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Expanded psychrometric landscapes for radiant cooling and natural ventilation system design and optimization

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Abstract

Maintaining the thermal comfort of building occupants is a challenge typically negotiated by air based heating and cooling systems that rigidly maintain supply air temperatures and humidity levels. Such a practice overlooks several other design variables, including the mean radiant temperature, T_{MRT}, which is responsible for a significant portion of an occupant's thermal comfort, or air velocity, v_{air}. The increased deployment of low exergy cooling strategies such as evaporative cooling and radiant cooling allows temperature potentials to be efficiently and effectively leveraged. However, the precise execution and subsequent control of these potentials in air based or radiant systems is driven by incomplete empirically based standards, removing heuristic guiding. Deciding where system setpoints should be for systems that go beyond simple air based cooling is difficult to arrive at through intuition and current metrics, as the inclusion and modulation of other thermal comfort variables such as air velocity, skin temperature, skin wettedness and metabolic rate are not entirely independent variables. The focus of this research is to approach thermal comfort with an occupant-centered stance, comparing heat loss through primary modes of heat transfer generated by an occupant's metabolic rate. In doing so, the holistic integration of all comfort variables currently missing from the literature opens a window into an integrated design landscape including air temperature, T_{MRT}, and relative humidity as the relevant independent variables for thermal comfort. Building on the array of low exergy building systems with integrated evaporative and radiative cooling systems in the literature, this new landscape will be presented as a tool for assessing a new radiant cooling system.

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1. Introduction

In a broad sense, buildings act as barriers between biological thermal engines and ambient environmental conditions, providing protection from undesirable conditions that would otherwise direct heat and coupled mass transfer to the engine at rates incongruent with engine output. In this analogy, a building is abstracted as a heat and mass

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exchanger for a human body, with dynamically linked conductive, convective, and radiative modes available to tune the rate of heat loss or gain. Yet despite the depth of our understanding regarding thermoregulation and radiant heat transfer, the majority of HVAC systems control for comfort using air based metrics. And when radiant systems are installed, they rarely are controlled adequately with T_{MRT} values. Even if such controls existed, our familiarity with air based systems has led to an intuition for air temperature set points, however the same could not be said for radiant systems or air velocities. As such, the overarching goal of this research is to reimagine comfort criteria with intuitive visualizations for design and control of more complex systems.

Nomenclature

A	area
MR	metabolic rate
P	partial pressure
Q	heat
T	temperature
h	heat transfer coefficient
v	air velocity
w	skin wettedness
ϵ	emissivity
σ	Stefan-Boltzmann constant
$_{wb}$	wet bulb
$_{dp}$	dew point
$_{e}$	evaporative
$_{c}$	convective
$_{r}$	radiative
$_{skin}$	skin property
$_{air}$	air property
$_{MRT}$	mean radiant temperature

Heat transfer in buildings occurs through radiative and convective exchanges, convection linked explicitly to evaporative mass transfer, and conductive exchanges. However, standard practice attempts to maintain historically-dictated stringent guidelines, referred to as the “comfort zone”, which uses operative temperature and moisture content in air as the two tunable parameters through which comfort is achieved. Academically, thermal comfort is well researched, and empirical and analytical relationships exist between thermal comfort and a full set of climatic conditions for a building space [1,2]. A full framework for human comfort has been proposed through the frame of exergy destruction [3,4].

Using the heat transfer analogy, it becomes clear that a static comfort zone is true for a subset of conditions only. Such a dimensional reduction, however, excludes many facets of heat transfer that could more efficiently maintain comfort. Still, a conventional comfort zone dictated by air temperature and relative humidity only. This approach neglects the influence of mean radiant temperature, air velocity, skin wettedness, and an individual’s metabolic rate. A phenomenal tool was created by the Berkeley Center for the Built Environment that takes inputs for each of these parameters, however variables are still fixed and trends are not easily discerned with precision [5].

2. Methods

Applying a reductionist approach to thermal comfort yields seven key variables acting within 3 interconnected modes of heat and mass transfer (radiative, convective, and evaporative, neglecting conduction for this analysis). The 7 variables are air temperature, T_{air}, mean radiant temperature, T_{MRT}, relative humidity, $\%RH$, skin temperature, T_{skin}, air velocity, v_{air}, skin wettedness, w, and metabolic rate, MR. Clothing level is also an important factor to consider, however this is a variable parameter that can easily be added later to calibrate a specific model.

For this abstracted model of human comfort, the comfort condition is defined as equality between heat removed and metabolic rate. Metabolic rates are well defined and independent of size, and are therefore a robust metric to serve as the basis of this analysis [2]. Specifically 1.2 met (69.8 W/m^2) is the metabolic rate of an individual performing light office work such as typing, and 2 met (116.3 W/m^2) is one’s metabolic rate when walking briskly. These values of metabolic rate were chosen to serve as the boundary of the office space comfort zone, or in other words this range describes the range a building system must be able to operate within to remove heat between 69.8 and 116. 3 W/m^2 from an individual.