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Experimental investigations and computational thermal simulation on human thermal comfort during performing office tasks

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Abstract. Thermal have significantly impact the productivity of work as well as the occupants' satisfaction to their surroundings. The objective of this study is to evaluate the implication of thermal environmental conditions to human/manikin in a ventilated air conditioning space using CFD simulations. The thermal distributions of environmental parameters, which were air velocity, air temperature, radiant temperature, inside an office room with air-conditioning system were simulated. The design of experimental study was utilised through the controlled conditions based on the real laboratory studies and real case studies which were later on utilised as the external validity of the field studies. The model of the office environment has been built in the ANSYS Engineering simulation software. The thermal distributions, spatial profiles of PMV are obtained to illustrate thermal conditions intuitively. The distribution of PMV indicated that operative temperature at the 23 $^{\circ}$C shows that the PMV is at the level of comfort. Meanwhile the value of PMV for the operative temperature at 23 $^{\circ}$C is at 0.79 near the skin of manikin. The research outputs provide useful information for engineers especially in designing air-conditioning system in order to design and build a comfortable indoor environment climate especially in the office environment.

1. Introduction

Complaints about air-conditioning in offices are very common - it is either too hot or too cold. The temperature varies drastically through the day. The draughts are terrible. It's not only the temperature that affects how people feel, but also the humidity levels, air movement and people and electronics surrounding that's means increasing heat in the space.

Thermal comfort is the occupants' satisfaction with the surrounding thermal conditions. It can only be maintained when the heat produced by metabolism equals the heat loss from the body. However,

thermal comfort is difficult to measure because it is highly subjective. Each experiences sensations a bit differently based on their physiology and state. Moreover, the temperature of the skin is not consistent with all areas of the body [1]. There are variations in different parts of the body which reflect the differences in blood flow and subcutaneous fat. Additionally, the indoor thermal sensation within the same building could deviate significantly because of different room orientations, facade designs or effects of buildings in the neighbourhood [2].

Typically, senses or feeling comfortable relate to the definition of comfort when human in a home or building. Hensen [3] defined thermal comfort as a state in which there are no driving impulses to correct the environment by the behaviour. So, whatever the meaning of thermal comfort is, Djongyang et al. [4] pointed out it will be influenced by personal differences in mood, culture and other individual organizational and social factor. There were studies reported that emphasized the judgment of comfort is a cognitive process involving many inputs influenced by physical, physiological and psychological [5]. Cena and Clark [6] reviewed their categories of science that influenced the thermal comfort, namely:

  i.   Physics: How human regulates the thermal environment, including clothing
  ii.   Physiology: The mechanisms of thermoregulation and acclimatization and their variation with age and health
  iii.   Psychology: The perception of comfort and discomfort and its relation to other competing stimuli

In order to evaluate the thermal comfort, a subjective and comprehensive index, PMV (predicted mean vote) proposed by Fanger [7] is used to quantitatively assess the thermal sensation of occupants by combining the environmental factors with human factors [7]. The PMV means the expected mean value of the thermal sensation votes of a large group of occupants in a sensation scale expressed from -3 to +3 corresponding to the categories 'cold', 'cool', 'slightly cool', neutral', 'slightly warm', 'warm', and 'hot' as illustrated in Table 1 [8]. Fanger [7] developed the Predicted Percentage of Dissatisfied (PPD), a method used to estimate unacceptable conditions for occupants. According to the PPD method, if 95 % of the occupants in the building are satisfied, then the environment is classified as comfortable. However, PPD is based on PMV, which is used to predict an occupant's thermal sensation followed by the environmental parameters. Therefore, to obtain PPD, the PMV must calculate first.

There are six necessary environmental parameters to calculate PMV values, as shown in Figure 1, such as air temperature, air velocity, radiant temperature, relative humidity, metabolic rate and clothing insulation.

Parsons [9] defined air temperature (Ta) is a measurement that determines how cold or hot the air is. More specifically, temperature describes the kinetic energy or energy motion of the gases that make up air. As gas molecules move more quickly, air temperature increases. Alternatively, Ta is the dry bulb temperature, which is the most significant factor in determining the energy balance, comfort, discomfort, thermal sensation and perception of air quality. It can be measured by mercury in glass thermometer shielded from direct heat radiation and suspended in the air [10]. The ISO 7726 [11] defines the radiant temperature is the uniform temperature of an imaginary enclosure in which radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure. Furthermore, the radiant temperature of the human body can be calculated from the warmth of surrounding surfaces and their orientation concerning the human body.

Air velocity is defined in [12] as the average speed of the air to which the body is exposed, with respect to the location and time. The human body is very sensitive with air movement, especially in some parts like the neck, the head and the feet, and it also depends on the person's sensitivity. If the flow rate is too high or irregular, then local thermal discomfort appears. Thus, it's essential to easily control the air velocity and the flow direction [13].
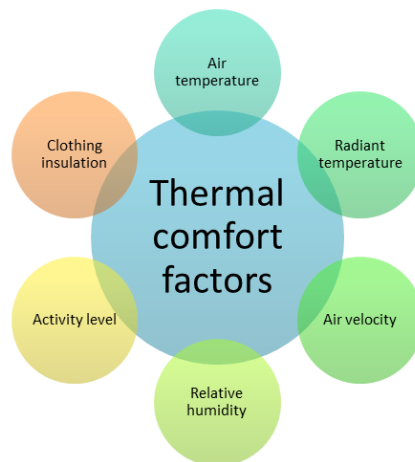
Figure 1. Thermal comfort factors.

Table 1. Standard thermal sensation scale.

Thermal Sensation	Vote Number (PMV)
Hot	+3
Warm	+2
Slightly Warm	+1
Neutral	0
Slightly Cool	-1
Cool	-2
Cold	-3

Typically, there are two approaches available for investigation of the indoor environment, that is, Computational Fluid Dynamics (CFD) simulation and experimental investigation [14,15]. In principle, the direct experiment can get the most realistic information of the environmental parameters, such as air temperature, air velocity, relative humidity and contaminant concentrations at limited, interested locations. However, the measurement is always with high expenses to get all spatial airflow data and time-consuming to install the measurement devices. CFD simulations can economically obtain airflow patterns and thermal environment for further evaluation of indoor thermal comfort. Therefore, the objective of this study is evaluating the thermal environmental conditions of air conditioning with CFD simulations.

2. Methodology

The overall methodology used in this study involves a controlled chamber where the subjects were exposed to a different temperature. Meanwhile, thermal comfort votes were collected from the subjects. Details of methodology in the following subsections.

2.1. Environmental chamber

This study was designed to controlled conditions of the laboratory studies and applicability and external validity of the field studies. To achieve this model office environment has been built in an environmental chamber. The experiments were carried out at the Workplaces Ergonomic Simulator Chamber (WES-103) in Universiti Malaysia Pahang (UMP). Figure 2 shows the model of the office room in an environmental chamber. For this study, the York Prestige Ceiling type of air conditioner was used to explore the environment climate in the chamber. This model is ideally suited for use in the hot climate in Pahang. The dimension of this air conditioner is 21.8 cm × 108 cm × 63 cm. The

material of the environmental chamber is Polyurethane insulated panels. Table 2 presented the details of the specification of the climate chamber.
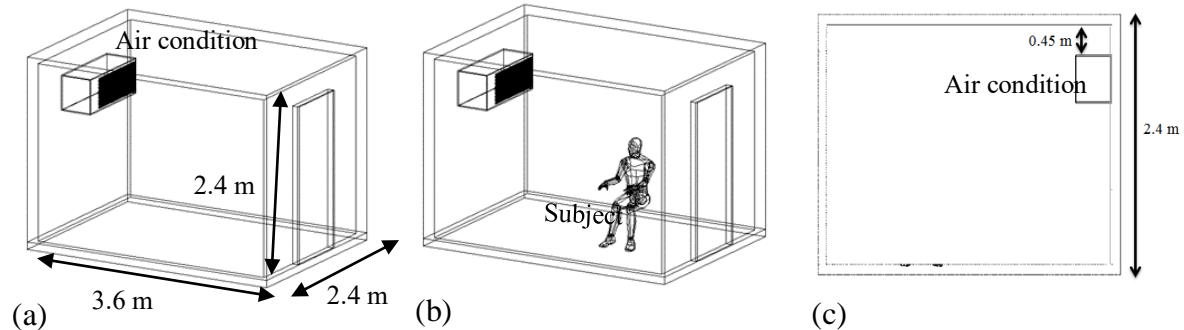
Figure 2. The layout of the environmental chamber: (a) Environmental chamber with empty, (b) Environmental chamber with occupied and (c) Environmental chamber in side view.

Table 2. Specification of environmental chamber.

Property	Result
Density	40-45 kg/m^3
Thermal conductivity	0.017 W/mK
Compressive strength	180-250 kPa
Thermal coefficient	0.239-0.151 W/(mK)
Operating temperature	-68 to 121 ^{o}C

Thermal comfort tests with human subjects were conducted to test the thermal comfort and thermal sensation of human for various thermal conditions. Fifteen volunteers (eight males and seven female) were recruited in this study. The number of subjects in the study was agreed by Goldman [16]. Goldman has 50 years' experience in the field of human thermal comfort and state that the minimum subject for the study of human comfort is as many as six people.

All fifteen subjects were used in this study to measure thermal comfort and productivity while doing multitask in the chamber (represent an office room). There are three tasks the subjects must follow, such as relaxing while sitting, typing or writing and printing paperwork, as shown as in Table 3.

Table 3. Types of the task with the metabolic rate.

No	Types of the task	Metabolic rate (Met)
1	Thinking	1.0
2	Sitting while typing	1.2
3	Printing	1.6

The steps and duration of experiment were shown in Table 4. The subjects entered the chamber and spent 10 min in the chamber before the test acclimatizes with the room temperature [17-19]. All the three tasks of activities during which the subjects were exposed to multiple thermal conditions. All tasks which are explained in Table 4 were repeated with three temperature setting of air conditioning (21, 23 and 26 ^{o}C). The actual test had three tasks and lasted for three hours 20 min with two breaks.

Thermal conditions of this range from sedentary activity and neutral room temperatures to high metabolic activity and high room temperatures which fall clearly outside the comfort zone based on ASHRAE Standard 55 [12]. One of the premises of this study is that thermal comfort is a psychological phenomenon and can be achieved even the physical conditions suggest otherwise.

Table 4. Steps and duration of the experiment.

Step	Activity	Duration (min)

1	Measured demographics of subjects	30
2	Standby in a waiting room	10
3	Start the measurement with Task 1 (21, 23 and 26 $^{\circ}$C)	10 x 5 = 50
4	Break	5
5	Task 2 (21, 23 and 26 $^{\circ}$C)	10 x 5 = 50
6	Break	5
7	Task 3 (21, 23 and 26 $^{\circ}$C)	10 x 5 = 50
	Total	200

2.2. Computational fluid dynamics (CFD)

In this study, the comfort parameter of the room is influenced by the air-conditioner temperature. Thus, CFD is performed to predict the results of comfort parameter's distribution of environment and thermal parameters of the human manikin at different from the air-conditioner output temperature. Table 5 listed the initial conditions that are included in the CFD environment for the flow analysis.

Table 5. Initial conditions of flow simulation.

Parameter	Surface/Components	Value
$T_{wall,1}$	Wall 1, Wall 2	24.5 °C
$T_{wall,2}$	Wall 3, Wall 4, Door	23.5 °C
$T_{wall,3}$	Ceiling, Floor	24.5 °C
T_{fan}	Inlet air-conditioning	21, 23, 26 °C
$T_{environment}$	Surrounding	27 °C
$P_{environment}$	Surrounding	101 325 Pa
$Q_{manikin}$	Manikin	144 W
RH	Surrounding	70 %
Gravity	X	0 m/s^2
	Y	-9.81 m/s^2
	Z	0 m/s^2
Fluid type	Air	Laminar and turbulent

3. Results and Discussion

The importance of air conditioning is to ensure the rationality of indoor air distribution because it is closely related to the effect of adjusting indoor temperature, air conditioning energy consumption, human body comfort and health status. The rationality of the airflow in a room with air conditioning not only influences indoor air adjustment but also directly affects the air conditioning system. Furthermore, it determines the impact of indoor air quality on human health. Therefore, the reasonable indoor air distribution must meet the requirements of energy saving, comfortable and healthy.

Heat transfer inside the human body is calculated for a given level of activity (metabolic rate), using the two node human thermoregulation model. Prediction of metabolic heat dispersal to the surroundings is accomplished by a Computational Fluid Dynamics (CFD) code. Results for different cases with varying supply air velocity, temperature and radiant temperature as well as the human metabolic rate are obtained to predict thermal comfort conditions in the room, using several comfort indices.

Results are obtained in empty (Table 6) and occupied room (Table 7) cases to show the effect of human occupation in a ventilated room on parameters such as radiant temperature (Tr), air temperature (Ta), air velocity (va), PMV and PPD indices. All results are presented in side view as, illustrated in Table 6 and 7.

Table 6. Results CFD for empty room.

Operative temperature, T_o (^{o}C)	21	23	26
Air temperature, T_a (^{o}C)			
Radiant temperature, T_r (^{o}C)			
Air velocity, (v_a)			
PMV			
PPD			

Table 6 and 7 show the results air temperature of non-occupied and occupied at different operative temperatures. The results of air temperature in this study showed that they are not significantly different, non-occupied and occupied. Table 6 and 7 also indicates that the higher the supply air temperature, the faster the air temperature rises.
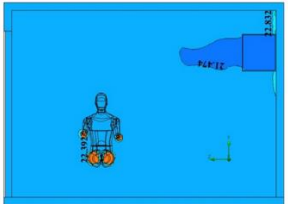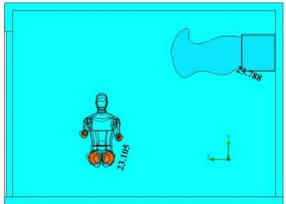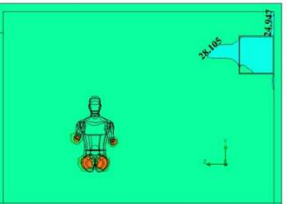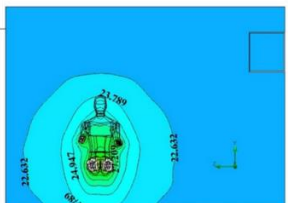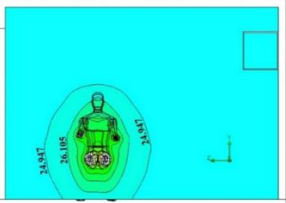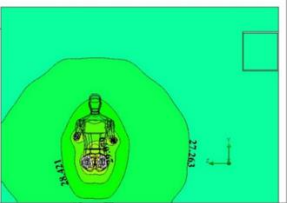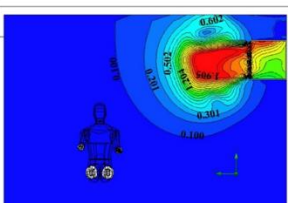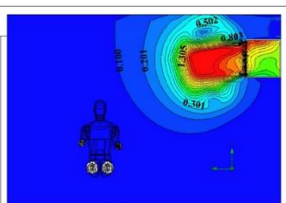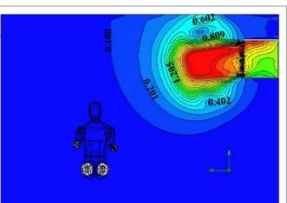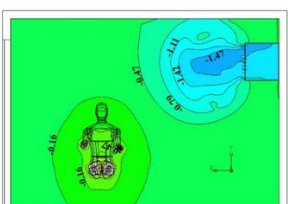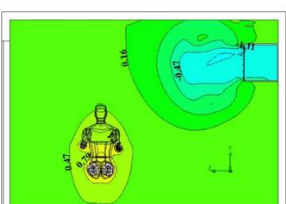
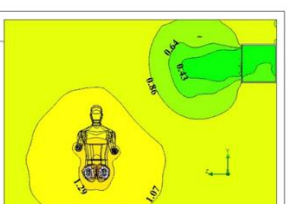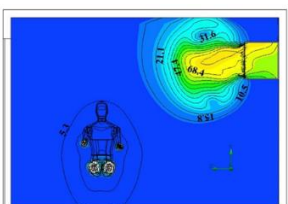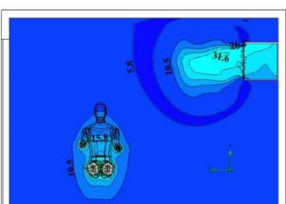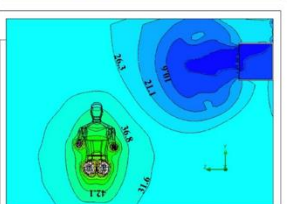Radiant effects commonly sensed by the occupants of offices occur. The presence of a strong thermal radiant field can also become a serious issue in the context of productivity. In many offices, due to limited space or other reasons, two or more people can occupy the same relatively small room. Imagine the situation where the one sitting near the wall or window with a strong, radiant field is the one who prefers to be on the cooler side of thermal sensation and the one sitting near the inner wall prefers the warmer side of thermal sensation. In such a situation, different thermal preferences due to the presence of radiant asymmetry can create thermal comfort tension. In general, the radiant
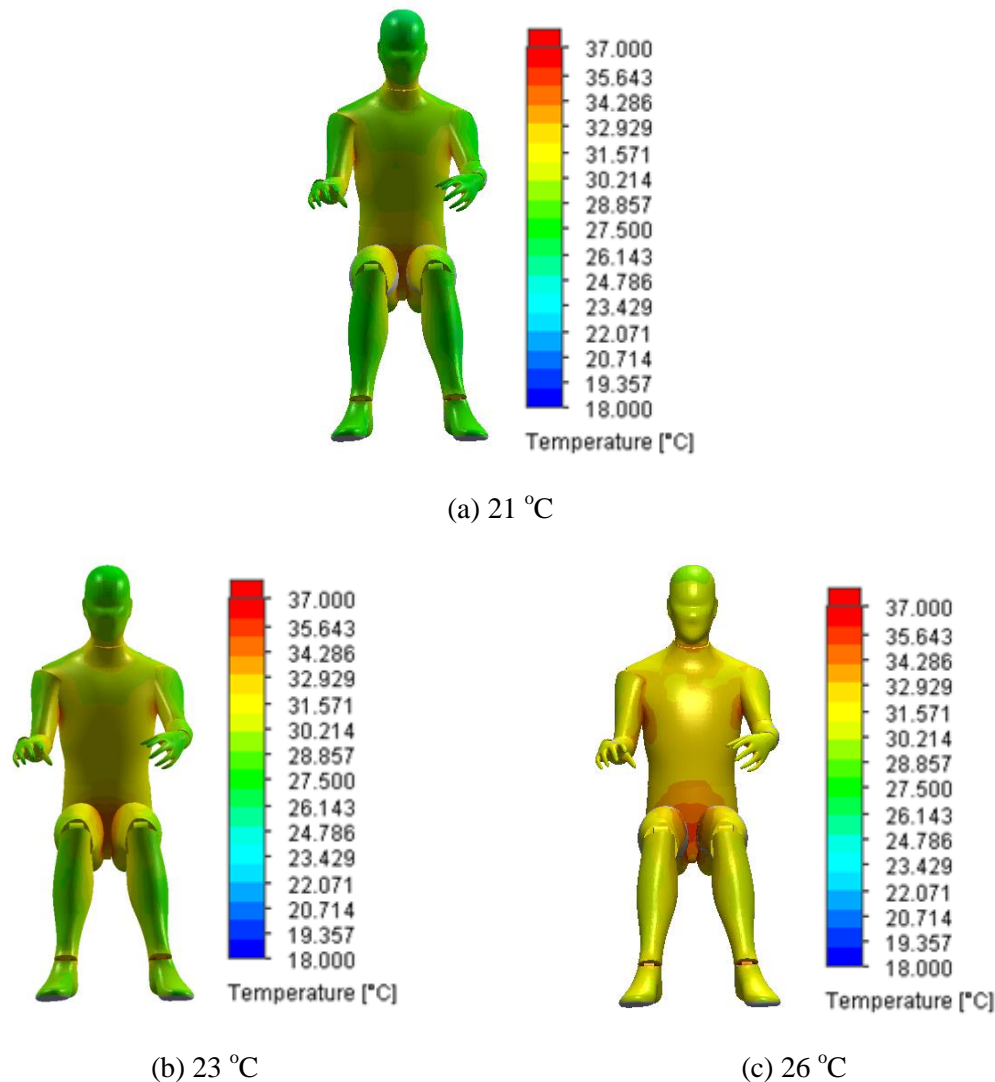
temperature was related to the human body surface. In this study, the radiant temperature comparatively higher in the occupied space compares to the non-occupied space.

The air velocity is one of the essential parameters for the human thermal comfort; an increased air velocity will aid the evaporation of sweat thus leading to a cooling effect, mainly if loose clothing is worn [20]. However, if the air velocity is too high, it may cause discomfort and a sensation of draughtiness. Table 6 and 7 shows a comparison of air velocity at each supply air temperature between non-occupied and occupied space. It shows that supply air temperature at 21 ^{o}C, 23 ^{o}C and 26 ^{o}C for non-occupied is higher than the occupied space, which are 0.16 m/s, 0.22 m/s and 0.08 m/s respectively.

Table 7. Results CFD for occupied room.

Operative temperature, T_o (^{o}C)	21	23	26
Air temperature, T_a (^{o}C)			
Radiant temperature, T_r (^{o}C)			
Air velocity, (v_a)			
PMV			
PPD			

(a) 21 ^{o}C

(b) 23 ^{o}C   (c) 26 ^{o}C

Figure 3. Effect of Tmanikin at different room temperature; (a) 21 °C (b) 23 °C and (c) 26 °C.

The PMV value has a range of 3.0 to be -3.0, corresponding to the hot to cold thermal conditions. The result PMV shows that non-occupied is higher than occupied. Meanwhile, supply operative temperature 21 oC and 26 oC are slightly warm. Supply operative temperature at the 23 oC indicates that the PMV is comfortable. Comparison of the finding states that air room temperature setting effect in 23 oC is comfort than others. The value of PMV in a room temperature setting 23 oC is 0.79 near the skin of an occupant. The PMV value near the human body is higher than the surrounding. Since the radiant temperature is a result of the radiation exchanges between the surfaces and the human body, its value depends on the complex interaction of these factors.

PPD is the reflection from PMV. PPD is aimed to predict how many people feel uncomfortable due to a particular thermal condition in a room. The supply operative temperature at the 23 oC shows that PPD is lower than 20 %, this result indicates that 80 % are satisfied with the environment.

Thermal discomfort rapidly increases when increasing operative temperature up to 26 °C compared to temperatures above 26 °C. However, thermal comfort vote evenly increases around both sides of neutral thermal conditions when changing a warmer or cooler thermal environment to neutral. Body temperature that stimulates physiological and behavioural thermoregulatory follows occupant thermal

sensation and discomfort. Behavioural adaptation provides long-term thermoregulation, while physiological responses give a short-term solution.

4. Conclusions

In this study, the CFD simulation approach to determine the thermal environment and PMV values with an air conditioning system. By analyzing the simulation results between non-occupied and occupied space, based on the PMV model, the assessment of the thermal comfort of the office environment is performed. The study found that operative temperature at the 23 $^{\circ}$C indicates that the PMV is comfortable. The value of PMV in a room temperature setting 23 $^{\circ}$C is 0.79 near the skin of an occupant.

References

[1]   Nikolina P and Sandro N 2017 Thermal comfort in office buildings: General issues and challenges *24th International Symposium On Heating, Refrigerating And Air Conditioning*

[2]   Robinson D 2006 Some trends and research needs in energy and comfort prediction *Proceedings of comfort and energy use in building* (Windsor UK)

[3]   Hensen J L M 1991 On the thermal interaction of building structure and heating and ventilating system Ph.D Thesis (Eindhoven University of Technology, Netherlands)

[4]   Djongyang N Tchinda R and Njomo D 2010 Thermal comfort: A review paper *Renewable and Sustainable Energy Reviews* **14** p 2626-2640

[5]   Lin Z and Deng S 2008 A study on the thermal comfort in sleeping environments in the subtropics: Developing a thermal comfort model for sleeping environments *Building and Environment* **43** p 70-80

[6]   Cena K and Clark J A 1981 *Physics, physiology and psychology* In: Cena K and Clark J A Bioengineering, thermal physiology and comfort, Studies in Environmental Science **10** Elsevier

[7]   Fanger P O 1970 *Thermal comfort: Analysis and applications in environmental engineering* Danish Technical Press (the University of Michigan)

[8]   Nielsen P V 2015 Fifty years of CFD for room air distribution *Building and Environment* **91** p 78-90

[9]   Parson K 2003 *Human thermal environments: The effects of hot, moderate and cold environments of human health, comfort and performance* 2nd ed (London) Taylor & Francis

[10]   Moss K J 1998 *Heat and mass transfer in building services design* (London and New York) E & FN Spon

[11]   ISO 7726 1998 *Ergonomics of the thermal environment: Instruments for measuring physical quantities* International Standard Organization (Geneva)

[12]   ASHRAE 2013 *Thermal environmental conditions for human occupancy* In: ANSI/ ASHRAE standard 55, American Society of heating, refrigerating and air-conditioning engineers p 1-26

[13]   Riachi Y and Clodic D 2014 A numerical model for simulating thermal comfort prediction in public transportation buses *International Journal of Environmental Protection and Policy* **2** p 1-8

[14]   Nielsen P V 2004 Computational fluid dynamics and room air movement *Indoor Air* **14** p 134–143

[15]   Yuan X, Chen Q Y, Glicksman L R, Hu Y and Yang X 1999 Measurements and computations of room airflow with displacement ventilation *ASHRAE Transactions* **1** p 105–340

[16]   Goldman R F 2005 Environmental ergonomics: Whence what wither *Proceeding of the 11th International Conference on Environmental Ergonomics* p 39-47

[17]   Gagge A P, Stolwijk J A J and Nishi Y 1969 The prediction of thermal comfort when thermal equilibrium is maintained by sweating *ASHRAE Transaction* **75** p 108-125

[18]   Strigo I A, Carli F and Bushnell C 2000 Effect of ambient temperature on human pain and temperature perception *Anesthesiology* **92** p 699-707

[19]   Tanabe S, Nishihara N and Haneda M Indoor temperature, productivity and fatigue in office tasks *HVAC & R Research* **13** p 623-633

[20]   Catalina T, Virgone J and Kuznik F 2009 Evaluation of thermal comfort using combined CFD and experimentation study in a test room equipped with a cooling ceiling *Building and Environment* **44** p 1740-1750