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Energy saving method for improving thermal comfort and air quality in warm humid climates using isothermal high velocity ventilation

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ABSTRACT

Increased air velocity improves thermal sensation in warm humid climate under certain conditions. In halls and enclosed public zones, a great volume of room air needs to be exchanged with fresh air. This is crucial to keep the air quality up to a desired degree. Air conditioning requires relatively high amount of energy for cooling and dehumidification, especially by high moisture content. Although fresh air can be provided by exposing the space to the outdoor environment via windows or moving partitions, improving thermal sensation and air quality in such space will not take place in calm wind conditions due to the lack of air movement. This paper investigates the effect of inducing outdoor air via ceiling confluent high velocity air supply to mix it with and eventually replace existing air in the semi-outdoor space. The generated results from the conducted CFD simulations indicate high air change rate, low air velocity at human height and increased thermal comfort without the need for cooling or dehumidification. The presented method of room conditioning suggests a low energy solution for spaces in adjacent location to the outdoor context that can generate new and more urban spaces.

1. Introduction

1.1. Impact of air movement on thermal comfort in humid climates

The search for low energy cooling solutions is imperative. Especially in warm humid climates where dehumidification requires high amount of energy. While cooling is crucial in public zones, e.g. galleries, exhibitions, cafes … etc., air quality is another essential element that affects the level of hygienic comfort. Clearly, supplying large volumes of conditioned fresh air demands technical complexity and energy consumption. Passive cooling methods applied in the traditional architecture of many hot-humid locations suggest many intelligent solutions that can be integrated into contemporary buildings.

As important as it is to develop solutions to maintain indoor environmental quality (IAQ), investigating methods to provide better climates in outdoor spaces is also imperative. This further applies to spaces that are partially open or located at the interface between outdoors and indoors which can be called semi-outdoor spaces. The impact of these spaces on the quality of cities from an urban design perspective cannot be ignored.

Unlike in traditional and vernacular villages, great values of human interaction with nature and urban environments are lost in contemporary metropolises because outdoor spaces in today's cities are much less developed than indoor spaces and do not receive the same level of attention in most cases. Outdoor spaces in contemporary cities in hot humid climates are used much less than indoor environments. Obviously, these spaces are less favored due to the vast amount of required air conditioning to cool these spaces using conventional means.

Today's public spaces follow a clear trend of creating airtight, insulated and fully air-conditioned living, working and entertainment environments that are totally isolated from their urban context. A short reason for the rapidly increasing number of enclosed shopping malls in developing countries is the need to provide a better climate, and thus shopping, experience for people. However, the technical complexity that is required in the construction and operation of such active building systems is tremendous. In addition to the energy required to cool the ambient fresh air before it is delivered into the room, great technical effort must be made for dehumidification and extraction of moisture to meet human comfort. Conversely, dry air requires less effort for humidification, which may be achieved using a combination of passive and active techniques.

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Nomenclature

ACH	Air change rate (h^{-1})
AoA	Age of air in seconds (s)
E	Euler's number (2.718)
ΔPt	Pressure ratio
Δh	Change in enthalpy (kJ/kg)
f_{cl}	Clothing surface area factor
h	Enthalpy (kJ/kg)
h1	Discharge enthalpy (kJ/kg)
h2	Supply enthalpy (kJ/kg)
I_{cl}	Clothing insulation (clo)
R_{cl}	Clothing thermal resistance (m^2.K/W)
L	Thermal load (W)
M	Metabolic rate (W)
m'	Mass of air flow (kg/h)
Out_z	Height of air supply (m)
h_c	Convective heat transfer coefficient (W/m^2.K)
PMV	Predicted mean vote
Pw	Required electrical power (kW)
Q'c	Cooling thermal power (W)
Q'e	Electric power (W)
R_{cl}	Clothing thermal resistance (m^2.K/W)
t_a	Outdoor air temperature (°C)
t_{cl}	Surface temperature of clothing (°C)
t_{dp}	Dew point temperature (°C)
t_r	Mean radiant temperature (°C)
ts_c	Ceiling surface temperature
$ts_{fi,\ n}$	Floor surface temperature (°C)
t_{supply}	Air supply temperature (°C)
ts_w	Wall surface temperature (°C)
v	Air velocity (m/s)
V'	Volume of air flow (m^3/h)
v_{supply}	Air supply velocity (m/s)
W	External work (assumed = 0)
ρ	Density (kg/m^3)
p_w	Partial vapor pressure of water in air (Pa)

almost 50% of the total energy produced in the U.S. are consumed by buildings. Also, 75% of the inland electricity production is reserved for the operation of buildings. Globally, greater percentages are expected [1]. However, this ratio may increase in non-industrial nations. Reducing the carbon footprint of modern cities starts from rethinking the way human comfort is met. Nonetheless, providing low-tech solutions to increase human comfort in outdoor spaces may lead to new spatial models that offer better human experiences and less hazardous impacts on the environment.

Human comfort is determined by many interrelated objective and subjective physical parameters. Within the scope of thermal comfort, it is helpful to identify which factor has which effect and under which conditions. Increasing air flow velocity can, under certain conditions, remarkably improve human thermal comfort [2–8]. This is one of the reasons why narrow alleys that are oriented toward prevailing wind directions provide better comfort experiences in traditional Oriental cities. Reference [2] is a good quality source of information that provides a wide-ranging list of research work that explored the impact of air movement on thermal comfort as well as the boundaries of developing air velocity.

While temperature difference between air and skin impacts the conductive heat gain in the human body, the rate of heat exchange correlates with air velocity and clothing. Conversely, there is no direct relationship between the relative humidity and the heat load operating on the body. However, the relative humidity affects the evaporative capacity of air which obviously impacts the perspiration process. By extremely hot air temperatures, the humidity level determines the limits of endurance time by limiting the total evaporation [9].

The body's heat exchange mechanisms include latent and sensible heat exchange. In the latent heat transfer process, if the dew point of the surrounding air is lower than the skin temperature, sweat on the human skin evaporates. This helps lower the body temperature and maintain it at its healthy level, i.e. 37 °C. However, after evaporation, the air in contact with the skin which contains water vapor becomes saturated. This happens too in specific environment where the ambient air is close to the saturation point and with high internal latent loads, e.g. people. Moreover, the body generates more fluid as perspiration continues due to the high ambient temperature to remain within the comfort condition.

Sensible heat transfer is another heat exchange mechanism of the human body. It simply describes the process of heat dissipation to the environment via the skin using convection. Therefore, the increased air velocity helps extract heat from the skin surface via sensible heat exchange and thus helps substantially improve the level of thermal comfort of the human body. However, draft that can be caused by high air velocity must be avoided as it can cause local cooling of parts of the body and lead to discomfort [10].

Basically, to achieve comfortable climatic condition, saturated air must be removed either mechanically, or passively, using natural ventilation. Therefore, it is important to seek passive or low-tech solutions that move large volumes of air with less mechanical effort. Further, while comfort today can be met using active systems (e.g. air conditions), a combination of passive and active solutions can lead to acceptable results using less energy and technical complexity. This paper presents and validates a method to provide thermal comfort in hot humid climates using a high velocity air supply that can be provided by jet nozzles, for instance.

The field and test chamber experiments conducted by Tanabe et al. showed that thermal sensations at air velocities higher than 0.5 m/s were much lower than those under lower air velocities. They also stated that higher air velocity is desired for increased temperature and humidity [6].

Khedari et al. [5] noted, based on their experiments in Thailand, that less thermal response time is reported by increasing air velocity due to the relatively fast heat exchange between the human body and the surrounding environment. According to Thailand comfort chart which was developed by the authors too, the neutral temperature among the different subjects takes place in the range of 27–31 °C with air velocities varying between 0.1 and 1.68 m/s. The study also found that the thermal acceptability is a few degrees beyond common comfort limits for summer conditions that were defined by the international standards at the time of the conducted research.

Further studies by Arens et al. [7] concluded that elevated air velocity can be a great alternative to air cooling in warm conditions, especially when considering that the risk of draft arises in conditions where the air temperature exceeds 22.5 °C. The results of the investigations indicate an increased desire to increase air velocity by increased degrees of thermal sensation. They also show the significant effect of the clothing factor. With lighter clothes, people accept higher operative temperatures. Another important result of