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Portable personal conditioning systems: Transient modeling and system analysis

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HIGHLIGHTS

- A new concept of portable personal conditioning system introduced.
- Expected building energy savings in the range 10–30% with improved thermal comfort.
- Equations for multi-domain dynamic modeling of four such systems discussed.
- Weight, battery performance, cost comparison calculated for each system.
- Payback period and economic considerations of the technology discussed.

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ABSTRACT

The existing Personal Conditioning Systems (PCS) have a limited market potential in spite of their energy savings potential and improved thermal comfort due to a combination of factors like retrofit costs, cooling limited to regions near installation and addition to building heat loads. We propose a novel concept of Portable Personal Conditioning System (PPCS) to address these challenges. PPCS includes a cooling system on an automated platform, which follows occupants to keep them comfortable. Four such cooling systems are presented: a vapor compression system (VCS), a chilled water based system, an ice storage based system and a phase change material storage based system. First-principles-based, transient multi-physics models were constructed for each system using Modelica to gain a more complete understanding of system performance and to quantify performance criteria such as minimum system weight and battery life. The article quantifies the trade-offs from the use of each system and is expected to motivate the development of portable personal cooling devices. System weights range from 19 to 31 kg with the chilled water system being the heaviest. The VCS consumes 40% more battery while delivering 170 W cooling at roughly twice the price of the chilled water system. The ice and phase change material based systems have weights comparable to the VCS and power consumption comparable to that of the chilled water based system.

1. Introduction

Climate change and global warming have been topics of intense research over past few decades. The United Nations Intergovernmental Panel on Climate Change has identified the building industry as the one with the most climate mitigation potential [1]. Building sector accounts for about 41% of the primary energy consumption in the United States, with space heating and cooling taking up 21.5% and 11.8% of that fraction, respectively [2]. Since this is a sizable portion of the total energy consumption, there are many ongoing efforts to achieve improved building heating and cooling efficiency.

1.1. Current state of HVAC & R research

Current approaches can generally be categorized as novel configurations of Heating, Ventilation and Air Conditioning (HVAC) components, improved designs of components and more strategic use of existing system through different control and optimization strategies [3]. Technologies being developed to reduce energy consumption in building HVAC include, but are not limited to thermoelectric systems [4,5], shifting peak demand with phase change materials [6–8], variable refrigerant flow systems [9], use of new refrigerant mixtures [10], ground-source heat pump systems [11,12], desiccant cooling [13,14], ejector systems, use of thermally activated building systems [15], novel

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Nomenclature

$\mathbb{V}$	voltage [V]
A	area [m^2]
a	acceleration [$m\,s^{-2}$]
C	capacity of cell [C]
c	specific heat capacity [$J\,kg^{-1}\,K^{-1}$]
E	energy density [$J\,m^{-3}$]
F	force [N]
g	acceleration due to gravity [$m\,s^{-2}$]
h	specific enthalpy [$J\,kg^{-1}$]
I	current [A]
K	thermal degradation parameter [$-$]
k	thermal conductivity [$W\,m^{-2}\,K^{-1}$]
k_C	degradation [C]
L	latent heat of melting [$J\,kg^{-1}$]
m	mass [kg]
n	number of items
P	power [W]
q	heat flux [$W\,m^{-2}$]
Q_{abs}	absolute value of charge transferred to and from cell [C]
R	resistance [Ω]
r	radius [m]
S	surface area [m^2]
SOC	state of charge [$-$]
T	temperature [K]
t	time [s]
u	Kirchoff temperature [K]
V	volume [m^3]

Greek

α	heat transfer coefficient [$W\,m^{-2}\,K^{-1}$]
ρ	density [$kg\,m^{-3}$]
θ	inclination angle [°]

Subscript

a	acceleration
bat	battery
cell	cell
d	drag
ext	external
f	friction
g	gravity
i	inner
ice	ice
in	inlet
j	grid point in the discretized control volume
L	liquid
m	melting temperature
o	outer
out	outlet
p	parallel arrangement of cells
S	solid
s	series arrangement of cells
t	total
tube	refrigerant tubing
w	water

heat exchangers [16], controllers based on optimization of energy consumption [17], and energy efficient design of building envelope [18–20].

However, even though these new approaches for enhanced HVAC performance tend to save operational costs, capital investment is greater compared to conventional air conditioning systems [21–23]. Furthermore, most of them require retrofitting, which is not cost-effective because of much longer service life of the building components (e.g., residential HVAC systems are designed for 10–25 years)[24]. The average life span of residential buildings is about 30–40 years [25], during which building owners are not motivated to invest on retrofitting due to longer payback periods (typically greater than 5 years [2]). By retrofitting existing roof-top units with advanced controls, Wang et al. [26] observed average 57% energy consumption savings. Thus, there is a great scope in saving building energy consumption and it is essential to develop technologies that can be implemented in existing buildings in a cost-effective manner.

Secondly, much of building HVAC energy consumption goes into maintaining narrow indoor temperature ranges that building operators consider necessary for comfort, however, this is not actually true [27]. Current practice persists because there is a substantial reluctance in the building and real estate industry to try new measures for indoor comfort control [28]. In a broad overview of best practices for the design of offices, Aronoff and Kaplan [29] argue that because the thermal conditions that individuals find comfortable are so variable, the ideal solution would be to allow everyone to set the conditions that they find comfortable. However, improved spatial control requires a reconfiguration of the building interior or complete replacement of the building HVAC units. It is highly unlikely that spatial control with current building HVAC technologies will reach the resolution of the individual occupant [28]. This calls upon a need to develop fundamentally new ways of delivering comfort for occupants.

1.2. Personal conditioning systems

Hoyt et al. [30] demonstrated the energy savings potential from extending building thermostat set-points. They concluded that if it were possible to relax the temperature set-point in either the hot or cold direction, total HVAC energy is reduced at a rate of 10% per °C. To enable expansion of building set-point temperatures without affecting occupant thermal comfort, one option is to provide supplementary Personal Conditioning System (PCS), which consumes significantly lower energy. PCS offers dual benefits of energy saving and increased comfort [31]. Energy is used to modify the local thermal envelope around the human body rather than the building, thus allowing the thermostat to be relaxed without compromising the occupant comfort. This was confirmed in the experimental studies carried out by several researchers with human subjects using their respective PCS [32–34]. By offering personalized comfort, PCS are able to deliver comfort to every individual rather than the conventional HVAC systems which cater to the average population. Percentage satisfaction as high as 100% has been reported in the literature with well-designed PCS [35]. Some additional benefits of PCS are lower capital installation costs and ease of implementation when compared to novel HVAC solutions.

Due to these benefits, a large number of PCS exist which are summarized in the review articles by Zhang et al. [31] and Veselý and Zeiler [36].

Task ambient conditioning systems [37–39,35] are typically space conditioning systems, typically installed in office buildings. The occupants can control the thermal conditions in the small regions surrounding them. Recently, the application of these systems is being explored in bedrooms to increase thermal comfort in sleeping environment and at the same time reduce energy use [37,40]. There is a lot of variation in design of these systems, but usually they consist of air nozzles to supply air to the upper body and a radiant panel for heating the legs. They provide conditioning only to the limited space surrounding the office desk towards which the air nozzles and radiant