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The effect of temperature, metabolic rate and dynamic localized airflow on thermal comfort

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HIGHLIGHTS

- An energy saving microclimate design strategy is tested using human subjects.
- Tests were conducted to determine the effect of localized dynamic airflow on human subjects.
- 30-s Pulsed air yielded the maximum cooling sensation in high metabolic conditions.
- Subjects preferred more airflow even when they were feeling slightly cool.
- Distributing the same amount of airflow to various locations on the body is more effective than head-only cooling.

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ABSTRACT

The conventional approach to thermal environment design is concerned with delivery and distribution of the air inside the spaces rather than designing the airflow patterns to provide comfort in the occupied zone. Air has a relatively low heat capacity and using airflow solely for its energy carrying capacity, and not for its dynamic properties, underutilizes this medium as a thermal comfort factor. However, there is increasing evidence that airflow around the human body provides thermal comfort even in cool temperatures and varying airflow is more effective in providing a cooling sensation than the constant airflow. A human subject test was designed to study the cooling effectiveness of dynamic airflow conditions which was directed to the head, hands and the feet of the people for neutral (23.9 °C) and warm (28.3 °C) ambient temperatures as well as sedentary (1.2 Met) and high metabolic rate (4 Met) conditions. The concept of *Dynamic Localized Airflow* was introduced. Results showed that most subjects were either satisfied with the increased airflow speeds or preferred more airflow in all conditions. Airflow preference did not differ for neutral and warm room temperatures. The 30-s pulsed airflow was more effective in providing a cooling sensation than constant airflow and 60-s pulsed airflow. In addition, the simultaneous head/hands/feet airflow was more effective in providing cooling sensation that the head only airflow. It was concluded at the end of the study that people can tolerate warm room temperatures even in high metabolic conditions provided that airflow is present with a certain pattern around them.

1. Introduction

ANSI/ASHRAE Standard 55-2004 defines thermal comfort as the state of mind where a person expresses satisfaction with the thermal environment [1]. This definition stresses the significance of the psychological state of a person in evaluating the thermal environment. The thermoregulation center in the hypothalamus collects data from skin thermoreceptors as well as from the internal organs through the bloodstream and generates a thermal sensation response which can vary between extremely cold to extremely hot. Schlader et al. [2] showed that, it is possible to provide a heating or cooling sensation with the stimulation of the skin thermoreceptors even without the change in skin temperature. Thermal comfort is, on the other hand, an emotional response based on the thermal environment and the state of mind contrary to the thermal sensation which is a rational response [3]. In warm environments, airflow on the skin surface creates cool sensations by two mechanisms. The first one is through the stimulation of the cold thermoreceptors by temporarily changing the local skin temperature. The second one is through the increased heat loss from the body. The two mechanisms are intertwined for the majority of the airflow conditions. One of the objectives of this study is to increase the effectiveness of the first mechanism by periodically stimulating cold sensors on the skin surface to create and sustain an awareness of cooling while preventing thermoreceptor adaptation.

Several studies showed that dynamic airflow with higher power spectrum, varying air velocities and high turbulence intensities has

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Nomenclature

DR	draft rating (%)
PMV	predicted mean vote
PPD	predicted percentage dissatisfied
MW	net metabolic heat (W/m^2)
HL_n	heat loss from the body (W/m^2)
M	metabolic rate (W/m^2)
RH	relative humidity (%)
T_a	ambient temperature (°C)
Tu	turbulence intensity (%)
α	statistical significance level
x	raw thermal response data
z	normalized thermal response data
μ	population mean
σ	population standard deviation

more cooling effect than the constant airflow [3–6]. Dynamic airflow prevents skin thermoreceptors from adapting to the airflow conditions which reduces the effectiveness of airflow. Turbulence intensity increases the convection coefficient, thus the convective heat loss on the skin surface. Previous studies also showed that localized thermal sensation at thermally sensitive regions of the body can significantly shift the overall thermal sensation of people [5,7–12]. Among the different regions of the body, head, neck, hands and feet are the most sensitive regions.

Various previous studies showed the effect of dynamic airflow and the effect of localized cooling on thermal comfort. Our study focused on the cooling effectiveness of the combined localized and dynamic airflow which is referred to as the *Dynamic Localized Airflow*. Creating a dynamic airflow and directing it to thermally sensitive regions of the body has the potential to create an enhanced cooling sensation with reduced amounts of airflow since less air is required to cool a relatively small region of the body.

The energy savings potential of the personalized ventilation systems is well-documented [13,14]. The tested thermal conditions in our study combined the personalized systems with the dynamic airflow systems which allows a reduction in total airflow required for comfort. In addition, existing air inside the room was used for forced convection which is at room temperature. Thermal conditions tested in this study has the potential to extend the energy savings potential of the personalized ventilation systems without compromising the thermal comfort.

2. Literature survey

The established approach in thermal comfort design is providing thermally neutral environments which will ensure thermal satisfaction for the majority of the occupants. This approach of optimizing the environment for a group of people requires keeping the environmental variables constant since people's thermal responses are more complex when thermal conditions are constantly changing. However, occupants of the air-conditioned buildings become sensitive to changes in operative temperatures and develop expectations for a narrow band of temperatures in which minor deviations result in higher than normal dissatisfaction [15].

The human body is equipped with the thermal mechanisms such as vasodilatation and vasoconstriction to work under transient thermal conditions. Recent studies showed that maximal thermal comfort, which is not possible under steady environments, was achieved under transient conditions [16,17]. In fact, a variable environment is preferred by the building occupants [18]. The literature survey presents the previous studies on the effects of changing thermal conditions on thermal comfort.

2.1. Temperature and airflow

Fountain et al. [19] studied the airflow preferences of test subjects for 25, 26, 27 and 28 °C with an average airflow speed of 0.21 m/s. They found that 50% of the people wanted more air for a given operative temperature where the draft rating (DR) model of ASHRAE 55-1992 specifies 15% dissatisfaction. Therefore, the DR model does not necessarily reflect peoples' preferences for air. The relevant literature reveals models which take into account the interaction between different factors in providing a thermally comfortable environment. ANSI/ASHRAE Standard 55 allows a 1.7 °C (3 °F) increase in temperature where there is a 0.5 m/s increase in air velocity. Nicol [20] proposed a model which calculates the allowable increase in comfort temperature where the air velocity is above 0.1 m/s. According to this model, a 3.4 °C (6.1 °F) increase above a neutral temperature can be compensated with 1 m/s airflow. This value is consistent with Toftum [21] and Tanabe and Kimura [3]. Epstein and Moran [22] established trade-offs between the six thermal comfort factors such that an increase of 17.5 W (above resting level) is equivalent to a 1 °C increase in T_a. In addition, a change in 0.1 m/s in wind speed is equivalent to a change in 0.5 °C (0.9 °F) in T_a (up to 1.5 °C). Zhang et al. [23] also found that comfort temperatures for people exposed to a 0.20–0.95 m/s air velocity were 1 °C (1.8 °F) higher than people exposed to air velocities smaller than 0.20 m/s.

The steady state effect of temperature on thermal comfort is well-documented in the literature. The dynamic approach to the thermal comfort problem suggests that a time dependency exists for each thermal comfort variable. Gagge et al. [24] measured the time dependency of thermal comfort and sensation of subjects who were exposed to 12, 18, 22 and 28 °C for 4 h. Thermal comfort and sensation decreased for all cases except the 28 °C temperature. This means transient perception of thermal comfort still exists even when all the comfort variables are constant.

2.2. Dynamic airflow

Recent studies on the effect of airflow on thermal comfort suggest that building occupants desire more airflow even when they feel "slightly cool" [23,25]. Zhang et al. [23] showed that 60% of the building occupants feel that airflow enhances their work ability, while only 15% feel that airflow interfered with their work; and there are twice as many people preferring more air movement than people preferring less air movement. Conventional mechanical systems maintain constant or slow changing airflow inside the spaces. However, skin thermoreceptors adapt to the constant airflow stimulus and the cooling effect is reduced in time [26]. Varying the airflow speed in the occupied zone is a viable strategy to overcome this problem. Previous studies showed that dynamic airflow yields a higher cooling sensation than constant airflow [3,4]. Internal warmth sensations can be balanced with the cool warnings from the skin thermoreceptors [27].

Tanabe and Kimura [3] compared the thermal sensations for 60-s pulsed air, various sinusoidal air, random and constant air. They found that 30-s and 60-s sinusoidal flows are more effective in yielding a cooler thermal sensation than other airflow types. In this