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Effect of ventilation on thermal comfort measured by DTS-Application to a typical home in Algerian conditions

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In northern Algeria, use of ventilation by ceiling fans is widespread in mosques and other public buildings during the hot season, but is seldom used in private houses. In the first part of this study, the impact of this mode of cooling on indoor thermal comfort is investigated. A thermal comfort model for transient conditions is developed in order to calculate an instantaneous thermal comfort index. In order to simulate the thermal behaviour of a human body as accurately as possible, the latter is divided into 17 segments and a heat balance equation is written for each segment. The results indicate that even during hot days, an appreciable thermal comfort can be achieved if ventilation at constant air speed is used. Moreover, it is shown that it is not necessary to increase ventilation speed beyond a given level, as thermal comfort gains become negligible.

In the second part of the study, the impact of solar radiation on thermal comfort is evaluated. Thermal sensation of a human being partially exposed to direct solar radiation is calculated. The results show that a discomfort sensation is quickly felt when a person is exposed to sun fluxes, which confirms the importance of shading devices.

1. Introduction

Algeria, a country in quick development, sees its demand for electric power increasing every year by a rate of 5%. This rate is also sustained by the rapidly growing demand of the housing sector. Given the fact that the Algerian government intends to build 1 million housing units and that the demand for air-conditioners-synonymous with thermal comfort for the Algerian population- is in growth, it becomes imperative to think about alternative cooling strategies. These should be more economical, yet possibly achieving comparable levels of thermal comfort. In order to obtain a comfortable space for human beings without wasting energy, cooling systems must be in harmony with human thermal comfort requirements.

Over the years, a large number of thermal comfort models have been developed. The Fanger PMV (Predict Mean Vote) [8,16] and the Gagge SET (Standard new effective temperature) [11,23] are the two most widely used thermal comfort indexes. Both models were developed for uniform thermal environments, thus limiting their application range. Many studies have proposed various multi-segmental models of thermoregulation, such as the Stolwijk's 25-node model [17,19], the modified Stolwijk model [20], the Fiala's dynamic thermal comfort model [10], or the Berkeley multi-node model [12]. These models are used to define the conditions under which thermal neutrality is achieved in buildings. On the other hand, a number of studies show that the observed neutral temperature in air-conditioned buildings differ from that in naturally ventilated ones [5,7].

Burton et al. [4] exposed subjects wearing boxers (0.3–0.4 clo) to temperatures ranging from 26.3 °C to 29.1 °C, and a ceiling fan with varying speed. The subjects were found to prefer air velocity of 1.2 m/s at 29.1 °C. Tanabe et al. [21] conducted similar preferred horizontal air speed tests at 50% relative humidity, they found the preferred speed to be 1.0 m/s at 28 °C, 1.2 m/s at 29.6 °C, and 1.6 m/s at 31.3 °C. Arens et al. [2] studied the relative effect on comfort of 'naturally' fluctuating air speeds as opposed to more constant air speeds. The experiments have demonstrated that it is possible to maintain comfortable conditions up to 31 °C (1.0 met) and 29 °C (1.2 met) if an air speed of 1 m/s or greater is available over the upper body. Liping et al. [13] tested four (4) different natural ventilation strategies (no ventilation, day time ventilation, night time ventilation, and full-day ventilation) with the combination of various construction materials for buildings in Singapore. They

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Nomenclature

BF	Heat exchange by blood flow [W]
C	Heat capacity [Wh/°C]
Ch	Shivering heat production [W]
Clds	Integrated cold signal [°C]
DTS	Dynamic thermal sensation
E	Evaporative heat loss [W]
E_{max}	Maximum evaporative heat loss [W]
Error (1,1)	Error signal from head core [°C]
F_{cl}	Clothing factor
f_{sk}	function of skin temperature
h	Heat transfer coefficient [W/m^2 °C]
km	Local multiplier
Isun	Incident solar radiation [W/m2]
MBF	Muscle blood flow [l/h]
MBF_0	Basal muscle blood flow [l/h]
P	Vapor pressure [kPa]
q	Heat exchange rate [W/m2]
SBF	Skin blood flow [l/h]
SBF_0	Basal skin blood flow [l/h]
Skinc	Distribution coefficient of skin layer for vasoconstriction
Skins	Distribution coefficient of skin layer for sweat
Skinv	Distribution coefficient of skin layer for vasodilatation
T	Temperature [°C]
v	Air speed [m/s]
W	External work [W]
Wrms	Integrated warm signal [°C]

Subscripts

a	Ambient
c	Convection
cd	Conduction
cl	Clothing
hy	hypothalamus
i	Segment number
j	Layer number
m	mean
sk	Skin
r	Radiation
res	Respiration

Greek letters

α	Solar absorbance
ε	Emissivity
ρ	Solar reflectance
σ	Stephane Boltzmann constant [W/m2.K4]
τ	Solar transmittance
τ_+, τ_-	Function of positive/negative rates of change
ø	Function of core temperature
ψ	function collecting dynamic components

found that the full-day ventilation provided better thermal comfort in the case of the hot-humid climate of Singapore.

The traditional dwellings of Algiers integrate central patios that can refresh the interior atmosphere by creating draughts. Nevertheless, for newer buildings, natural ventilation alone is not an efficient solution. It must then be supplemented by mechanical ventilation.

Nielson et al. [14] measured thermal comfort of a thermal manikin placed at different locations in a room ventilated by both mixing ventilation and displacement ventilation. The authors found that the vertical temperature gradient seems to be a major source of local discomfort in displacement ventilation, while the temperature gradient is small in mixing ventilation. Based on all cited references and from the thermal comfort point of view, it can be deduced that ceiling fans represent a potentially efficient mechanical ventilation solution.

The objectives of the present study are:

1- To develop a model of thermal comfort perception in dynamic conditions.
2- To evaluate the impact of sun radiation on occupants thermal comfort.
3- To determine the effect of ceiling fans ventilation on comfort during summer.

2. Mathematical modelling

A human body inside a building does not react uniformly to thermal solicitations, since different body parts can be exposed to non-uniform thermal environment and are subject to different metabolic mechanisms. Therefore, the thermal model adopted in the present study divides the whole body into 17 body segments: head, face, chest, back, pelvis, left upper-arm, right upper-arm, left lower-arm, right lower-arm, left hand, right hand, left thigh, right thigh, left leg, right, leg, left foot, and right foot. All these segments are considered of cylindrical form, except the head which is considered as half-spherical. Each of these segments is itself composed of four tissue layers (core, muscle, fat and skin tissues). Heat transfer between layers is assumed to occur only by conduction in the radial direction. Heat exchange with the ambient atmosphere can occur through convection, radiation, evaporation and respiration. On the other hand, blood circulation through arteries and veins does also contribute to heat transfer between body parts. This allows to device a simplified thermal model based on a series of nodes for each segment, with different heat exchange coefficient adapted to each case. Such a model is schematically shown in Fig. 1.

In normal conditions, heat is generated in the body only by the metabolism corresponding to a given physical activity. The balance between heat production by the metabolism and heat loss to the environment is dynamically maintained to preserve the internal temperature within a narrow range of 36–38 °C.

The human body detects its thermal state through thermoreceptors, which are free nerve endings located mainly in the skin and the hypothalamus. These thermoreceptors are of two types: those responding to warm stimulations and those responding to cold stimulations. The brain, by integrating signals received from thermoreceptors, can detect if a state of thermal equilibrium between body and environment does exist. Otherwise, the thermoregulatory system is activated through physiological responses. In a cold environment, the vasoconstriction process is activated first. If this action proves to be insufficient, additional metabolic heat is generated by shivering. In a hot environment, the physiological response of the human body consists of two control processes: sweating and vasodilatation. Taking into account all these considerations, the general form of the heat balance equation for a segment ‘i’ of the body can be written as follows: