *Physical parameters set during the first experiments.*

Air temperature [°C]	RH [%]	Condition name
26	50	E
28	45	B
30	40	C
32	36	A
34	32	D

Combinations of temperature and relative humidity were set in order to keep constant the absolute humidity at 12 g/kg, since subjects' skin transpiration is sensible to this parameter.

For each condition, after a period of adaptation without airflow from the fan, subjects were exposed to different air velocities, decided by the experimenter; then they were allowed to regulate the velocity as they preferred, while in the last step subjects were asked not to change the setting they decided. Only constant airflows were used during this type of experiment. The schedule of each experiment follows:

	26 °C / Condition E				
Time [min]	00:00-00:45	00:45-01:00	01:00-01:15	01:15-01:30	01:30-01:45
Air movement	Fan off	0.6 m/s	1 m/s	Free adjust	Fixed

	28 °C / Condition B					
Time [min]	00:00-00:45	00:45-01:00	01:00-01:15	01:15-01:30	01:30-01:45	01:45-02:00
Air movement	Fan off	0.6 m/s	1 m/s	1.5 m/s	Free adjust	Fixed

	30 °C / Condition C					
Time [min]	00:00-00:45	00:45-01:00	01:00-01:15	01:15-01:30	01:30-01:45	01:45-02:00
Air movement	Fan off	0.6 m/s	1 m/s	1.5 m/s	Free adjust	Fixed

	32 °C / Condition A					
Time [min]	00:00-00:45	00:45-01:00	01:00-01:15	01:15-01:30	01:30-01:45	01:45-02:00
Air movement	Fan off	1 m/s	1.5 m/s	2 m/s	Free adjust	Fixed

	34 °C / Condition D					
Time [min]	00:00-00:45	00:45-01:00	01:00-01:15	01:15-01:30	01:30-01:45	01:45-02:00
Air movement	Fan off	1 m/s	1.5 m/s	2 m/s	Free adjust	Fixed

The sequence of air velocities did not follow the same order in each experiment, but a random one was decided. Thus it has been possible to analyze each type of exposure without considering the possible effects of the previous ones (for example in condition E two sequences were used: 0.6 m/s - 1 m/s and 1 m/s - 0.6 m/s).

After every interval of exposure the subjects were asked to fill in a questionnaire; for experiment E they filled in five questionnaires in total, while for the other six.

During the whole session subjects could use their own laptop, or the one we provide them with.

They were asked to work, perform assignments, and listen to music, reading etc., in order to keep the metabolic activity at the same level of a typical office work situation.

The placement of each subject was random; in this way potential differences in environmental parameters between the eight desks were not considered. Particularly, air velocity provided by the fans could be slight different from a desk to another using the same setting, because of differences between the fans themselves and because of the different location of workstations, being some of them near the wall while other in a centered position.

For every experiment the preferred air velocity for each subject was found and recorded as fan-setting. Therefore the average constant preferred air velocity was calculated and used as a background to make a comparison with a dynamic airflow in the second type of experiment.

2.11.2 - Second type experiment

The purpose of the second exposures was to compare the effect on human perception of thermal comfort of two airflows with the same average velocity, but with different dynamic characteristic: constant airflow and natural wind simulation airflow. The average velocity to use for the constant airflow was found in the first experiment, where subjects decided which setting they preferred.

Once known this value for each condition, measurements to find fan-setting and distance to obtain the same average velocity with the wind simulation were performed.
The room was then arranged placing desks at the proper distance in order to expose subjects to the same average velocity with both the type of flow patterns.
Not all the five conditions of the previous experiment were investigated, but only the ones reported in the following table:

Table 4 *Physical parameters set during the second experiment.*

Air temperature [°C]	RH [%]	Condition name
28	45	2
30	40	1

The experiments consisted in two hours of exposure to the two airflows, one hour to the constant one, one to the dynamic one. Also in this case the order of the two exposures was random.
The subjects were asked to fill in three questionnaires, one immediately after entering the chamber, one after the first hour, one after the second one.
The schedule of the exposures follows:

	28 °C / Condition 2	
Time [min]	00:00-01:00	01:00-02:00
Air movement	Constant flow	Natural wind simulation
Mean air velocity	0.82 m/s	0.89 m/s

	30 °C / Condition 1	
Time [min]	00:00-01:00	01:00-02:00
Air movement	Constant flow	Natural wind simulation
Mean air velocity	1.03 m/s	1.03 m/s

The questionnaires the subjects were asked to fill in were similar to the previous experiment.
During the whole experiment they were asked to use only the laptops we provided them with. Between the questionnaires some tasks were given, such as typing exercises and link-numbers games. In this way it has been possible from one hand to keep constant the metabolic level, from the other hand to have a task-performance assessment, to evaluate how in warm condition and under airflows exposure the ability to carry out assignments changes.

Chapter 3 - RESULTS

3.1 - Fans

A description of the fans used is reported in the previous chapter Methods. The velocities decided to analyze are reported in the experiments' schedules.
To find out which were the distances and the fan's settings to use in order to obtain these velocities, values from Chinese experimenters' previous analysis were considered.
Once the whole experiment was finished, new measurements were performed to check again the correspondence between expected values and actual values, and to verify the trend of the airflow during time. Two different type of anemometers were utilized, Sensoanemo and Swema instruments. Below some results from these last tests are reported.

3.1.1 - First type experiment

The following table shows the results of measurements obtained from the fan placed on desk 3 in the experimental chamber, using a Sensoanemo anemometer. The distance between the fan and the sensor of the instrument was 80 cm, the height of the sensor was 120 cm. These values come from the average position of subjects' face, when sitting at the desk in our chamber. The columns report in the order: setting of the fan used, expected air velocity from previous measurements with that setting $v_{a,\ expected}$, average air velocity measured with our instrument and correspondent standard deviation $v_{a,\ measured}$ ± St Dev, maximum and minimum values measured $v_{a,\ max}$ and $v_{a,\ min}$.

Table 5 *Air velocities expected and measured for first experiment fans' settings with Sensoanemo anemometer.*

Setting	$v_{a,\ expected}$ [m/s]	$v_{a,\ measured}$ ± St Dev [m/s]	$v_{a,\ max}$ [m/s]	$v_{a,\ min}$ [m/s]
type 1, 0 lights	0,6	0,79±0,04	0,85	0,59
type 1, 2 lights	1,0	1,01±0,07	1,14	0,85
type 4, subtype 2	1,5	1,30±0,13	1,49	0,94
type 1, 9 lights	2,0	1,83±0,11	2,02	1,50

Similar tests were performed with a different fan and with a different instrument. The results are reported in Appendix B.

The first observation regards the differences found between expected and measured test value of the velocities recorded. While for the lowest, 0.6 m/s, the measured actual value is higher, for 1.5 and 2 m/s is lower. This trend is found also with other fans and instruments. The maximum differences between previous and following measurements are around 0.2 m/s, an amount that should be consider when evaluating subjects' assessments.

In order not to create confusion with different numbers to identify the same airflow exposures, expected values of air velocity (table 5) are kept also in the following discussions, remembering otherwise the not negligible differences found.

The second observation regards the differences between maximum and minimum values of the air velocities, higher than 0.5 m/s in some cases. This shows how the trend of the airflow generated by the fan is not particularly constant, presenting peaks and valleys. These aspects are more clearly visible using graphs.

The following Figure 25 presents the trend of the airflow for the setting that should provide a constant trend with 0.6 m/s of air velocity. Airflows from two different fans are shown in the same graph; the instrument was the same, Sensoanemo anemometer. The data were recorded for tree minutes, as done in the previous experimenters' measurements. Sample rating was set on 2 seconds.

Fan number 3 clearly presents a more stable trend, but provides an average velocity of about 0.8 m/s. Fan number 2 otherwise generates an average velocity closer to the one wanted, but the trend is very unstable.

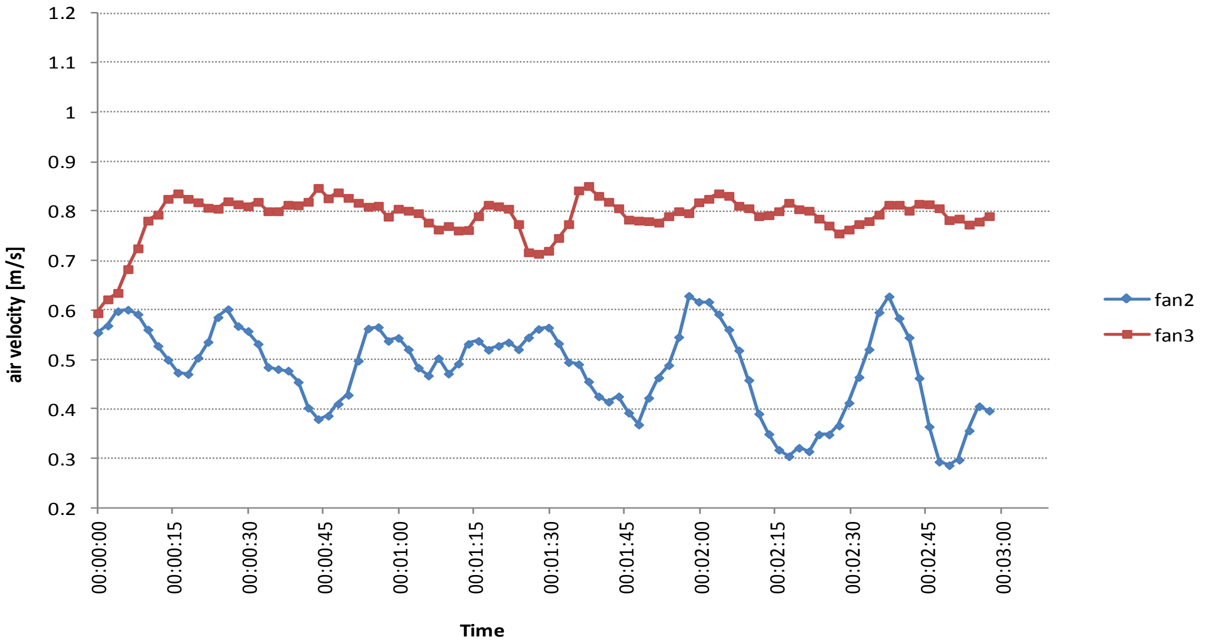


Figure 25 *Airflow trends for fans' setting that should provide 0.6 m/s of constant air velocity. Instrument used Sensoanemo, fan number 2 and 3 recorded.*

The same interval of time has been recorded with Swema anemometer for fan number 3, with an higher sample rate set on 0.1 seconds. The graph in the following page shows the trend, clearly similar to the one recorded with the other anemometer. Obviously it presents a much higher density of points, since sample rate is much higher.

Moreover, the differences it is possible to note are higher maximum and lower minimum values recorded. Thus the two types of instruments are characterized by a different sensibility.

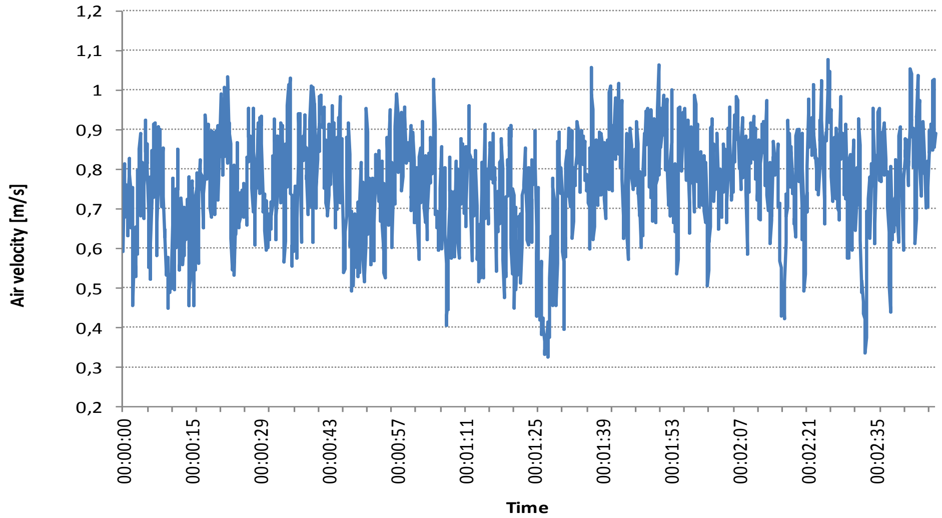


Figure 26 *Airflow trend for fan' setting that should provide 0.6 m/s of constant air velocity. Instrument used Swema 3000, fan used number 3.*

Graphs for every exposure's velocity are reported in Appendix B. They compare the flows generated by fans two and tree recorded with Sensoanemo instrument, and what was registered by Swema anemometer for fan 3 in the same interval of time.

3.1.2 - Second type experiment

Constant and dynamic flows were checked for the second type of experiment as well. The following table reports what has been found in our measurements for the constant airflow of the exposure with 28°C. Distance between fan and sensor was 90 cm, height of sensor 120 cm, fan checked was number tree. The instrument used was Sensoanemo. The values presented in each column are the same of the previous Table 5.

Table 6 *Air velocities expected and measured for second experiment fans' setting that should provide 0.82 m/s of constant air velocity. Instrument used Sensoanemo anemometer.*

Setting	$v_{a, expected}$ [m/s]	$v_{a, measured}$ ± St Dev [m/s]	$v_{a, max}$ [m/s]	$v_{a, min}$ [m/s]
Type 4, subtype 1	0,82	0,89±0,12	1,14	0,45

In this case is possible to see how the previous and the actual measured value are similar, and especially considering the standard deviation, the two values fall in the same interval. However it has been found that air velocities close to 1 m/s result similar in average in both the measurements, while moving away the differences grow.

On the other hand observing maximum and minimum values it is clear how the trend is not very stable; the next graph in Figure 27 that reports the condition summarized in the table shows it.
The interval of time recorded in this case has been one hour, since the measurements were taken at the same moment of natural wind simulation ones, for which one hour of exposure is necessary as explained previously.

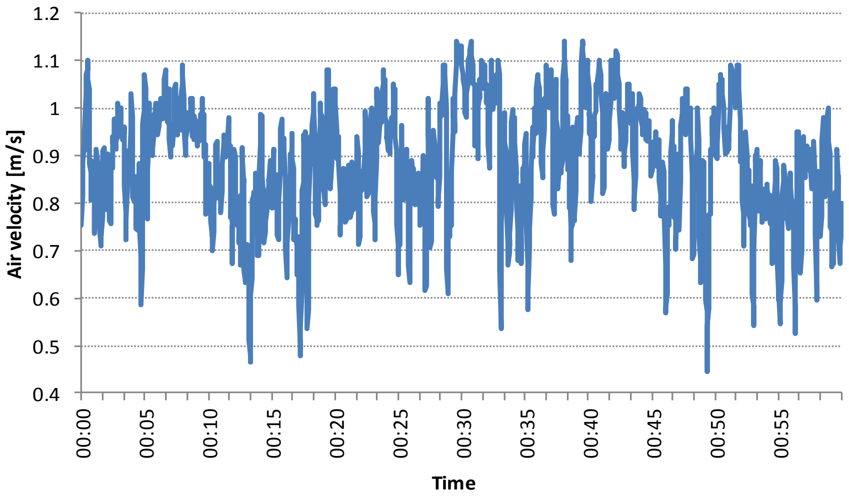


Figure 27 *Airflow trend for fan' setting that should provide 0.82 m/s of constant air velocity. Instrument used Swema 3000, fan used number 3.*

The two following tables report measurements of natural wind simulation flow, performed with Swema and Sensoanemo anemometers respectively. The exposure analyzed is the 28°C one, sensor is placed at 90 cm of distance from the fan and 120 cm of height. Data from fan on desk two are recorded. The sampling time has been of one hour, since the pattern performed by the fan in this setting repeats just after this interval of time.

Table 7 *Average air velocities expected and measured for wind simulation fans' setting. Both instruments used.*

Swema 3000				
Setting	$v_{a, expected}$ [m/s]	$v_{a, measured} \pm$ St Dev [m/s]	$v_{a, max}$ [m/s]	$v_{a, min}$ [m/s]
type 2, lowest	0,89	0,71±0,32	2,69	0,10

Sensoanemo				
Setting	$v_{a, expected}$ [m/s]	$v_{a, measured} \pm$ St Dev [m/s]	$v_{a, max}$ [m/s]	$v_{a, min}$ [m/s]
type 2, lowest	0,89	0,62±0,23	1,64	0,12

The two instruments were recording in the same interval of time.
In this situation there is a mismatch between expected velocity and the values we found as well. Particularly, with Sensoanemo instrument results that the difference is even of 0.27 m/s.
The wide range between maximum and minimum values is not relevant in this case, since the airflow pattern is the dynamic one. High values of standard deviation are due to the same reason. The difference between the maximum values recorded by Swema and Sensoanemo is relevant instead, as of about 1 m/s. Therefore there is a not negligible difference between the characteristics of the sensors.

The trend of the whole natural wind simulation pattern, for the exposure of 28°C, is reported in the following graph:

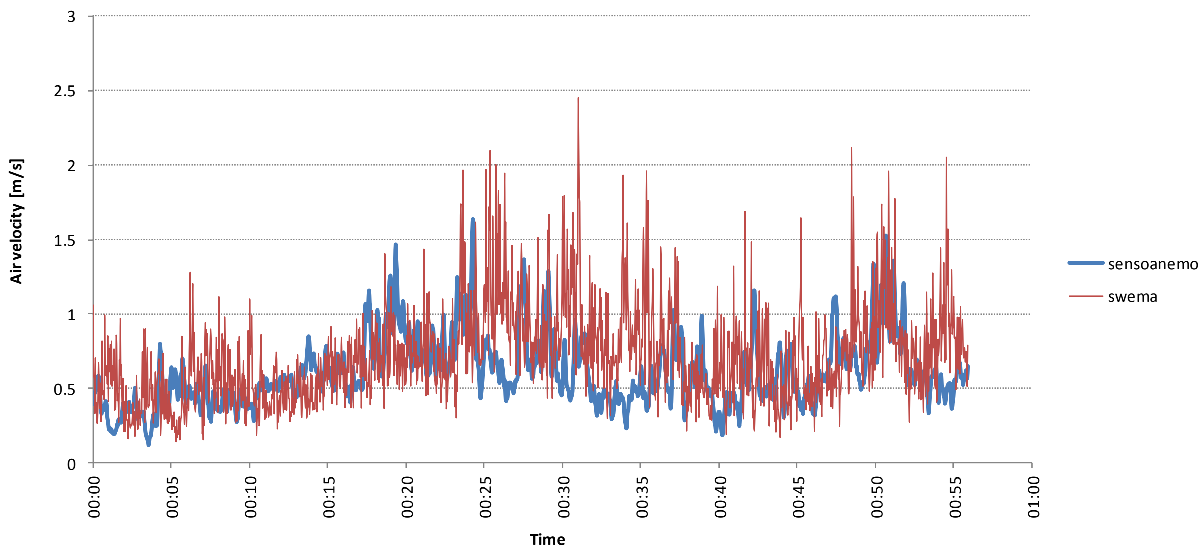


Figure 28 *Airflow trends for wind simulation fans' setting for 28°C condition. Both instruments used.*

The airflow is obviously unstable since it is reproducing a dynamic model. It is possible to see a lot of peaks, which simulate typical wind gusts. The trend reported is similar for the two instrument used, but as observed in the table, peaks of values recorded with Swema anemometer are much higher than the ones of the other sensor.

Table and graph for the condition with 30°C are reported in Appendix B.

3.2 - Thermal manikin tests

Both the types of experiments were tested and documented using thermal manikins. For the second experiment all the exposures were repeated; for the first experiment only 26°C, 28°C and 30°C conditions, and only the intervals controlled by the experimenter ("no fan" and "decided velocities"). All the data were recorded during steady state conditions; it means the change in the average body temperature of the manikins in an interval of time was very low. In this way it is possible to make a comparison with subjects' assessment of the thermal environment, since their evaluations refer to a precise moment and not to the past thermal history. Selected results of exposures are reported below.

3.2.1 - First type experiment

<u>Exposure 26°C</u>

A graph with equivalent temperature of each part of the manikin's body is reported below. On the same figure the tree airflows exposures are shown.

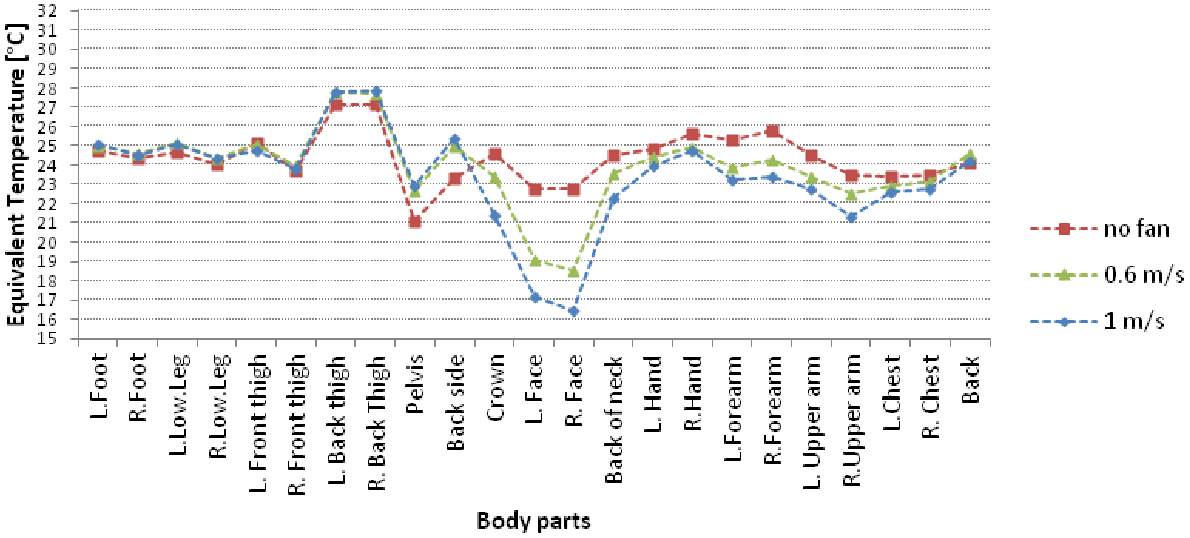


Figure 29 *Body parts equivalent temperatures for 26°C exposure. Settings no fan, 0.6 m/s, 1 m/s.*

Using comfort equation control, exposure with no fan simulates human thermal behavior in absence of airflow at 26°C (relative humidity is not relevant since the thermal manikin is only measuring dry heat loss). The average equivalent temperature for the whole body is around 25°C in this condition.

Two aspects are particularly evident:
1) Average manikin's body equivalent temperature decreases with increasing of air velocity. This represents a clear demonstration of the cooling effect of airflow on human body. The biggest difference is between exposures with and without airflow. Changing form 0.6 m/s to 1 m/s the air velocity no high differences are present.
However the trend of the temperature on the different body's part is almost parallel, changing the air velocity.
2) Not all the body segments present a decrease of temperature. Switching on the fan, it is possible to see how equivalent temperature decreases only for few parts of the body, especially for the two sides of the face. In these sites the temperature decreases from about 23°C to almost 16°C with 1 m/s of velocity. This is clearly due to the location of the manikin and to the direction of the airflow: the fan is placed in front of the person, with an angle which is in the subject's face direction. Moreover, the presence of the desk prevents any airflow to come in the lower part of the body.
Some parts of the body, as back, pelvis and thighs, show instead a little increase of temperature rising air velocity.

It is possible to see a parallel trend with the graphs regarding heat loss in the same exposures, as shown in Figure 30 below. Even in this case the highest difference is between absence of fan and using it, and the body parts more interested are the two sides of the face. In these sections the heat loss goes from about 60 W/m^2 with no airflow to almost 80 W/m^2 with 0.6 m/s, reaching a value close to 90 W/m^2 using 1 m/s. Arms and hands show an increase of heat loss as well, though not so relevant as for face sites. The other parts of the body instead do not present significant variations.

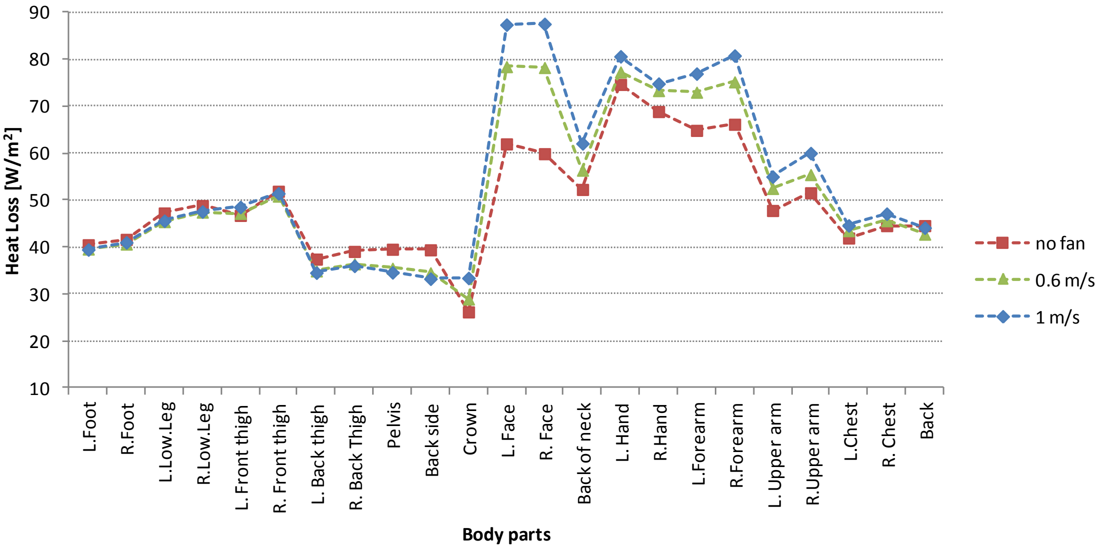


Figure 30 *Body parts heat losses for 26°C exposure. Settings no fan, 0.6 m/s, 1 m/s.*

Comparison between temperatures

It is interesting to compare the changes in equivalent temperature and heat loss for different temperatures of the environment. For this purpose the following graphs (Figure 31 and Figure 32) show equivalent temperature and heat loss of the different parts of the manikin's body at different air temperatures while keeping the air velocity constant at of 0.6 m/s.

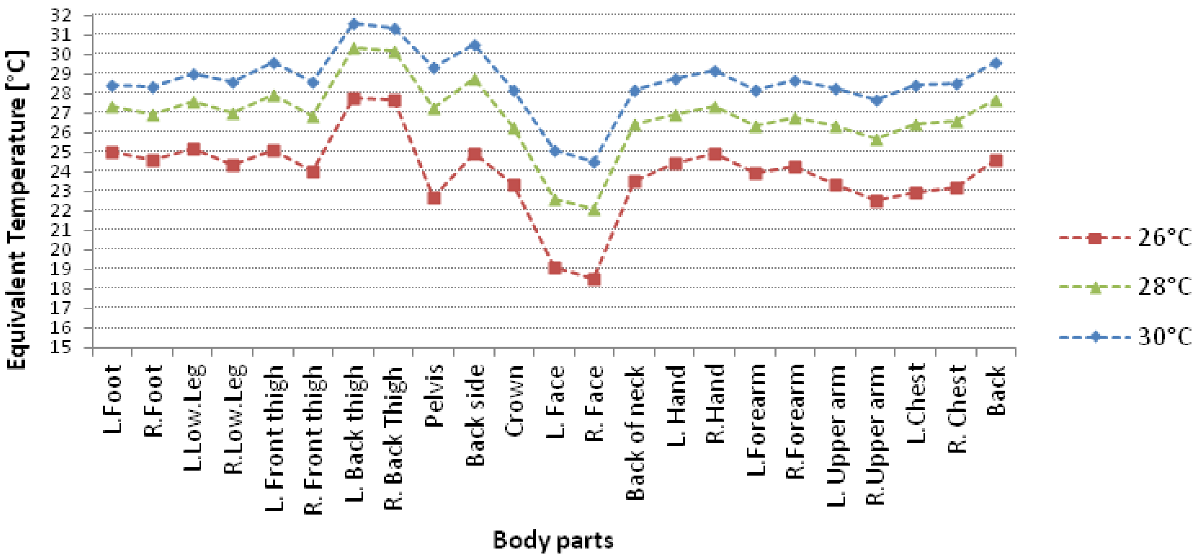


Figure 31 *Body parts equivalent temperatures for 26°C, 28°C, 30°C exposures. Fan's setting 0.6 m/s.*

The trend of the local equivalent temperature is quite parallel for the tree different exposures. It is evident as well how increasing the temperature of the environment, the equivalent temperatures increases. The amount is similar for many sites of the body. Considering particularly the two sides of the face, temperatures go from values included in the band 18°C - 19°C, for 26°C of exposure, to values between 24°C and 25°C, for 30°C of exposure, reaching an increment of about 6°C, the highest in the whole body.

Similar considerations come out from the graph reporting heat losses, shown in the next page. The trend is almost parallel for the tree setting temperatures. The highest heat loss is presented with the lowest temperature. As regard local values, the face presents the biggest difference between the exposures, where the heat loss goes from about 50 W/m^2 for 30°C of chamber's temperature to almost 80 W/m^2 for 26°C.

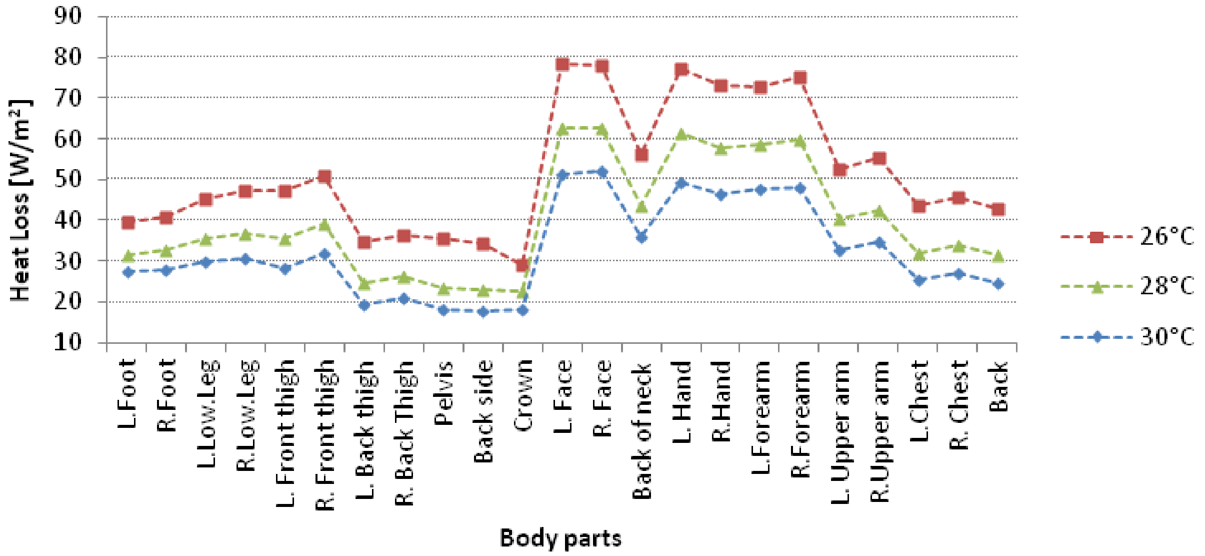


Figure 32 *Body parts heat losses for 26°C, 28°C, 30°C exposures. Fan's setting 0.6 m/s.*

The trend of these two graphs in conclusion shows how a decrease of the cooling effect with an increase of the environmental temperature occurs. This is what we expected, since the heat flux is mainly due to the convective mechanism; particularly, it depends on the difference between surface of the body and room air temperatures, and it increases increasing this difference.

Summary

The table below summarizes the results for these first experiments, showing values for the head region and average for the whole body. Data confirm what already said:

- higher air velocity and same temperature, lower equivalent temperature, higher heat loss;
- higher temperature and same air velocity, higher equivalent temperature, lower heat loss;
- same temperature and air velocity, head region on average presents lower temperature and higher heat loss compared to the average for the whole body.

Table 8 *Whole body and head region equivalent temperatures and heat losses for the first type experiment investigated.*

	no fan	0.6 m/s	1 m/s	1.5 m/s	no fan	0.6 m/s	1 m/s	1.5 m/s
	Equivalent temperature whole body [°C]				Heat loss whole body [W/m²]			
E = 26°C	24.9	24.7	24.3		47.3	48.2	49.7	
B = 28°C	27.8	27.5	26.9	26.5	35.1	36.6	39.1	40.4
C = 30°C	29.7	29.2	29.0	28.8	27.5	29.6	30.3	31.3
	Equivalent temperature head [°C]				Heat loss head [W/m²]			
E = 26°C	23.9	21.4	19.6		45.5	54.6	61.2	
B = 28°C	26.6	24.5	22.7	21.6	35.6	43.2	49.7	53.8
C = 30°C	28.7	26.7	25.9	25.1	28.1	35.4	38.1	41.1

3.2.2 - Second type experiment

In this case, two hours of exposure were measured for both the temperature of the room. One hour with constant airflow, one with simulation of natural wind airflow. Below only some results are plotted, while all the values are reported in a following summary table.

Exposure 28°C

The two graphs in Figure 33 and 34 represent the local equivalent temperatures for constant airflow and natural wind simulation airflow respectively, as average of one hour exposure.

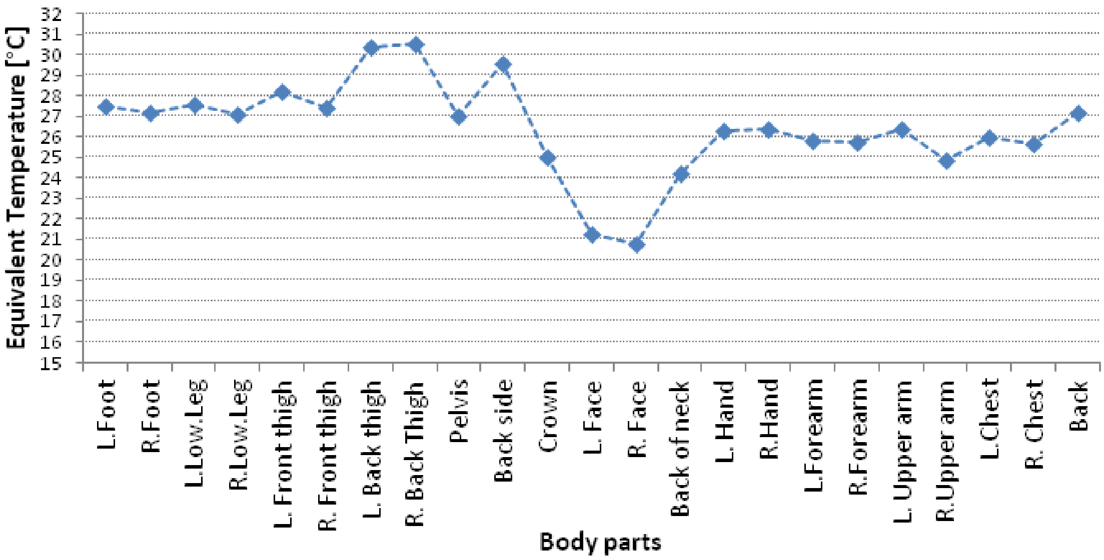


Figure 33 *Body parts equivalent temperatures for 28°C exposure. Setting constant airflow.*

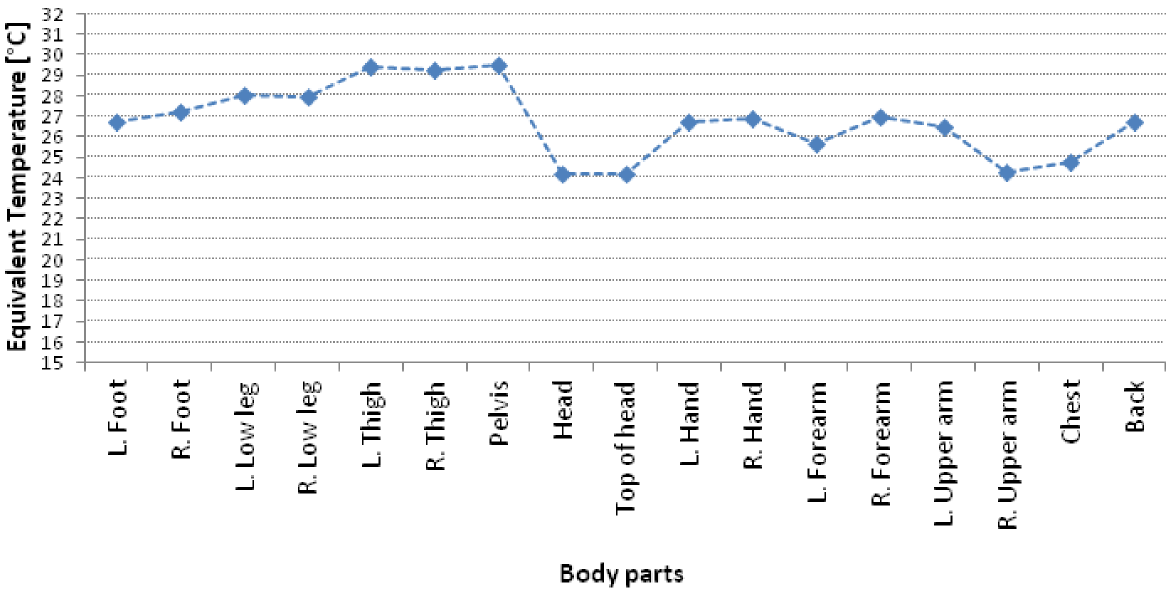


Figure 34 *Body parts equivalent temperatures for 28°C exposure. Setting wind simulation.*

There is not a complete coincidence between each part of the body for the two exposures. This is due to the fact that two different manikins were used to record values of heat loss and equivalent temperatures of the body, one for each airflow pattern; the "old" manikin is divided in 17 body parts, the "new" one in 23. For this reason it is difficult to plot the two exposures in the same graph. Particularly, the heads are divided in many different sections; being this site the most interesting, since the airflow is mainly directed here, an average value of heat loss and equivalent temperature for the whole head has been calculated.
For those parts divided in the same manner for both the manikins, is easy to see how the differences in average for the equivalent temperatures are negligible between the two exposures.
Same considerations are valid for the values of the heat loss.

Comparison between temperatures

Figure 35 and 36 show the trend of local equivalent temperature and heat loss for the natural wind simulation exposure, for both the experiments. In this case it is possible to plot the trends together since the manikin used was the same.

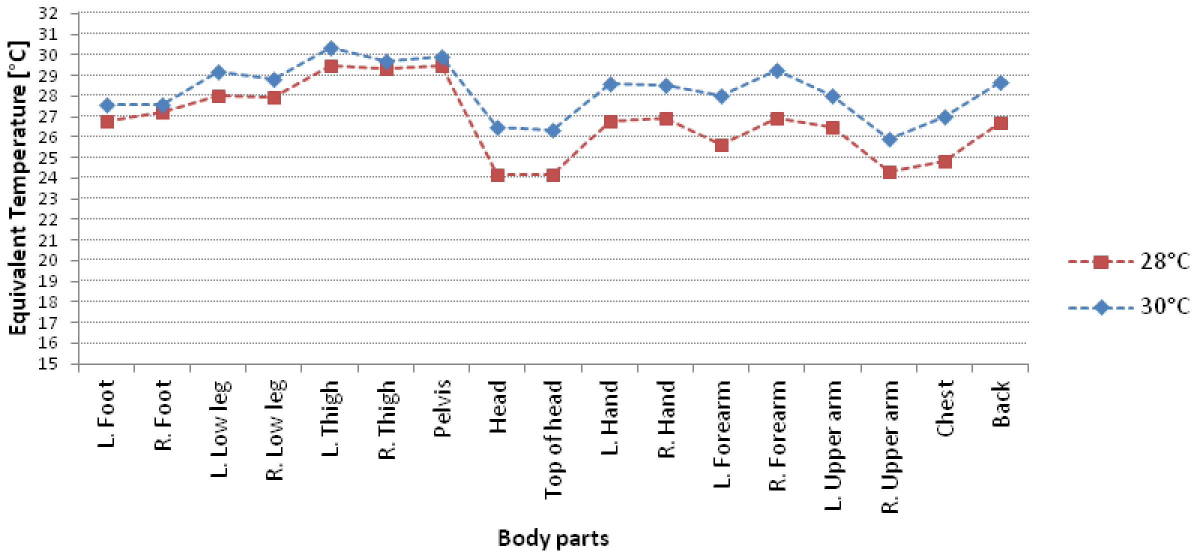


Figure 35 *Body parts equivalent temperatures for 28°C and 30°C exposures. Setting wind simulation.*

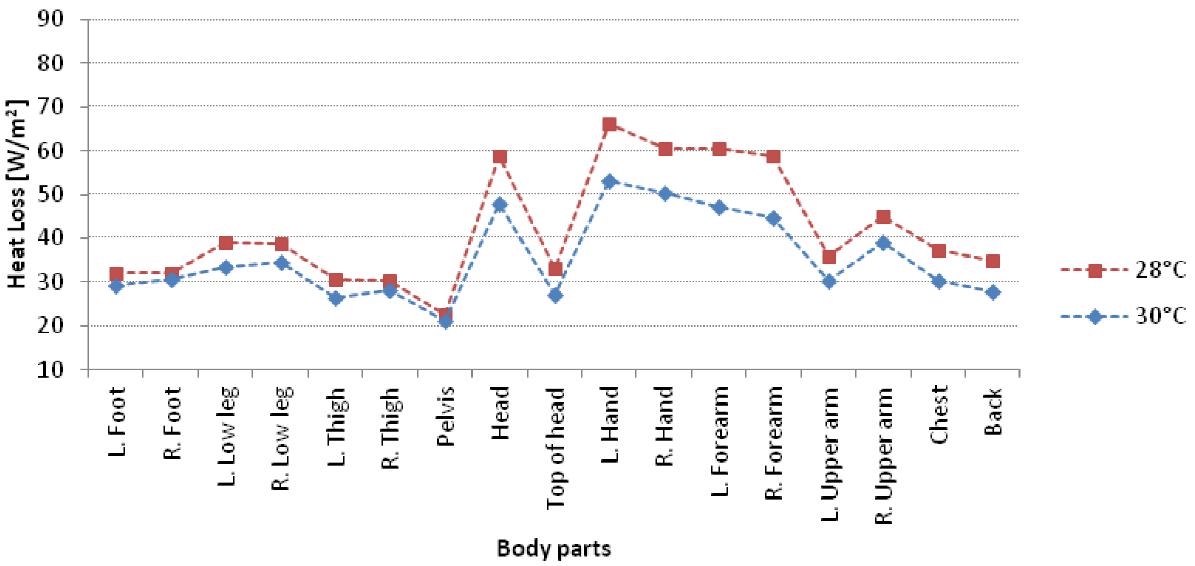


Figure 36 *Body parts heat losses for 28°C and 30°C exposures. Setting wind simulation.*

As observed in the previous experiments, an increase in temperature involves a decrease in heat exchange. Moreover head and hands regions present the highest difference between the two exposures, where for head the equivalent temperature rises of about 2°C increasing the temperature, heat loss decreases of more than 10 W/m^2.
Parallel observations could be done analyzing the graphs for the constant flow exposure.

Summary

The summary table below shows the whole body and head equivalent temperatures and heat losses. Some considerations follow.

Table 9 *Whole body and head region equivalent temperatures and heat losses for second type experiment.*

	constant	natural wind	constant	natural wind
	Equivalent temperature whole body [°C]		Heat loss whole body [W/m^2]	
2=28°C	27.2	27.3	37.7	37.6
1=30°C	28.5	28.6	32.3	32.1
	Equivalent temperature head [°C]		Heat loss head [W/m^2]	
2=28°C	23.0	24.4	48.6	47.2
1=30°C	25.5	26.6	39.7	38.5

- on average for the whole body negligible differences are present between the two airflows;
- on average for the head region, constant airflow seems to generate a slightly stronger cooling effect, since equivalent temperature is lower, heat loss higher;
- head region presents consistently higher heat loss and lower equivalent temperature compared to the body average.

Conclusions therefore are that airflows with the same average air velocity create similar physiological effects, even if the flow pattern is completely different.
Head region again shows the largest influence from the use of fans.

It is fair to say that in this case we are talking about measured values; for the human being assessments of the thermal environment many other parameters should be considered, and particularly it should be taken into account the subjective differences between each person, that could bring to quite different evaluation of comfort under the same condition. For example even if the average air velocity is the same between constant and dynamic exposure, wind simulation present gusts; some persons could feel a local thermal discomfort because of this, while other less sensitive not.

3.3 - Room conditions

As already said in the chapter Methods, room conditions were controlled by different systems. To control temperature a mixing ventilation system was used. For humidity seven humidifiers were placed in the chamber and controlled manually by the experimenter. The sensor for the control of the room temperature was placed in the centre of the room, at 1.1 m of height. In the same site two HOBO data loggers were placed, one at 1.1 m and one at 0.6 m, as reported in the scheme of the experimental room. All these sensors recorded relative humidity as well. Data coming from these tree instruments were analyzed, to check if experiments' conditions were reached, and particularly which was the trend of temperature and humidity during the exposures. Values coming from the room's centre were indeed considered representative of the whole environment.

3.3.1 - First type experiment

26°C - condition E

The following graph in Figure 40 shows the trend of the average temperatures of all the experiments performed for the same condition (26°C in this case), using data coming from sensors of HOBO data loggers. Mean values were calculated for 15min-time intervals, and reported on the graph when subjects were filling in the questionnaires (after 45 minutes from the beginning, 1 hour, 1 hour and 15 minutes, 1 hour and 30 minutes, 1 hour and 45 minutes); it means that for example the point after 1 hour represents the average from 45 minutes to 1 hour from the start of the exposure, considering particularly the 10 minutes included in the centre of this interval. Values after 30 minutes were considered as well to have a better idea of the trend in the first period of exposure.

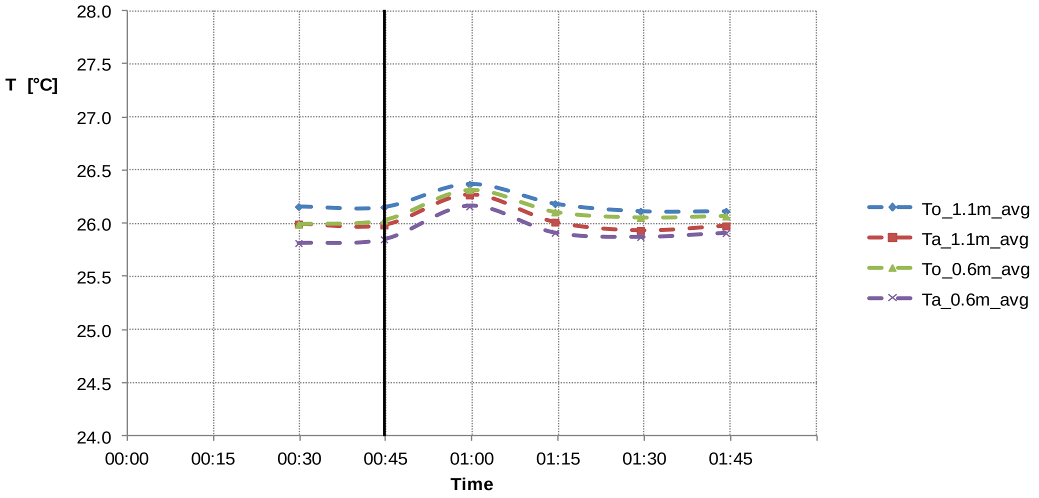


Figure 37 *Average operative and air temperatures for all tests with 26°C condition, room's centre, 1.1 m and 0.6 m of height.*

Operative temperature and air temperature at 1.1 m and 0.6 m of height are reported. The lines are not continues because representative of a supposed trend; the known values are only the averages in the time intervals already mentioned. Since the sensor for the room control was placed at 1.1 m, the most interesting trend is the one at this height.
There is only a small difference between values of operative and air temperature at the same height that stays under 0.2°C. This is also expected as there are no surfaces at different temperature compared to air temperature. Actually the trend with radiant temperature a little higher than air temperature was found in almost each exposure.

A black vertical line is placed after 45 minutes, since it corresponds to the instant in which the period of adaptation ends; after this period subjects started to fill in the first questionnaire. In this way, the trend of temperature before this moment can be considered less important.
A relevant observation is that temperatures stay always inside the band of ±0.5°C centered on the desired value 26°C. In this case both temperatures at 1.1 m and 0.6 m of height are included in this zone.

Air temperature and relative humidity at 1.1 m of height are shown in Figure 38 and 39. Data trends come from values recorded with HOBO data loggers for the single exposures.

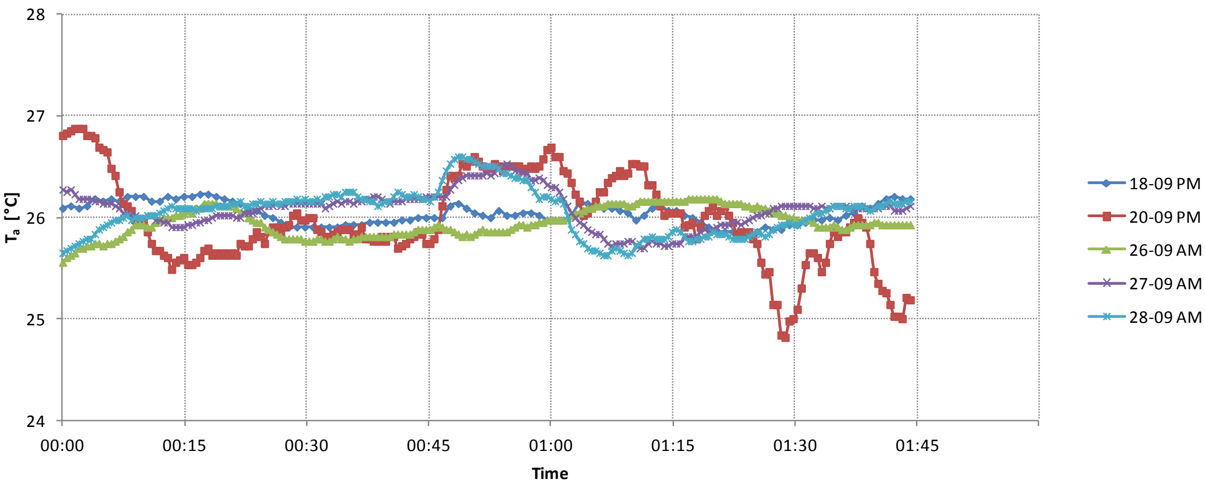


Figure 38 *Air temperatures' trends for all the 26°C exposures at 1.1 m of height, room's centre.*

It is clear that the trend of the single experiment is very unstable compared with the average. Especially there were some days when it was more difficult to keep stable temperature conditions (for example the 20th of September). The other days the fluctuations were very small, within ±0.2K. Reasons for the fluctuations are partly related to the type of chamber used for the experiments, as already said when describing the climatic room used.

Also relative humidity presents an unstable trend, as shown in Figure 39. The most relevant aspect is that in the exposure of the 20th of September we did not manage to reach the wanted condition of 50% of relative humidity. For the other tree experiments, values were comprised in the band ±5%.

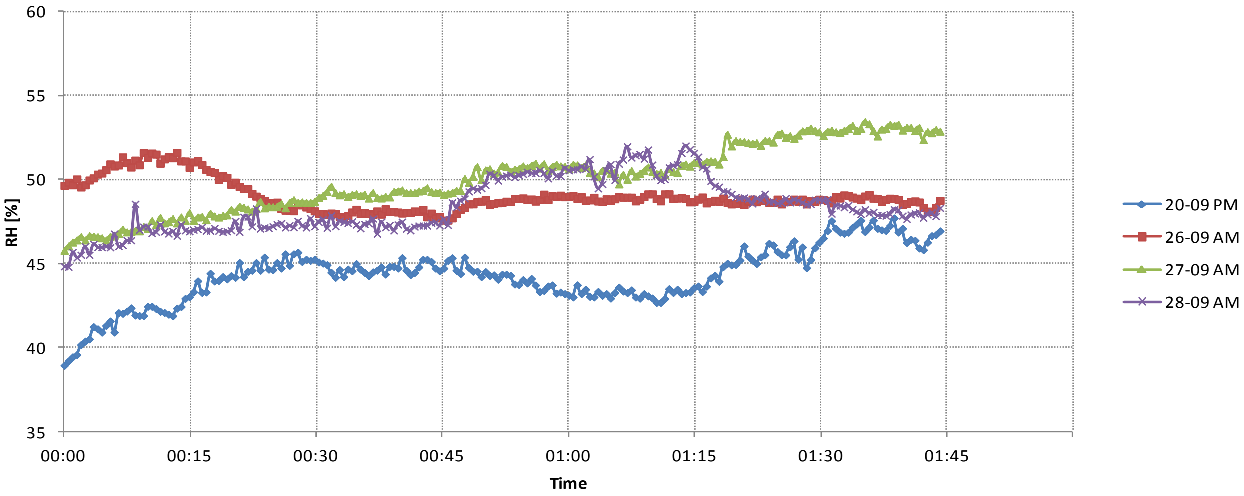


Figure 39 *Relative humidity's trends for all the 26°C exposures at 1.1 m of height, room's centre.*

A summary table is reported below (Table 10). It presents average values considering all the exposures for:

- temperature recorded by the sensor of the room control system;
- operative temperature recorded by HOBO data loggers;
- air temperature recorded by HOBO data loggers;
- relative humidity recorded by HOBO data loggers;
- relative humidity recorded by the sensor of the room control system.

Each value is shown for both the heights, except for values from the sensor of room control system, since it was placed only at 1.1 m from the floor.

Table 10 *Average values for the 26°C exposure, room's centre.*

		1,1 m	0,6m
T_{room}	[°C]	26,0	
T_{op}	[°C]	26,2	26,1
T_a	[°C]	26,0	25,9
RH	[%]	48	50
RH_{room}	[%]	49	

Considering 1.1 m of height and values from the HOBO data logger, it is possible to say that on average we managed to keep the wanted temperature of 26°C. Relative humidity was also very close to the desired value of 50%.

28°C - condition B

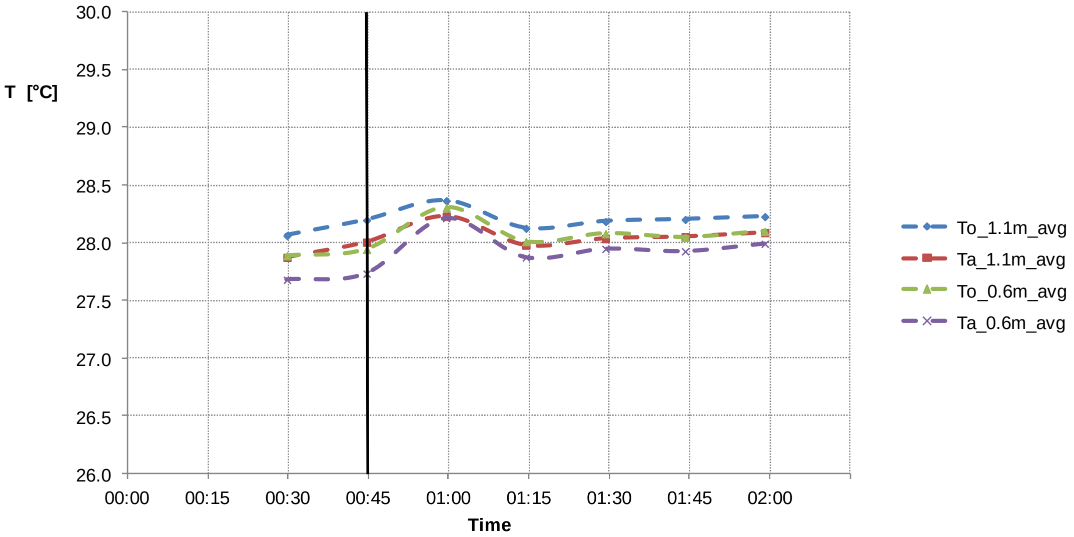


Figure 40 *Average operative and air temperatures for all tests with 28°C condition, room's centre, 1.1 m and 0.6 m of height.*

Also in this case the differences between operative and air temperature at same height are only about 0.2K. Differences between 0.6 m and 1.1 m of height for same temperatures are only about 0.2K as well.
Values stay always inside the band ±0.5K centered on the desired 28°C.

Additional graphs with temperatures and relative humidity can be found in the Appendix A.

The summary table indicates that the value of 28°C on average was kept for all the experiments, and the relative humidity was 1% below the expected value.

Table 11 *Average values for the 28°C exposure, room's centre.*

		1,1 m	0,6m
T_{room}	[°C]	28,0	
T_{op}	[°C]	28,2	28,1
T_a	[°C]	28,0	27,9
RH	[%]	44	46
RH_{room}	[%]	44	

30°C - condition C

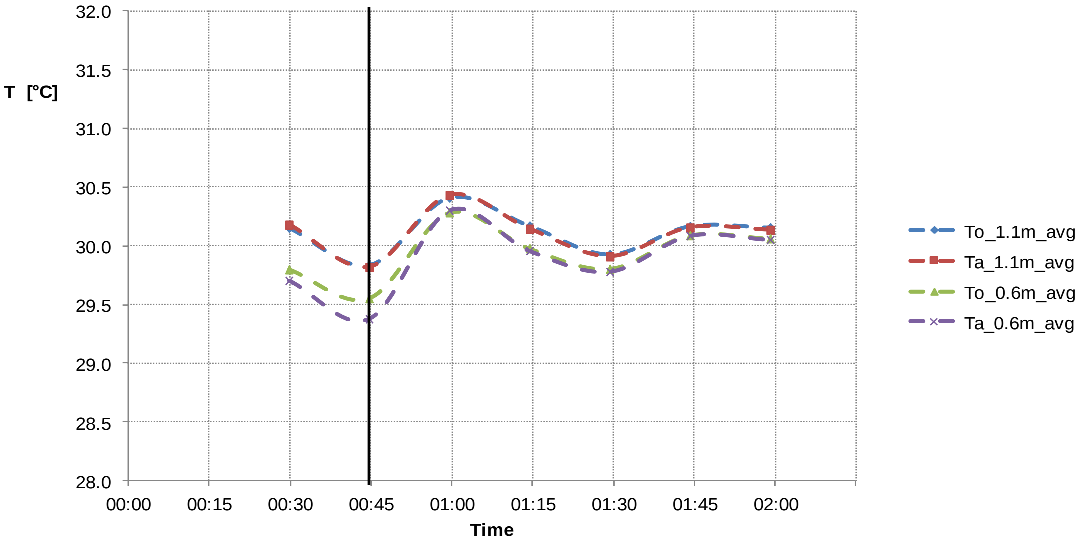


Figure 41 *Average operative and air temperatures for all tests with 30°C condition, room's centre, 1.1 m and 0.6 m of height.*

In this case there were some small fluctuations, but values of temperature at 1.1 m of height were always inside ±0.5°C band from the wanted value. Particularly, at this height air and operative temperatures are exactly equal on average.

Both average air temperature and humidity were at the desired levels.
Considering the tree first exposures presented until now, and especially the trends of the single experiments that can be seen in the Appendix A, it seems that increasing the set temperature involves more difficulties in reaching and keeping stable the temperature scheduled, while less for the relative humidity conditions.

Table 12 *Average values for the 30°C exposure, room's centre.*

		1,1 m	0,6m
T_{room}	[°C]	30,0	
T_{op}	[°C]	30,1	29,9
T_a	[°C]	30,1	29,9
RH	[%]	40	42
RH_{room}	[%]	38	

32°C - condition A

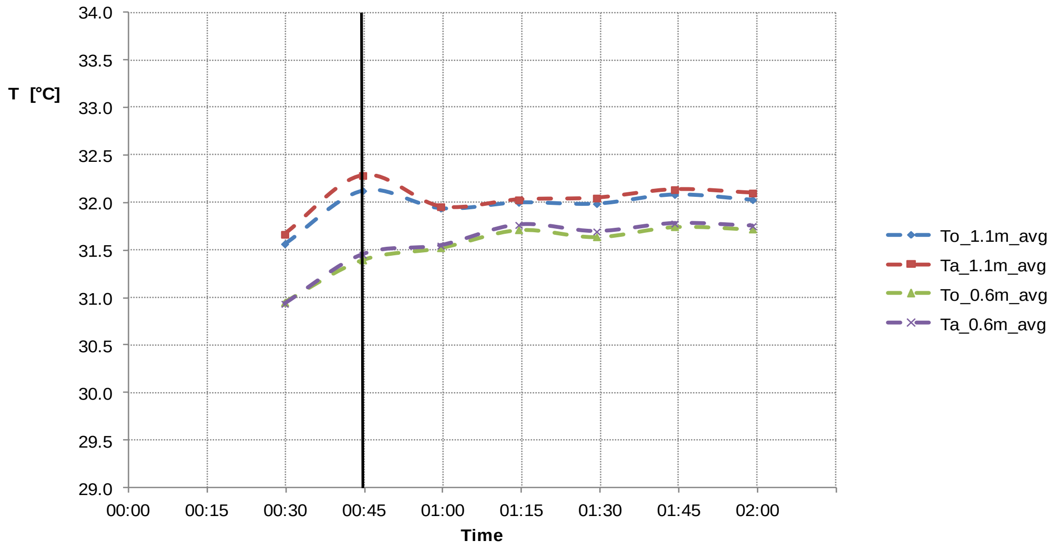


Figure 42 *Average operative and air temperatures for all tests with 32°C condition, room's centre, 1.1 m and 0.6 m of height.*

Air and operative temperature at the same heights are quite similar. Differences are present only between the two different heights, where sometimes more than 0.5K separates the two trends.
The progress is very stable, especially after the first 45 minutes.
However, single exposures temperatures' trends were found very unstable, with many peaks and valleys. Relative humidity courses are pretty stable instead.

As presented in the summary table, average temperature value was perfectly reached; for the relative humidity the data recorded on average were only 2% higher than the value expected.

Table 13 *Average values for the 32°C exposure, room's centre.*

		1,1 m	0,6m
T_{room}	[°C]	32,0	
T_{op}	[°C]	32,0	31,5
T_a	[°C]	32,0	31,6
RH	[%]	38	41
RH_{room}	[%]	35	

34°C - condition D

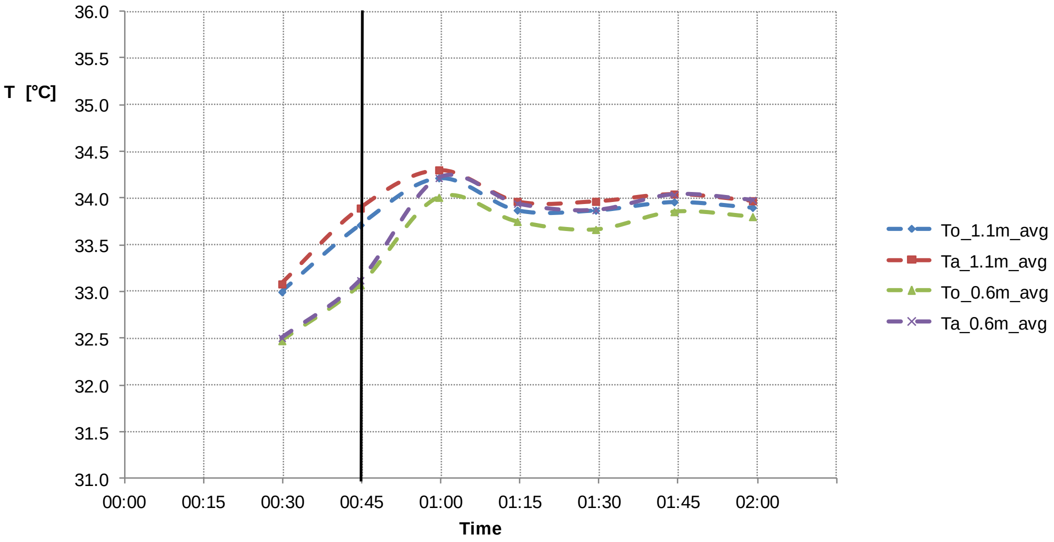


Figure 43 *Average operative and air temperatures for all tests with 34°C condition, room's centre, 1.1 m and 0.6 m of height.*

It took some time to reach the desired temperature level of 34°C. On the other hand, considering values only after the step of adaptation consisting in the first 45 minutes, the ±0.5°C band is respected for 1.1 m of height, and after one hour the trend becomes pretty stable.
The operative and air temperatures are also very similar during the experiment.

The following summary table shows that the overall average for each exposure is basically equal to 34°C and relative humidity was only 3% higher than the desired value of 32%.

Table 14 *Average values for the 34°C exposure, room's centre.*

		1,1 m	0,6m
T_{room}	[°C]	33,9	
T_{op}	[°C]	33,8	33,5
T_a	[°C]	33,9	33,7
RH	[%]	35	37
RH_{room}	[%]	33	

Considerations on exposures of first experiment type

Analyzing the trends of temperatures and relative humidity (see Appendix A) from the lowest temperature of exposure 26°C to the highest 34°C is possible to get some conclusions.

Increasing the room setting temperature, the system presents more difficulties in keeping stable the parameters; especially on the highest it was difficult also to reach the wanted values for temperature. Explanations for this behavior could be found in the differences between outdoor and indoor conditions, since while inside we set even 34°C, outside during the period in which the experiments were performed there were less than 10°C in some moments. The system takes some air from outside, therefore there could be some difficulties to warm enough the air mass when the difference between inside and outside temperature is high; particularly it should be take into account that if it is necessary to reach a temperature inside the chamber, coming from a lower one, the temperature of the air used to achieve the condition has to be much higher than the indoor temperature desired. It means higher difference between inside and outside temperature, and potential difficulties for the air conditioning system. Another aspect to consider regards the type of climatic chamber used. As already explained in the chapter methods, we did not use a "classic" climatic chamber that means a room inside a building, without any direct connection with the external environment. In our case many surfaces of the room where directly exposed to outside, especially on a wall great part of the surface consisted of windows. That means more dispersions, and therefore difficulties in keeping stable the indoor conditions.
As already said as well, the presence of many objects inside the room created a thermal inertia, that brought to higher oscillations before reaching an almost stable progress of temperatures; chairs, tables etc. need more time to reach the set temperature, therefore, for example in case of heating, it is necessary to reach an higher air temperature to lead them to the same temperature wanted for the room. Finally, it should be also considered the moment in which subjects were entering the room, since opening the door created an airflow of different temperature from the corridor to the room, or vice versa, in any case altering the inside conditions.

As regard humidity, different considerations could be done, going from the lowest chamber temperature to the highest one. With 26°C the average value of 50% of relative humidity was not reached, since lower percentages were present in each exposure; during the experiments at this temperature all the humidifiers were switched on, but it was not sufficient. Increasing the temperature was easier to obtain the wanted value, particularly with 30°C the average relative humidity was exactly 40%. It is possible to say therefore that even if the combination temperature-RH was set to keep the dew point constant at 14.8°C, decreasing the temperature increases the difficult in reach this condition.
For the highest temperatures used in the experiments, that are 32°C and 34°C, the humidity value is on average higher than the expected one. According to what found for the lowest temperatures, increasing relative humidity is easier increasing temperature; especially in these last cases, humidity coming from subjects inside the chamber, by transpiration and breath, probably was more than enough to obtain the desired value. Often indeed all the humidifiers were switched off.

3.3.2 - Second type experiment

<u>28°C - condition 2</u>

Below the graph with the average temperatures for all the exposures at the same condition is reported. Also in this case the points are during the time when subjects were filling in the questionnaires: beginning, after one hour and after two hours. Average values were calculated considering the first five minutes of exposure, to have a kind of background; then for ten minutes before one hour, and for ten minutes before two hours.

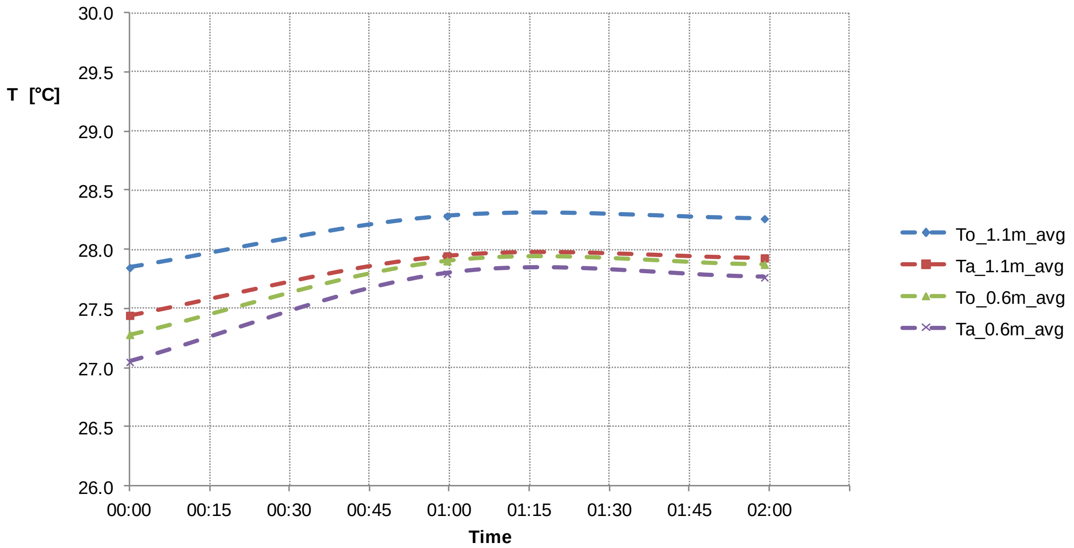


Figure 44 *Average operative and air temperatures for all tests with 28°C condition, room's centre, 1.1 m and 0.6 m of height.*

In the first part of the exposures average temperatures are not close to the desired value of 28°C. However subjects were filling in questionnaires we used for the evaluations after one and two hours, when values were very good instead.

As regard single exposure air temperatures, the graph in Figure 45 shows some stable progresses, but also other particularly variable, especially the 3rd of October and the 8th of October.
For the first one, the explanation comes from the particular experimental session we had: not all the subjects arrived on time, and especially we arranged two different experiments in the same moment, since one subject needed to perform the 28°C condition of the first type of experiment. For this reason we opened many times the door, so likely this created instability in room conditions, and therefore problems to the air conditioning system to keep less oscillatory the trend.
During the session of the 8th of October, only one subject was in the room; the door was not opened except in the beginning. Thus the only explanation we found regarded the air conditioning system, that was particularly unstable in the control of temperature that day.

A part from these two exposures, for the other the trend was pretty stable, especially after a first period of adjustment; temperatures were inside the ±0.5K band after one and two hours from the start, when subjects were performing assessments on the thermal environment.

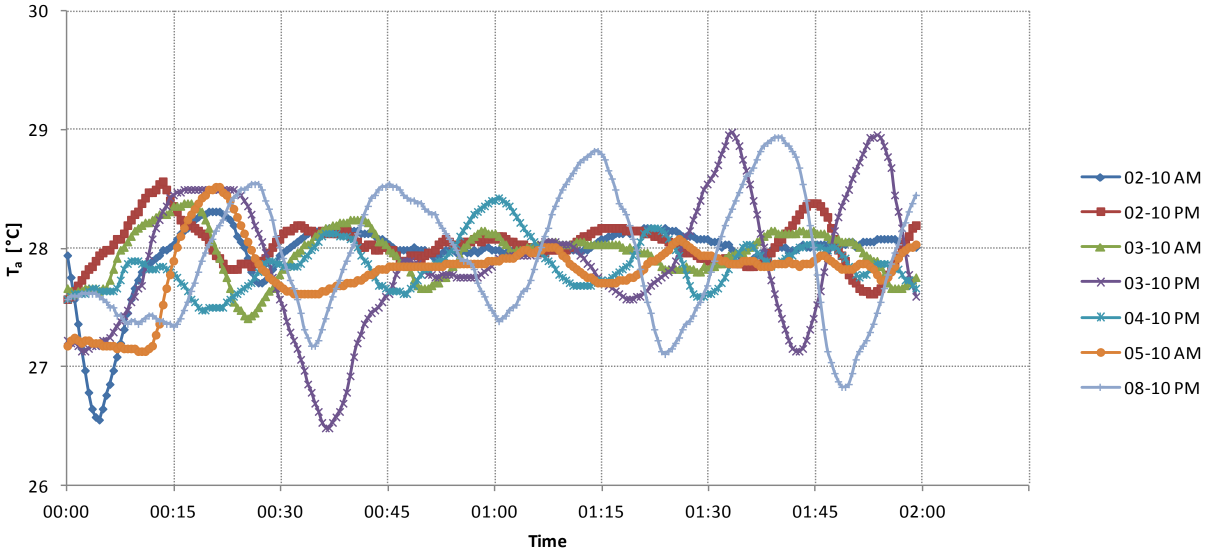


Figure 45 *Air temperatures' trends for all the 28°C exposures at 1.1 m of height, room's centre.*

Relative humidity in Figure 46 presents trends always inside 45% ±5%, except for the 3rd and the 8th of October; the problems we had in these sessions have been already explained. For the other, values are particularly stable and close to the desired.

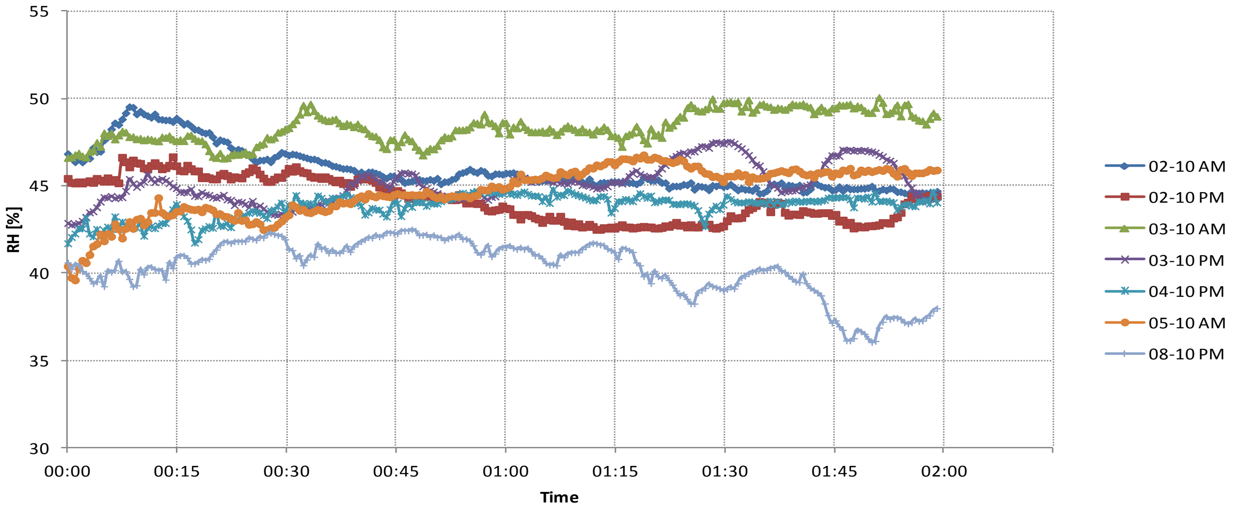


Figure 46 *Relative humidity's trends for all the 28°C exposures at 1.1 m of height, room's centre.*

The summary table below reports that the average air temperature was close to the desired value of 28°C, being only 0.2K lower; moreover observing the graph with the average of the temperatures for the tree intervals, it is clear that lower temperatures were often present only in the beginning of the exposures, without compromising therefore the assessments carried out after one and two hours.
Relative humidity presents a negligible difference of 1%.

Table 15 *Average values for the 28°C exposure, room's centre.*

		1,1 m	0,6m
T_{room}	[°C]	27,8	
T_{op}	[°C]	28,1	27,7
T_a	[°C]	27,8	27,5
RH	[%]	44	47
RH_{room}	[%]	44	

30°C - condition 1

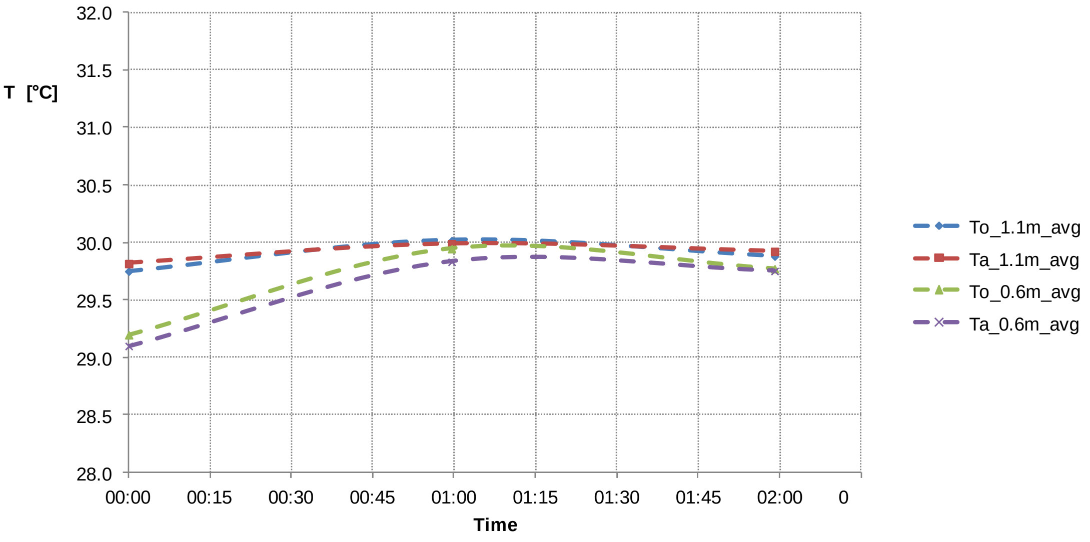


Figure 47 *Average operative and air temperatures for all tests with 30°C condition, room's centre, 1.1 m and 0.6 m of height.*

Air and operative temperature at 1.1 m of height are pretty similar. Moreover the trends are very close to the desired value of 30°C. At 0.6 m of height, the two temperatures present a slight difference of about 0.1K, while the trends of values are more unstable, growing of almost one degree during the exposures. Graphs for the single exposures are reported in Appendix A.
The summary table shows how desired value were basically reached, since on average the air temperature was 0.1K lower than 30°C, humidity 1% higher than 40%.

Table 16 *Average values for the 28°C exposure, room's centre.*

		1,1 m	0,6m
T_{room}	[°C]	30,0	
T_{op}	[°C]	29,9	29,6
T_a	[°C]	29,9	29,6
RH	[%]	41	43
RH_{room}	[%]	40	

Conclusions from the thermal environment conditions of these two second experiment's exposures are more difficult to be found, since only two temperature were investigated.
It is just worth to say that some fluctuations during the tests were present, but on average both temperatures and humidity levels were at the desired conditions.

3.4 - Subjects

A total of 27 Scandinavian subjects participated in the experiment, most of them being Danish university students. The choice of people from the same area has been made in order to compare the results of a previous experiment performed in China.

All the subjects were volunteers, paid to take part in the experiment, and only persons in good health were allowed to participate. They were asked to sleep well, avoid alcoholics and spicy food the days before the experimental sessions.

Moreover, it was requested to wear typical summer garments: panties/briefs, bra (if female), T-shirt, jeans or normal trousers, light socks, trainers or normal light shoes. In this way, the overall clothing insulation resulted of 0.54 clo, and was considered a fixed variable in the computation of the PMV-index.

Table 17 *Clothing ensemble and insulation values*

Garment	Insulation value [clo]
briefs	0.03
light socks	0.02
trainers	0.04
jeans	0.25
T-shirt with sleeves	0.1
chair	0.1
Total	**0.54**

Before the first session, subjects were instructed on the experimental procedure and on how to fill in the questionnaires. In addition, height and weight were measured. The following table summarize anthropometric data of the subjects.

Table 18 *Anthropometric data of subjects*

Sex	No. of subjects	Age	Height	Weight	Body Max Index	Du Bois Area
[-]	[-]	[years]	[cm]	[kg]	[kg/m^2]	[m^2]
females	11	22±5	167±13	59±11	21.4±4.7	1.66±0.15
males	16	24±9	178±9	72±24	22.9±8.4	1.89±0.22
total	27	23±10	173±19	66±30	22.1±9.2	1.78±0.33

3.4.1 – Metabolic rate (or activity)

As already introduced, we checked subjects' heart rates to obtain their metabolic activity during all the exposures. Performing typical office work, we were expecting to obtain a value of 1.2 met on average for all of them. Particularly, this value comes from a method based on observation of subject activity presented on Standard ISO 8996 [19].
The same standard presents another procedure to obtain the metabolic level when the heart rate is known, that should give more precise results.
In our case, the value obtained from these measurements was 1.3 met on average that means 0.1 Met higher than the expected one. However it is fair to say that not all the belts were working during the experiments, therefore we do not have data from all the subjects. Moreover the kind of instrument used to check heart rate is designed for sport activities, and can results in higher errors when used to record low activities. Methodology presents an error as well, reported of about ±10% in the Standard.
In conclusion, we decided to use 1.2 met for the metabolic rate, since we wanted and tried to keep this value during all the exposures, and we could have had some discrepancies for the reasons just mentioned.

3.4.2 - Predicted Mean Vote

The following table summarize calculations for PMV (ISO EN 7730 [2]) obtained by a software in which is possible to set all the environmental parameters relevant for the global thermal sensation of the subject. Height from which data of operative temperature, relative humidity and air velocity are taken is 0.6 m, since occupants were seated. Values are on average for all the exposures at the same temperature.

Table 19 *Parameters for PMV calculation for each condition and corresponding PMV values.*

Condition	t_o 0.6m	RH 0.6 m	v_a 0.6 m	st_dev v_a	Activity	I_{cl}	PMV av	PMV max	PMV min
	[C]	[%]	[m/s]	[m/s]	[met]	[clo]			
E	26.1	50	0.18	0.06	1.2	0.54	0.3	0.4	0.2
B	28.1	46	0.19	0.08	1.2	0.54	0.9	1.0	0.8
C	29.9	42	0.18	0.10	1.2	0.54	1.4	1.5	1.4
A	31.5	41	0.16	0.08	1.2	0.54	2.0	2.0	1.9
D	33.5	37	0.20	0.13	1.2	0.54	2.6	2.6	2.5
2	27.7	47	0.14	0.06	1.2	0.54	0.8	0.9	0.8
1	29.6	43	0.16	0.07	1.2	0.54	1.4	1.4	1.3

Air velocity values as already said come from a sensor put on the stand, placed close to a desk without subject, or when all the desks were occupied, behind a subject; in this way, the air velocity registered is the one occupants were exposed to only in the first step, when fans were turned off.

In the following steps the anemometer was registering a kind of background air movement, not generated directly by fans. This consideration should be taken into account when comparing PMV and TSV.

Moreover, it should be considered the variability of this background air velocity during the experiment, since changing the setting of the fans, especially to the higher air velocities, it could increase or result more unstable. Therefore, average standard deviation of air velocity recorded for each exposure has been calculated as well, and considered in the computation of the Predicted Mean Vote as maximum and minimum value achievable during the experiments.

3.5 - Human responses

3.5.1 - Assessments on thermal environment first experiment

As already mentioned, during the experiments subjects were asked to fill in questionnaires with many questions regarding the thermal environment in which they were. Particularly, they provided assessments at the end of each interval in which the experiment was divided. In this way it is possible to see how responses on thermal stimuli change during the whole exposure.
Following results considered more significant are reported for each condition.

26°C - condition E

The following summary table presents in the first two lines the schedule of the experiment, in terms of time (minutes) and setting of the fans used. It is then possible to see the trend of some main values coming from the questionnaires, reported on average for the 27 subjects: Thermal Sensation Vote and its standard deviation, Acceptability of thermal environment with standard deviation, Thermal Comfort Vote with standard deviation, responses to the question "would you like to be", responses to the question "would you prefer".

Table 20 *Average TSV, average Acceptability of the thermal environment, average Thermal Comfort Vote (TCV), request for being warmer/cooler, request for more/less air movements from questionnaires for 26°C exposure, first experiment.*

	00:00-00:45	00:45-01:00	01:00-01:15	01:15-01:30	01:30-01:45
	no fan	0.6 m/s	1 m/s	change	fix
TSV ± St Dev	0.4±1.0	-0.2±0.8	-0.1±0.9	-0.2±0.7	-0.2±0.7
ACP ± St Dev	0.3±0.6	0.4±0.6	0.4±0.6	0.6±0.5	0.5±0.6
TCV ± St Dev	-0.9±0.8	-0.6±0.5	-0.8±0.8	-0.7±0.8	-0.5±0.6
Warmer	3	4	4	3	4
No change	10	18	17	17	19
Cooler	14	5	6	7	4
More air mov.	10	2	2	0	0
No change	16	15	13	23	22
Less air mov.	1	10	12	4	5

The scales to evaluate every answer are different. For the TSV, the scale is the same ±3 of the PMV already introduced. The acceptability of the thermal environment is presented with a ±1 scale, where +1 correspond to a "clearly acceptable" environment, -1 "clearly unacceptable", 0 divides "just acceptable" from "just unacceptable". Thermal Comfort Vote has a scale that goes from 0, corresponding to "comfortable", to -3 "very uncomfortable", passing through "slightly uncomfortable" and "uncomfortable".
For the last two questions, is reported the number of subjects answering one of the tree options in each test interval.

For this exposure graphic representations of these values are reported to provide a better view of the trends; for the next only a summary table is presented.

Thermal Sensation Vote is plotted in Figure 48. The biggest difference during the whole exposure is between absence of air flow (no fan) and presence (each other condition). Considering the first two steps, TSV indeed goes from 0.4 to -0.2, while for the following it stays almost constant and pretty close to the thermal neutrality. 0.6 m/s exposure presents a slightly lower value of TSV compared to 1 m/s, which we would expect to be the opposite; this is most likely due to the sequence often used for condition E, in which we put as first exposure 1 m/s, second 0.6 m/s; in this way subjects were influenced by the previous cooler exposure in the assessment of the second one.

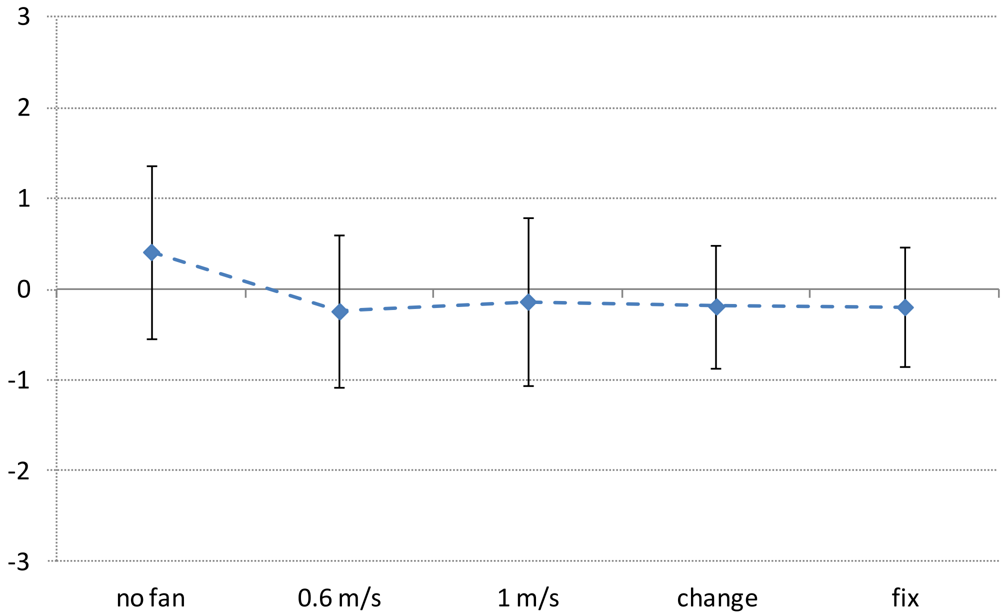


Figure 48 *Average TSV with standard deviation for each step of the 26°C exposure.*

In the next page Figure 49 shows that thermal environment acceptability is on average always in the field of "acceptable", and particularly increases for the last two steps, where subjects modified the airflow provided by the fan.

To note the high range of standard deviation, meaning subjects' assessments were particularly different.

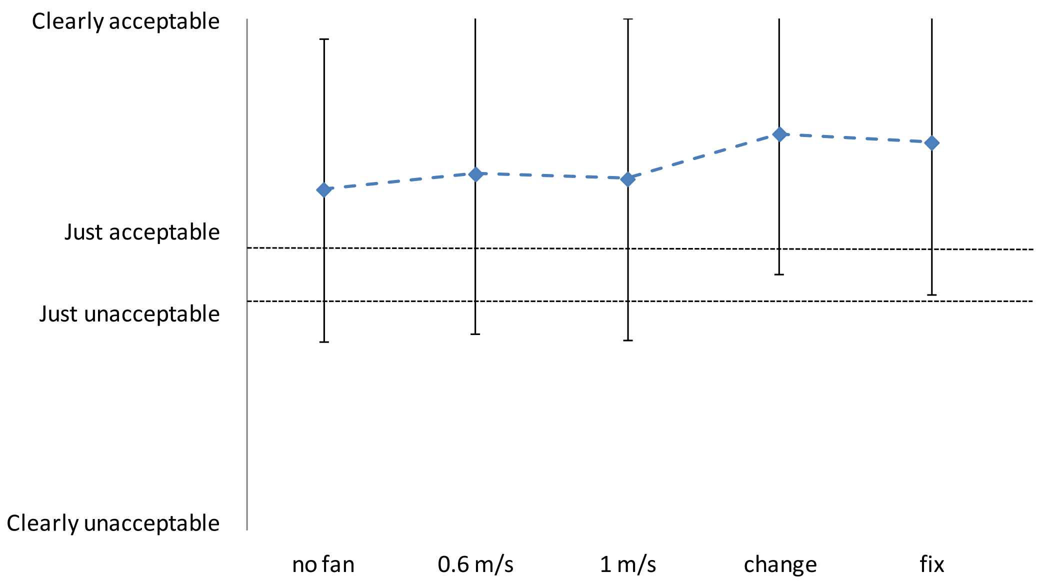


Figure 49 *Average acceptability of the thermal environment with standard deviation for each step of the 26°C exposure.*

Thermal comfort vote on average stays for each step in the range between "comfortable" and "slightly uncomfortable", as report in Figure 50. The best assessment is for the last step, when subjects were exposed to their preferred air velocity. Also in this case standard deviations are pretty high.

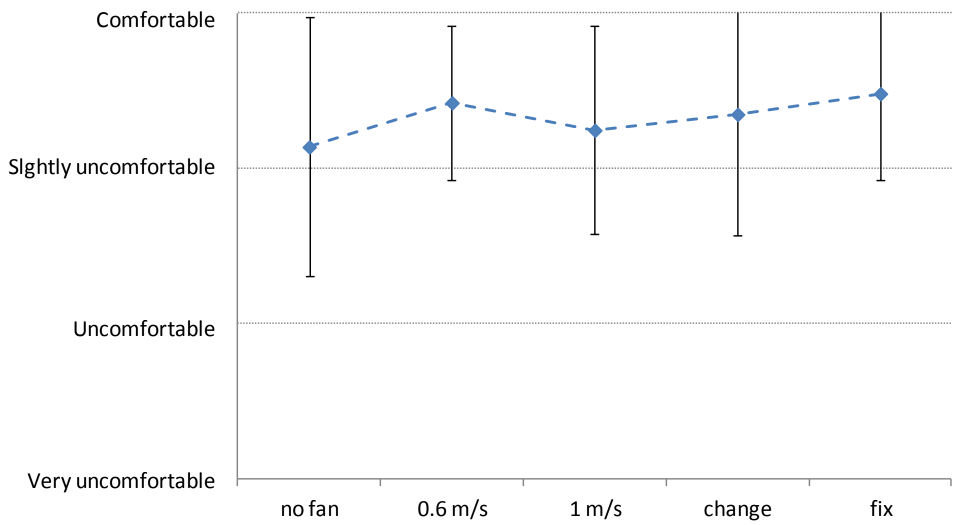


Figure 50 *Average TCV with standard deviation for each step of the 26°C exposure.*

Requests of being warmer, cooler or not to have changes show how switching on the fans many subjects change their assessments from "cooler" to "no change", while after the trend is almost constant. Particularly, a few numbers of subjects ask in every step to be warmer (Figure 51).

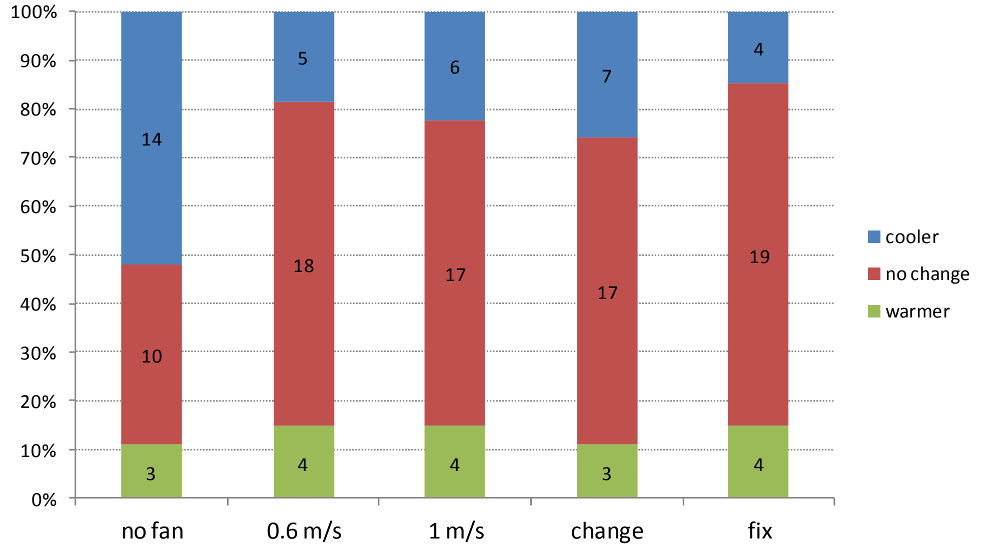


Figure 51 *Number of subjects asking for being warmer/cooler for each step of the 26°C exposure.*

Finally, requests for air movements change between the two first periods, when turning on the fans less subjects ask for more air movements and more for less air movements. Then, when occupants have the possibility to choose, requests for more or less air movements decrease, and "no change" is the most common assessment.

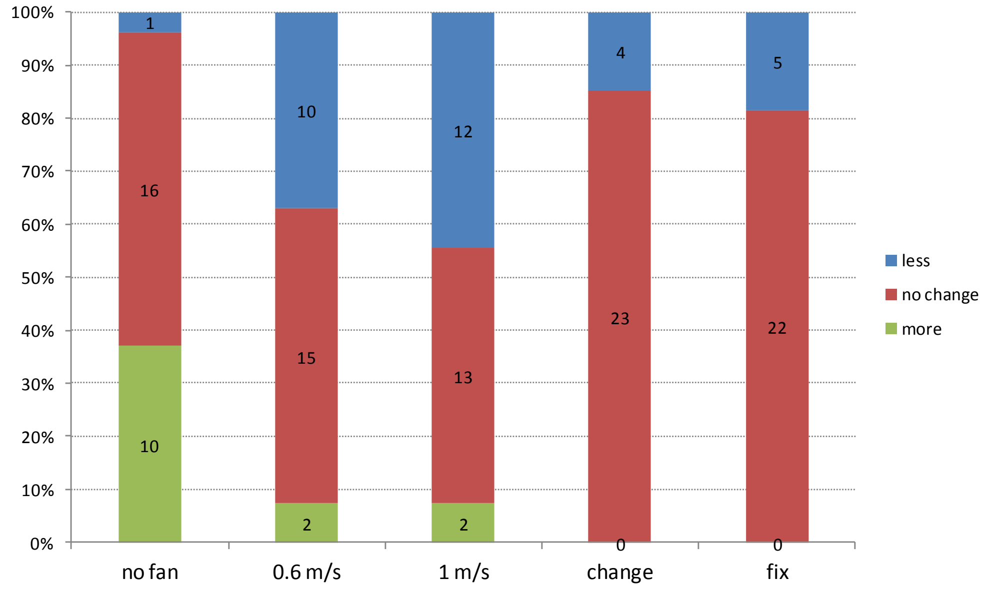


Figure 52 *Number of subjects asking for more/less air movement for each step of the 26°C exposure.*

28°C - condition B

Table 21 *Average TSV, average Acceptability of the thermal environment, average Thermal Comfort Vote, request for being warmer/cooler, request for more/less air movements from questionnaires for 28°C exposure, first experiment.*

	00:00-00:45	00:45-01:00	01:00-01:15	01:15-01:30	01:30-01:45	01:45-02:00
	no fan	0.6 m/s	1 m/s	1.5 m/s	change	fix
TSV ± St Dev	1.2±0.8	0.1±0.5	0.1±0.8	-0.1±0.8	0.1±0.4	0.3±0.5
ACP ± St Dev	0.2±0.5	0.4±0.5	0.4±0.4	0.4±0.4	0.6±0.3	0.5±0.4
TCV ± St Dev	-1.1±0.8	-0.7±0.6	-0.7±0.6	-0.8±0.7	-0.6±0.6	-0.5±0.4
Warmer	0	2	6	5	0	0
No change	6	12	11	14	18	18
Cooler	21	13	10	8	9	9
More air mov.	20	5	3	1	0	1
No change	7	18	13	8	26	23
Less air mov.	0	4	11	18	1	3

Thermal Sensation Vote, Acceptability of the environment and Thermal Comfort Vote show how the highest difference in assessments is again between the exposure without fan and the ones with air velocities. TSV stays almost constant and close to neutrality during the exposures with airflow; only in the last step, when subjects were exposed to their preferred fan's setting, the value goes slightly higher. Acceptability, after the first step, stays about in the middle of the field between "clearly acceptable" and "just acceptable". Comfort assessments, apart from the first part, stay in the band between "slightly uncomfortable" and "comfortable".
To note the high value of standard deviation for these two last parameters.
Moving from the first to the last step, requests for a cooler sensation decrease, while for no change increase. As regard desire of air movement, after the first step few people still want more, at 1 m/s and 1.5 m/s many ask for less, while after changing the setting by themselves subjects stated no change as the preferred option.

30°C - condition C

Table 22 *Average TSV, average Acceptability of the thermal environment, average Thermal Comfort Vote, request for being warmer/cooler, request for more/less air movements from questionnaires for 30°C exposure, first experiment.*

	00:00-00:45	00:45-01:00	01:00-01:15	01:15-01:30	01:30-01:45	01:45-02:00
	no fan	0.6 m/s	1 m/s	1.5 m/s	change	fix
TSV ± St Dev	1.5±0.8	0.8±0.8	0.7±0.8	0.6±1.0	0.7±0.7	0.7±0.7
ACP ± St Dev	-0.2±0.5	0.1±0.4	0.1±0.5	0.2±0.5	0.2±0.5	0.3±0.4
TCV ± St Dev	-1.7±0.8	-1.3±0.7	-1.1±0.8	-1.4±0.8	-0.9±0.7	-1.0±0.7
Warmer	0	1	1	1	0	0
No change	4	5	8	9	9	8
Cooler	23	21	18	17	18	19
More air mov.	20	14	9	3	0	2
No change	7	9	11	10	26	23
Less air mov.	0	4	7	14	1	2

TSV as in the previous exposures presents a decrease when turning on the fans, dropping from a value between "warm" and "slightly warm" to a one little lower than "slightly warm".
Without air flow, this thermal environment condition is on average stated as unacceptable, while through the next steps the assessment improves. The comfort vote stays always in the band between "uncomfortable" and "slightly uncomfortable", a part for the two last steps where the assessment becomes little better.
Request of a cooler thermal sensation stays pretty high during the whole exposure, while warmer desire is stated only by one subjects in some intervals.
Demand for "more air movement" decreases drastically step by step, reaching 0 when subjects have the possibility to change the air velocity. "No change" is stated by most of the occupants in the two last intervals.

32°C - condition A

Table 23 *Average TSV, average Acceptability of the thermal environment, average Thermal Comfort Vote, request for being warmer/cooler, request for more/less air movements from questionnaires for 32°C exposure, first experiment.*

	00:00-00:45	00:45-01:00	01:00-01:15	01:15-01:30	01:30-01:45	01:45-02:00
	no fan	1 m/s	1.5 m/s	2 m/s	change	fix
TSV ± St Dev	2.1±0.4	1.2±0.7	1.3±0.6	0.8±0.8	1.0±0.8	0.9±0.7
ACP ± St Dev	-0.5±0.4	-0.1±0.5	-0.1±0.5	0.0±0.4	0.1±0.4	0.0±0.4
TCV ± St Dev	-2.0±0.7	-1.6±0.7	-1.6±0.7	-1.5±0.7	-1.4±0.8	-1.6±0.8
Warmer	0	0	0	0	0	0
No change	0	2	1	2	3	4
Cooler	27	25	26	25	24	23
More air mov.	23	11	8	3	1	3
No change	4	11	12	9	23	19
Less air mov.	0	5	7	15	3	5

TSV presents a parallel trend compared to all the previous conditions, standing of course around higher value since the temperature of the exposure is increased. Once again, the biggest difference is between using and not using the fan. Particularly, without the thermal sensation is perceived as "warm". For the first tree intervals, the environment is assessed as "not acceptable" on average, reaching the evaluation "just acceptable" only when subjects have the control of the fan's setting.

Comfort vote is stated "uncomfortable" without the fan, while for the next exposures stays between "uncomfortable" and "slightly uncomfortable".

No subject asks for "warmer" sensation for every exposure, and just few in the last intervals for "no change". Trends of request for more/less air velocity are pretty similar to the previous condition, where many occupants in the last two exposures state "no change", and "less air movement" is assessed from less subjects step by step.

34°C - condition D

Table 24 *Average TSV, average Acceptability of the thermal environment, average Thermal Comfort Vote, request for being warmer/cooler, request for more/less air movements from questionnaires for 34°C exposure, first experiment.*

	00:00-00:45	00:45-01:00	01:00-01:15	01:15-01:30	01:30-01:45	01:45-02:00
	no fan	1 m/s	1.5 m/s	2 m/s	change	fix
TSV ± St Dev	2.3±0.4	1.6±0.8	1.6±0.7	1.4±0.7	1.5±0.7	1.4±0.9
ACP ± St Dev	-0.2±0.4	0.1±0.5	0.1±0.5	0.2±0.5	0.2±0.4	0.3±0.5
TCV ± St Dev	-2.3±0.7	-2.0±0.8	-1.9±0.7	-1.8±0.8	-1.8±0.7	-1.7±0.7
Warmer	0	0	0	0	0	0
No change	0	0	0	2	0	4
Cooler	27	27	27	25	27	23
More air mov.	22	18	13	4	3	3
No change	5	9	10	11	21	19
Less air mov.	0	0	4	12	3	5

TSV in absence of airflow reaches a value over "warm". The trend is after pretty constant, where the lowest value is with 2 m/s of air velocity, and stays always between "slightly warm" and "warm" sensation. The thermal environment with such a high temperature of the room is always stated as unacceptable, and particularly without airflow subjects on average assessed a value close to "clearly unacceptable". The last two test intervals present the best values, reaching almost "just unacceptable" as evaluation. Thermal Comfort Vote presents a similar trend, since the worst vote is with fans turned off and close to "uncomfortable", while "slightly uncomfortable" is obtained when subjects decided which setting for air velocity to use.
The question regarding request for warmer/cooler sensation shows a trend similar to the previous exposure: the choice "warmer" is never stated, while "no change" only from few subjects in the steps with 2 m/s and decided air velocity fixed.
More air velocity is requested by less subjects step by step, while "less" comes high with 2 m/s, dropping down when subjects could decide the fan's setting; here indeed "no change" is the most stated sentence.

3.5.2 - Assessments on thermal environment second experiment

This second experiment consist in two sections of one hour, one with exposure to constant flow, and one to natural wind simulation (in random order). The investigated conditions were 28°C and 30°C with preferred average velocities, resulting from the first experiment, of 0.82 m/s for 28°C, and 1.03 m/s for 30°C. The settings used for the natural wind simulation exposures provided about the same average air velocity on one hour

During the two total hours of exposure, the occupants filled in three questionnaires, one immediately after entering the chamber, while the other two at the end of each exposure at different type of air velocity.

Results from subjects' assessments are reported in tables 25 and 26.

28°C - condition 2

Table 25 *Average TSV, average Acceptability of the thermal environment, average Thermal Comfort Vote, request for being warmer/cooler, request for more/less air movements from questionnaires for 28°C exposure, second experiment.*

	00:00-00:05	00:05-01:00	01:00-02:00
	no fan	constant	natural
TSV ± St Dev	0.7±0.6	0.1±0.7	-0.2±0.8
ACP ± St Dev	0.2±0.4	0.4±0.4	0.2±0.5
TCV ± St Dev	-1.0±0.7	-0.7±0.6	-0.8±0.6
Warmer	0	4	5
No change	8	11	12
Cooler	19	12	10
More air mov.	18	3	0
No change	8	14	9
Less air mov.	0	10	17

Thermal Sensation Vote presents the highest differences between presence and absence of airflow, while slightly difference is found moving from constant to natural wind flux. When exposed to both the settings of the fans, occupants stated a vote close to neutrality.

Acceptance of thermal environment and Comfort vote show the best results for the exposure with constant airflow. However, the environment is always evaluated as acceptable, and TCV for both the airflow exposures results in the band between "comfortable" and "slightly uncomfortable".

Request for being cooler decreases from absence of airflow to constant and then to natural flow, while "no change" and "warmer" increase.

Similar trend for demand of air movement, where "more" reaches 0 with natural wind, while "less" increases moving through the tree steps.

30°C - condition 1

Table 26 *Average TSV, average Acceptability of the thermal environment, average Thermal Comfort Vote, request for being warmer/cooler, request for more/less air movements from questionnaires for 30°C exposure, second experiment.*

	00:00-00:05	00:05-01:00	01:00-02:00
	no fan	constant	natural
TSV ± St Dev	1.2±0.6	0.7±0.6	0.5±0.6
ACP ± St Dev	0.0±0.4	0.3±0.4	0.2±0.4
TCV ± St Dev	-1.4±0.8	-1.0±0.6	-1.2±0.7
Warmer	1	0	0
No change	4	8	10
Cooler	22	19	17
More air mov.	23	6	1
No change	4	16	11
Less air mov.	0	5	15

TSV shows the most relevant change between "no fan" and settings with, while in "constant" and "natural" the assessments are pretty close. With airflow thermal environment is stated as acceptable. Comfort vote instead stays in the band between "slightly uncomfortable" and "uncomfortable" for all the exposures.
Almost nobody asks to be warmer in the tree steps, while demand for "cooler" slightly decreases through the tree exposures, increasing "no change".
Request for more air movement drastically decreases turning on the fans, while on the other hand "less" rises, reaching the maximum with natural wind simulation.

3.6 - Skin Temperature

3.6.1 - First type experiment

The following table reports the average values of skin temperature from all the subjects. Mean values for every experiment's interval have been calculated.

Table 27 *Average skin temperatures for each step of each exposure, first experiment.*

26°C	setting	0	0.6 m/s	1 m/s	change	fix	
	skin temp. [°C]	32.9	32.2	32.0	32.0	32.1	
28°C	setting	0	0.6 m/s	1 m/s	1.5 m/s	change	fix
	skin temp. [°C]	32.9	32.3	32.1	32.0	32.2	32.3
30°C	setting	0	0.6 m/s	1 m/s	1.5 m/s	change	fix
	skin temp. [°C]	33.7	33.3	33.1	33.1	33.2	33.2
32°C	setting	0	1 m/s	1.5 m/s	2 m/s	change	fix
	skin temp. [°C]	34.0	33.8	33.7	33.7	33.7	33.7
34°C	setting	0	1 m/s	1.5 m/s	2 m/s	change	fix
	skin temp. [°C]	34.5	34.3	34.3	34.2	34.3	34.2

Very small differences are present between intervals with different air velocity from the fans. Therefore is difficult to draw some conclusions regarding effect of different airflow velocity on subjects' skin temperatures. It is however possible to see a more significant decrease between the first step and the other, meaning that airflow contributes to reduce skin temperature of subjects. Comparing same airflow velocities with different temperatures, is clear to state that increasing the environment's temperature, skin temperature increases.

3.6.2 - Second type experiment

Table 28 reports findings from the exposures of the second experiment type.

Table 28 *Average skin temperatures for each step of each exposure, second experiment.*

28°C	setting	continuous	natural
	skin temp. [°C]	32.3	32.1
30°C	setting	continuous	natural
	skin temp. [°C]	32.8	32.8

No significant differences are present between average values of skin temperatures between exposure to constant and dynamic airflow. It is worth to say however that with 28°C wind simulation seems on average to reduce slightly more the skin temperature.

Chapter 4 - DISCUSSION

4.1 - Human responses first type experiment

Goals of this first type of analysis were to check reactions of occupants to different thermal environments and to different constant airflows exposures. Particularly:

- find which are the conditions in which is actually possible to reach the thermal comfort of the occupants increasing temperature;
- on average, which was the preferred air velocity provided by the fans, chosen by the occupants during the different exposure, in order to make a comparison, in the second experiment, between a simulated natural wind airflow with the same mean air velocity.

4.1.1 - Thermal Sensation Vote - Predicted Mean Vote

Comparing the five different temperatures used for our exposures, it is possible to find a similar trend during the intervals of the experiments for the TSV: first a consistent decrease, when turning on the fan, and then an almost constant progress, with the lowest values usually for the step with the highest air velocity fixed by the experimenter. Indeed, when subjects are allowed to change the setting of the fan, the TSV value slightly increases; this probably means that even if the thermal sensation is a little bit more distant from neutrality, occupants prefer to feel warmer than to be annoyed by the airflow, that reaching value of 1.5 m/s or 2 m/s may be too intense.
The following graph in Figure 53 shows the values on average obtained for the TSV during the intervals in which subjects could change the air velocity provided by the fans. This interval has been chosen since in theory could provide the best value for each parameter of subjective evaluation of the thermal environment, therefore is the most representative of the possibility to reach our objectives. The progress is almost linear, the two biggest differences are between 28°C - 30°C and 32°C - 34°C, however negligible. Condition A, with 32°C, is the last in which is possible to reach assessments under "slightly warm" sensation.

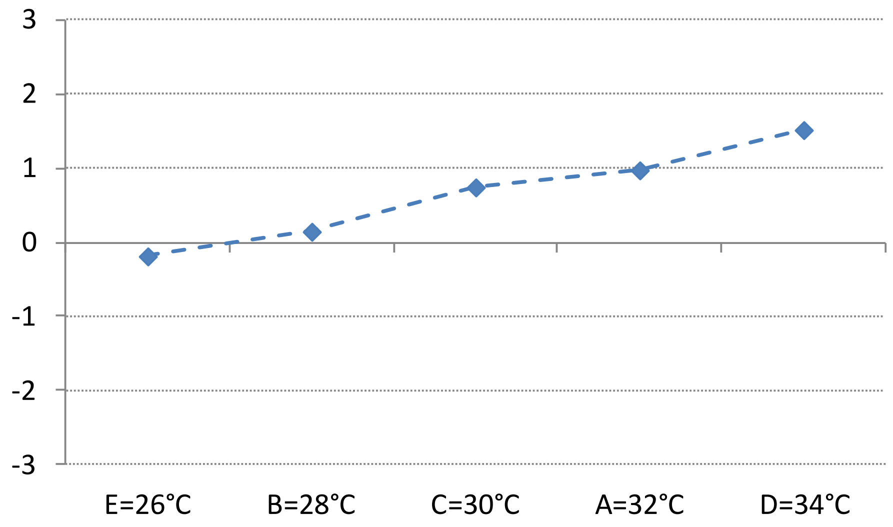


Figure 53 *Average TSV values, conditions first experiment, step "change".*

As an index for the global thermal comfort, PMV calculated for the average condition of each temperature's exposure is compared with subjects' evaluation of Thermal Sensation Vote.
Figure 54 shows the situation for 30°C. Next to TSV with its standard deviation, PMV with maximum and minimum values for the whole exposure is reported. The band between the two extreme values of PMV is pretty small, and comes from standard deviations of air velocities recorded during the experiments at the same temperature, as already said when presenting PMV table in Results chapter.

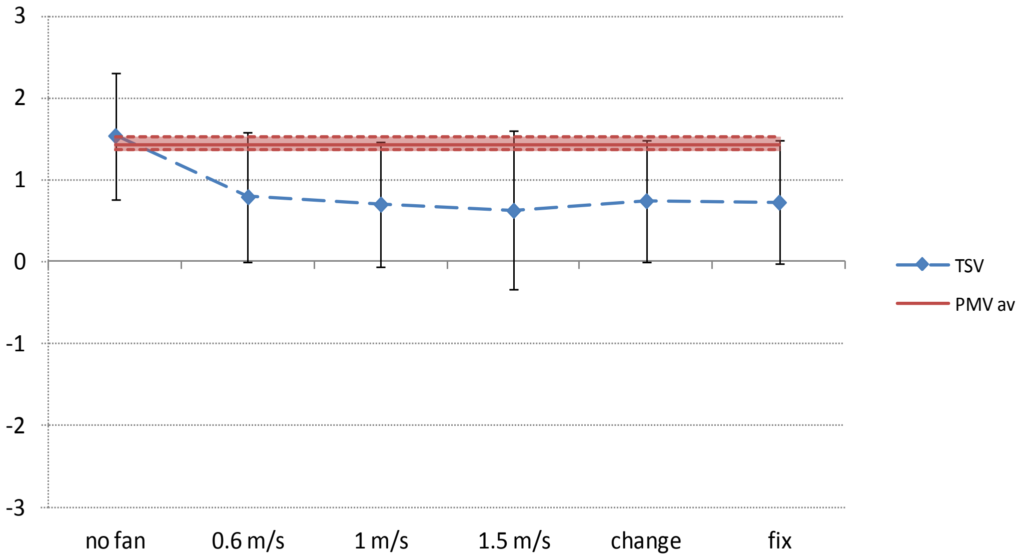


Figure 54 *Comparison of PMV and TSV values for each step of the 30°C exposure, first experiment.*

As expected, in the first interval, when fans were switched off, PMV results a good index for the Thermal Sensation Vote stated on average from occupants. The slightly higher value of TSV with "no fan" is presented in most of the five exposures and can suggest that Danish people are a little more sensitive to warm condition. However, the difference is very low, and for 34°C PMV results higher than TSV instead.
When fans are turned on, TSV stays always under PMV average value and its band of maximum/minimum. The conclusion is obviously that the local airflow perceived by subjects influences their global thermal sensation, and brings them to state the environment as less warm than what is expected without direct exposure to the airflow.

4.1.2 - Acceptability of the thermal environment

Even if the trends for the different exposures are not so parallel, it is possible to recognize an almost constant improvement in the assessments of the acceptability of the environment from the first to the last interval during the experiments, taking into account that the best evaluations are for the test part where air velocities were controlled by the subjects. Results show that 30°C is the highest temperature in which is possible to get on average an "acceptable" statement. For 32°C the last test interval falls between "just acceptable" and "just unacceptable" (that is a field not possible to choose for the subjects in the questionnaires, but that derives from average calculation) while for 34°C not even "just unacceptable" is reached. On the other hand it is fair to say that standard deviation for the acceptability assessments is pretty high, being present a great variability in the evaluations from subject to subject for each condition.

To have an idea on how much subjective assessments are different for this question, the two following graphs are reported, where responses for the interval "change" on the extreme conditions 26°C and 34°C are shown for each subject:

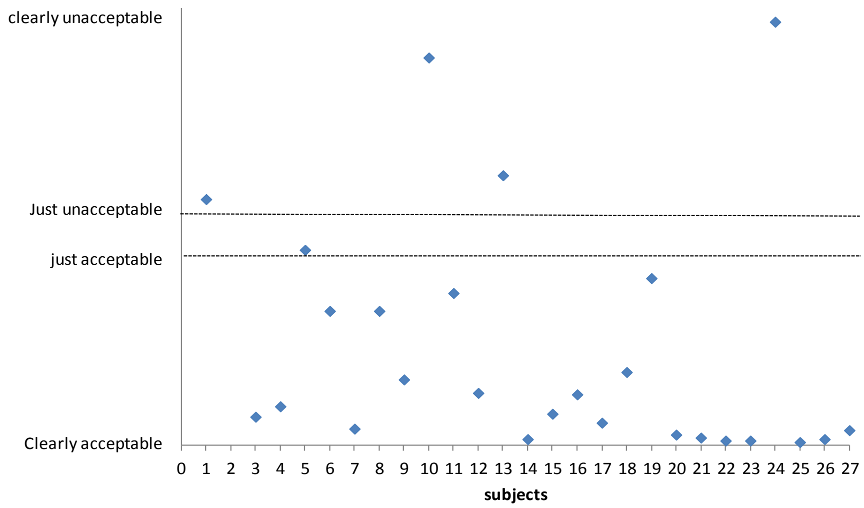


Figure 55 *Assessments of each subject to the acceptability of the thermal environment, 26°C, "change".*

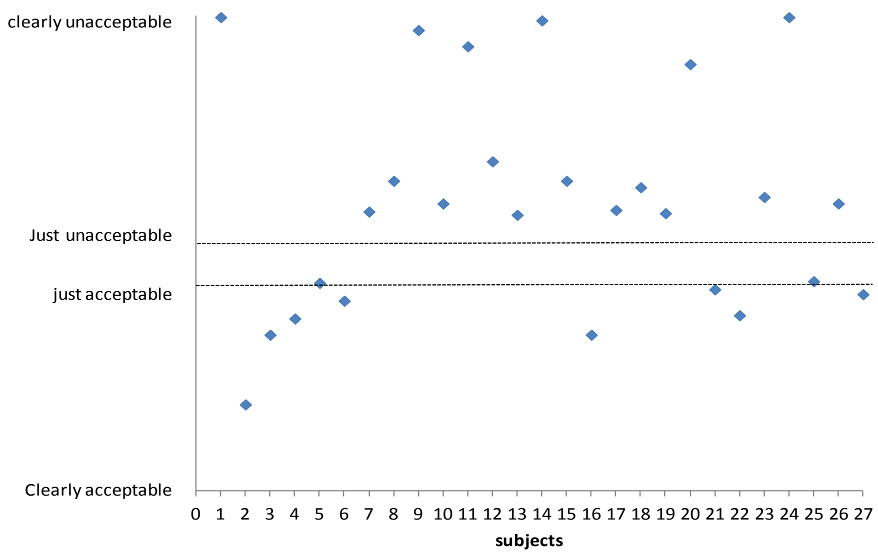


Figure 56 *Assessments of each subject to the acceptability of the thermal environment, 34°C, "change".*

While for 26°C most of the occupants assessed acceptable the environment, and especially many said it was "clearly acceptable", with 34°C there is a big dispersion of the evaluations.
Standard deviation is in any case pretty high since some subjects always provide a response completely different from the average; for example in the first graph two occupants stated almost "clearly unacceptable" an environment assessed as "clearly acceptable" from the majority. In this way it is demonstrated once again how subjective assessments could be pretty different from what is expected.

4.1.3 - Thermal Comfort Vote

Conclusions from this parameter are quite similar to what is found about acceptability of the environment: 30°C is the highest usable temperature to keep on average comfort condition, as the following graph, referred to the test interval "change", shows.

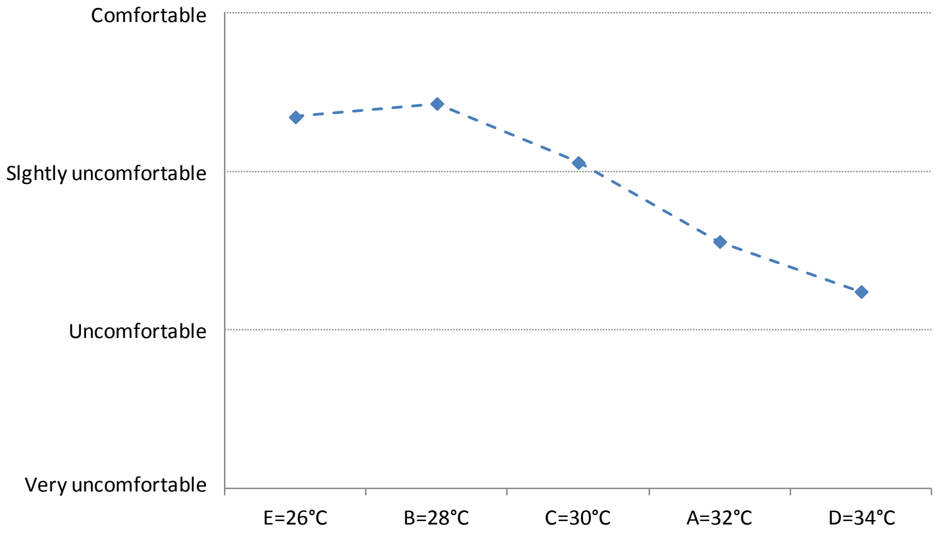


Figure 57 *Average TCV values, conditions first experiment, step "change".*

It seems that 28°C are better tolerated compared to 26°C; this could be due to the fact that presence of airflow can create more problems of draught whit low temperatures. Particularly, data from the question regarding demand of airflow show that less subjects asked for less air velocity with 28°C than with 26°C at the same test intervals.
Increasing the temperature from 28°C there is a linear decreasing of the comfort assessment, where the 34°C reaches almost "uncomfortable" evaluation. Especially, the exposure with the highest temperature presents a trend pretty flat changing the air velocity in comfort assessments, meaning that with such an extreme condition the cooling effect provided by fans is negligible in terms of thermal comfort; indeed TSV results indicate the same difficulty in providing a low thermal sensation at this temperature.
Almost each test interval with 26°C and 28°C is better assessed than "slightly uncomfortable"; 30°C instead presents only the two last intervals around this value, while the previous are under. Particularly with this temperature, 1.5 m/s of air velocity seems to be less comfortable than all the other airflow exposure, indicating probably a contrast between the request of more air to cool down and the bothering created by the airflow itself.

4.1.4 - Request of being warmer/cooler

It is clear that this question goes along with the TSV evaluation, since when Thermal Sensation Vote increases, the number of subjects requesting to be cooler increases as well. Particularly, with the lowest temperature this assessment decreases significantly when the fans are turned on, while with 32°C and 34°C subjects almost always ask to be cooled down. With 26°C and 28°C is reached in the last two steps a number of around 18 subjects stating "no change" in this question, which means in these conditions using fans is a functional way to provide the necessary cool effect to occupants. 30°C presents instead an average behavior between the highest and the lowest temperatures, since there are always a consistent number of persons asking to be cool down; in this way it is not possible to state that fans achieve their goal.

4.1.5 - Request of air movements

Demand for air movement shows a similar trend in each temperature exposure: increasing the air velocity the request for more air movement decreases, particularly for the lowest temperatures where, as already said, the cooling effect and the potential discomfort due to draught are higher.
Even with the highest temperatures, demand for less air movement rises increasing the velocity of air, and reaches the maximum in every exposure when the fan is set with the highest airflow velocity fixed by the experimenter. 28°C exposure presents the maximum number of subjects (18) asking for less air movement at the velocity of 1.5 m/s, meaning that this temperature is too low for such an high velocity, that most likely creates bother to many occupants because of draught local discomfort.
Graph for the 30°C exposure is following reported in Figure 58, showing how with this temperature almost every subject when allowed to decide the fan's setting assessed "no change" in the request for air movement, while for 1.5 m/s fixed velocity half of them asked for "less".

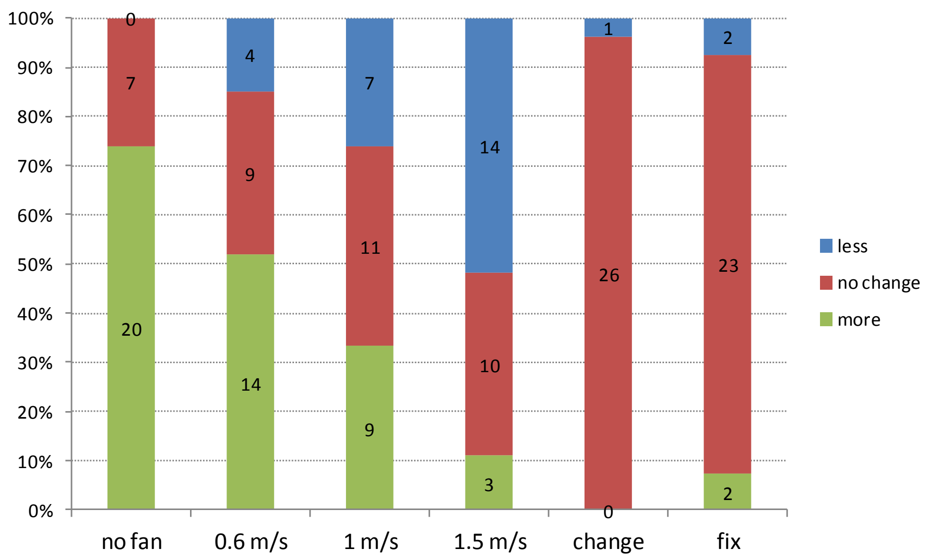


Figure 58 *Number of subjects asking for more/less air movement for each interval of the 30°C exposure.*

4.1.6 - Summary first type experiment

Analyzing the results in the assessments for the previous parameters some findings can be reported:

- the biggest changes in all the evaluations are between the first and the second interval, that means between absence of air flux, and presence at the lowest velocity. Anyway it is fair to remind that the sequences of the exposures were random, having for example in some cases as second setting the highest air velocity fixed by the experimenter; however, during the analysis the intervals were reorganized to compare same air velocity exposures. In this way, what is possible to say is that the most relevant differences are between absence and presence of airflow, while between different settings of the fans less relevant changes in evaluations are present.

- Usage of fans as a cooling system to offset increases in air temperature with a constant airflow pattern results useful until 30°C room's temperature, where is still possible to get assessments of comfort and acceptability on average when occupants are allowed to change the fan's setting.
It is otherwise worth to say that variability of the two parameters is pretty high.

- Bother for excess of air velocity is not only due to draught, intended as an undesired local cooling effect. Indeed request for less air movement especially in the intervals with the highest fixed air velocity are always present, in each exposure, while the assessments on demand for being warmer/cooler show that in the highest temperatures subjects always ask for a cool sensation. Moreover, many comments present in the questionnaires showed how high velocities of air create many annoyances such as dryness of eyes and lips and problems of noise.
It is therefore possible to say that while for lower temperatures high air velocities result annoying also for an excess in cooling (especially there are subjects still assessing desire for a warmer sensation with 26°C and 28°C), for higher other additional reasons are present.

- "change" is the test interval that gets the best results for the parameters analyzed, followed by "fix", meaning occupants were exposed to their preferred air velocity.
Especially regarding demand for changes in air movement, the interval when they were allowed to decide the setting presents a pretty high number of assessments "no change". On one hand is true that, during the exposure, subjects could continuously modify the air flux provided by the fan, which means adjusting it every time they felt a kind of bother; from the other, when filling in the questionnaires they were exposed to the velocity fixed for the next step. In this way, it is possible to say that the psychological effect regarding the possibility of control of the thermal environment parameters is present, since even if exposed to the same airflow condition, subjects stated as less pleasant the situation in which they could not modify anything to improve their thermal sensations.

- PMV is a good indicator for subjects' thermal sensation only when no local external factors are present. Airflow directed on some parts of the body brings occupants to a lower global thermal assessment.

4.2 - Human responses second type experiment

Main target of this second exposure type is to find differences in human thermal environment perceptions and assessments between the two airflow patterns studied, constant and natural wind simulation types. Below discussions about the evaluated parameters already introduced are reported. Since we had only two temperatures of exposure in this second experiment, values for both are plotted in the same graph, in order to make a more effective comparison.

4.2.1 - Thermal Sensation Vote - Predicted Mean Vote

The following graph in Figure 59 shows TSV values on average for the intervals in which the experiments were divided, with standard deviation as error bar.

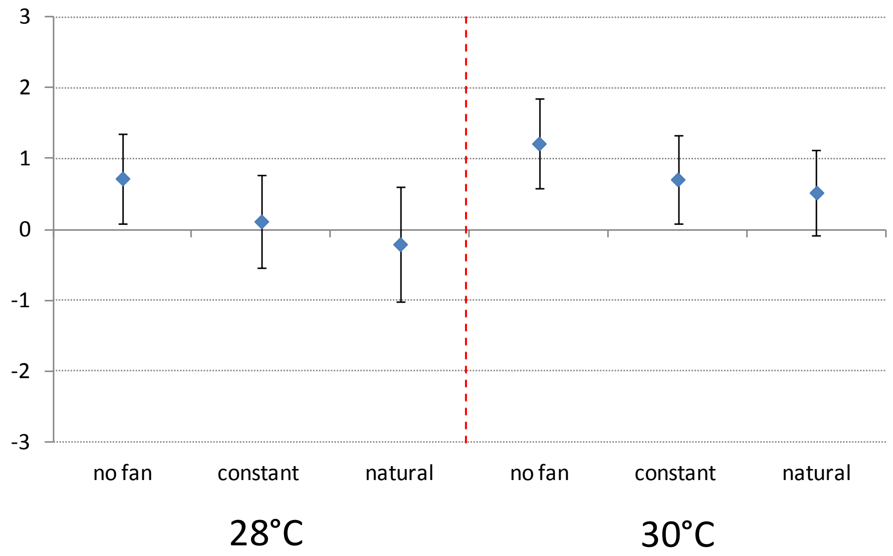


Figure 59 *Average values of TSV with standard deviation for each step of both exposures, second experiment.*

Trends for 28°C and 30°C are parallel, where obviously the higher temperature presents the higher values. In each case airflows allowed TSV assessments under "slightly warm", while natural pattern seems to provide a cooler sensation. This is in accord with previous studies' findings.

Comparison between Thermal Sensation Vote and Predicted Mean Vote for 30°C exposure is reported in Figure 60. As already found for the first type of experiment, PMV is a good indicator for subjective thermal sensation only in absence of airflow. When occupants are exposed to a local air velocity, TSV goes away from what is expected with PMV, reaching lower values.

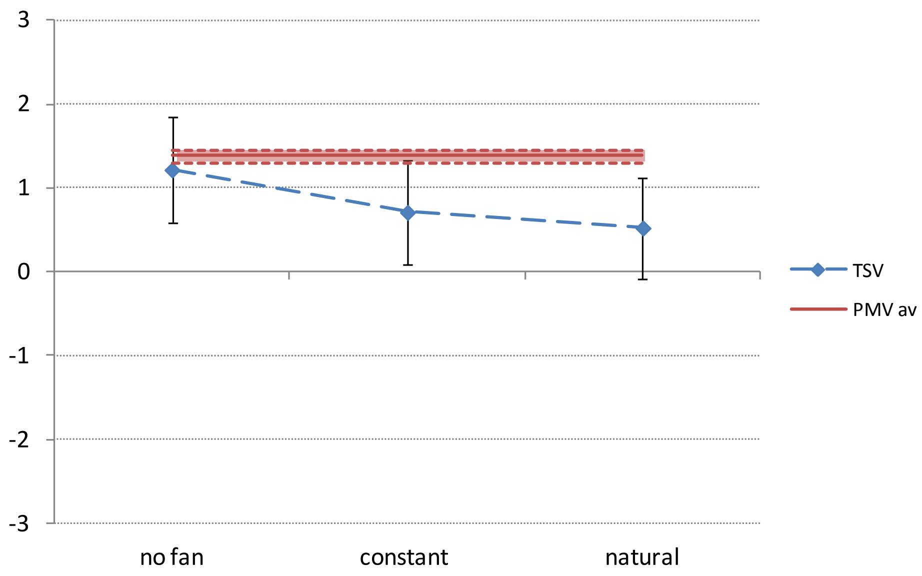


Figure 60 *Comparison of PMV and TSV values for each step of the 30°C exposure, second experiment.*

4.2.2 - Acceptability of the thermal environment

The graph in Figure 61 shows how the presence of airflow in both conditions improves the acceptability evaluations, but constant setting results more acceptable compared to wind simulation one. This is more evident for the lower temperature, where probably draught effect is more relevant and a constant breeze is preferable. Anyway elevated variability of assessments is present since standard deviation errors plotted are large.

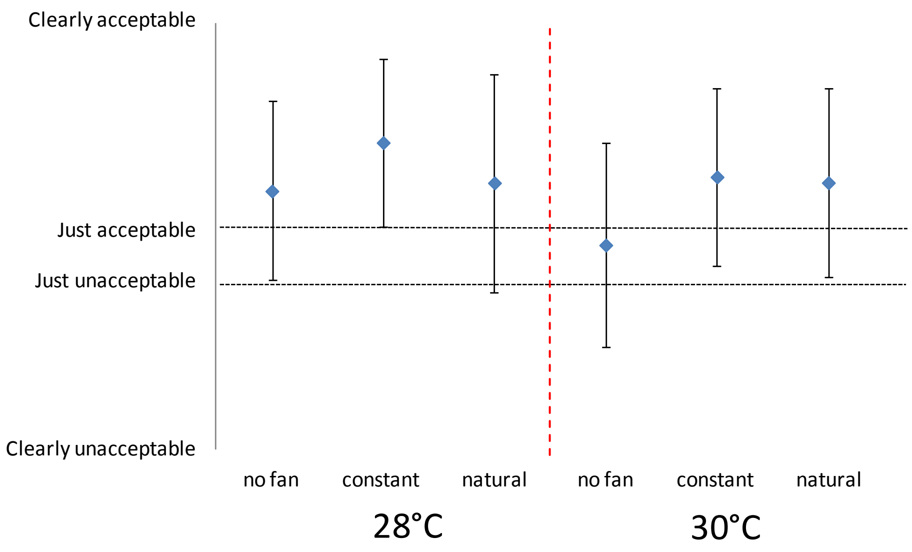


Figure 61 *Average values of acceptability of the thermal environment with standard deviation for each step of both exposures, second experiment.*

4.2.3 - Thermal Comfort Vote

Same conclusions come from TCV, since constant airflow gets better evaluations compared to natural wind simulation. Particularly, with 30°C only constant setting reaches "slightly uncomfortable", while "natural", and obviously "no fan", stay under.

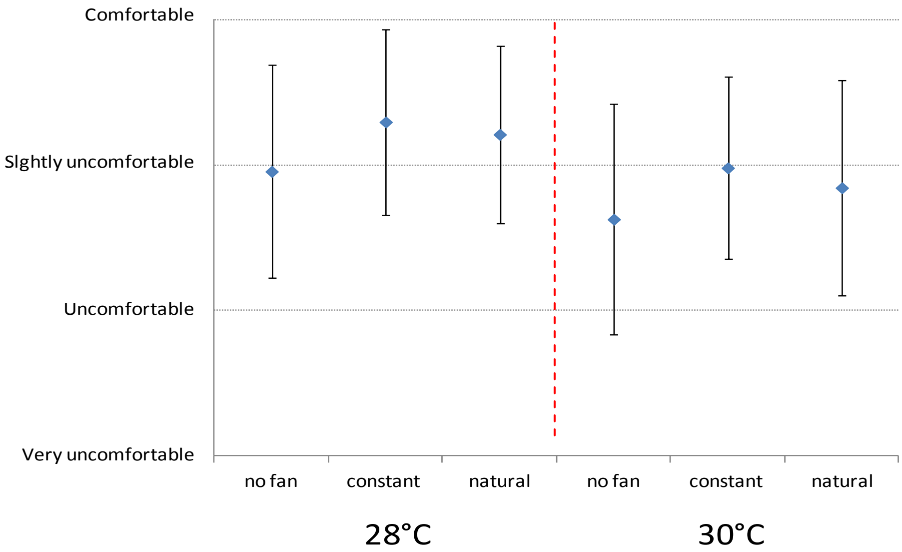


Figure 62 *Average values of TCV with standard deviation for each step of both exposures, second experiment.*

4.2.4 - Request of being warmer/cooler

Demand for cooler sensation slightly decreases moving from constant airflow to wind simulation. With 28°C, warmer demand slightly increases instead. This clearly shows how an air flux with high variability in intensity generates a cooler sensation on people.

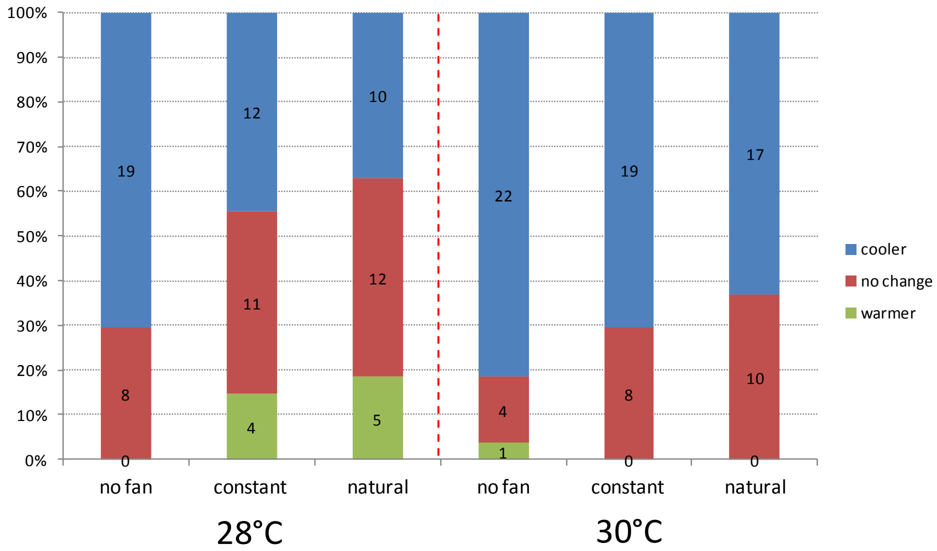


Figure 63 *Request of being warmer/cooler for each step of both exposures, second experiment.*

4.2.5 - Request of air movements

The direct question regarding air movements confirms considerations coming from previous parameters analyzed: wind simulation pattern is perceived as less pleasant than constant airflow. Indeed the following graph in Figure 64 shows how moving from "constant" to "natural", demand for less air movement significantly increases, while "no change" and "more" decreases.

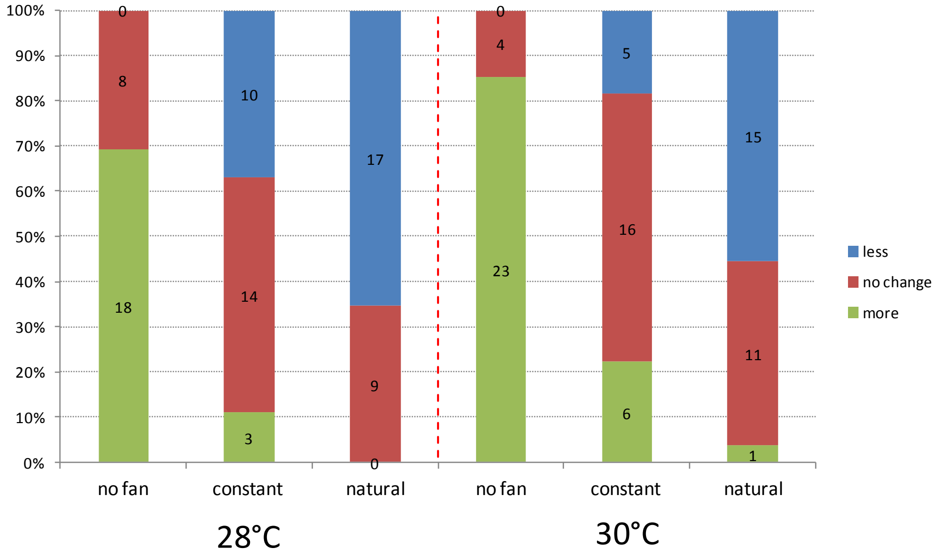


Figure 64 *Request of more/less air movement for each step of both exposures, second experiment.*

4.2.6 - Summary second type experiment

The exposures studied to compare differences between subjects' assessments on two different airflow patterns give some findings:

- Even if the average air velocity of the two airflow types, to which the subjects were exposed, was the same, the natural wind simulation generated clearly a cooler sensation.

- Even if the request of being warmer/cooler gets the major answers of "no change" with wind simulation exposure, subjects stated more pleasant the constant flow. Acceptability and Comfort Vote present better assessments in this case, and especially request of air movements shows the highest number of subjects stating "no change" with the constant pattern.
Reasons for this can be found in the discomforts created by the type of pattern provided by the natural wind reproduction: not only draught as excessive cooling sensation should be considered, since many subjects were still asking for a cooler sensation with this exposure.
The high velocities sometimes generated by the fans provoked many annoyances, like dryness of lips or eyes; particularly many occupants wrote on the comments how the excess on changing velocity was surprising them up to be annoying.

- As already found with the previous experiment type, PMV results a good index for TSV only when persons are not exposed to a local "agent" influencing their global evaluations.

4.3 - Additional comparison TSV - PMV

Airflows generated by fans in our experiment create a local effect on the subjects, since directed towards the upper part of their body. Manikins' measurement confirmed it.
In this way, making a comparison between PMV calculated with thermal environment parameters recorded at 0.6 m and 1.1 m of height could lead to different results. Indeed the so-called background air movement, as already said used for the PMV calculation, presents different trends between the two heights.
It is fair to say that PMV is a global index, therefore human perception of the thermal environment expressed by this value cannot be divided in two "parts". However, the aim is to see if and how much the local impact of the airflow affects this index, and therefore if it is more correct to compare the TSV assessments with PMV at 0.6 m or 1.1 m of height.
The following Table 29 shows the results from the first type of experiment, where the values of TSV reported are for the last interval of each exposure, when subjects were thermally adapted and exposed to their preferred air velocity.

Table 29 *Comparison between TSV for step "fix", PMV at 0.6 m of height, PMV at 1.1 m of height.*

	TSV ± St Dev	PMV 0.6 m	PMV 0.6 m max	PMV 0.6 m min	PMV 1.1 m	PMV 1.1 m max	PMV 1.1 m min
E=26°C	-0.2 ± 0.7	0.3	0.4	0.2	0.3	0.4	0.2
B=28°C	0.3 ± 0.5	0.9	1.0	0.8	1.0	1.1	0.9
C=30°C	0.7 ± 0.7	1.4	1.5	1.4	1.4	1.5	1.4
A=32°C	0.9 ± 0.7	2.0	2.0	1.9	2.1	2.1	2.1
D=34°C	1.4 ± 0.9	2.6	2.6	2.6	2.6	2.6	2.6

Small are the differences between the two values of the PMV at the two heights, as their maximum and minimum value. Therefore it is demonstrated how the different trends of background airflows do not impact significantly on the prediction of the thermal sensation. Operative temperatures and relative humidity values at the two heights indeed were almost the same, not resulting in differences in PMV calculations.
Thus, as in guidelines and standards, comparison with TSV should be done using the PMV values calculated at 0.6 m of height, as already done for the considerations in the previous chapters.

TSV results for each condition lower than the correspondent PMV value. As already explained, while PMV has been calculated using air velocity values recorded from a stand not directly exposed to the airflow generated by fans, TSV reports subjects' assessments for each test intervals, particularly when occupants were directly exposed to airflows.
In the next page, Figure 65 shows values from the previous table. Standard deviation for TSV, maximum and minimum for PMV are not showed, to avoid overlap of the bars.

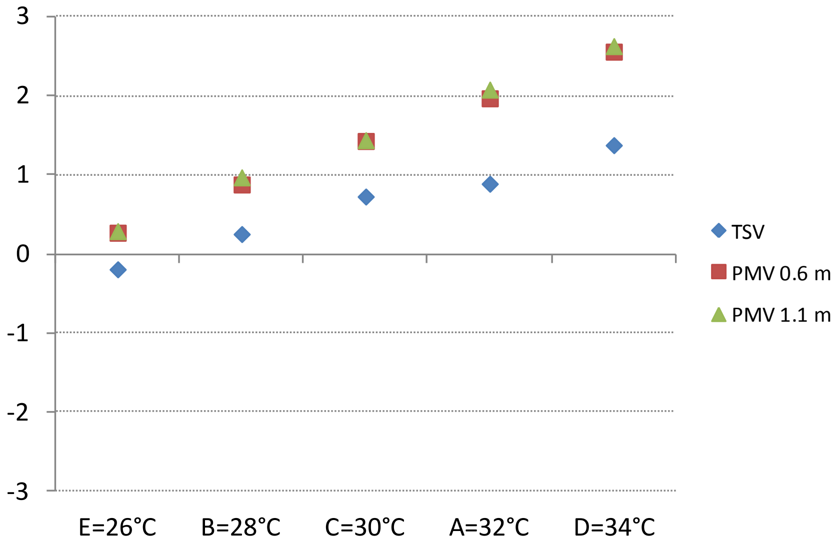


Figure 65 *Comparison between TSV for step "fix", PMV at 0.6 m of height, PMV at 1.1 m of height.*

As already said, PMV values at the two different heights, representative of standing and seated person, are basically coincident. The differences with TSV average assessments grow increasing the temperature: the local cooling effect of fans creates a higher discrepancy between prediction and perception of the thermal sensation when the temperature is high.

4.4 - Comparison TSV - Equivalent temperature

Results from subjects' assessments and manikins' measurements can be compared or directly correlated. Håkan Nilsson (et al. [20]) found an almost linear trend between TSV subjects' evaluations and equivalent temperatures from reproduction of the same conditions with thermal manikins. Figure 66 shows the findings of the present work: on the x-axis equivalent temperatures as average for the whole manikin's body are reported; on the y-axis, average TSV assessments for the correspondent test intervals. The shown values are representative of the exposure without and with fixed air velocities by the experimenter. A linear trend-line is shown for the temperature conditions of 26, 28 and 30 °C.

The linear correlation is more evident for the exposures at 28°C and 30°C. Those results are in agreement with the previous findings of Nilson et al. Manikins' measurements of equivalent temperatures could be used to predict thermal sensation of the actual occupants.

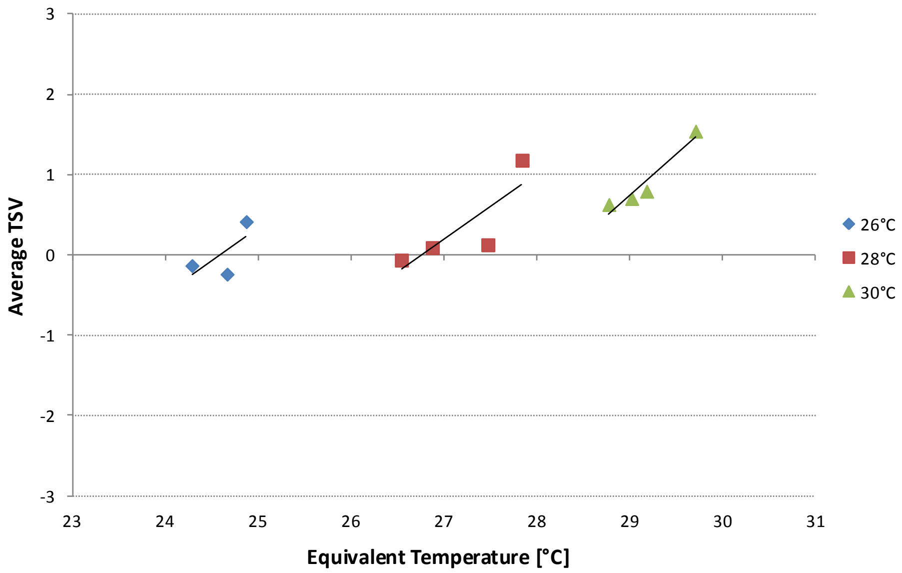


Figure 66 *Correlation TSV - equivalent temperature for 26°C, 28°C and 30°C exposures*

4.5 - Comparison between Chinese and Danish findings

The present experiment was performed on the basis of a previous one conducted in China. Particularly, Jinjing Hua (et al. [17]) realized a study with the same prototypal fans, comparing effects of constant mechanical air movement with simulated natural air wind on subjects. Climatic chamber experimental data of TSV, resulted from the two samples of population, are shown in Table 30 and following compared.

Table 30 *Results from same experiment type conducted in China and in Denmark.*

		chinese		danish	
		constant	natural	constant	natural
28°C	TSV ± St Dev	0.00 ± 0.47	-0.05 ± 0.32	0.1 ± 0.7	-0.2 ± 0.8
	TCV ± St Dev	-0.41 ± 0.40	-0.37 ± 0.29	-0.7 ± 0.6	-0.8 ± 0.6
30°C	TSV ± St Dev	0.58 ± 0.56	0.45 ± 0.38	0.7 ± 0.6	0.5 ± 0.6
	TCV ± St Dev	-0.70 ± 0.46	-0.56 ± 0.33	-1.0 ± 0.6	-1.2 ± 0.7

First of all, it is fair to say that a direct comparison could be done only in the condition with 30°C, since the air velocity used in both cases was on average about 1 m/s; while for 28°C Chinese experimenters were still using 1 m/s higher than 0.8 m/s used in the present study.
However, it is possible to state the followings:

- Thermal Sensation Vote of Danish subjects often is higher than Chinese assessments; therefore people used to cooler climate are likely slightly more sensitive to warm conditions.
- Thermal Comfort Vote of Danish subjects is on average worse than Chinese one; again this means that persons used to colder climates are less able to withstand warm environments.
- Chinese subjects stated on average higher level of comfort with simulated natural wind, while for the Danish population there was not difference. However, Danes expressed their preference about the constant air movement, as they found particularly annoying the air fluctuation generated in natural wind mode. It could be deduced that Chinese people are adapted and so less sensitive to high air velocity, and to the probable discomfort such as draught, or also lips and eyes dryness.
- Standard deviations of TSV of both populations are very close, meaning that subjective variability of assessments is not affected by local climates.

Preferred air velocity is another term of comparison used between the two samples of populations. The following graph (Figure 66) presents the values of the preferred constant air velocities stated on average by subjects from both the experiments.

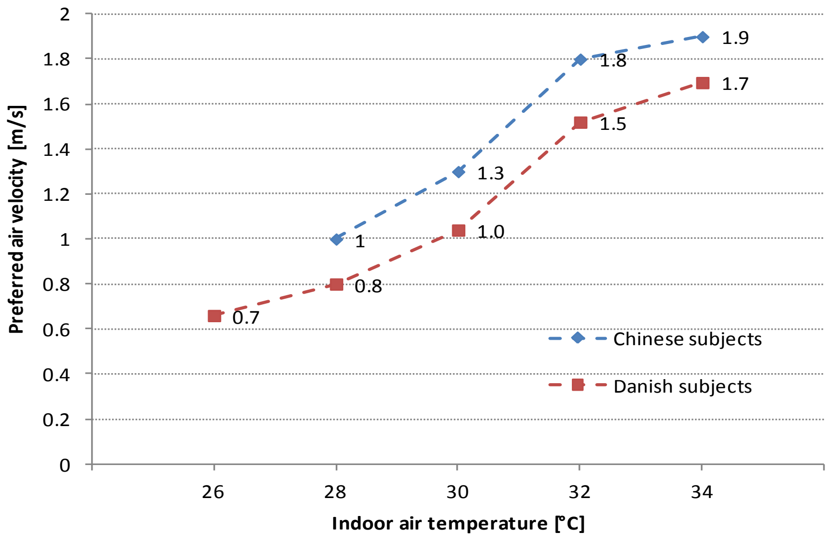


Figure 67 *Preferred constant air velocities of Chinese and Danish subjects.*

A difference of about 0.2 - 0.3 m/s is shown for each temperature's exposure. As already found from assessments about Thermal Comfort Vote, Chinese subjects seem to be less sensitive to high air velocities. The conclusion is that people from Beijing region can better exploit the potential of the airflows to be cooled.

The 26 °C condition was not investigated during the Chinese experiment. However could be interesting compare what standard ISO 7730 [2] presents regarding air velocities in design criteria. Table 31 reports values of maximum mean air velocities allowed for typical office space depending on the category of the building for summer condition.

Table 31 *Design criteria for office space according to ISO 7730 [2]*

Type of building	Activity	Category	Operative temperature	Maximum mean air velocity
	[met[		[°C]	[m/s]
office	1.2	A	24.5±1.0	0.12
		B	24.5±1.5	0.19
		C	24.5±2.5	0.24

Even if moving from category A to C the value of air velocity increases, the maximum value allowed is 0.24 m/s for category C that results much lower than the preferred one 0.7 m/s found in the present experiment. Different could be the reasons for this discrepancy.

First of all, it is fair to say that we analyzed the assessments of a small group of people, while standard's indications are based on a large amount of responses. This consideration could lead to state that Danish subjects can bear higher air velocities compared to the average population standard takes into account.
However another aspect is pretty relevant: maximum mean air velocity allowed for office space is understood deriving from a global assessment of the thermal condition. In our case air velocity is presenting a local effect, since directed only towards the upper body part, especially to the

face. Subjects, therefore, could have chosen a higher air velocity to determine their neutral thermal sensation, which was not done as the cooling effect was just local.

If the overall body is exposed to the airflow, subjects could have chosen lower value of air velocity as more parts of the body would be exposed and cooled down, having higher heat loss. In that conditions, results would better agree with what stated in the standard.

Conclusions

27 Scandinavians, performing office activities and wearing light clothes, were exposed to an increased air movement generated by a personal desk fan.
In the first experiments air velocities were fixed by the experimenter during the first intervals of exposure. This was followed by a period where the subjects could select their preferred air velocity.
In the seconds, the human participants were exposed to a comparison between constant and natural wind airflows. Different environmental conditions were analyzed, setting air temperature between 26°C and 34°C, keeping constant the absolute air humidity at 12.2 g/m^3.
Some of these conditions were repeated using thermal manikins.
The main results are following reported.

First experiment - comparison between constant airflows:

- Subjective assessments showed how it is actually possible to keep comfortable conditions for occupants increasing air movements in warm environments. On average the temperature limit to exploit fans' cooling effect is 30°C.
- No significant differences are present in thermal comfort evaluations changing air velocity. Neither skin temperatures show particularly differences. However, subjects were increasingly comfortable when allowed to change the fan's setting: personal control of the device leads to better perception of the environment.
- Manikins' measurements proved how the cooling effect of airflow increases with air velocity, while decreases with temperature. Moreover, only directly exposed body parts were cooled, which demonstrates that these fans create a local effect.
- Preferred air velocity decided by subjects clearly increases with environment's temperature.

Second experiment - comparison between constant and wind simulation airflows:

- Skin temperatures and manikins' tests reported no significant differences between the two types of airflows. Therefore, independently from the flow pattern, same average velocities results in same effects on physical parameters.
- Even if subjects reported a cooler sensation with natural wind simulation, they preferred the constant airflow. The reason for not preferring the natural wind is the gusts velocity. It is recommended to develop a pattern with damped peak of air velocity. Indeed, combination of cooler effect and better acceptability of the airflow could lead to higher comfort assessments of occupants.

Overall:

- Chinese subjects had a lower, close to neutral expressed in TSV and TCV compared to Danish and preferred higher air velocities in each environment's condition. Moreover they stated as more pleasant natural wind simulation airflow than constant airflow. In conclusion people used to warmer climate seem to be less sensitive to high temperature and to increased air velocities.

- PMV is a good indicator for subjects' thermal sensation only when no local external factors are presented. Airflow directed on some parts of the body brings occupants to a lower global thermal assessment.
- According to the author, further experiments could be performed to evaluate the effective energy saving achievable using fans. Comparison between power consumption of air conditioning systems and the usage of fans to keep the same thermal comfort conditions in a studied indoor environment could result particularly interesting.

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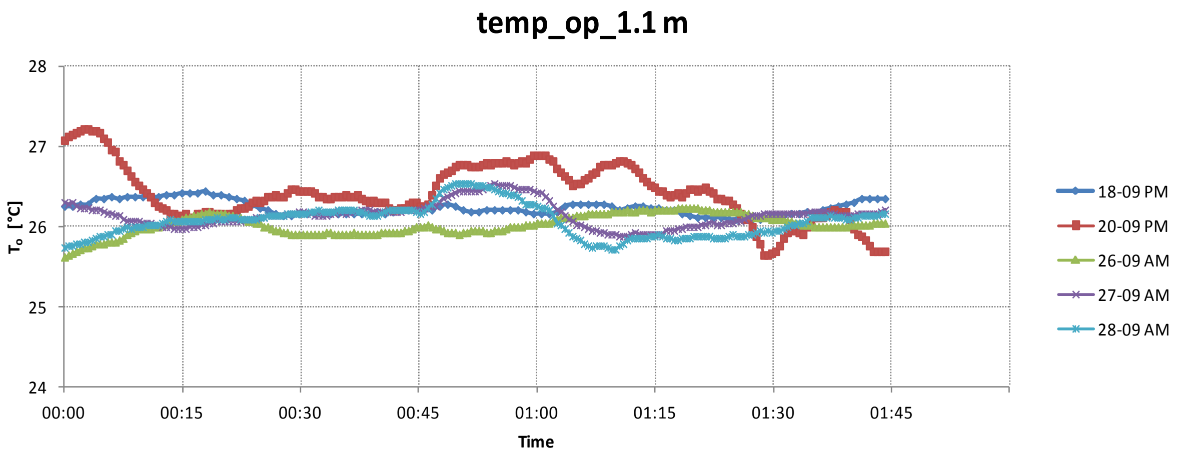
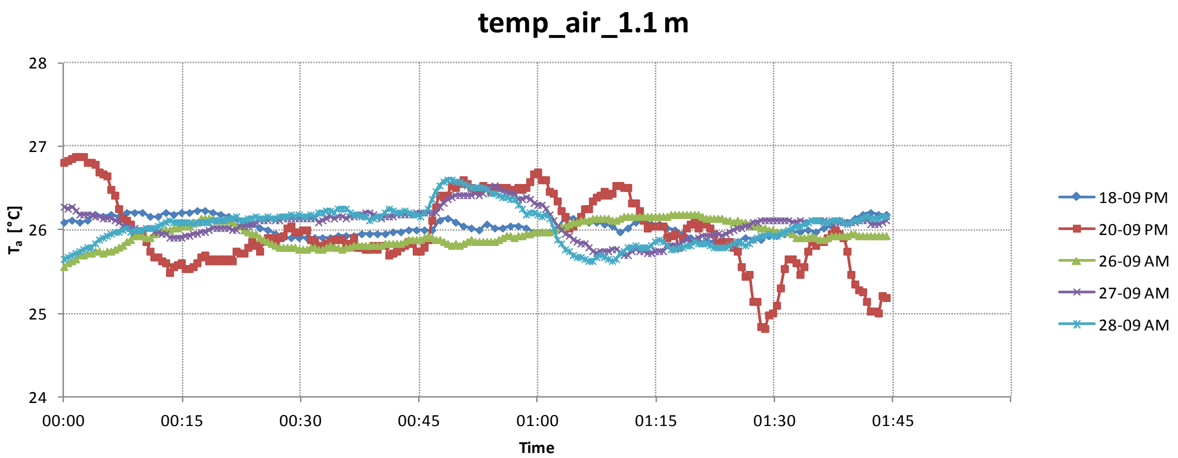
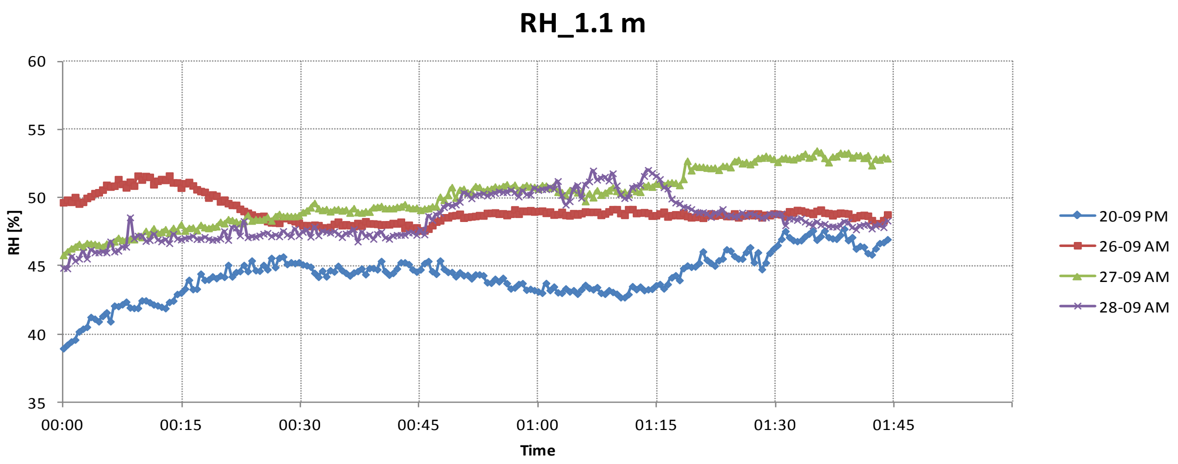
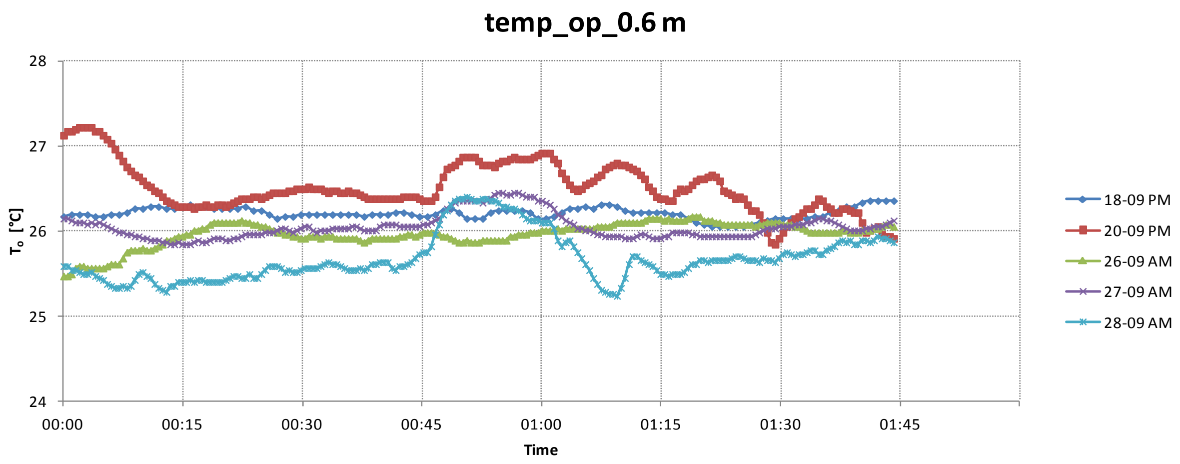
Appendix A - Physical measurements during exposures

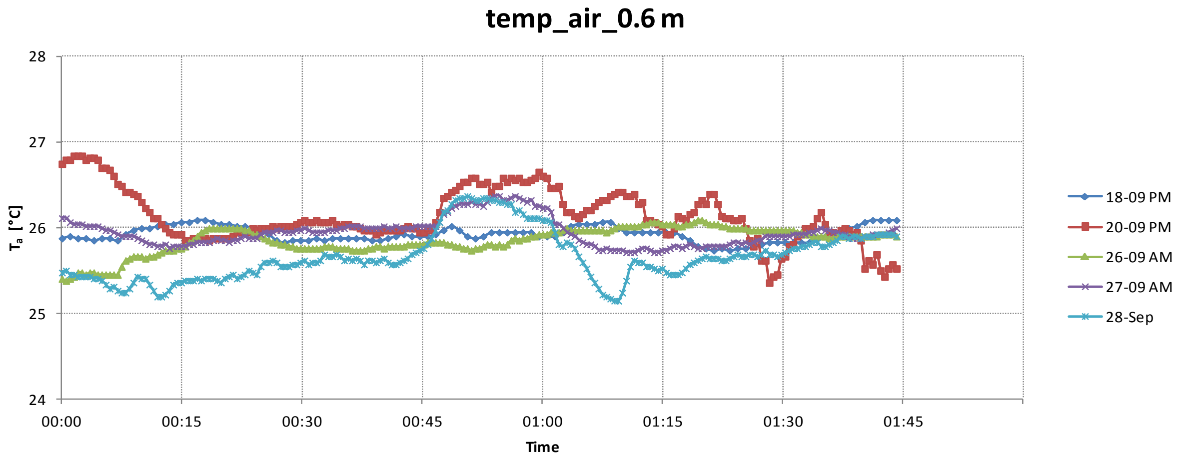
Condition E - 26°C

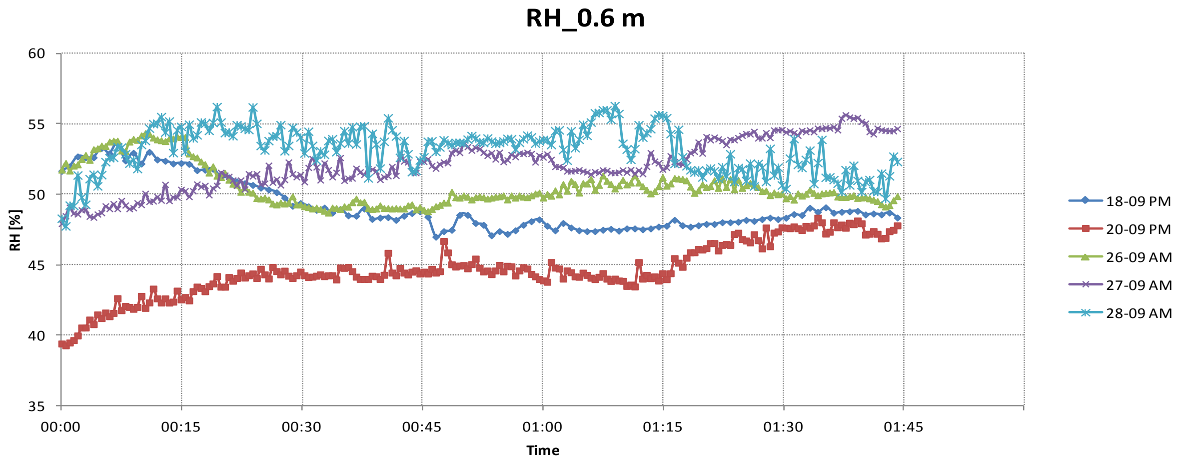


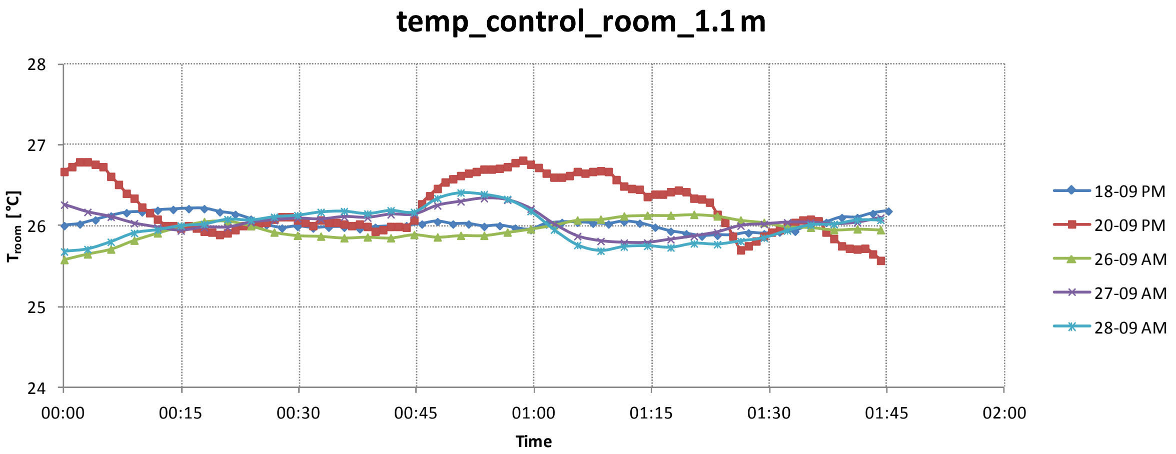


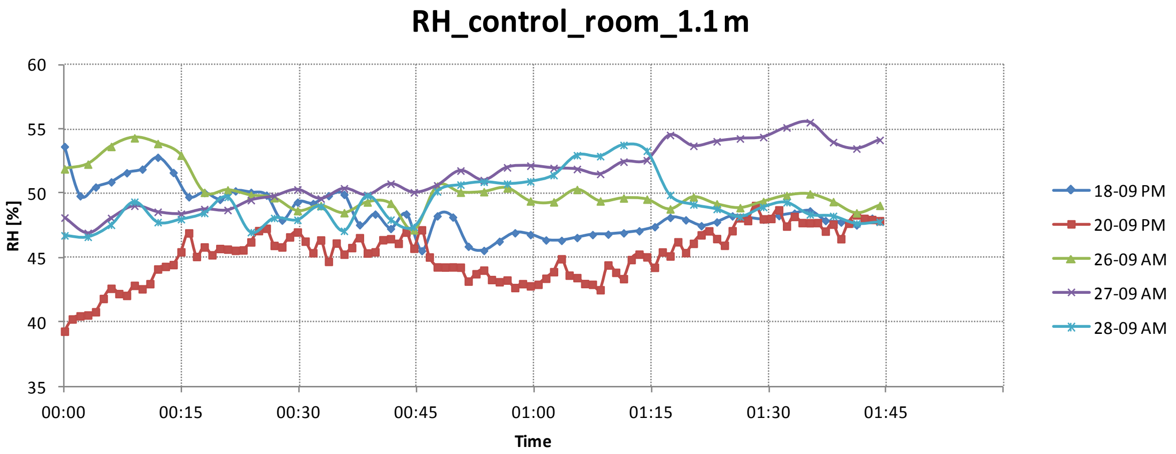



temp_op_0.6 m
28
27
26
25
24
T_o [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
Time
18-09 PM
20-09 PM
26-09 AM
27-09 AM
28-09 AM


temp_air_0.6 m
28
27
26
25
24
T_a [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
Time
18-09 PM
20-09 PM
26-09 AM
27-09 AM
28-Sep


RH_0.6 m
60
55
50
45
40
35
RH [%]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
Time
18-09 PM
20-09 PM
26-09 AM
27-09 AM
28-09 AM

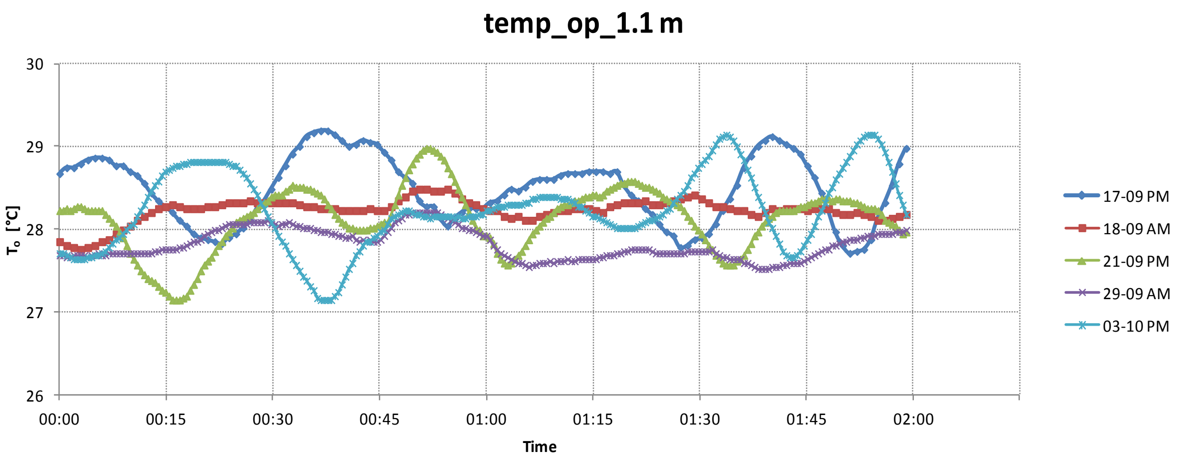


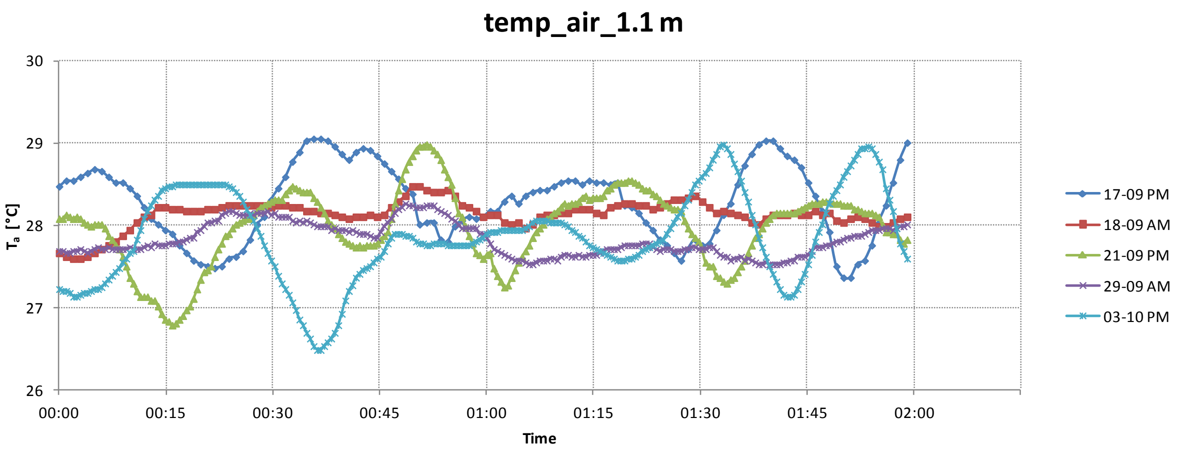


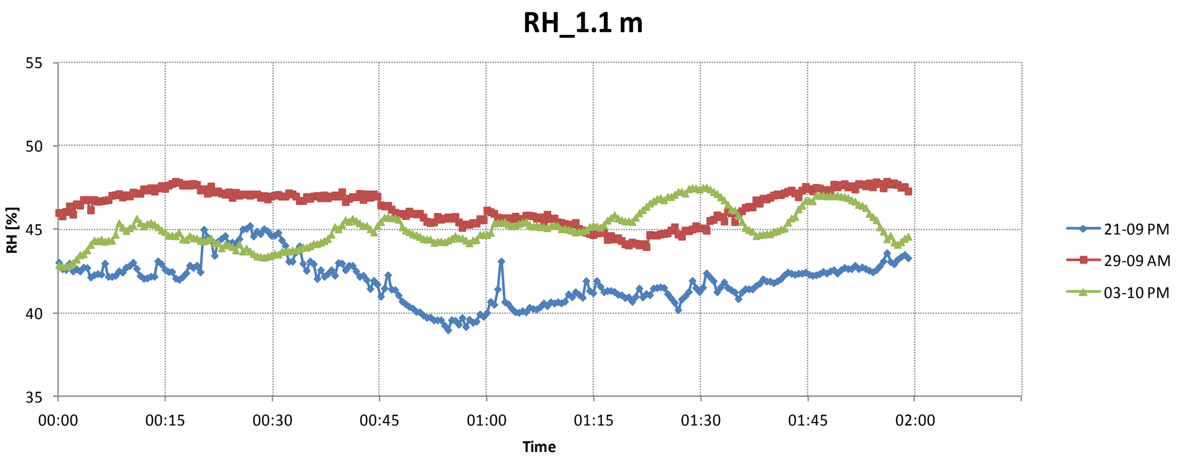
Average values

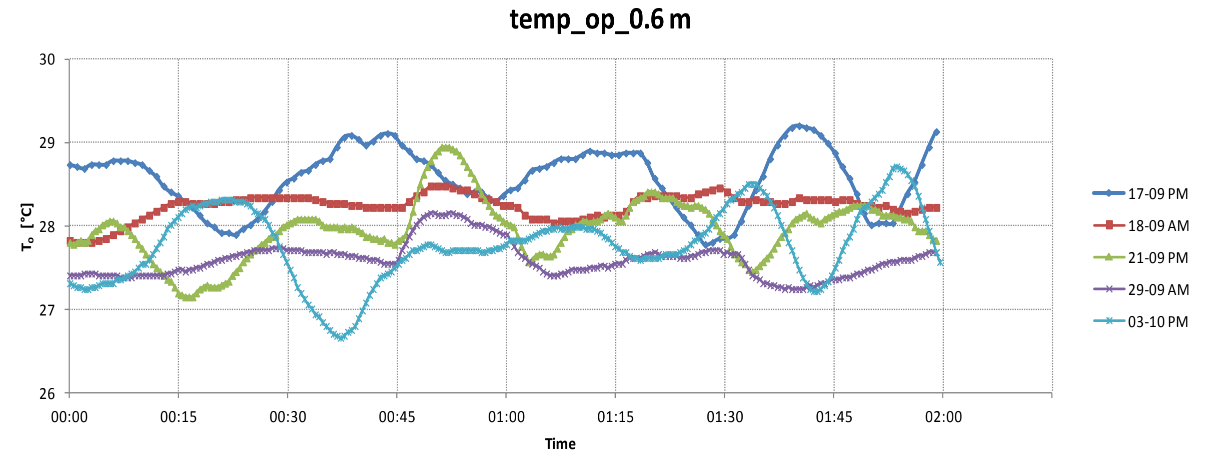
		1,1 m	0,6m
T_{room}	[°C]	26	
T_{op}	[°C]	26,2	26,1
T_a	[°C]	26	25,9
RH	[%]	48	50
RH_{room}	[%]	49	

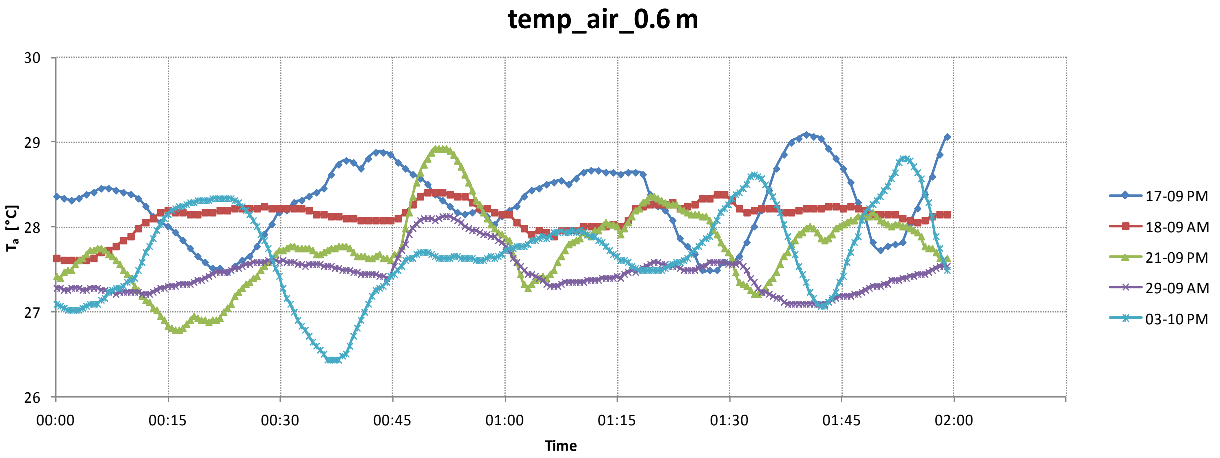
Condition B - 28°C

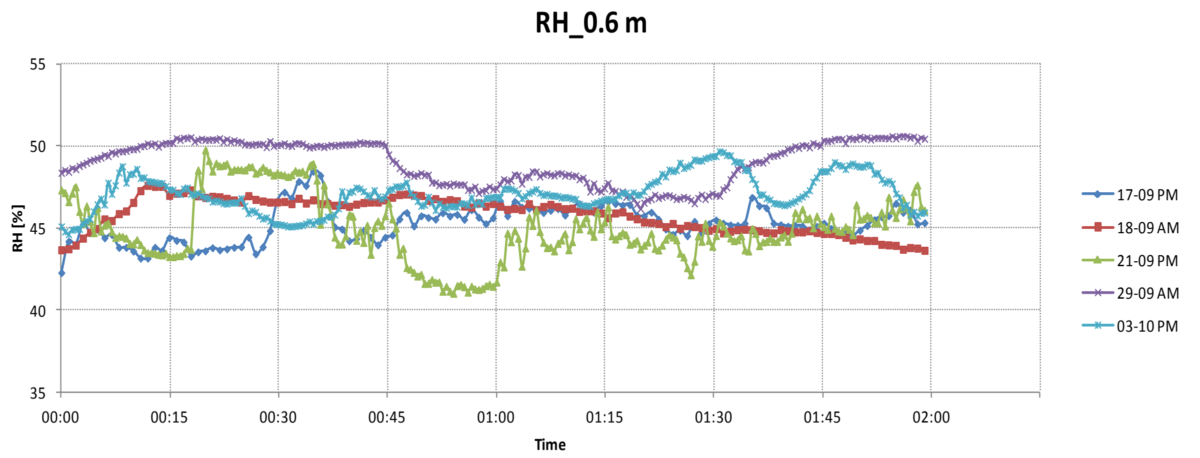


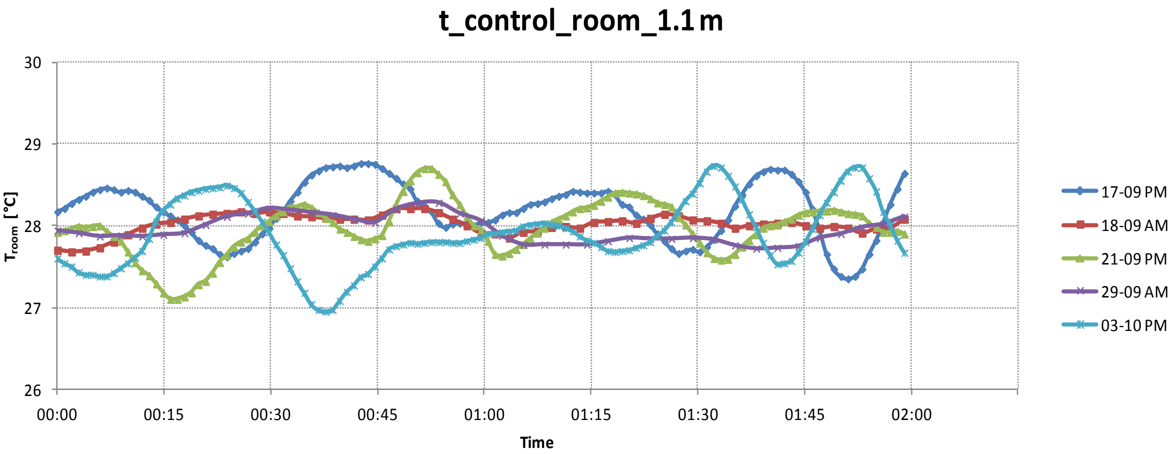


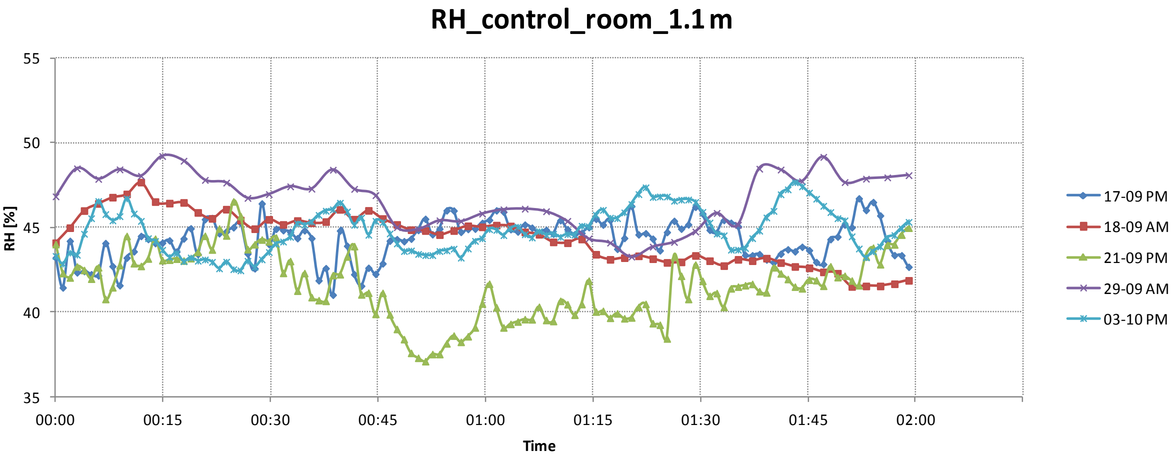



temp_op_0.6 m
30
29
28
27
26
T_o [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
17-09 PM
18-09 AM
21-09 PM
29-09 AM
03-10 PM


temp_air_0.6 m
30
29
28
27
26
T_a [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
17-09 PM
18-09 AM
21-09 PM
29-09 AM
03-10 PM


RH_0.6 m
55
50
45
40
35
RH [%]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
17-09 PM
18-09 AM
21-09 PM
29-09 AM
03-10 PM

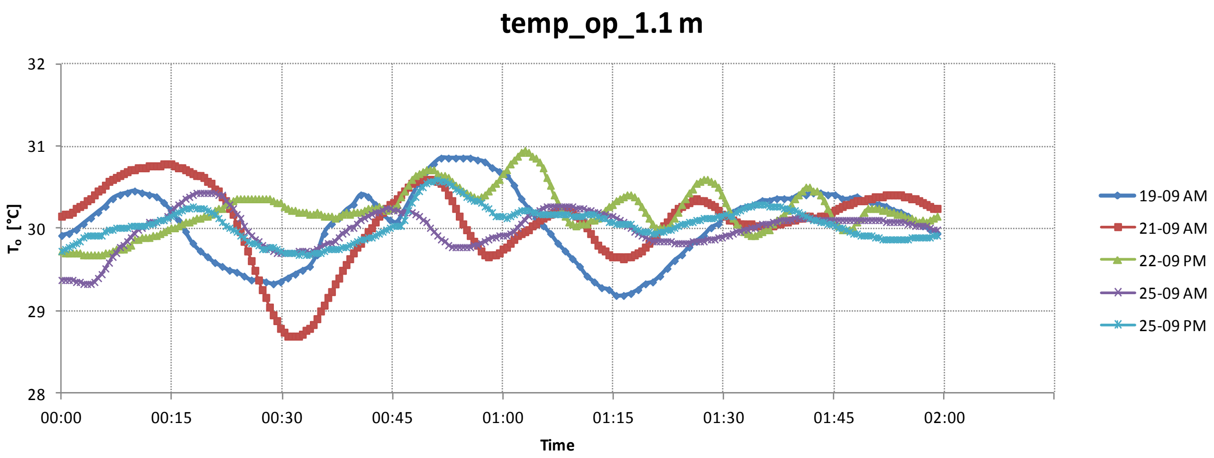


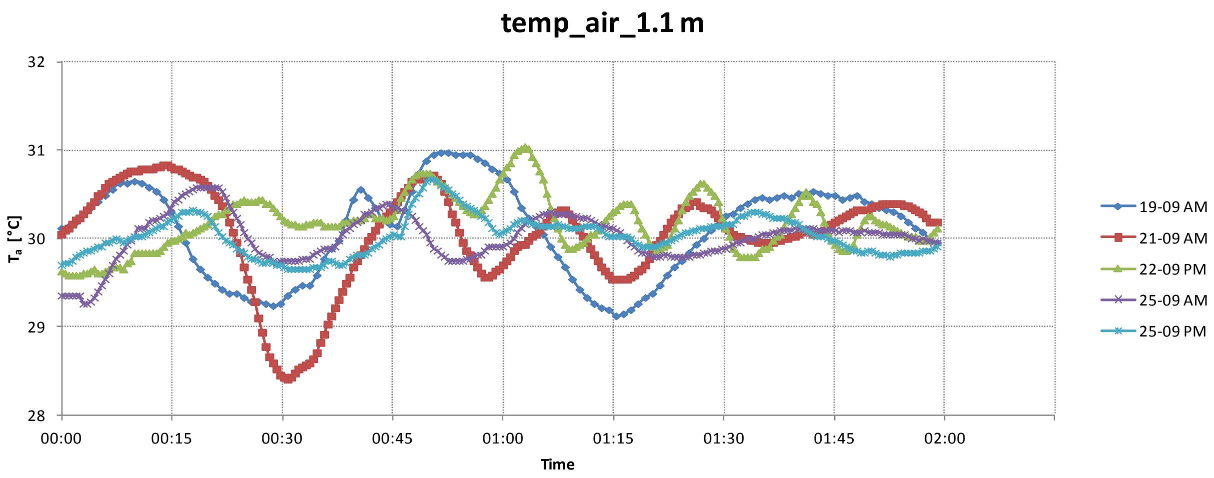


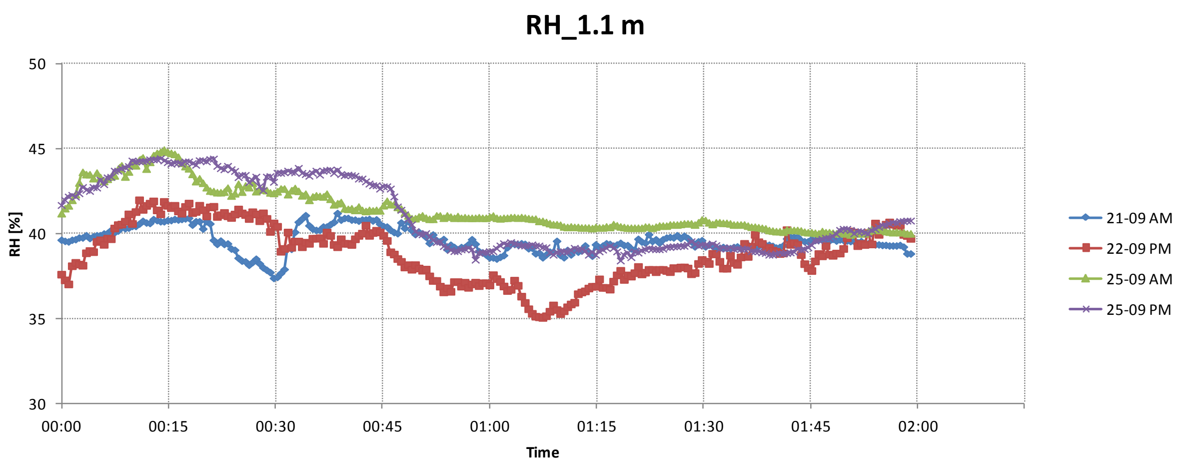
Average values

		1,1 m	0,6m
T_{room}	[°C]	28,0	
T_{op}	[°C]	28,2	28,1
T_a	[°C]	28,0	27,9
RH	[%]	44	46
RH_{room}	[%]	44	

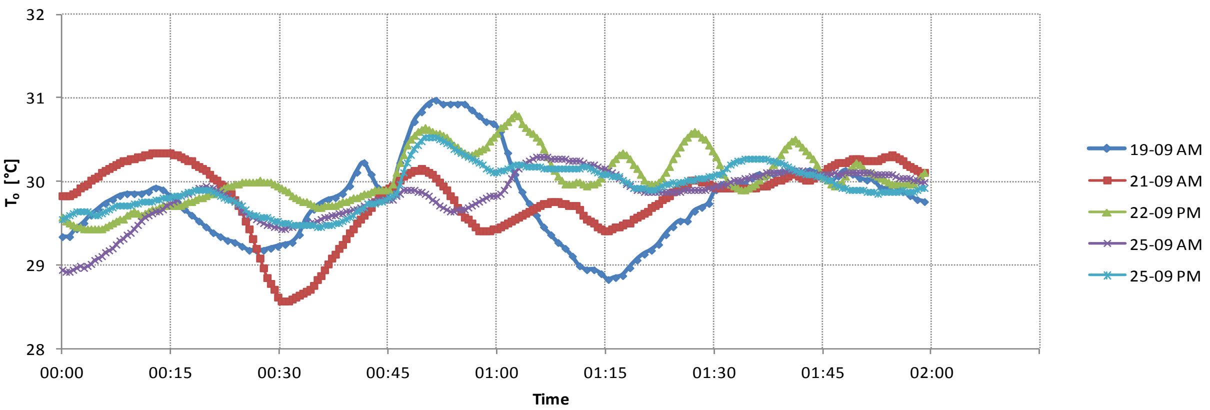
Condition C - 30°C



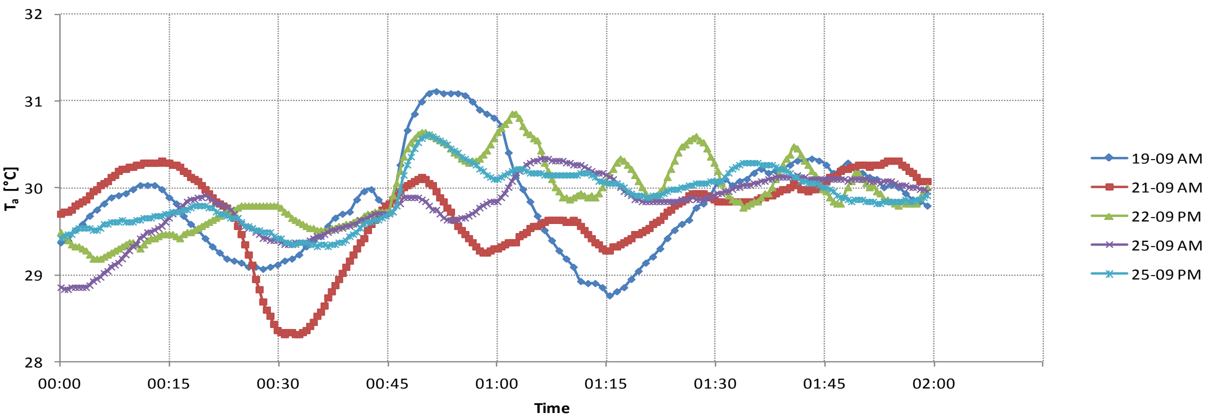




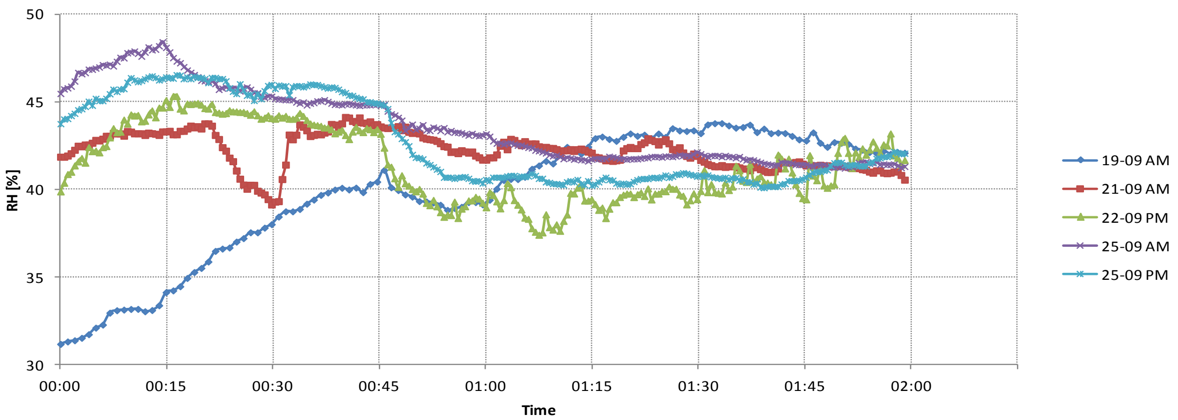
temp_op_0.6 m

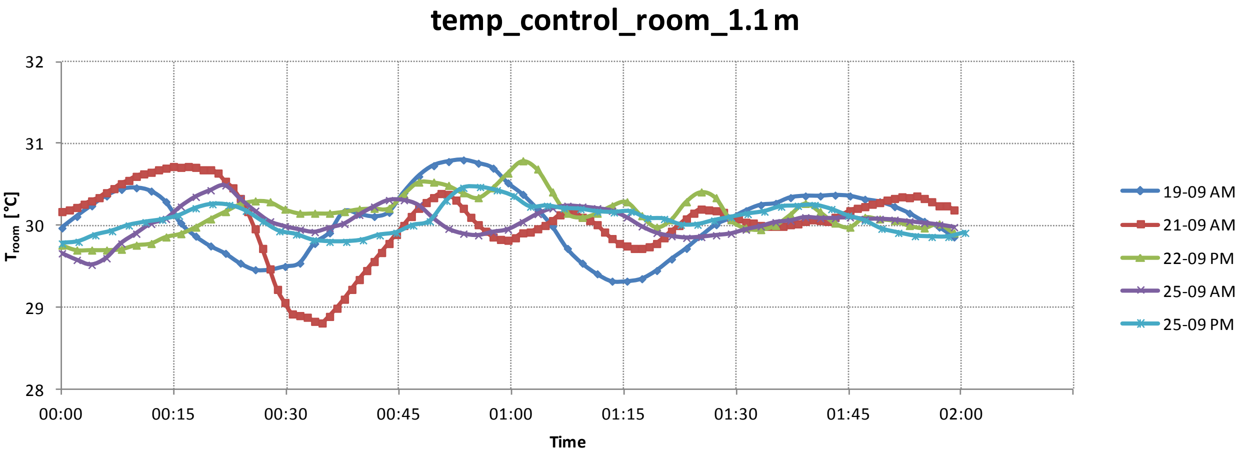


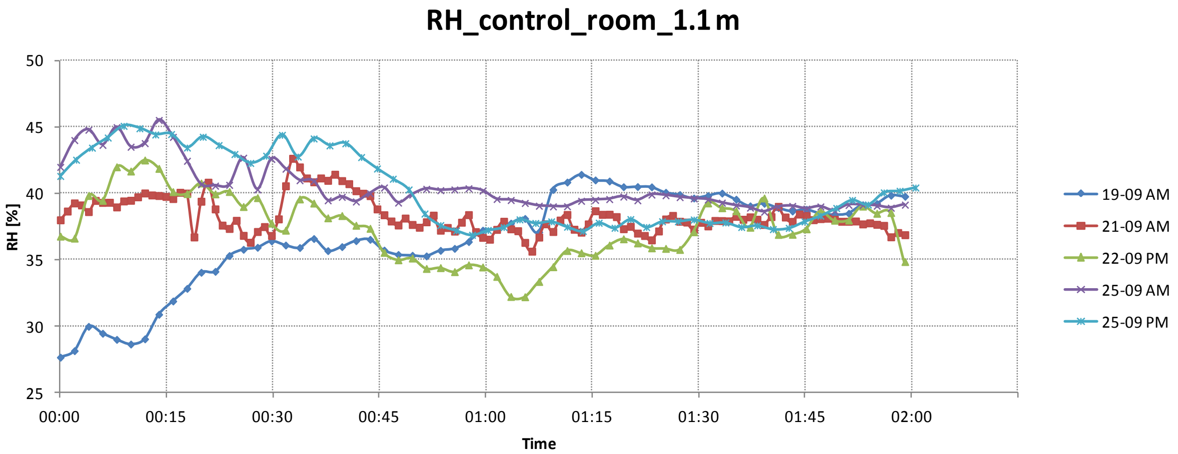
temp_air_0.6 m



RH_0.6 m



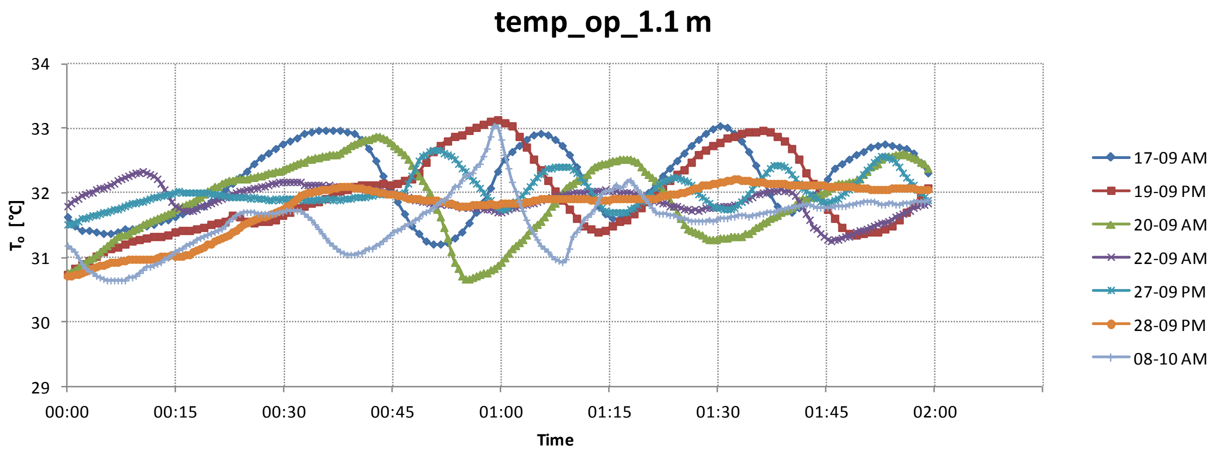


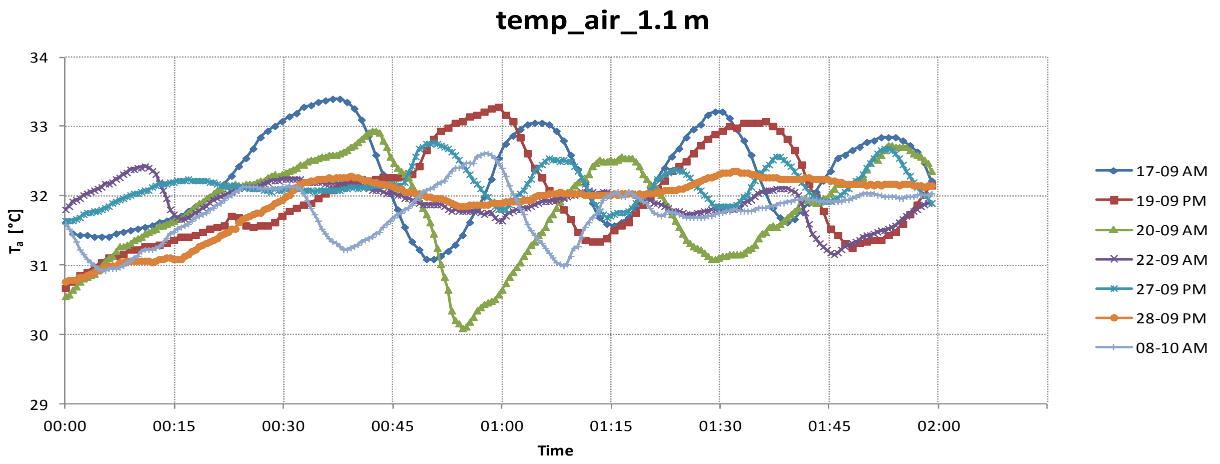


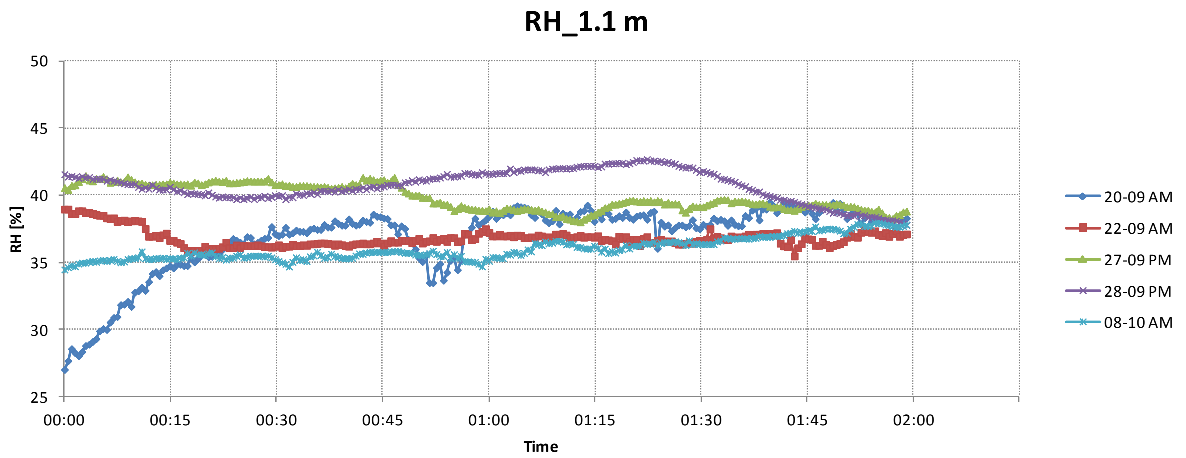
Average values

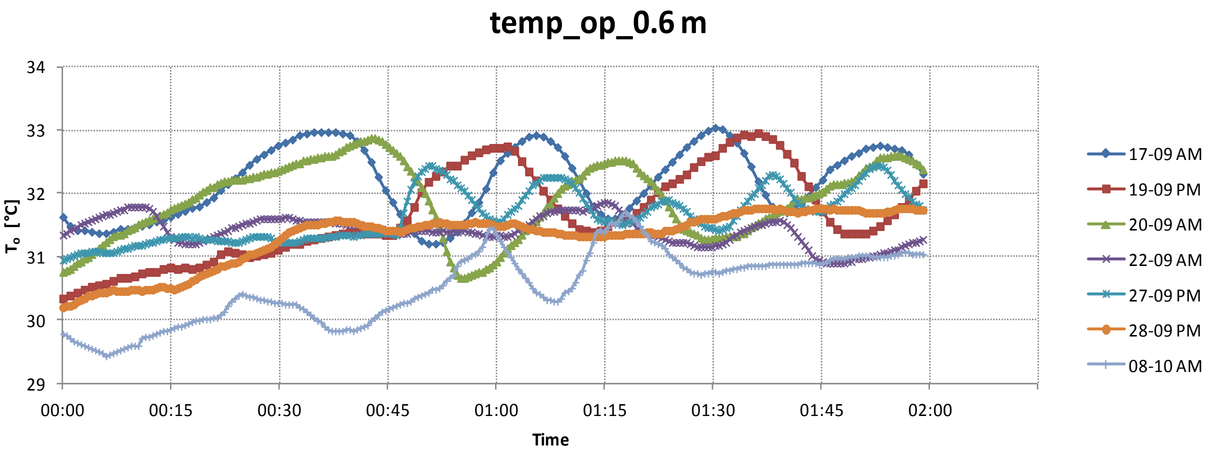
		1,1 m	0,6m
T_{room}	[°C]	30	
T_{op}	[°C]	30,1	29,9
T_a	[°C]	30,1	29,9
RH	[%]	40	42
RH_{room}	[%]	38	

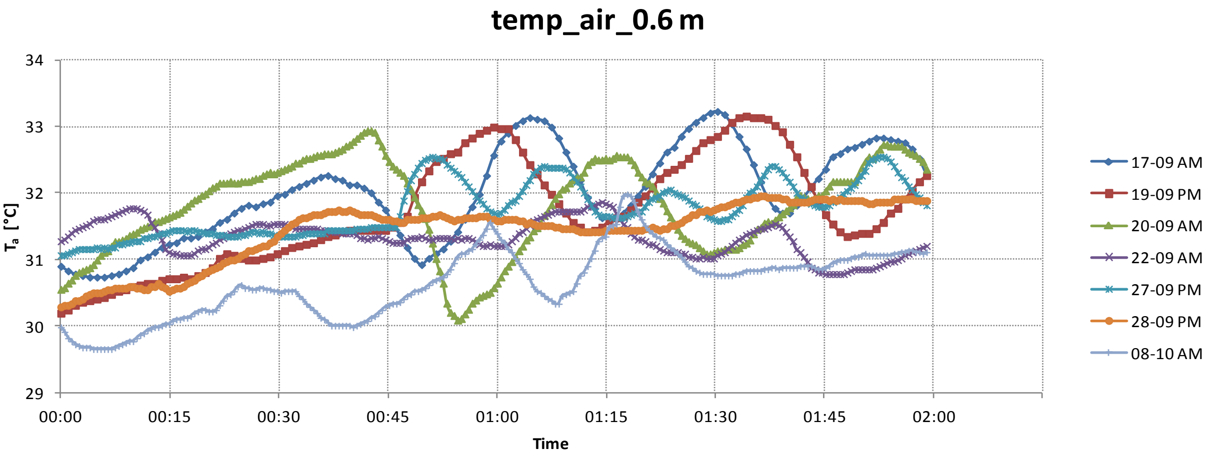
Condition A - 32°C

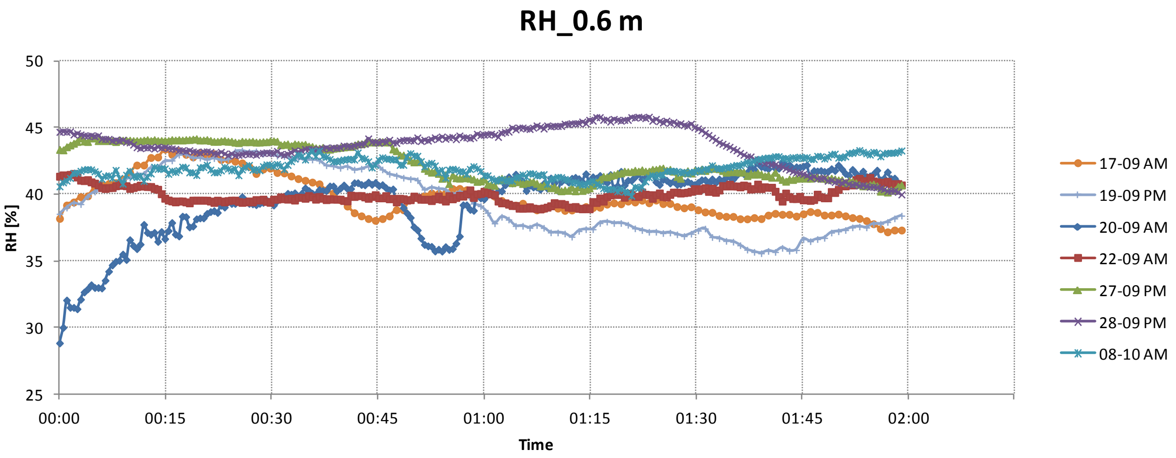


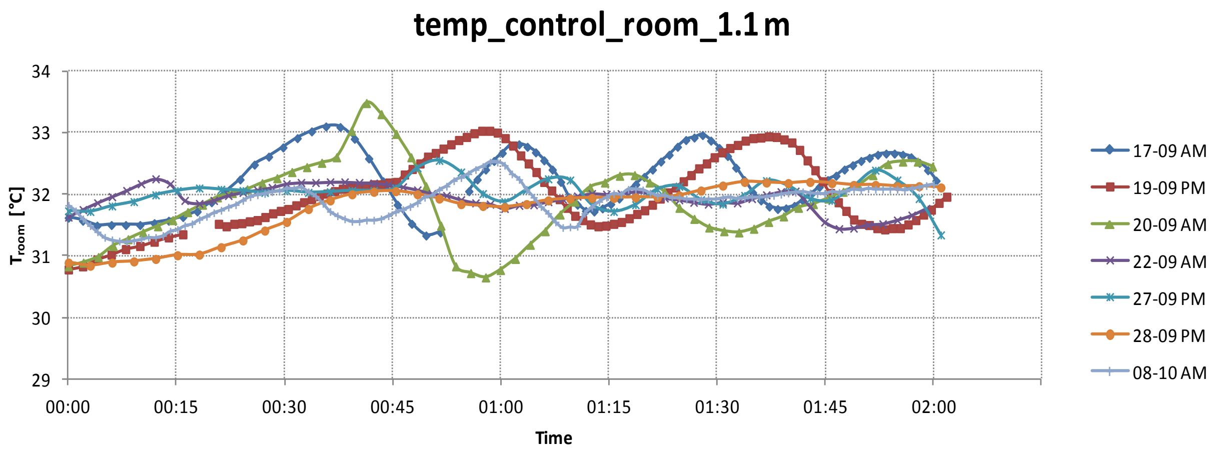


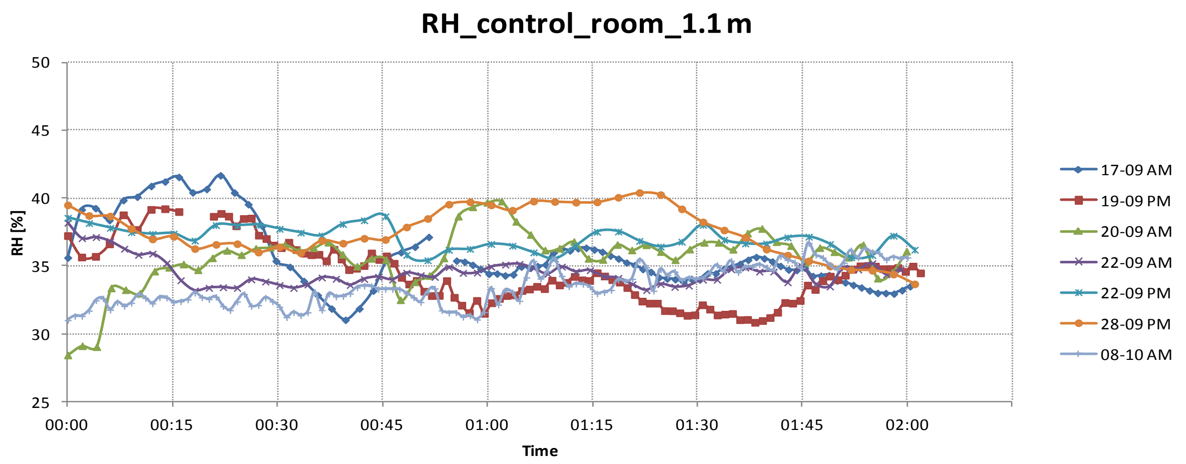



temp_op_0.6 m
34
33
32
31
30
29
To [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
17-09 AM
19-09 PM
20-09 AM
22-09 AM
27-09 PM
28-09 PM
08-10 AM


temp_air_0.6 m
34
33
32
31
30
29
Ta [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
17-09 AM
19-09 PM
20-09 AM
22-09 AM
27-09 PM
28-09 PM
08-10 AM


RH_0.6 m
50
45
40
35
30
25
RH [%]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
17-09 AM
19-09 PM
20-09 AM
22-09 AM
27-09 PM
28-09 PM
08-10 AM

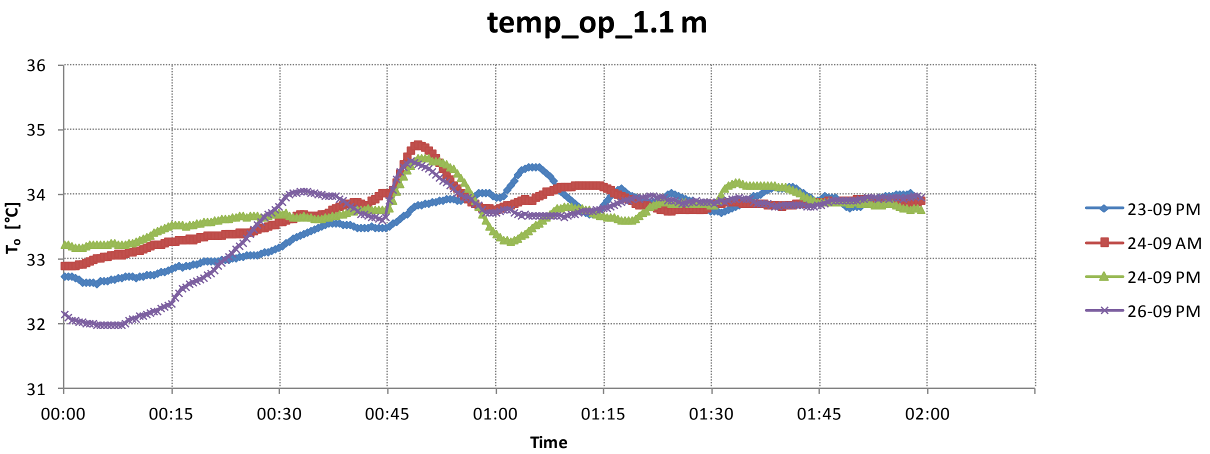


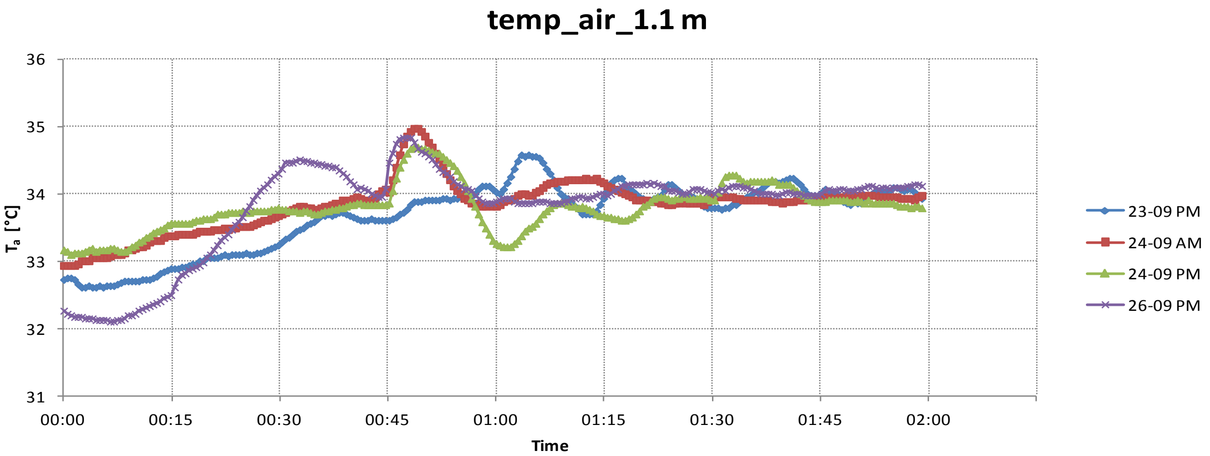


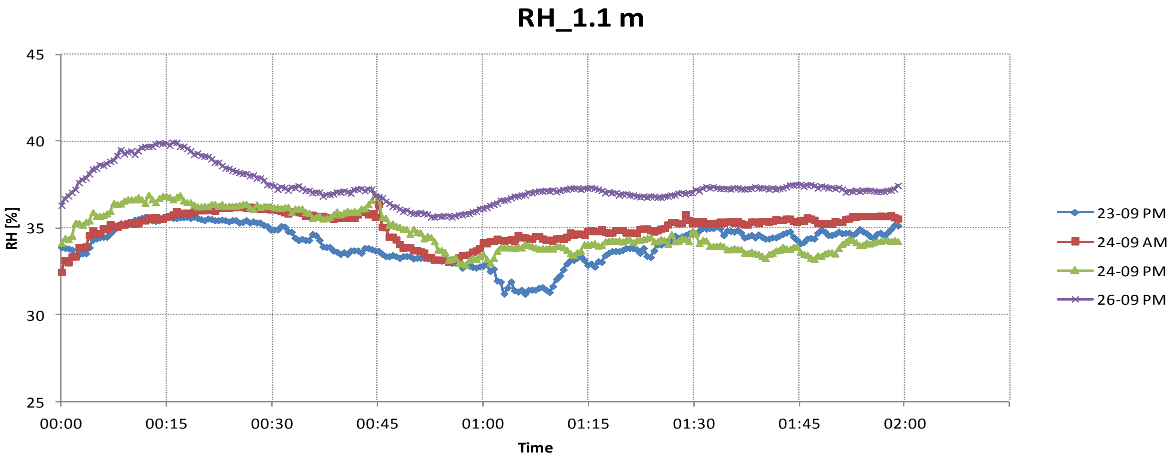
Average values

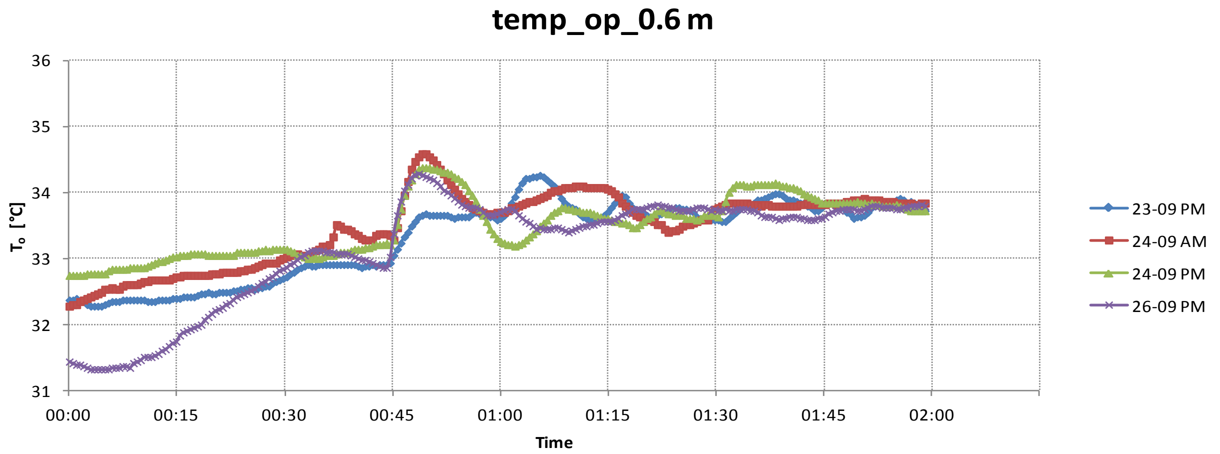
		1,1 m	0,6m
T_{room}	[°C]	32,0	
T_{op}	[°C]	32,0	31,5
T_a	[°C]	32,0	31,6
RH	[%]	38	41
RH_{room}	[%]	35	

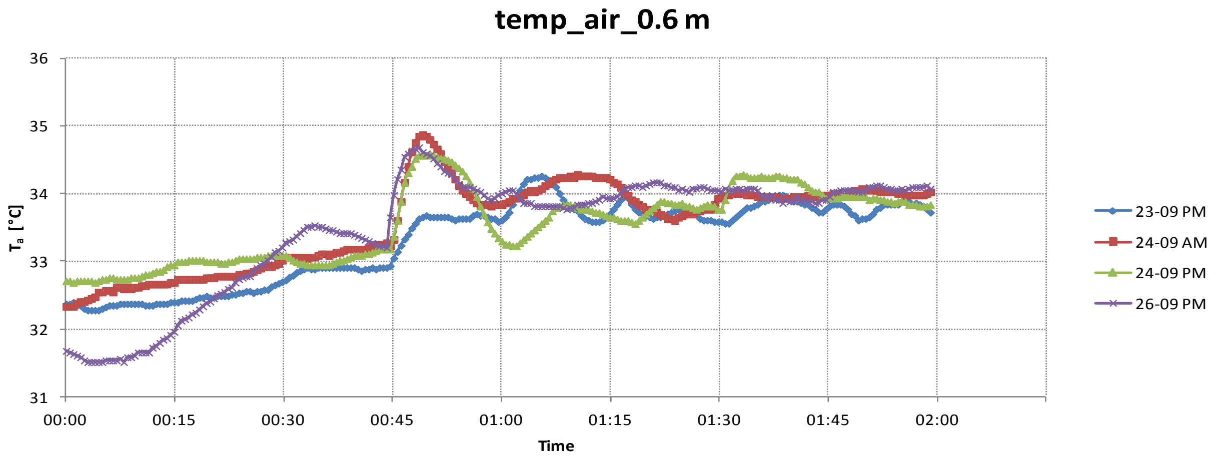
Condition D - 34°C

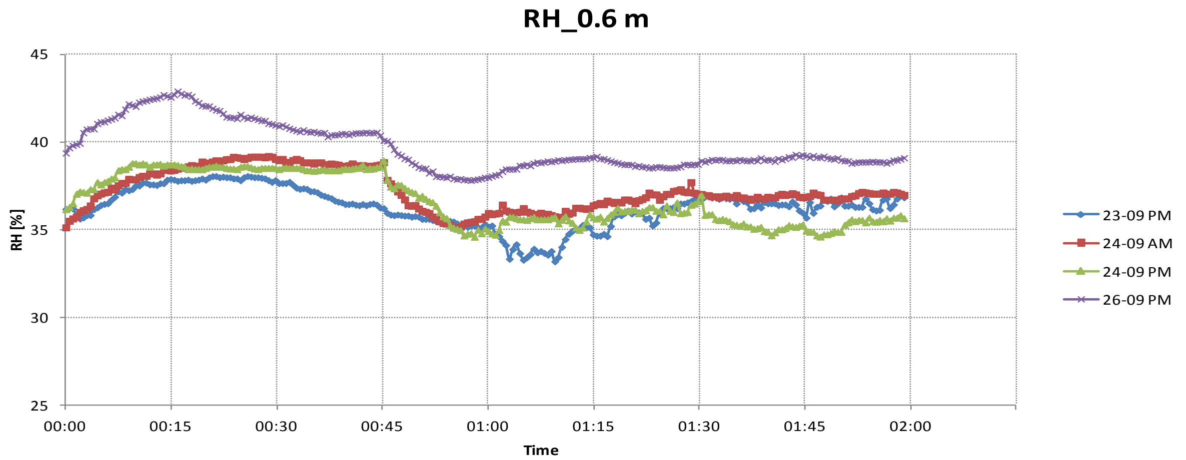


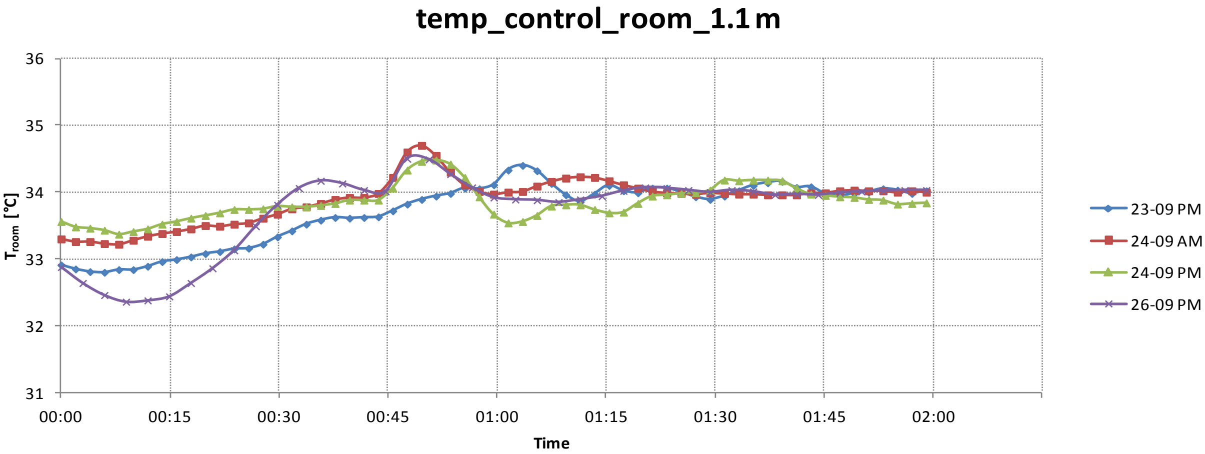


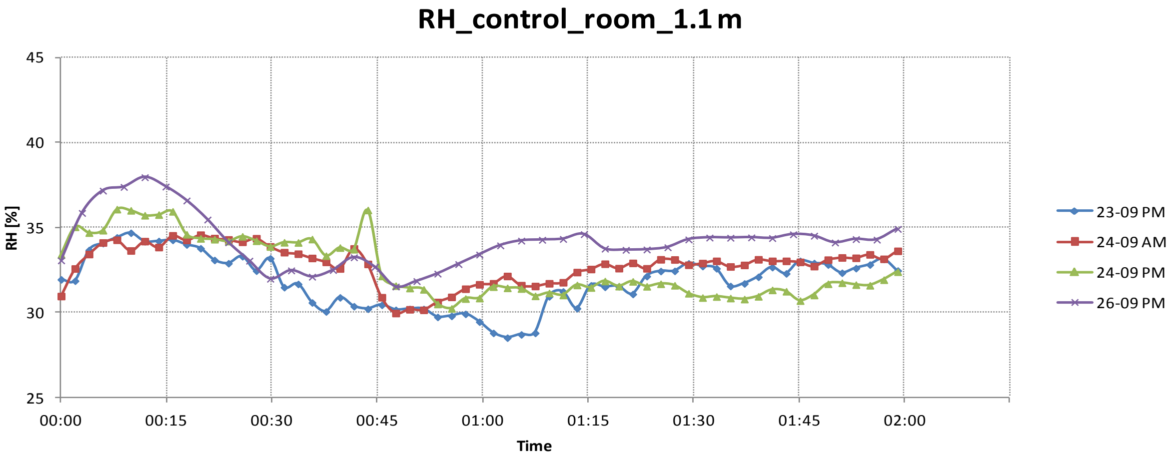



temp_op_0.6 m
36
35
34
33
32
31
T_o [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
23-09 PM
24-09 AM
24-09 PM
26-09 PM


temp_air_0.6 m
36
35
34
33
32
31
T_a [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
23-09 PM
24-09 AM
24-09 PM
26-09 PM


RH_0.6 m
45
40
35
30
25
RH [%]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
23-09 PM
24-09 AM
24-09 PM
26-09 PM

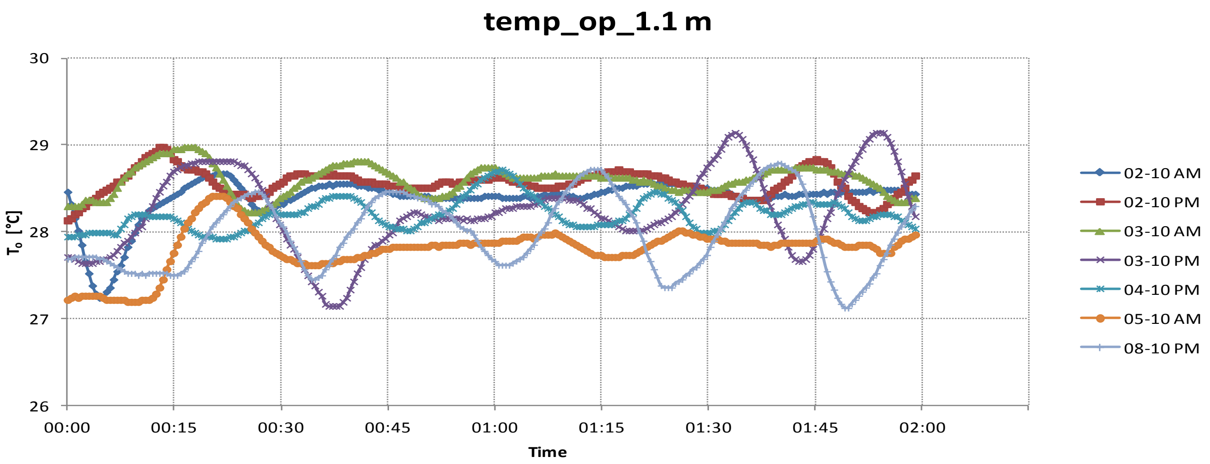


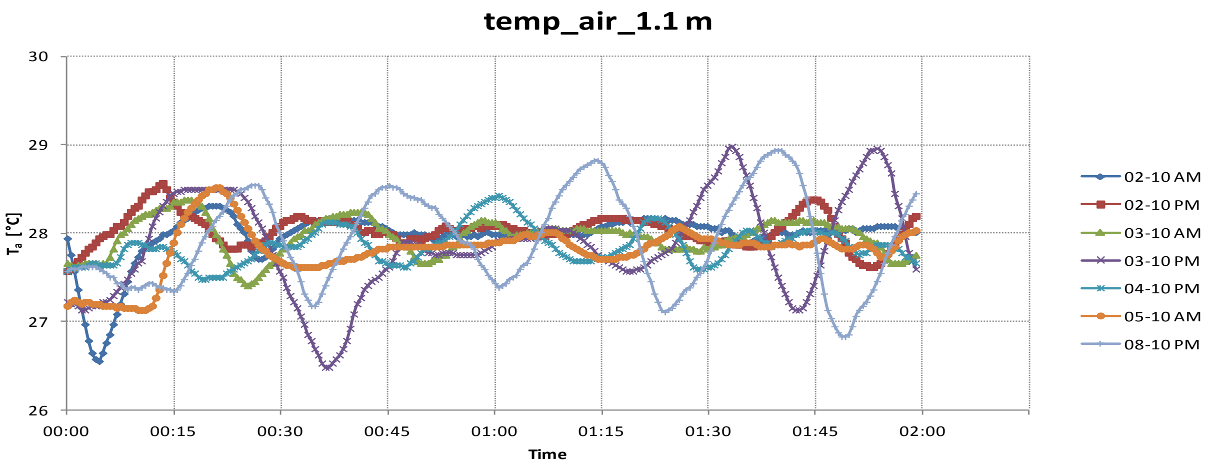


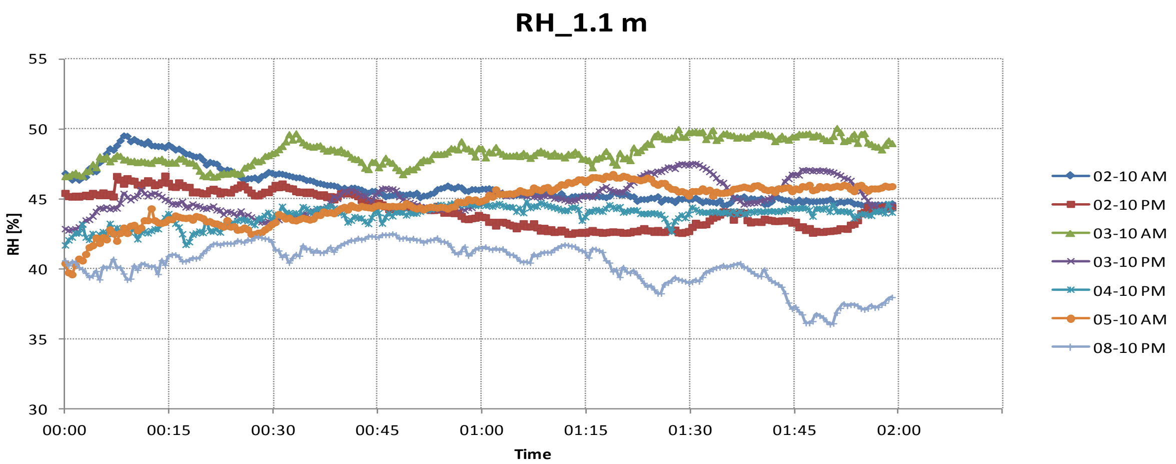
Average values

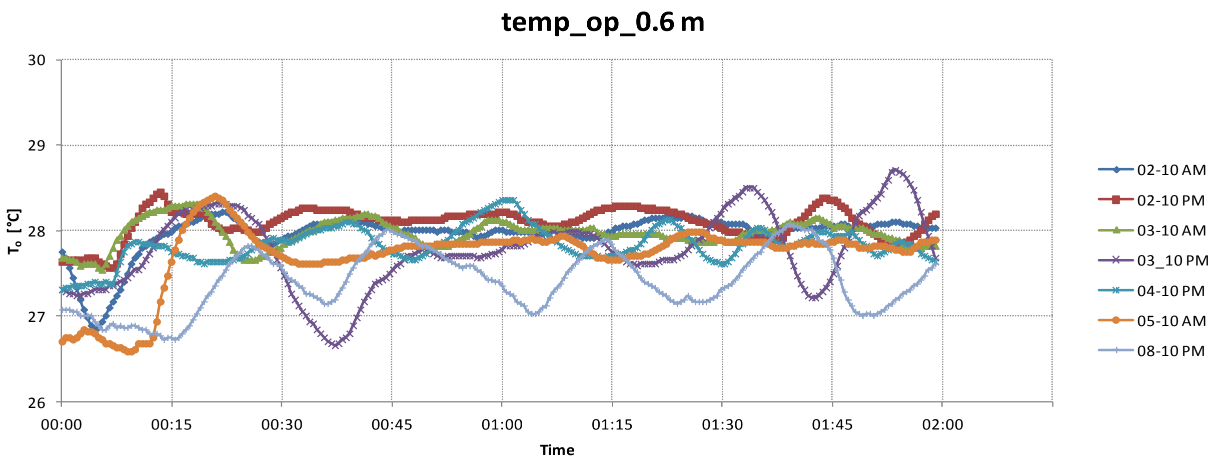
		1,1 m	0,6m
T_{room}	[°C]	33,9	
T_{op}	[°C]	33,8	33,5
T_a	[°C]	33,9	33,7
RH	[%]	35	37
RH_{room}	[%]	33	

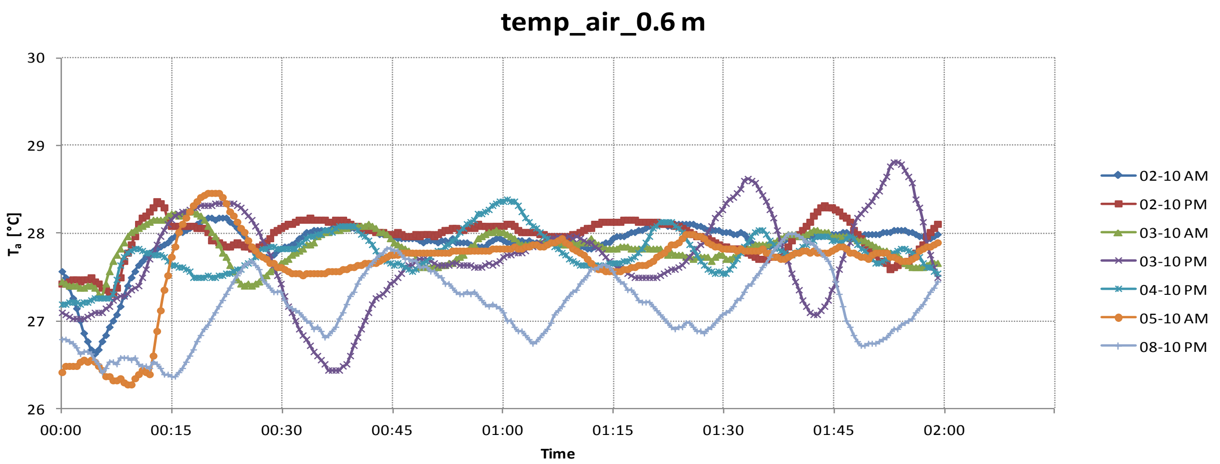
Condition 2 - 28°C

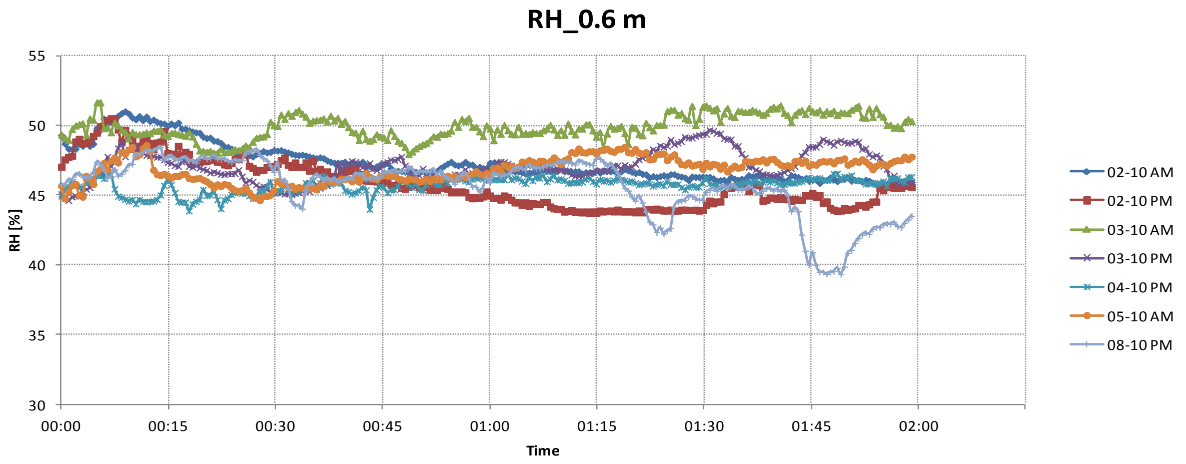


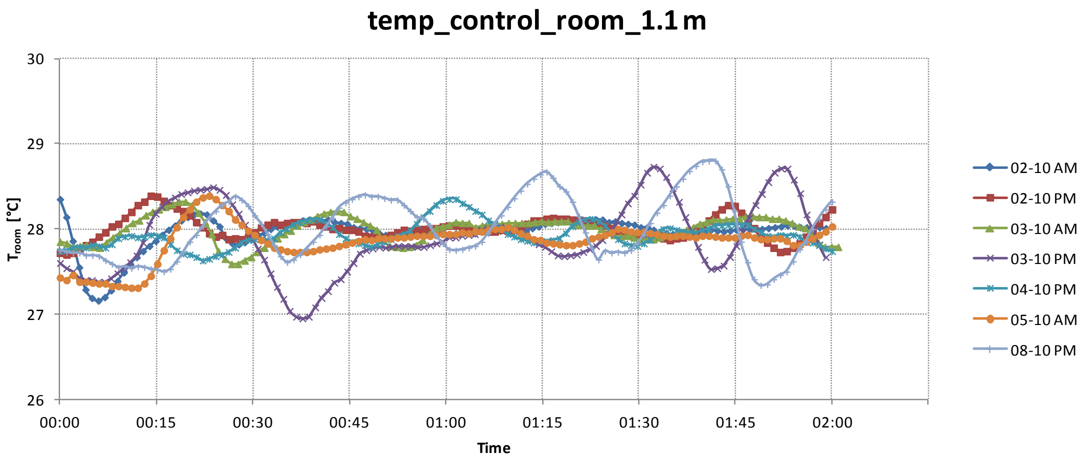


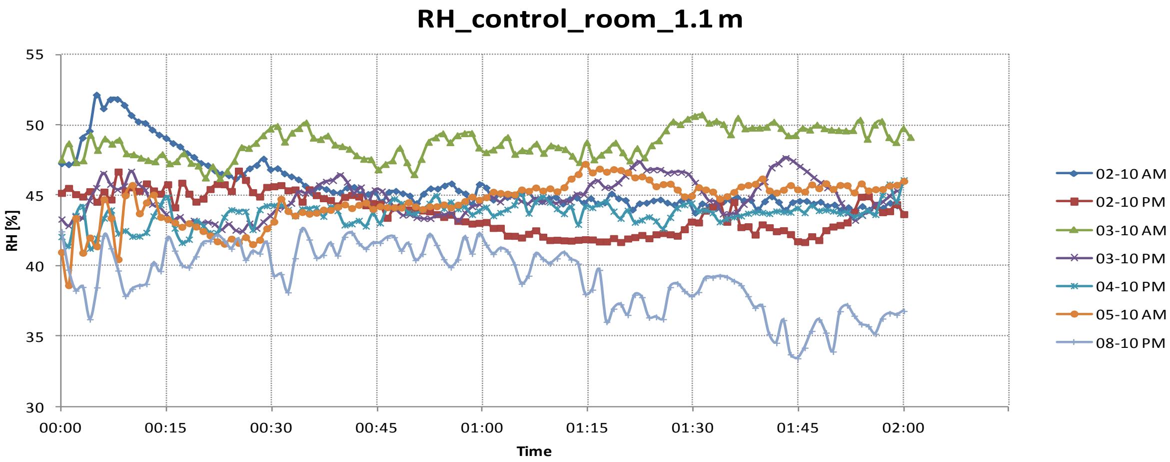



temp_op_0.6 m
30
29
28
27
26
T_o [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
02-10 AM
02-10 PM
03-10 AM
03_10 PM
04-10 PM
05-10 AM
08-10 PM


temp_air_0.6 m
30
29
28
27
26
T_a [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
02-10 AM
02-10 PM
03-10 AM
03-10 PM
04-10 PM
05-10 AM
08-10 PM


RH_0.6 m
55
50
45
40
35
30
RH [%]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
02-10 AM
02-10 PM
03-10 AM
03-10 PM
04-10 PM
05-10 AM
08-10 PM

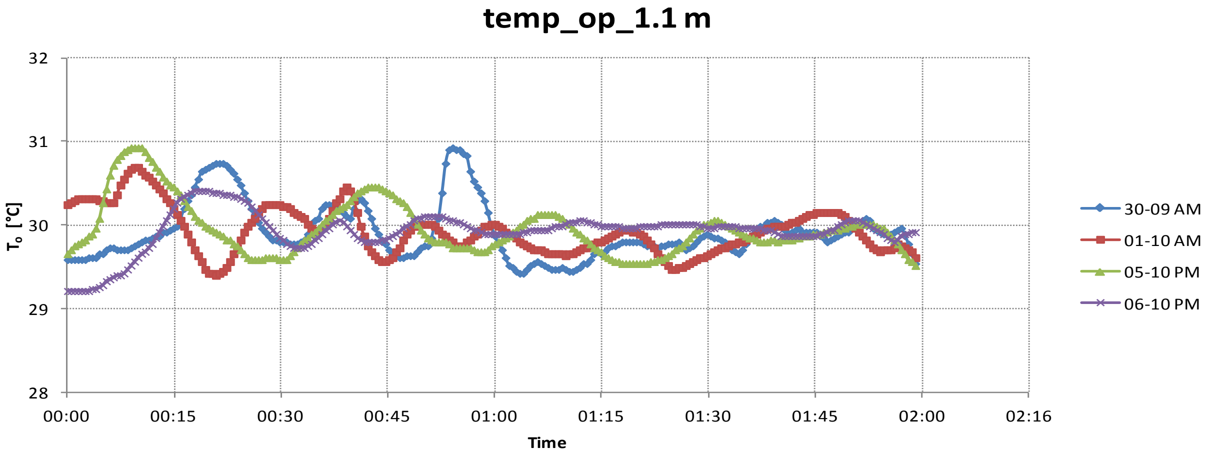


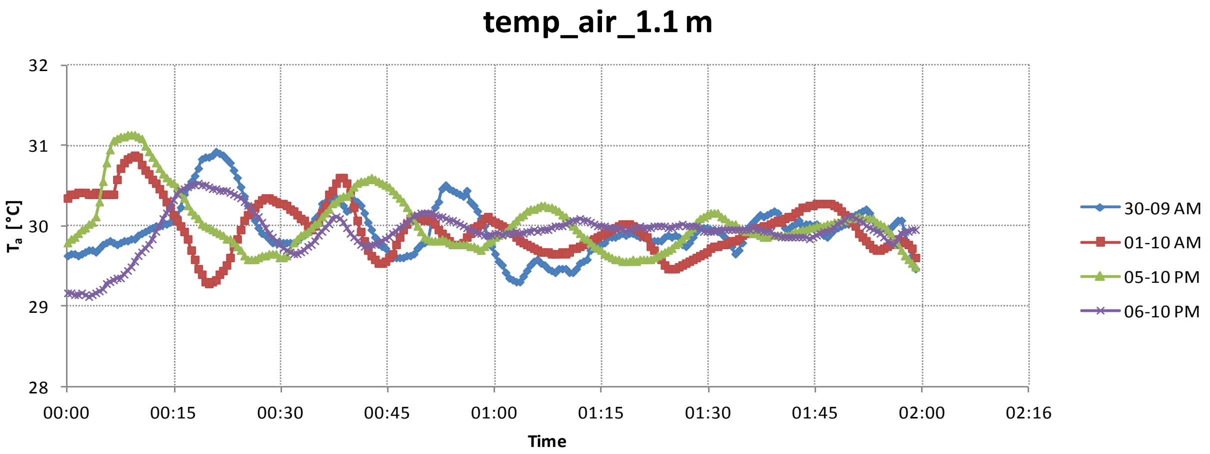


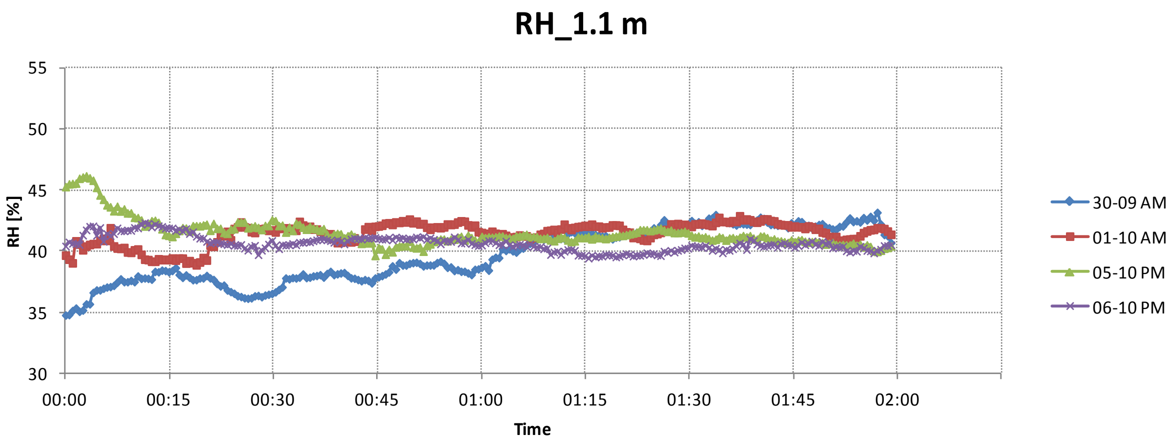
Average values

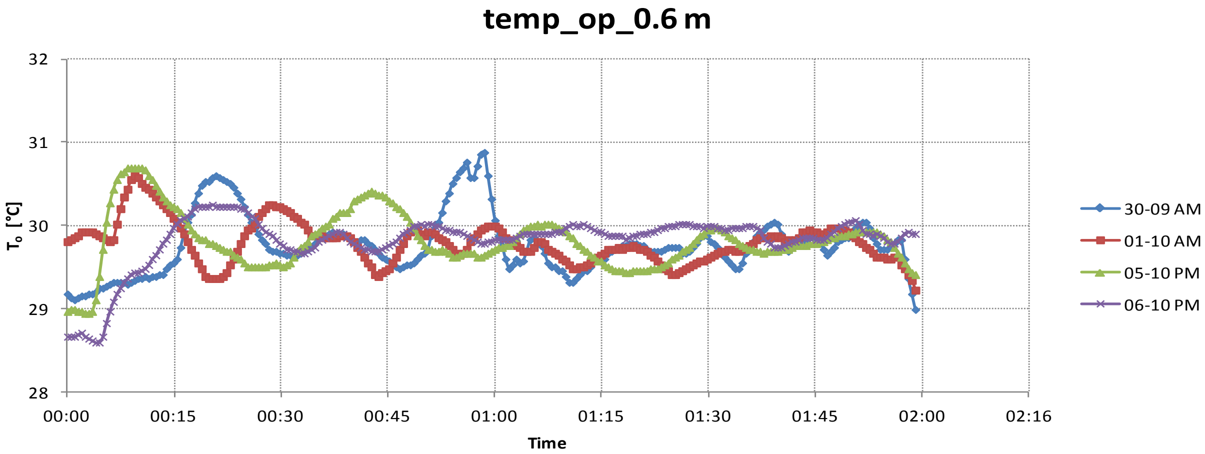
		1,1 m	0,6m
T_{room}	[°C]	27,8	
T_{op}	[°C]	28,1	27,7
T_a	[°C]	27,8	27,5
RH	[%]	44	47
RH_{room}	[%]	44	

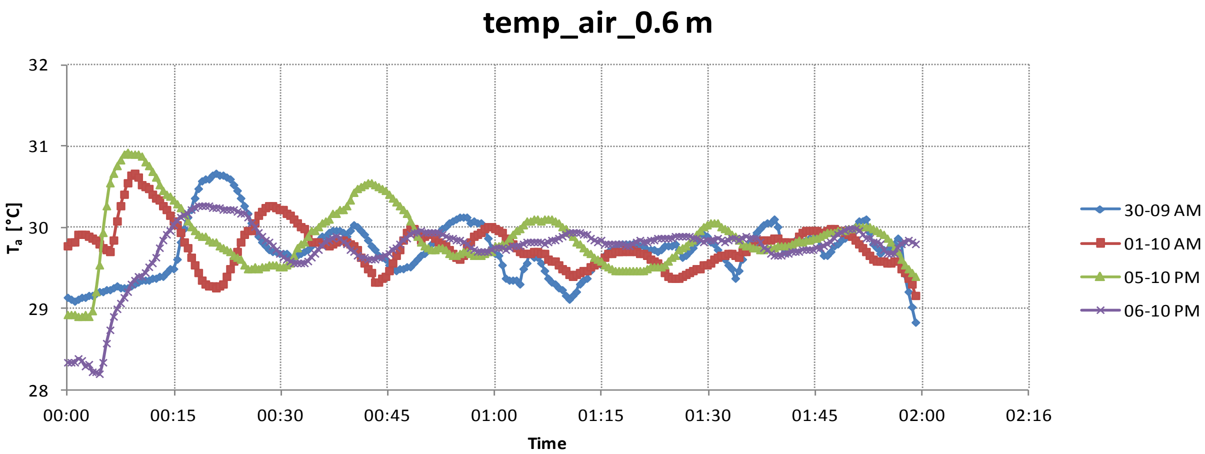
Condition 1 - 30°C

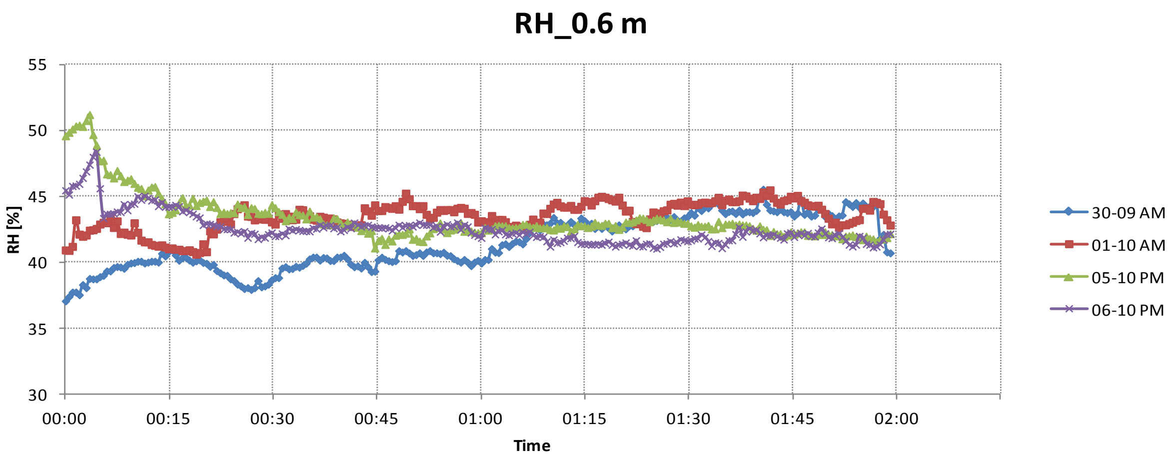


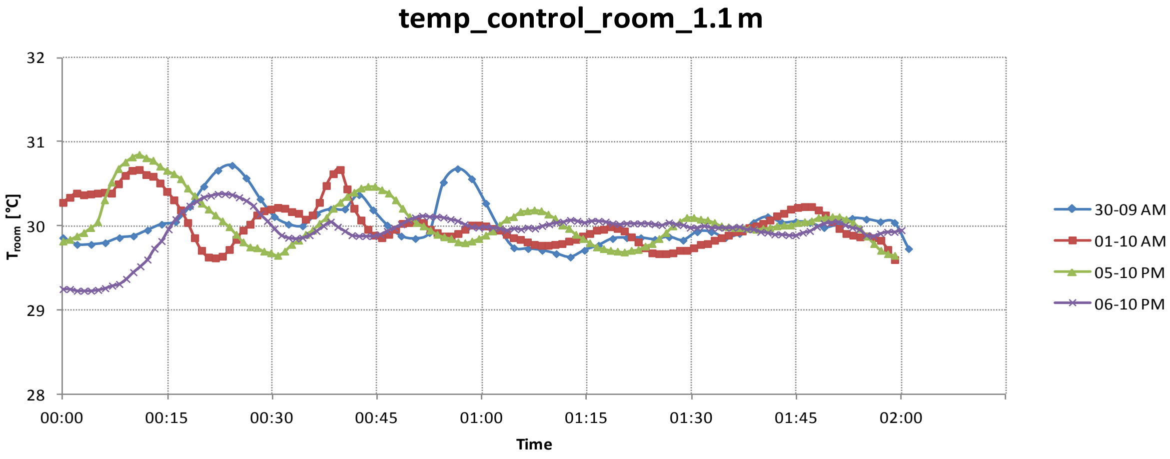


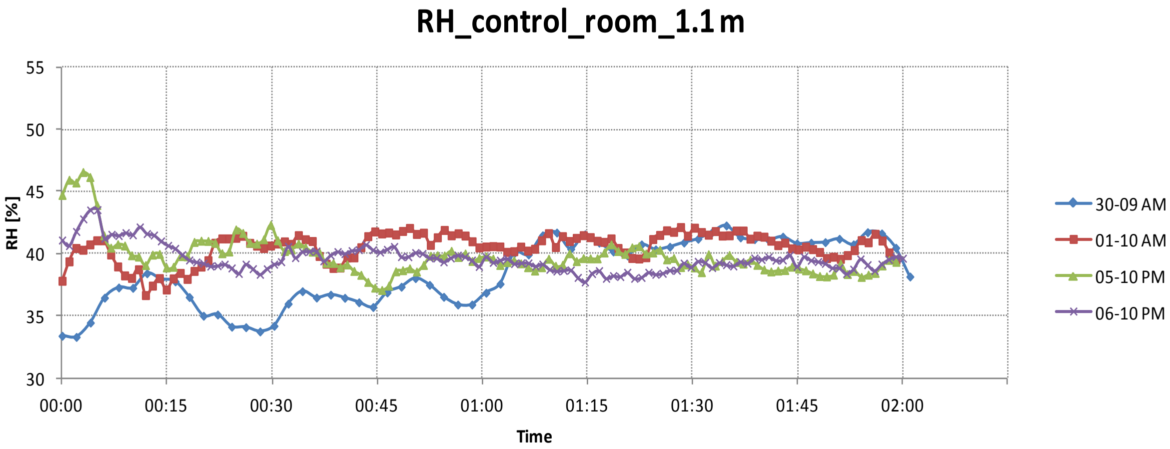



temp_op_0.6 m
32
31
30
29
28
T_o [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:16
Time
30-09 AM
01-10 AM
05-10 PM
06-10 PM


temp_air_0.6 m
32
31
30
29
28
T_a [°C]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
02:16
Time
30-09 AM
01-10 AM
05-10 PM
06-10 PM


RH_0.6 m
55
50
45
40
35
30
RH [%]
00:00
00:15
00:30
00:45
01:00
01:15
01:30
01:45
02:00
Time
30-09 AM
01-10 AM
05-10 PM
06-10 PM



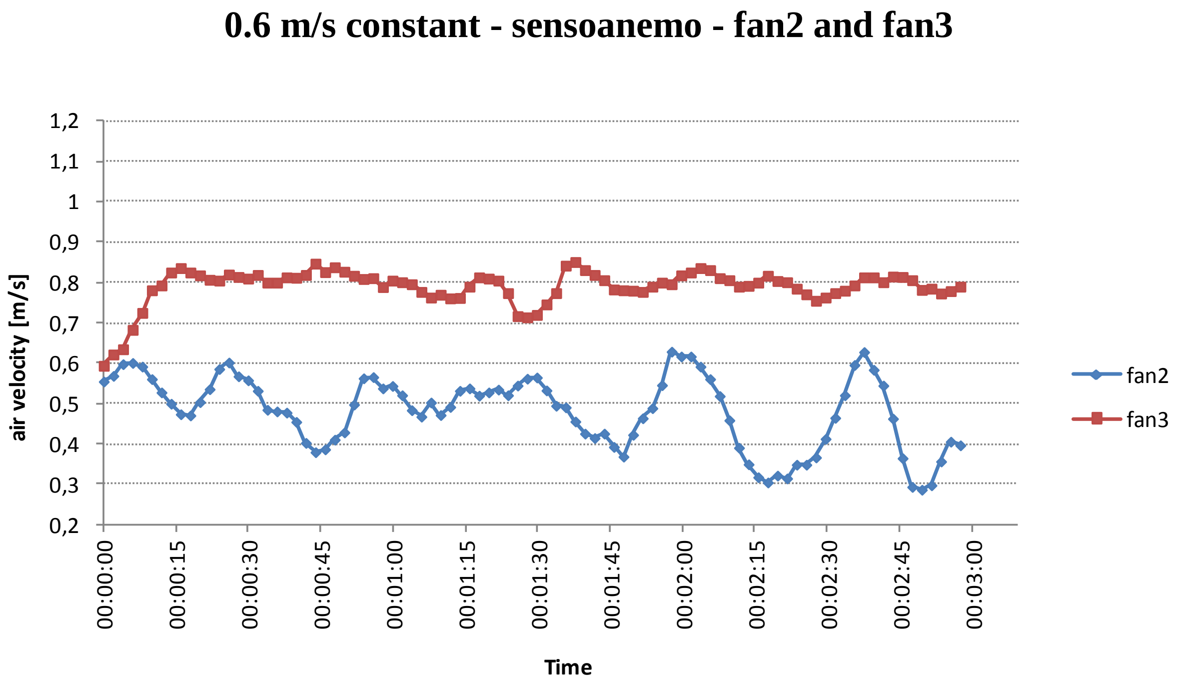


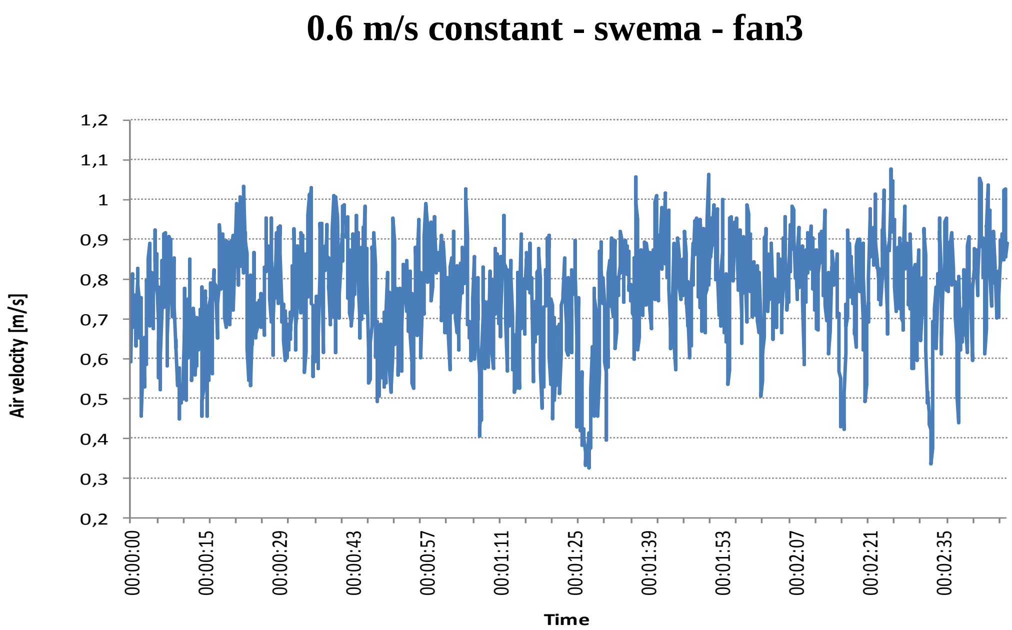
Average values

		1,1 m	0,6m
T_{room}	[°C]	30,0	
T_{op}	[°C]	29,9	29,6
T_a	[°C]	29,9	29,6
RH	[%]	41	43
RH_{room}	[%]	40	

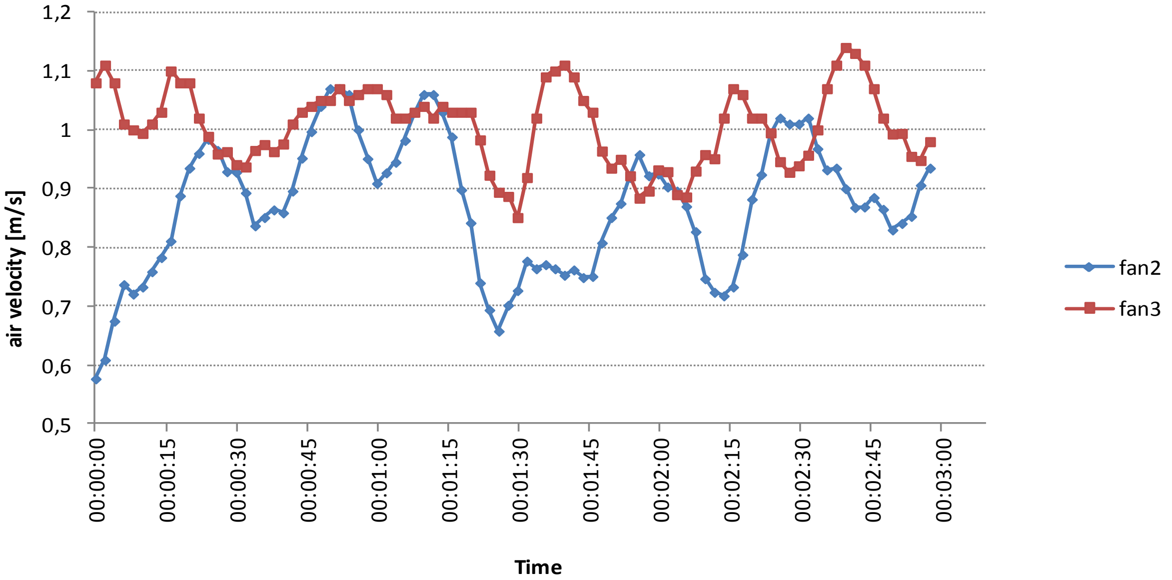
Appendix B - Airflows generated by fans

First experiment

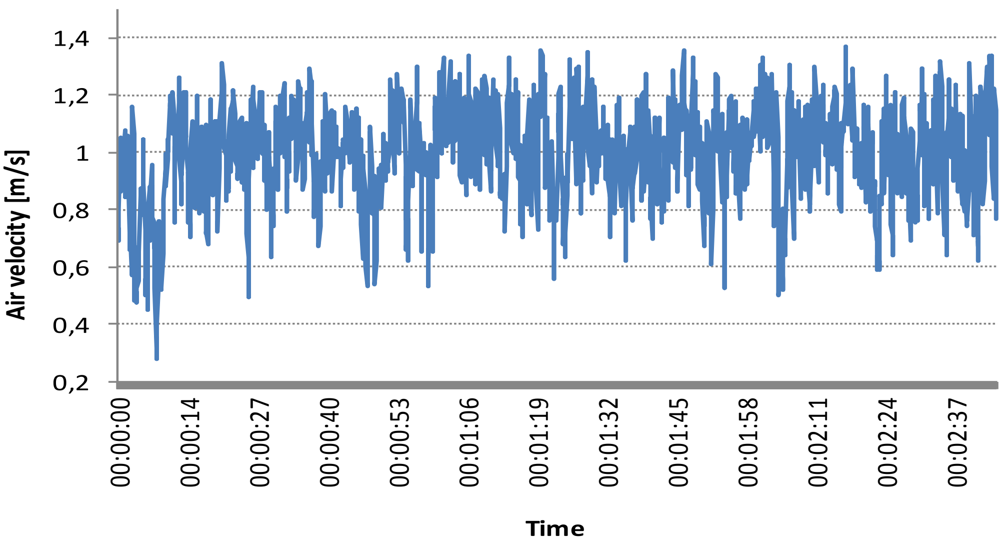




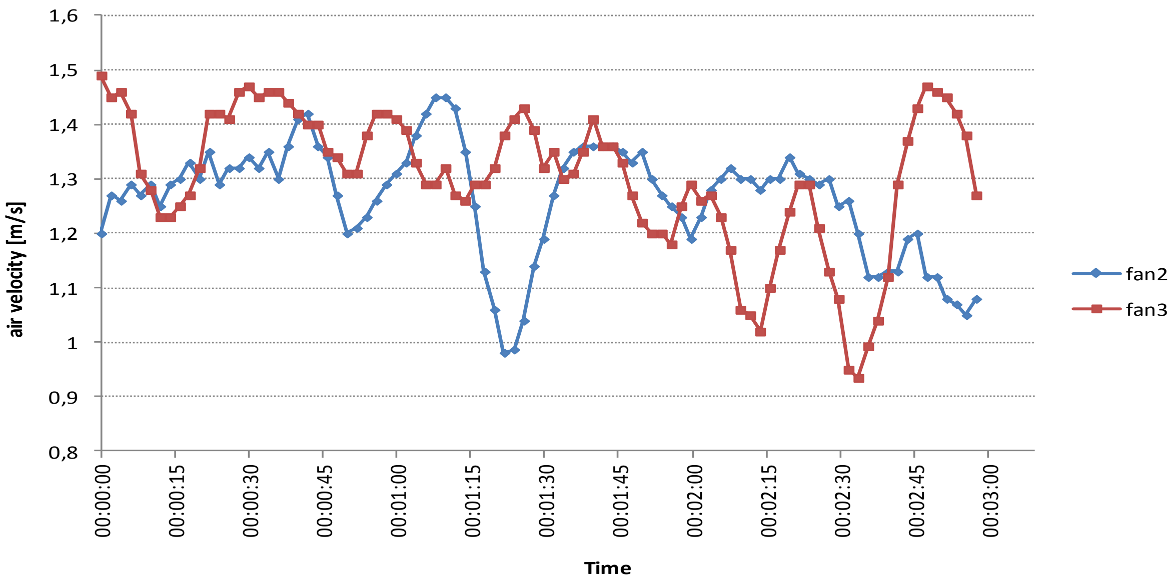
1 m/s constant - sensoanemo - fan2 and fan3



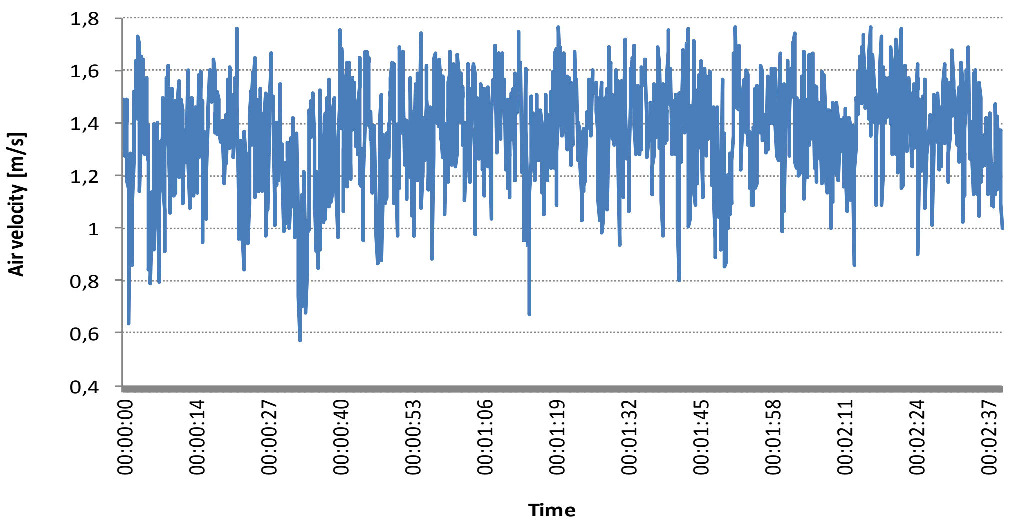
1 m/s constant - swema - fan3



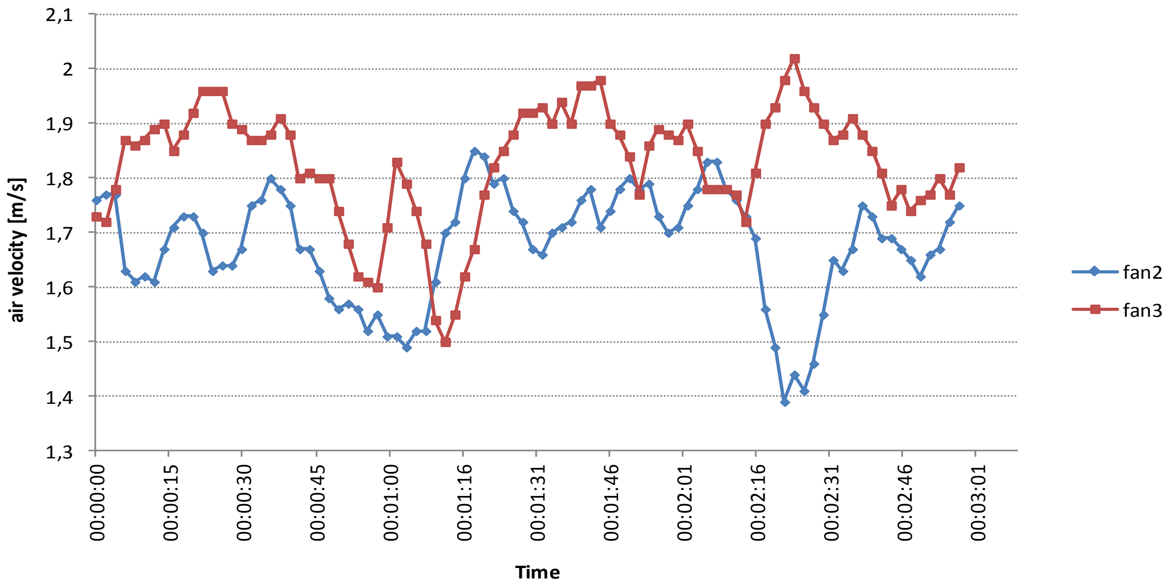
1.5 m/s constant - sensoanemo - fan2 and fan3



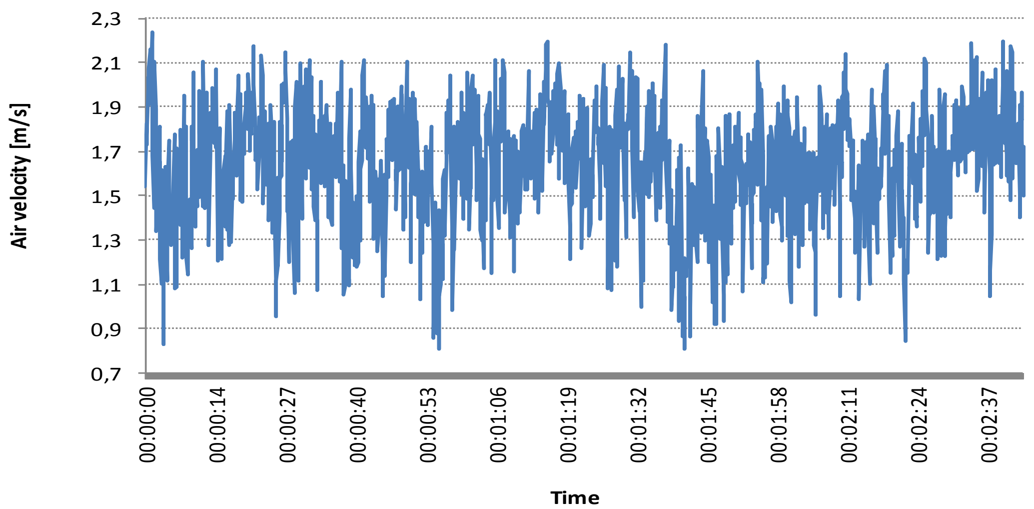
1.5 m/s constant - swema - fan3



2 m/s constant - sensoanemo - fan2 and fan3

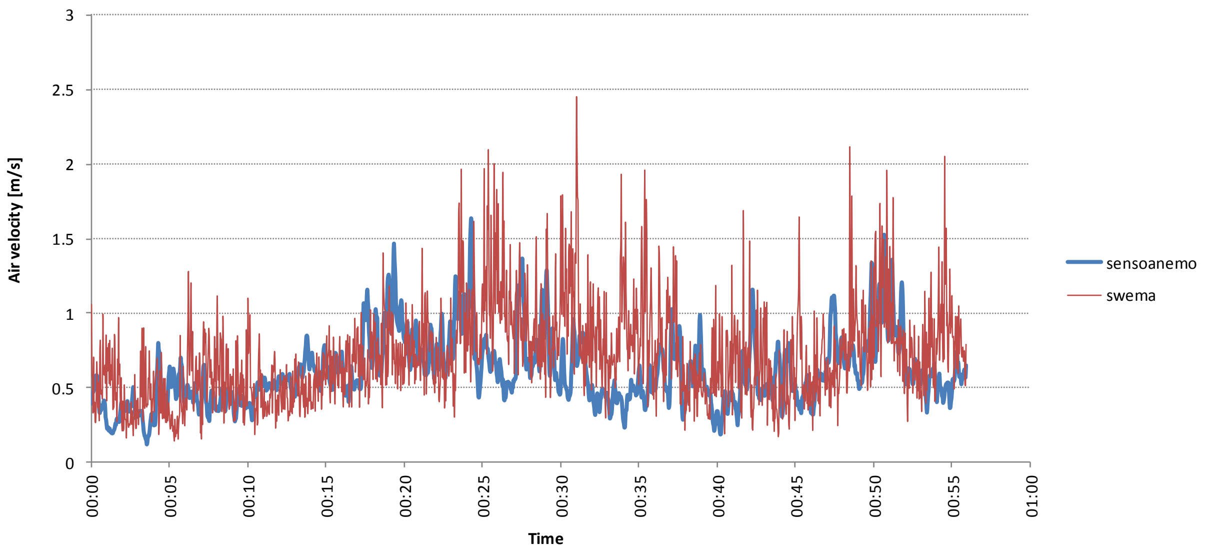


2 m/s constant - swema - fan3

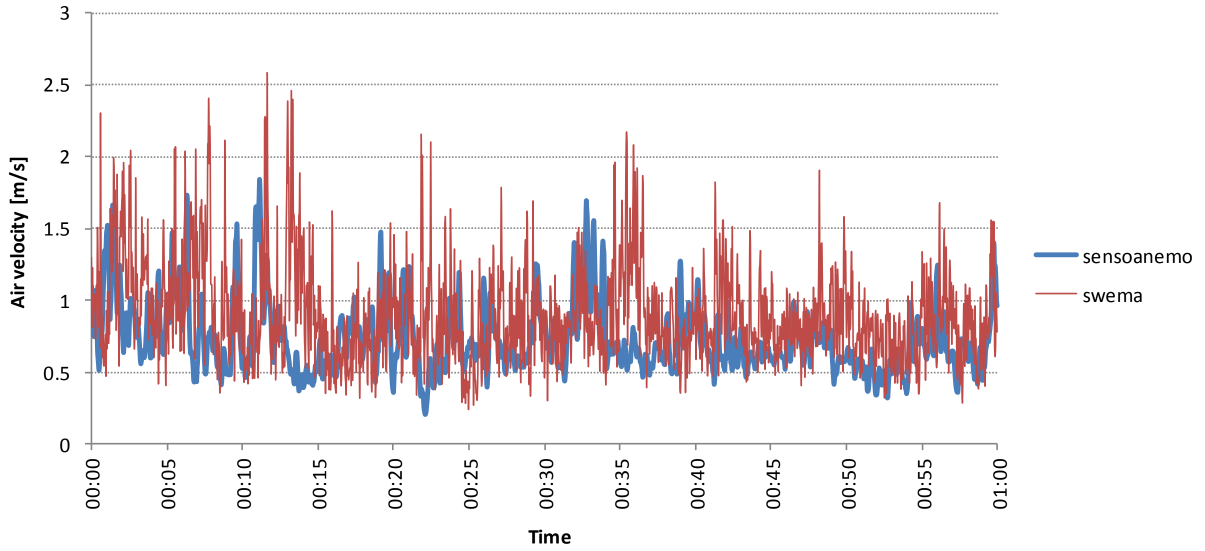


Second experiment

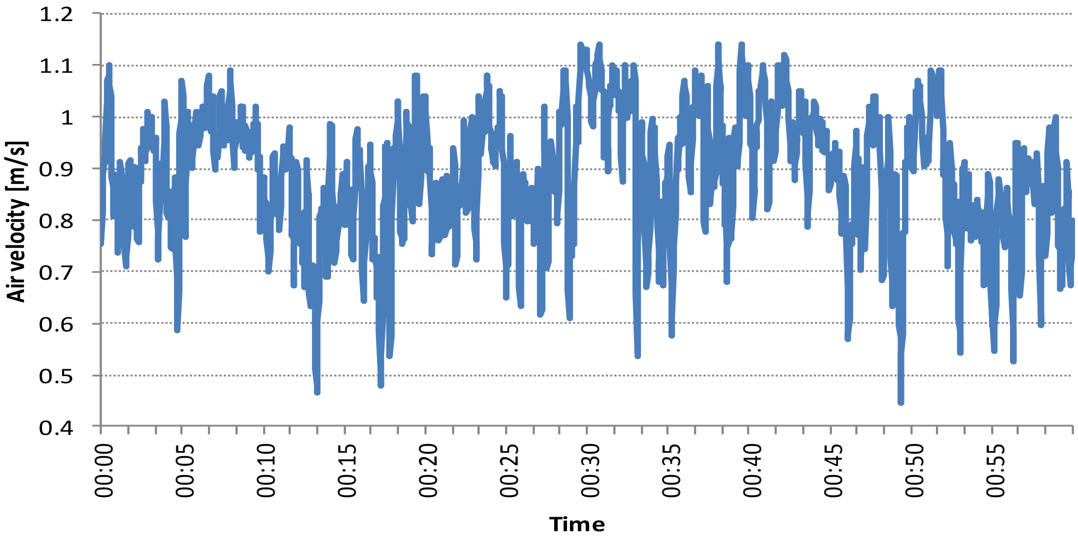
Natural wind simulation - condition 2 - 28°C



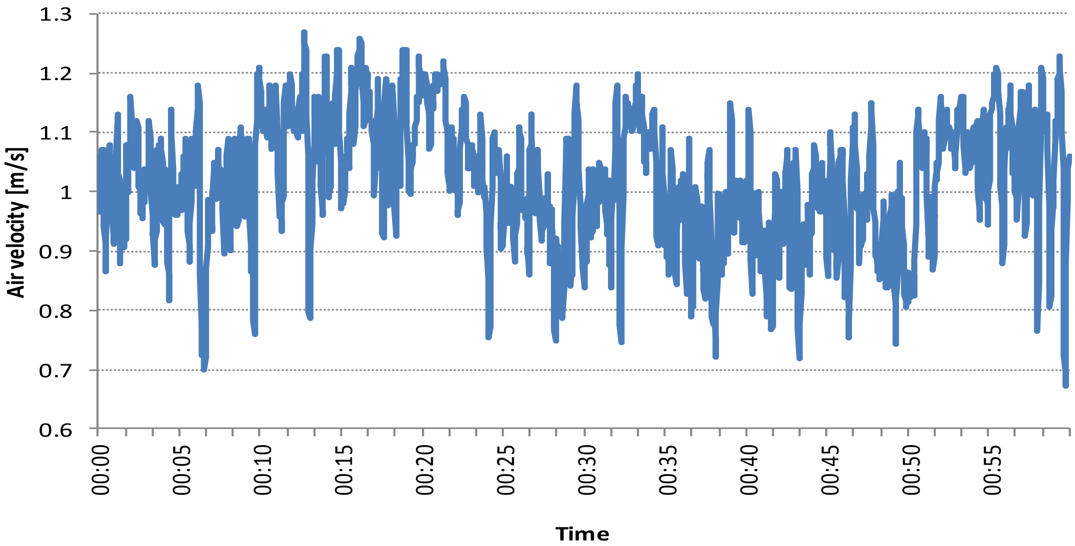
Natural wind simulation - condition 1 - 30°C



Constant condition 2 - 28°C - swema



Constant condition 1 - 30°C - swema



Summary tables

first experiment
distance 80 cm / height 120 cm

fan_desk2_anemo				
setting	$v_{a, expected}$	$v_{a, measured}$ ± St Dev	$v_{a, max}$	$v_{a, min}$
	[m/s]	[m/s]	[m/s]	[m/s]
type 1, 0 lights	0.6	0.48±0.09	0.63	0.29
type 1, 2 lights	1.0	0.87±0.11	1.07	0.58
type 4, subtype 2	1.5	1.26±0.10	1.45	0.98
type 1, 9 lights	2.0	1.68±0.10	1.85	1.39

fan_desk3_anemo				
setting	$v_{a, expected}$	$v_{a, measured}$ ± St Dev	$v_{a, max}$	$v_{a, min}$
	[m/s]	[m/s]	[m/s]	[m/s]
type 1, 0 lights	0.6	0.79±0.04	0.85	0.59
type 1, 2 lights	1.0	1.01±0.07	1.14	0.85
type 4, subtype 2	1.5	1.30±0.13	1.49	0.94
type 1, 9 lights	2.0	1.83±0.11	2.02	1.50

fan_desk3_swema				
setting	$v_{a, expected}$	$v_{a, measured}$ ± St Dev	$v_{a, max}$	$v_{a, min}$
	[m/s]	[m/s]	[m/s]	[m/s]
type 1, 0 lights	0.6	0.76±0.13	1.08	0.33
type 1, 2 lights	1.0	1.00±0.17	1.37	0.28
type 4, subtype 2	1.5	1.36±0.20	1.77	0.57
type 1, 9 lights	2.0	1.63±0.26	2.24	0.81

second experiment
distance 80-90 cm / height 120 cm

natural/28 deg./90 cm/desk2/swema				
setting	$v_{a, expected}$	$v_{a, measured}$ ± St Dev	$v_{a, max}$	$v_{a, min}$
	[m/s]	[m/s]	[m/s]	[m/s]
type 2, lowest	0.89	0.71±0.32	2.69	0.10

natural/28 deg./90 cm/desk2/anemo				
setting	$v_{a, expected}$	$v_{a, measured}$ ± St Dev	$v_{a, max}$	$v_{a, min}$
	[m/s]	[m/s]	[m/s]	[m/s]
type 2, lowest	0.89	0.62±0.23	1.64	0.12

natural/30 deg./80 cm/desk2/swema				
setting	$v_{a, expected}$	$v_{a, measured}$ ± St Dev	$v_{a, max}$	$v_{a, min}$
	[m/s]	[m/s]	[m/s]	[m/s]
type 2, lowest	1.03	0.89±0.35	3.51	0.18

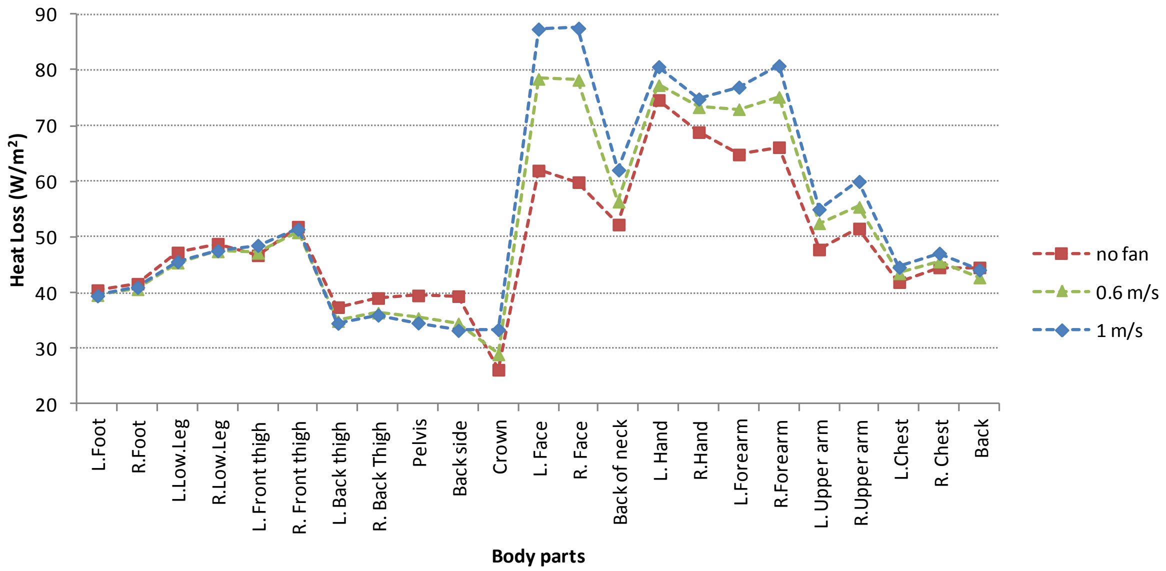
natural/30 deg./80 cm/desk2/anemo				
setting	$v_{a, expected}$	$v_{a, measured}$ ± St Dev	$v_{a, max}$	$v_{a, min}$
	[m/s]	[m/s]	[m/s]	[m/s]
type 2, lowest	1.03	0.73±0.25	1.84	0.20

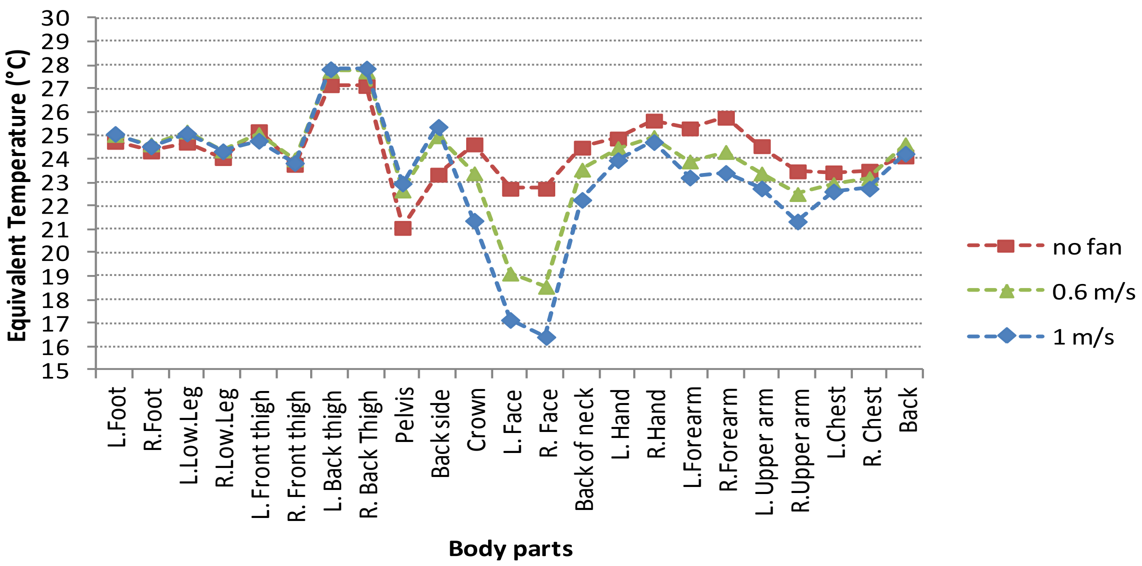
constant/28 deg./90 cm/desk3/anemo				
setting	$v_{a, expected}$	$v_{a, measured}$ ± St Dev	$v_{a, max}$	$v_{a, min}$
	[m/s]	[m/s]	[m/s]	[m/s]
Type 4,subtype 1	0.82	0.89±0.12	1.14	0.45

constant/30 deg./80 cm/desk3/anemo				
setting	$v_{a, expected}$	$v_{a, measured}$ ± St Dev	$v_{a, max}$	$v_{a, min}$
	[m/s]	[m/s]	[m/s]	[m/s]
type 1, 2 lights	1.03	1.02±0.11	1.27	0.67

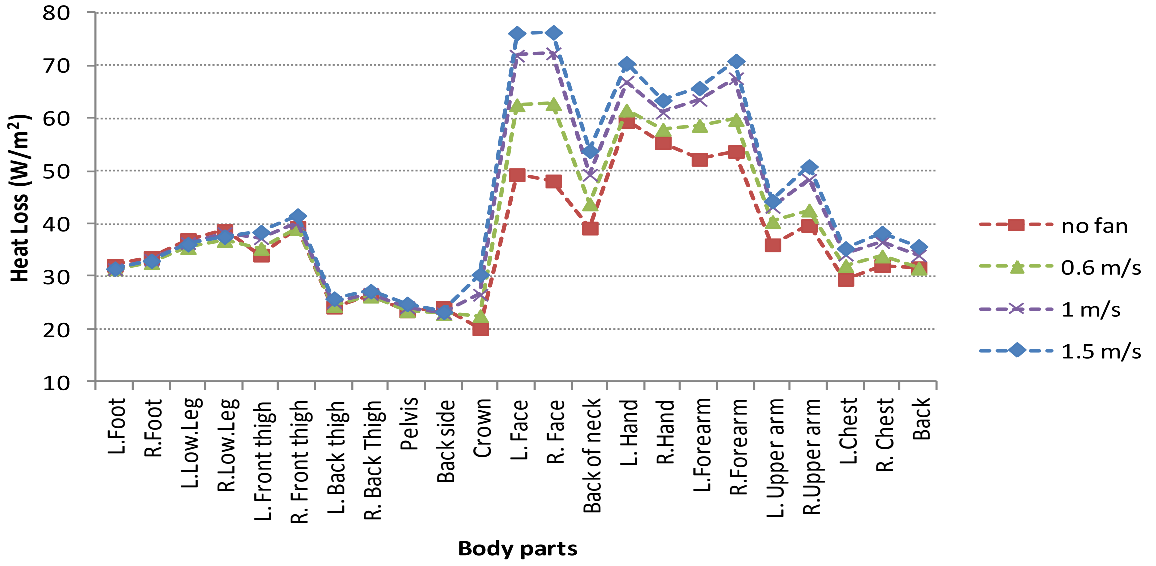
Appendix C - Manikins measurements

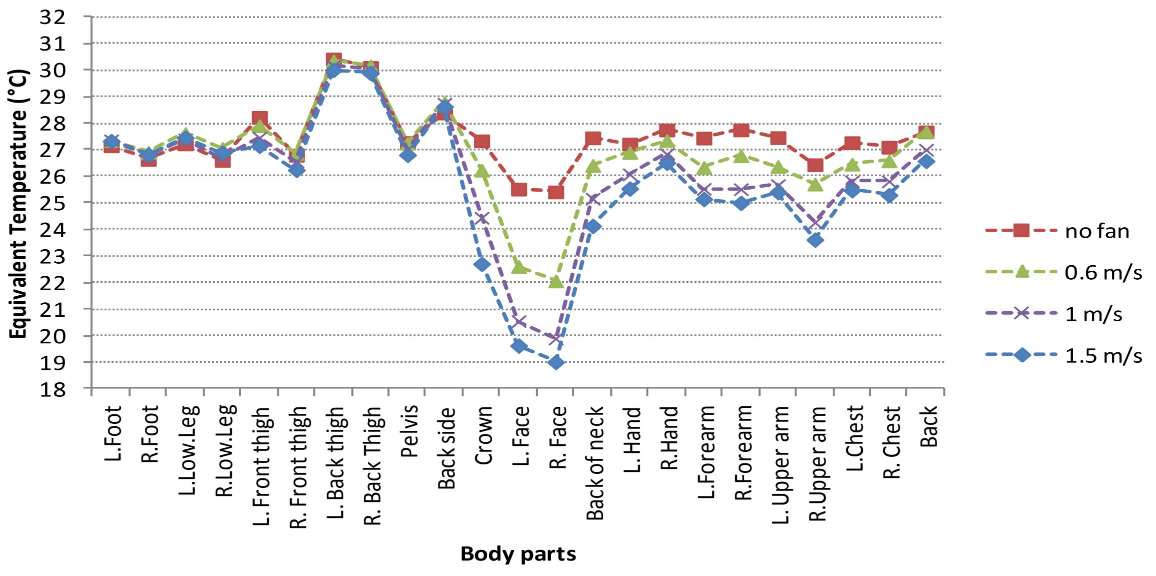
Condition E - 26°C



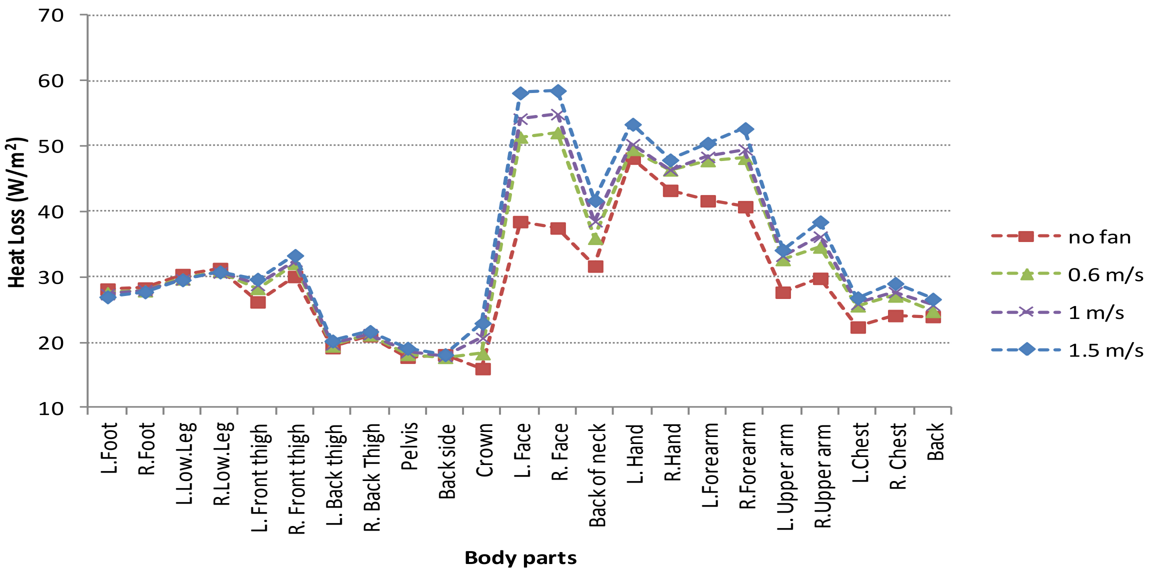


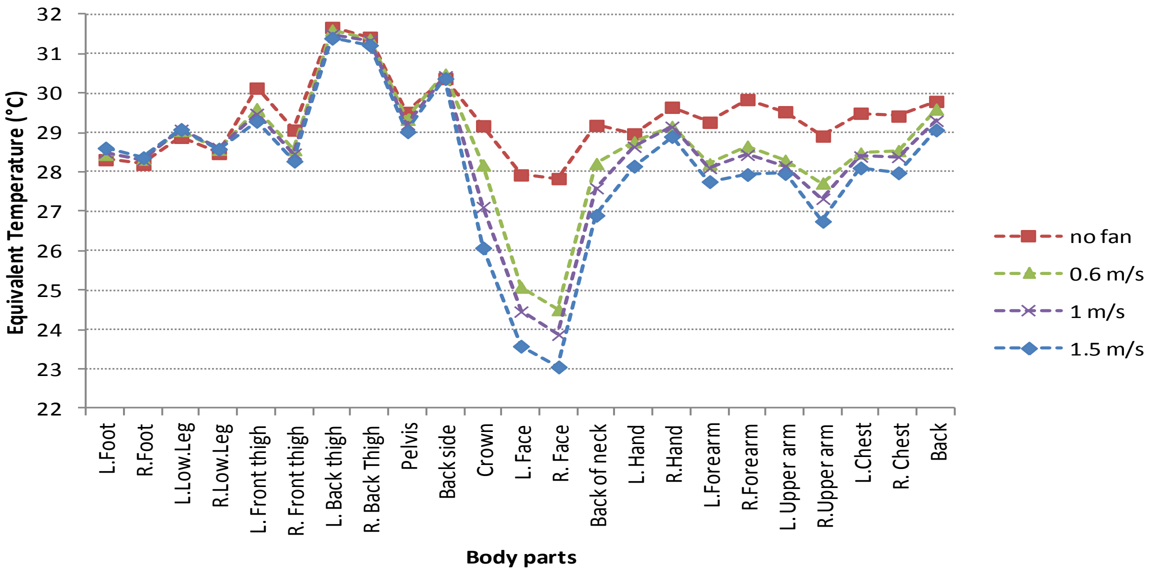
Condition B - 28°C



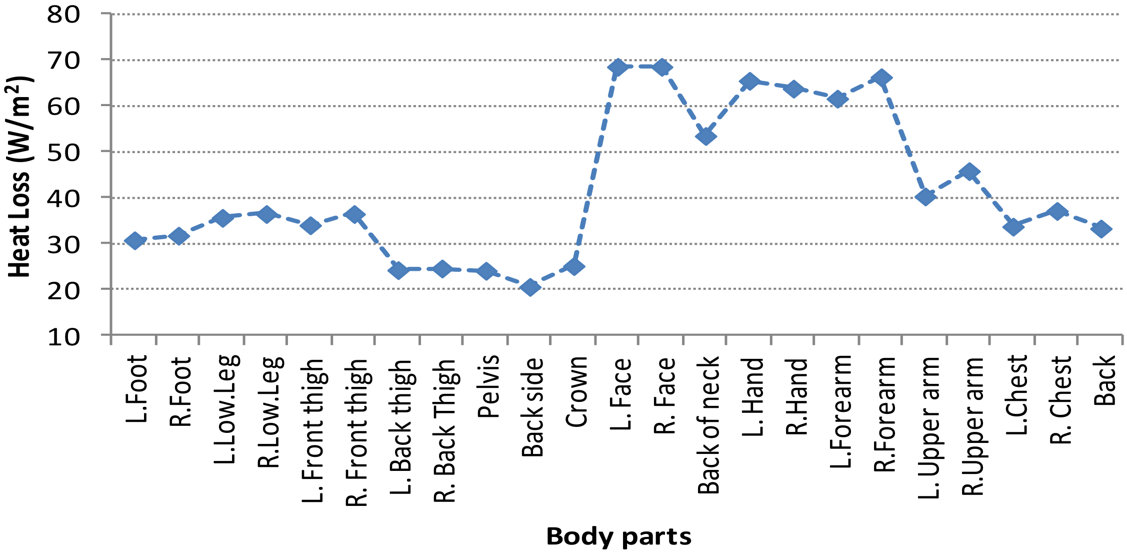


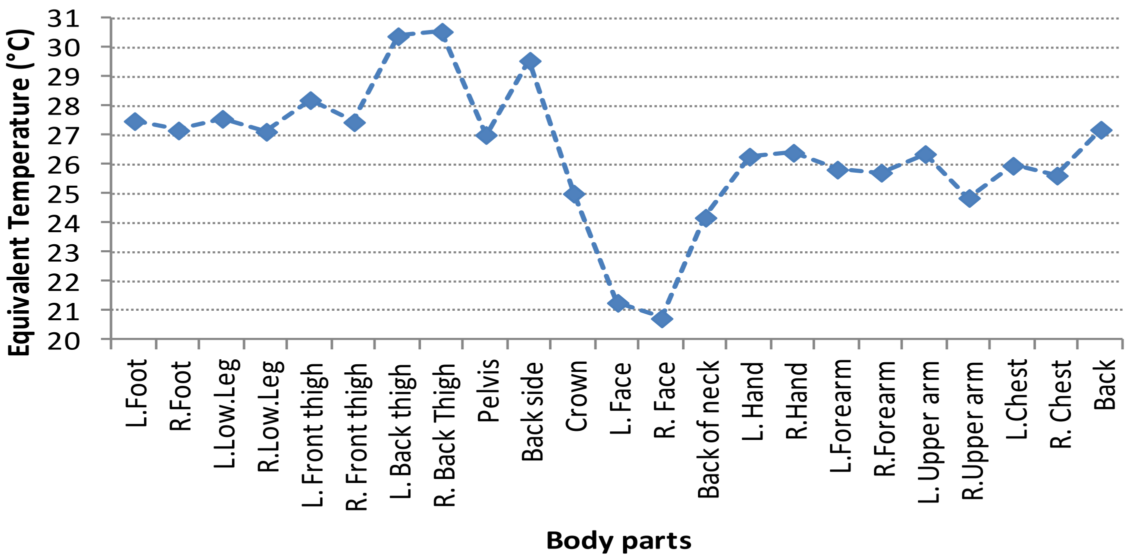
Condition C - 30°C



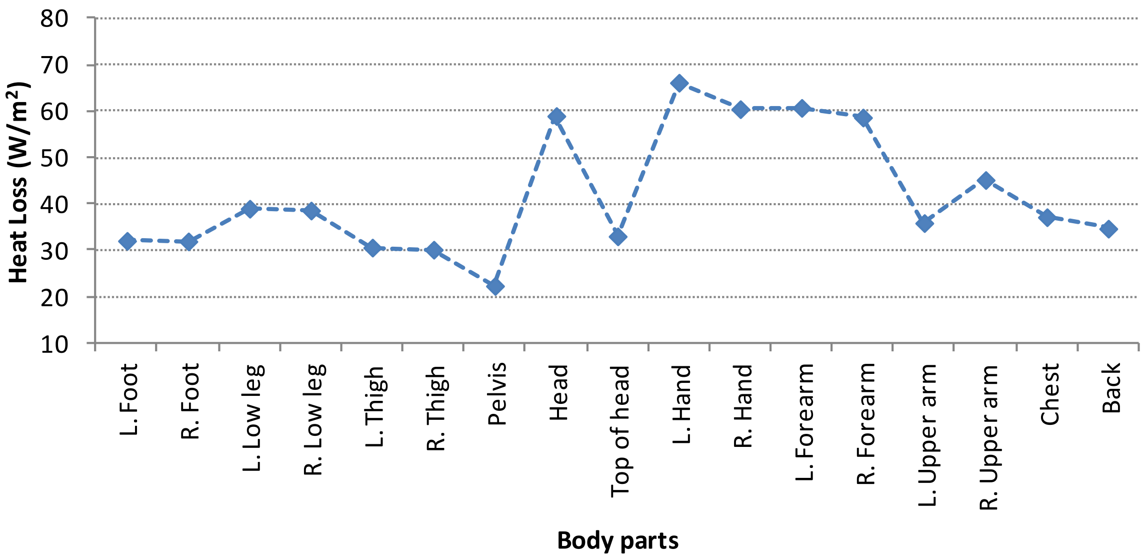


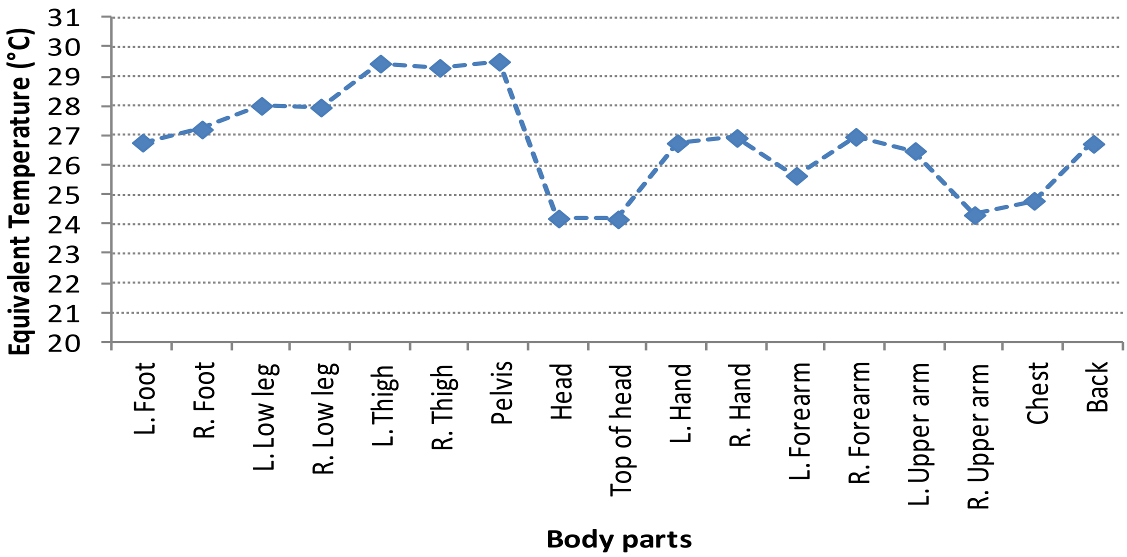
Condition 2 - 28°C - constant airflow



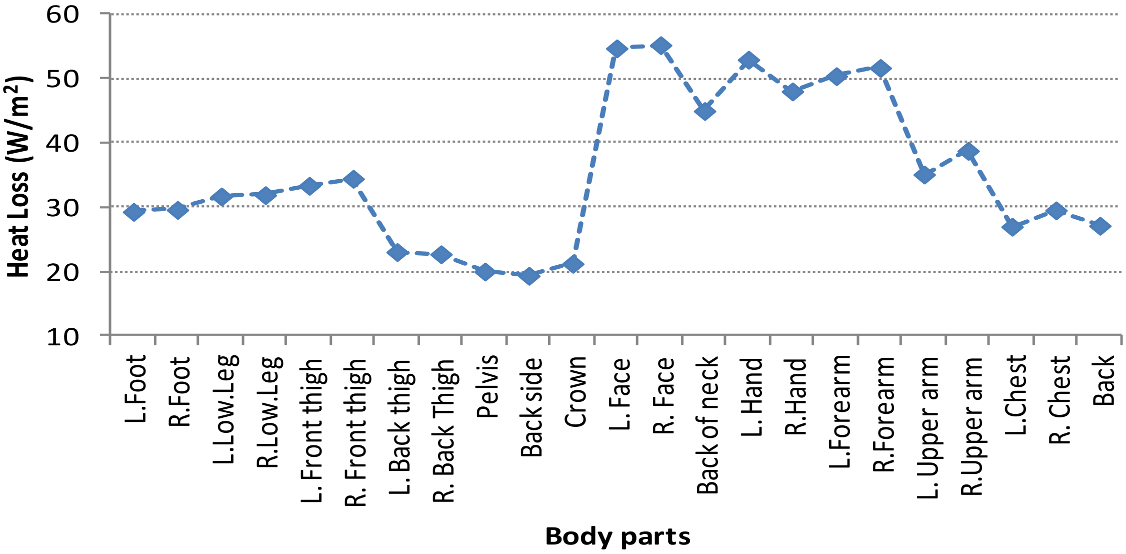


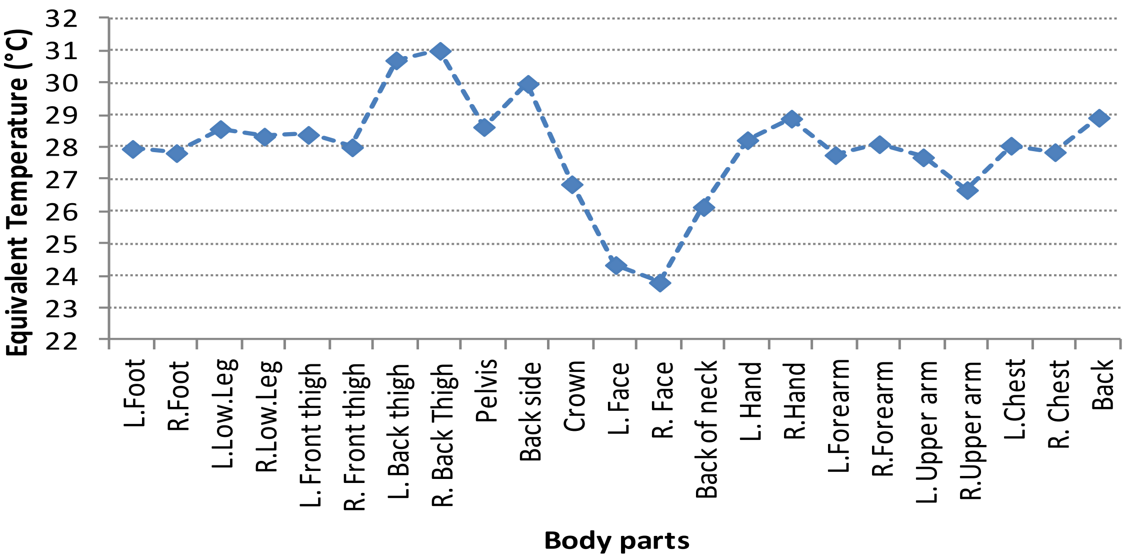
Condition 2 - 28°C - wind simulation airflow





Condition 1 - 30°C - constant airflow





Condition 1 - 30°C - wind simulation airflow