Title
Evaluation of the cooling fan efficiency index.

Authors
Schiavon, Stefano
Melikov, Arsen

Publication Date
2009

Peer reviewed

Evaluation of the Cooling Fan Efficiency index for a desk fan and a computer fan

Stefano Schiavon[1,2,*], M. Sc. PhD candidate, Arsen K. Melikov[2], Ph.D.

[1] Department of Applied Physics, University of Padova, Padova, Italy, www.dft.unipd.it
[2] International Centre for Indoor Environment and Energy, Department of Civil Engineering, Technical University of Denmark, Lyngby, Denmark, www.ie.dtu.dk

Corresponding email: *stefanoschiavon@gmail.com*

ABSTRACT

In a warm environment air movement with elevated velocity is a well-known cooling strategy. The air movement can be generated by cooling fans (e.g. ceiling fan, table fans, etc.). Appearance, power input and price are the main parameters considered today when purchasing cooling fans, while their cooling capacity and efficiency of energy use are unknown. Cooling fan efficiency index defined as the ratio between the cooling effect (measured with a thermal manikin) generated by the device and its power consumption is a measure of the efficiency of the fans. The index was determined for a desk fan and two identical computer fans working simultaneously. The results showed that the computer fans generated the same cooling effect (around -2°C) with less than half power consumption (7 W instead of 16-20 W). It means that the computer fan's efficiency is double than the efficiency of the desk fan. The computer fans caused a more homogeneous cooling effect than the desk fan.

INTRODUCTION

In a warm environment, elevated air movement is a widely used strategy for cooling of occupants. The air movement increase can be produced by several devices such as cooling fans (e.g. ceiling, floor standing, tower, and table fans), furniture-installed personalized ventilation, body-attached ventilation devices and, under certain conditions, with operable windows. The cooling capacity of cooling fans is limited because they operate under isothermal conditions, i.e. the cooling of the body is a result of increased velocity only. The use of cooling fans in practice is easy and does not require special installations. Appearance, power consumption and price are the main parameters considered when purchasing cooling fans, while their cooling capacity and efficiency of energy use are unknown. Other factors such as ergonomics, control options, etc., are also important. Usually the efficiency in cooling the occupants is unknown.

It has been suggested [1, 2, 3] that setting a high room temperature and cooling of the body by elevated air movement lead to a substantial energy saving. Schiavon and Melikov [4], by means of energy simulations, found that the required power input of the fan is a critical factor for energy saving. The results obtained for the boundary conditions of their study reveal that traditional cooling devices, such as ceiling, standing, tower and desk fans, may consume more electrical energy than is saved by not using a traditional HVAC system. Thus, knowledge on how efficiently fans of different types use the electrical energy for cooling occupants is needed in order to justify the use of the strategy of elevating the room temperature at increased air movement. Schiavon and Melikov [5] developed an index named Cooling Fan Efficiency (*CFE*) that is the ratio between the cooling effect generated by a fan and its power consumption. They measured the index for four cooling fans (floor standing, desk, tower and ceiling fans). They concluded that the desk fan had a significantly ($p<0.01$) higher efficiency than the other three fans tested. Watanabe et al. [6] and Sun et al. [7] used computer fans attached to a chair to cool the seated person. They found that the fans were able to cool the person.

The objective of this paper is to measure and compare the cooling effect and the cooling fan efficiency index of a desk fan and of computer fans in order to establish if it is more effective to cool people with the desk fan or with the computer fans.

COOLING FAN EFFICIENCY

Commonly, the efficiency is the ratio of output to input. It can be improved by reducing the input and/or improving the output. In the case of fans, used for cooling people in warm environments by increasing the air velocity around the human body, the input is the electrical energy needed for running the fan (the power requirement of a fan is almost constant and it can be used instead of energy in order to make the input variable time-independent) and the output is the body cooling effect [5].

Thermal manikins with full body size and a complex shape have been developed and used for determination of the heat loss from the human body under different environmental conditions [8, 9, 10]. Manikin's body is typically divided into several segments. Thermal manikins can be used to measure the fan cooling effect and thus to determine the cooling fan efficiency index. Thermal manikins that can measure dry heat loss from the human body are most commonly used today though sweating thermal manikins are under development as well [11].

The equivalent temperature (t_{eq}) is a well-known parameter that can be used for determining the cooling fan efficiency index. Equivalent temperature (former Equivalent Homogenous 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" [12].

The body cooling effect (Δt_{eq}) achieved by air movement can be quantified by the change in whole-body manikin-based equivalent temperature, t_{eq}, from the reference condition, t_{eq} * (similar indoor environmental conditions but without air movement), i.e. $\Delta t_{eq} = t_{eq} - t_{eq}$ *. The concept of Δt_{eq} has been already used by several authors to quantify the whole-body cooling effect of air movement [8, 9, 10, 13, 14]. Thus, the Cooling Fan Efficiency (*CFE*) is defined by Equation 1.

$$CFE = (-1)\frac{\Delta t_{eq}}{P_f} \quad (1)$$

where P_f is fan power, i.e the input power of the fan and Δt_{eq} is whole-body cooling effect. The measuring unit of *CFE* is °C/W. The higher the CFE index, the better the fan performance.

Knowing the cooling fan efficiency index (*CFE*) and its cooling effect (Δt_{eq}) will help customers to purchase a better fan, fan designers/manufacturers to assess and develop better products, and policymakers to fix minimum values or classes of fan efficiency as is usually done with other electrical appliances (e.g. air-conditioner, refrigerators, boilers, etc.). HVAC designers may choose the summer maximum allowed room temperature, depending on the cooling capacity of the fan, as well as evaluate the possibility for energy saving based on the strategy of increased air movement at elevated room air temperature.

METHODS

Experimental facilities

The fans used in the present study are described in Table 1 and shown in **Figure 1**. The rotation speed of the desk fans (velocity of the generated flow is expected to increase with the rotation speed), is defined by the manufacturers and can be varied in two steps. The computer fan is a direct current fan. The rotation speed of the fan can be controlled continuously. At the nominal voltage (12 V) the airflow is 80 m^3/h (22.2 L/s). Two computer fans are used one next to the other.

Experiments were performed in a real office room (5.8 m x 4.42 m x 3.5 m) with a suspended ceiling. A double pane strip window (5.80 m width and 1.85 m height) is located in one of the walls. The lower edge of the window is 1.15 m above the floor. The window faces north-west. Solar radiation was shielded with internal blinds. During the experiments, the outdoor temperature was always lower than 22°C. The room air temperature was set to 27°C and it was controlled with an electrical heater managed by a PID controller. The room was not equipped with ventilation and air-conditioning systems. A workplace was arranged in the room, and a desk was placed in the centre of the office.

Table 1. Main Characteristics of the Fans Used

Type	**Velocity levels**	**Number of fan**	**Dimension [m]**	**Power[a] [W]**
Desk Fan – axial fan	2	1	$Ø_{DF}$[b]= 0.22 ; h_{DF}[b]= 0.22	30
Computer Fan - axial fan[c]	Continuous	2	S_{CF}[d]=0.092; D_{CF}[d]=0.032	2.4

[a] Nameplate fan power declared by the company.
[b] $Ø_{DF}$ = external diameter of the blades of the desk fan; h_{DF} = height of the rotation axis of the desk fan.
[c] Direct current fans. The nominal voltage is 12 V.
[d] S_{CF}=external side of the computer fan, the fan is located inside a vane; D_{CF} is the thickness of the vane.

Measuring instruments

A thermal manikin was used to simulate an occupant and to evaluate the cooling effect of the fans. The thermal manikin is 1.68 m tall and shaped as an average size Scandinavian woman. The total surface area of the manikin is 1.48 m^2. The body of the manikin consists of 23 independently controlled segments, manufactured as polystyrene shells wound with embedded nickel wire, which serves to heat the body parts and monitor the ‘‘skin temperature’’. Low-voltage power is pulsed to each segment at a rate needed to keep the surface temperature of the manikin equal to the skin temperature of an average person in a state of thermal comfort. For each body segment the segmental equivalent temperature, $t_{eq,i}$, can be calculated. The t_{eq} for the whole-body is obtained by computing the area-weighted average over all the body segments. A multichannel low velocity thermal anemometer with omnidirectional velocity transducers was used to perform mean velocity, turbulence intensity and air temperature measurements at several points in the room. The characteristics of the anemometer comply with the requirements for such instruments specified in the standards [15, 16]. The room air temperature was measured also with a mercury thermometer. The relative humidity was monitored but not controlled. The resolution of the used hygrometer was 0.1% RH. The fan power input of the desk fan was measured with a power-meter, and for the computer fans with the variable voltage regulator.

Measurements uncertainty
The data were analyzed in accordance with the ISO guideline [17] for the expression of uncertainty. The sample uncertainty (confidence interval of 95%) of the equivalent temperature, t_{eq}, is ±0.21°C, of the whole body cooling effect, Δt_{eq}, is ±0.3°C and of the cooling fan efficiency, *CFE*, is ±0.009°C/W. The sample uncertainty of the fan air power is ±1.3 W. The room air temperature was measured with an accuracy of ±0.1°C. The measurement accuracy of the relative humidity sensor is ±3%. The air velocity was measured with an accuracy of 0.02±1% of the readings for velocity range between 0.05 and 1 m/s, and with an accuracy of ±3% of the readings for velocity range between 1 and 5 m/s.

Experimental conditions
Two velocity levels for the desk fan were explore and for the two computer fans the imposed voltage was 14 V (it correspond to a total current intensity equal to 0.48 A). Measurements were also performed in a still environment without fan. The experiments were performed in randomized order. Throughout the experiments the room temperature (set to 27°C) varied between 26.8 - 27.2°C and the relative humidity varied between 23.5 - 34.5%. The location of the fans relative to the manikin is shown in **Figure 1**. The desk fan was placed in front of the manikin on the table on the left side of the laptop at a distance of 0.66 m (three times its diameter) from the manikin. Two computer fans were placed one next to the other at the front edge of the desk. The distance between the fans and the manikin was around 0.4 m (more than four times the fan diameter). The computer fans were inclined upward of 60°, in this way the airflows were direct to the upper chest-neck area. The thermal manikin was dressed with a long-sleeved shirt, thin long trousers, panties, ankle socks and shoes. This typical summer office clothing was equal to 0.47 clo. The manikin was seated upright on an office chair (0.15 clo).

Figure 1. The desk fan, the two computer fans and the thermal manikin, and their location relative to the thermal manikin.

Experimental procedure
The output data from the manikin were recorded for 10 min after steady-state conditions were obtained. The fan power was manually recorded while logging the manikin data. The manikin was then moved from the desk and the mean air velocity and the turbulence were measured at its location at four heights (0.2, 0.6, 1.1, 1.25 and 1.7 m). Three-minute velocity measurements were performed as recommended in the indoor climate standards.

RESULTS

Cooling fan efficiency index

In Figure 2 the whole-body cooling effect determined is plotted versus the fan power measured. The relative uncertainties are shown. The whole-body cooling effect of the desk fan (Δt_{eq} almost equal to -2°C) is slightly higher than the cooling effect generated by the computer fan (Δt_{eq} almost equal to -1.5°C), but the computer fan needs less than half of the electrical power used by the desk fan (around 7 W compared to 16-20 W). With the cooling effect and the fan power is possible to calculate the cooling fan efficiency index. The *CFE* index calculated for the desk fan and the computer fan is plotted in Figure 3. The computer fan's efficiency is double than the efficiency of the desk fan.

The results are plotted in Figure 3 because this graph summarizes all the important parameters (cooling effect, fan power and *CFE*) involved in the evaluation of the efficiency of the fan. Figure 3 shows the cooling fan efficiency versus the fan power calculated at several levels of the cooling effect (Δt_{eq} = -1, -2, -3 and -4°C). It has been reported that a cooling effect of -4°C obtained by local body cooling can be acceptable for people [13]. An internet survey showed that the typical power consumption of cooling fans is lower than 90 W. The lines with constant cooling effect help to understand the behaviour of the index, i.e. *CFE* increases with the decrease of the fan power.

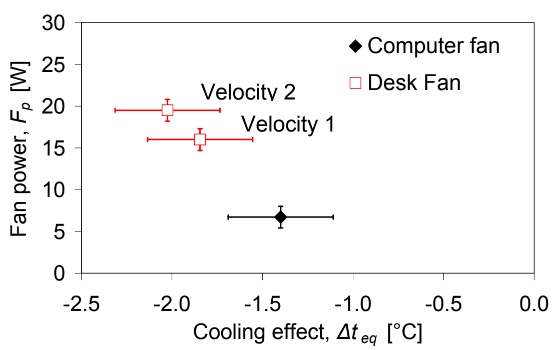

Figure 2. Cooling effect versus fan power for the computer fan and the desk fan. The room temperature was set to 27°C.

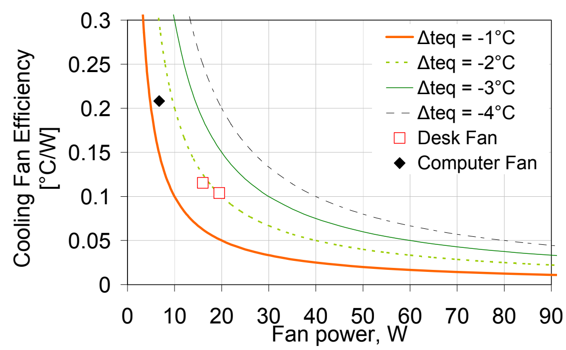

Figure 3. Fan power versus cooling fan efficiency index for power for the computer fan and the desk fan. Lines with constant cooling effect (Δt_{eq}) are plotted.

Cooling effect

The whole-body cooling effect (Δt_{eq}) discussed so far is the weighted average of the cooling effect of each body segment. The cooling of the body segments depends on the local flow field generated by the fans. Analyses of the local cooling effect obtained by the tested fans for each body segment were performed. The local cooling effect on each of the 22 body segments of the manikin is shown in Figure 4. The body of the thermal manikin consists of 23 independently controlled segments. During these experiments the left hand of the manikin was broken; therefore it is not included in the measurements and the calculations.

The body segments that are exposed to the air movement generated by the fan are cooler than the rest of the body. The local cooling effect of the lower part of the body (i.e. foot, legs, thighs, pelvis and back side) of the two fans is the same because the two fans tested do not increase the air velocity around that area of the body. The desk fan provides a non-uniform cooling effect of the body. The airflow generated by the fan attacks the manikin's body from the left (the fan is located only 0.66 m from the manikin). The coolest segments are those exposed to the flow generated by the fan, i.e. scull, left and right face, back of neck, left chest, left upper arm and left forearm. The desk fan had two velocity levels. The impact of the velocity level on the cooling effect is negligible (see Figure 2 and Figure 4). The computer fan provides also a non-uniform cooling effect of the body. The airflow generated by the fan attacks the manikin's body from the front. The coolest segments are those exposed to the flow generated by the fan, i.e. left and right face, back of the neck, and left and right chest.

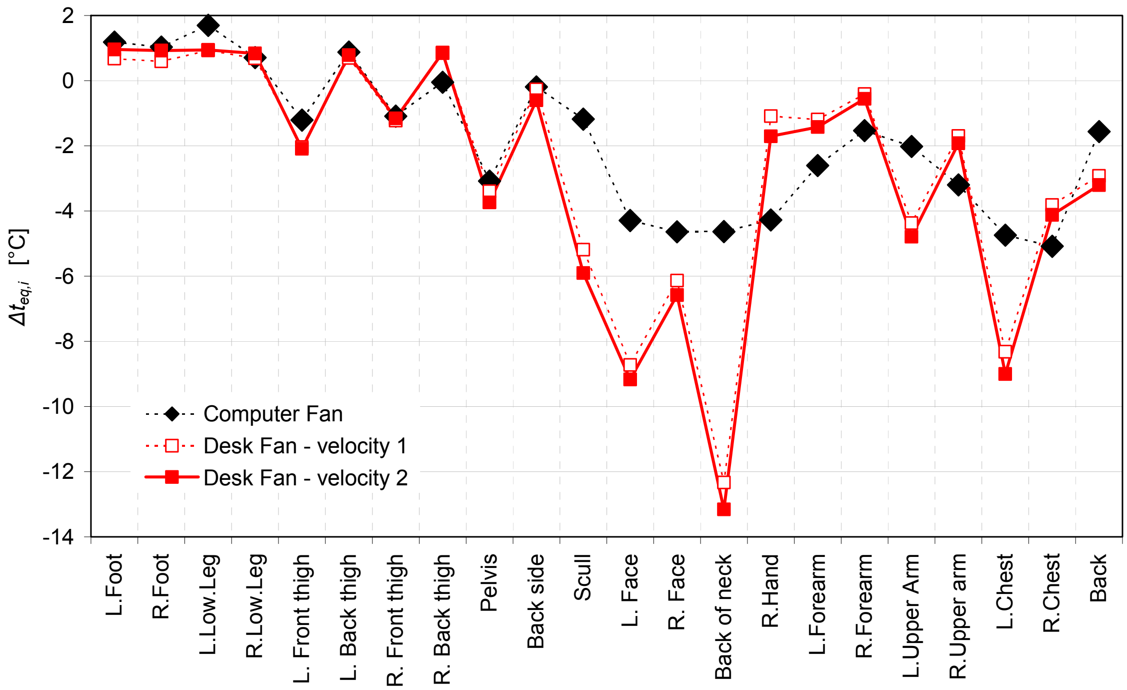

Figure 4. Change in manikin-based equivalent temperature ($\Delta t_{eq,i}$) on each body part from the reference condition (room temperature equal to 27°C and no devices used for air movement) for the computer fan and the desk fan.

The flow field generated by the fans was non-uniform and therefore caused non-uniform local cooling of the manikin's body. The asymmetric cooling on the body areas was investigated further. The average cooling effect for the upper body segments (right hand (left hand was broken), forearm (right and left), upper arm (right and left), chest (right and left), and back) and for the head (skull, face (right and left), back of neck) was determined. The total area of the upper body segments was 0.68 m^2, of the head it was 0.13 m^2 and of the whole-body it was 1.48 m^2. The results are compared in Figure 5. The cooling effect of the upper body parts and of the head is always higher than the cooling effect of the whole-body. The desk fan generates the largest non-uniformity in the local cooling effect. The head is much cooler than the reference condition (-8°C) and it is cooler than the whole-body (-6°C). As previously mentioned (see Figure 4) the velocity level of the desk fan does not affect the whole-body cooling effect. The computer fan generates a more homogeneous cooling. The head and the upper part of the body are -4°C cooler than the reference condition and -2°C than the whole-body.

The air velocities measured at 0.2, 0.6, 1.1, 1.25 and 1.7 m are shown in Figure 6.

The air velocity field generated by the two fans is similar. The higher velocities are generated around the upper body parts. For the desk fan the highest velocity (2 m/s) is measured at 1.1 m, for the computer fan (1.1 m/s) at 1.25 m.

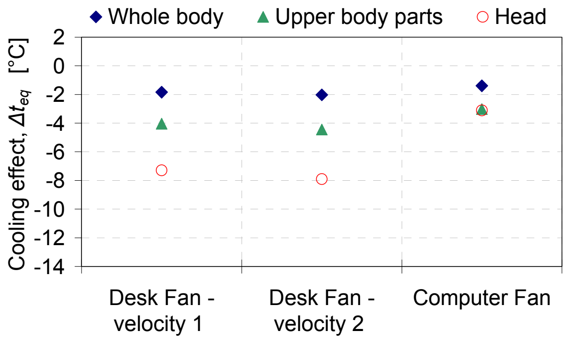

Figure 5. Cooling effect for the whole-body (22 body segments), the upper body part (12 body segments), and the head (4 body segments) for the computer fan and the desk fan.

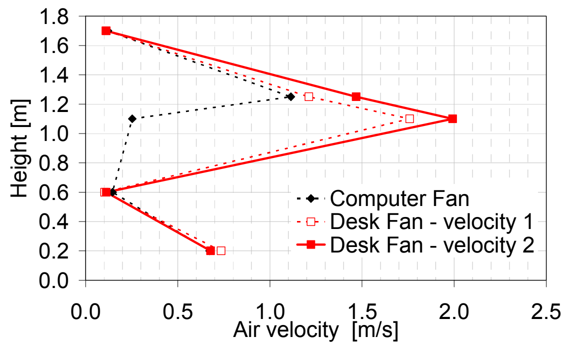

Figure 6. Air velocity measured at 0.2, 0.6, 1.1, 1.25 and 1.7 m height above the floor where the manikin was located during the experiments for the computer fan and the desk fan.

DISCUSSION

A considerable number of studies focused on the use of fans to cool people in a warm environment. The power consumption of cooling fans is commonly considered negligible (usually less then 90 W) and therefore it is not reported. However, as already discussed, it has been demonstrated that the required power input of cooling fans is a critical factor for an energy-saving strategy used in warm environment (Schiavon and Melikov 2008a). Based on comprehensive simulations as well as on defined outdoor conditions and building characteristics, it has been shown that in some buildings the use of cooling fans with power input of more than 20 W (similar to the consumption of the desk fan) will actually increase the energy consumption compared to the energy consumption needed to cool the whole building.

The experiments performed with a desk fan and two computer fans showed that it is possible to get almost the same cooling effect (around -2°C) with less than half power consumption (7 W instead of 16-20 W). Therefore, the computer fans have a cooling fan efficiency index double than the desk fan. The whole-body cooling effect generated by the fans was large enough to keep the occupant in comfort condition with a room temperature of 27°C. The desk fan generated a bigger non-uniformity of the local cooling effect then the computer fan. Computer fans are a good solution compared to desk fan for cooling people in warm environments, and their application, as the ones of Watanabe et al. [6] and Sun et al. [7], should be encouraged.

CONCLUSIONS

The comparison of a desk fan and two computer fans working simultaneously in terms of their cooling effect and cooling fan efficiency identified that the computer fans generated the same cooling effect (around -2°C) at power consumption of 7 W with is less than half of the power consumption (16-20 W) of the desk fan.

REFERENCES

1. Sekhar, S.C. 1995. Higher space temperatures and better thermal comfort a tropical analysis. *Energy and Buildings* 23:63-70.
2. Atthajariyakul, S., and Lertsatittanakorn C. 2008. Small fan assisted air conditioner for thermal comfort and energy saving in Thailand. Energy Conversion and Management 49:2499-2504.
3. Aynsley, R. 2005. Saving energy with indoor air movement. International Journal of Ventilation 4:167-175.
4. Schiavon, S., and Melikov, A. 2008. Energy saving and improved comfort by increasing air movement. Energy and Buildings 40 (10): 1954-1960 doi:10.1016/j.enbuild.2008.05.001.
5. Schiavon, S., and Melikov, A. 2008. Introduction to the Cooling Fan Efficiency index. (Submitted to HVAC&R Research)
6. Watanabe, S., Shimomuraa T., and Miyazakia, H. Thermal evaluation of a chair with fans as an individually controlled system. Building and Environment (2008), doi:10.1016/j.buildenv.2008.05.016. (Article in press).
7. Sun, W., Melikov, A.K., and Cheong, K.W.D. 2008. Local climate and heat loss from human body with a novel enhanced displacement ventilation system. Proceeding of Indoor Air 2008, Copenhagen, Denmark. Paper ID: 962.
8. Tanabe, S., Arens, E.A., Bauman, F.S., Zhang, H., and Madsen, T.L. 1994. Evaluating thermal environments by using a thermal manikin with controlled skin surface temperature. ASHRAE Transactions 100(1):39–48.
9. Tsuzuki, K., Arens, E.A., Bauman, F.S., and Wyon, D.P. 1999. Individual thermal comfort control with desk-mounted and floor-mounted task/ambient conditioning (TAC) systems. Proceedings of Indoor Air 1999, Edinburgh, UK, 2: 368–73.
10. Melikov, A.K., Cermak, R., and Majer, M. 2002. Personalized ventilation: evaluation of different air terminal devices. *Energy and Buildings* 34(8):829–36.
11. Psikuta, A., Richards, M.G.M., and Fiala, D. 2008. Single-sector thermopysiological human simulator. Physiological Measurements 29:181-192.
12. Nilsson, H., Holmér, I., Bohm, M. and Norén, O. 1999. Definition and theoretical background of the equivalent temperature. International ATA Conference, Florence, Italy, A4082.
13. Watanabe, S., Melikov, A., Knudsen, G., 2008, Design of an individually controlled system for an optimal thermal microenvironment, Ergonomics (submitted).
14. Sun, W., Tham, K.W., Zhou, W., and Gong, N. 2007. Thermal performance of a personalized ventilation air terminal device at two different turbulence intensities. Building and Environment 42:3974–3983.
15. ISO. 1998. ISO 7726, International Standard: Ergonomics of the thermal environment - Instruments for measuring physical quantities. International Organization for Standardization.
16. ASHRAE. 2005. ANSI/ASHRAE Standard 113-2005: Method of testing for room air diffusion. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers, Inc.
17. ISO. 1993. Guide to the expression of uncertainty in measurement. International Organization for Standardization.