TECHNIQUES FOR REDUCING ENERGY CONSUMPTION IN BUILDINGS THROUGH THERMAL AND VISUAL INTERVENTIONS

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Techniques for Reducing Energy Consumption in Buildings through Thermal and Visual Interventions

by

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Doctor of Philosophy

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Dedicated to my Mother and Grandmother

Certificate

This is to certify that the thesis entitled **"Techniques for Reducing Energy Consumption in Buildings through Thermal and Visual Interventions"** being submitted by **Rahul Kumar Sharma** to the Indian Institute of Technology Delhi, is worthy of consideration for the award of the degree of **'Doctor of Philosophy'** and is a record of the original bona fide research work carried out by him under our guidance and supervision at Department of Energy Science and Engineering, Indian Institute of Technology Delhi. The results contained in the thesis have not been submitted, in part or in full, to any other University or Institute for the award of any degree or diploma.

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Date: July 2025 Rahul Kumar Sharma

Abstract

The advent of the 21st century has witnessed an increase in urbanization, resulting in a rise in the number of residential and commercial buildings and, hence, the energy consumed by them. The United Nations Environment Programme (UNEP) expects the number of buildings to double by 2050. The increased demand is met directly or indirectly by fossil fuel-based systems, which are increasing the local temperatures and adversely affecting the planet Earth. The UNEP expects an increase in the cooling demand and an increase in energy consumption by two times.

The deteriorating indoor air quality and recurring instances of airborne diseases such as COVID-19 have mandated the incorporation of fresh air into closed spaces to dilute indoor air and, hence, reduce contamination levels. Further, exposure to natural daylight is observed to have a positive psychological effect and improve the productivity of occupants in a building. The incorporation of natural daylight also reduces the need for artificial light, subsequently reducing the energy consumption of a building. However, for tropical countries, the summers are hot, and such incorporation of fresh air and daylight can increase the cooling load considerably, subsequently increasing the energy demand of a building.

The present thesis analyzes the effect of precooling of fresh air on the cooling load and, hence, the energy savings achieved by the modified heating, ventilation, and air conditioning (HVAC) system. The thesis commences from an analytical study for designing a phase change material (PCM) incorporated pin fin heat exchanger to offset the peak load for different climatic zones. The PCM-incorporated system was able to offset the peak cooling load and hence provided a maximum energy saving of 4.7 % for Delhi, 2 % for Kolkata, and 2.75 % for Jaisalmer. The analytical study is followed by using multi-attribute decision-making methods for the selection of

an appropriate PCM for building applications. The selected PCM is considered for a numerical study, which incorporates PCM into the annulus of a concentric tube PCM heat exchanger used for cooling the fresh air.

The cooled fresh air is incorporated into the HVAC system, and its effect on energy savings is analyzed. The study also examines the effect of carrying the energy storage capacity of heat exchangers by varying the PCM thickness in the annulus, along with increasing the heat transfer by extruding longitudinal fins in the air. It was observed that the combination providing temperature drop for a longer period provided higher energy savings as compared to traditional HVAC systems. When the HVAC system is retrofitted with a heat exchanger with a PCM thickness of 20 mm, the 12-finned version yields the highest energy savings at 3.22 %. For a PCM thickness of 50 mm, the 24-finned variant offers peak savings of 5.22 %. As the PCM thickness increases to 75 mm and 100 mm, the energy savings rise to 6.64 % and 9.06 %, respectively, when using the 48-finned heat exchanger.

Further, an existing building is analyzed for different cooling loads, and a nano-enhanced PCM-incorporated concentric tube heat exchanger is utilized for cooling the fresh air. It was observed that in the summers, on average, the ventilation comprises 31% of the total load for three air changes per hour. The optimum configuration on the basis of pumping power and ventilation load reduction of the HVAC system is with 24 fins. Further addition of 1% of CuO to octadecane enhances the energy savings to 7.81% for 8 hours and can reach a maximum of 10%. While the LHESS melts completely in 8 hours of duration, the solidification from exhaust air solidifies it in 4 hours of operation.

An experimental study was conducted to increase the thermal mass of glazing to minimize solar heat gain while allowing daylight into the enclosed spaces. Octadecane is

incorporated into the glazing for its melting temperature in close vicinity to the human thermal comfort range. Further, the angle of inclination was varied as 0 and 45 degrees to analyze the effect of inclination on the temperature of enclosed air and illuminance level in the enclosed space. The incorporation of PCM led to air temperature reduction by 6°C, and the illuminance was reduced by 1490 lux and 498 lux as compared to glazing without PCM when the glazing is kept at an inclination of 0° and 45° facing south, respectively. The thesis provides policymakers with energy-efficient and sustainable solutions for designing HVAC systems and glazings, which can reduce energy demand and help combat climate change.

सारांश

21वीं सदी में शहरीकरण में वृद्धि देखी गई है, जिसके परिणामस्वरूप आवासीय और व्यावसायिक भवनों की संख्या में वृद्धि हुई है और साथ ही उनके द्वारा ऊर्जा की खपत में भी इज़ाफ़ा हुआ है। संयुक्त राष्ट्र पर्यावरण कार्यक्रम (UNEP) ने अनुमान लगाया है कि 2050 तक भवनों की संख्या दोगुनी हो जाएगी। इस बढ़ती मांग को सीधे या अप्रत्यक्ष रूप से जीवाश्म ईंधन आधारित प्रणालियों के माध्यम से पूरा किया जा रहा है, जो स्थानीय तापमान को बढ़ा रहे हैं और पृथ्वी पर प्रतिकूल प्रभाव डाल रहे हैं। UNEP ने ठंडक की मांग और ऊर्जा खपत में दोगुनी वृद्धि की उम्मीद जताई है।

खराब होती इनडोर वायु गुणवत्ता और COVID-19 जैसी वायुजनित बीमारियों के बार-बार होने वाले मामलों ने बंद स्थानों में ताजी हवा को शामिल करने की आवश्यकता को अनिवार्य कर दिया है, ताकि इनडोर वायु को पतला किया जा सके और संदूषण स्तर को कम किया जा सके। इसके अलावा, प्राकृतिक रोशनी के संपर्क में आने से सकारात्मक मनोवैज्ञानिक प्रभाव देखा गया है और भवन में निवासियों की उत्पादकता में सुधार होता है। प्राकृतिक रोशनी का समावेश कृत्रिम रोशनी की आवश्यकता को भी कम करता है, जिससे भवन की ऊर्जा खपत में कमी आती है। हालांकि, उष्णकटिबंधीय देशों में गर्मियों के दौरान ताजी हवा और प्राकृतिक रोशनी का यह समावेश ठंडा करने के भार को काफी बढ़ा सकता है, जिससे भवन की ऊर्जा मांग में वृद्धि होती है।

वर्तमान शोध में ताजी हवा को पहले से ठंडा करने के प्रभाव का विश्लेषण किया गया है, और संशोधित हीटिंग, वेंटिलेशन और एयर कंडीशनिंग (HVAC) प्रणाली द्वारा प्राप्त ऊर्जा बचत की जांच की गई है। इस शोध की शुरुआत अलग-अलग जलवायु क्षेत्रों के लिए अधिकतम भार को कम करने के लिए फेज़ चेंज

मटेरियल (PCM) वाले पिन फिन हीट एक्सचेंजर को डिज़ाइन करने के विश्लेषणात्मक अध्ययन से हुई। PCM को शामिल करने वाली प्रणाली ने दिल्ली में अधिकतम 4.7%, कोलकाता में 2% और जैसलमेर में 2.75% ऊर्जा बचत प्रदान की। विश्लेषणात्मक अध्ययन के बाद भवन अनुप्रयोगों के लिए उपयुक्त PCM का चयन करने के लिए बहु-विशेषता निर्णय लेने की विधियों का उपयोग किया गया। चुने गए PCM को संख्यात्मक अध्ययन में शामिल किया गया, जिसमें ताजी हवा को ठंडा करने के लिए एक समकेंद्री ट्यूब PCM हीट एक्सचेंजर के वलय में PCM को शामिल किया गया।

ठंडी ताजी हवा को HVAC प्रणाली में शामिल किया गया और ऊर्जा बचत पर इसके प्रभाव का विश्लेषण किया गया। अध्ययन ने यह भी दिखाया कि पारंपरिक HVAC प्रणालियों की तुलना में तापमान में अधिक समय तक गिरावट प्रदान करने वाले संयोजन ने उच्च ऊर्जा बचत प्रदान की। जब HVAC प्रणाली को 20 मिमी PCM मोटाई वाले हीट एक्सचेंजर के साथ रेट्रोफिट किया गया, तो 12 फिन वाले संस्करण ने 3.22% की उच्चतम ऊर्जा बचत प्रदान की। 50 मिमी PCM मोटाई के लिए, 24 फिन वाला संस्करण 5.22% तक बचत प्रदान करता है। जैसे-जैसे PCM की मोटाई 75 मिमी और 100 मिमी तक बढ़ाई गई, ऊर्जा बचत 48 फिन वाले हीट एक्सचेंजर का उपयोग करते समय क्रमशः 6.64% और 9.06% तक बढ़ गई।

इसके अतिरिक्त, मौजूदा भवन का विश्लेषण विभिन्न ठंडा भार के लिए किया गया और ताजी हवा को ठंडा करने के लिए नैनो-एन्हांस्ड PCM-शामिल समकेंद्री ट्यूब हीट एक्सचेंजर का उपयोग किया गया। यह देखा गया कि गर्मियों में औसतन, वेंटिलेशन कुल भार का 31% बनता है जब प्रति घंटे तीन बार हवा बदली जाती है। HVAC प्रणाली की पंपिंग पावर और वेंटिलेशन भार में कमी के आधार पर 24 फिन वाली प्रणाली को सर्वोत्तम कॉन्फ़िगरेशन पाया गया। इसके अलावा, ऑक्टाडेकेन में 1% CuO जोड़ने से ऊर्जा बचत को

7.81% तक बढ़ाया गया और यह अधिकतम 10% तक पहुंच सकती है। जबकि PCM 8 घंटे की अवधि में पूरी तरह से पिघल जाता है, निकास हवा से ठंडी हवा इसे 4 घंटे के संचालन में ठोस कर देती है।

एक प्रायोगिक अध्ययन किया गया जिसमें बंद स्थानों में प्राकृतिक रोशनी को बनाए रखते हुए सौर गर्मी प्राप्ति को कम करने के लिए ग्लेज़िंग की थर्मल मास को बढ़ाया गया। ऑक्टाडेकेन को इसके गलनांक के कारण ग्लेज़िंग में शामिल किया गया जो मानव थर्मल आराम सीमा के करीब है। इसके अलावा, बंद हवा के तापमान और रोशनी स्तर पर झुकाव के प्रभाव का विश्लेषण करने के लिए झुकाव के कोण को 0° और 45° पर बदला गया। PCM के समावेश से हवा के तापमान में 6°C की कमी आई, और झुकाव के कोण को 0° और 45° पर रखते समय, बिना PCM वाले ग्लेज़िंग की तुलना में रोशनी में क्रमशः 1490 लक्स और 498 लक्स की कमी आई। यह शोध HVAC प्रणालियों और ग्लेज़िंग डिज़ाइनों के लिए ऊर्जा-कुशल और टिकाऊ समाधान प्रदान करता है, जो ऊर्जा मांग को कम कर सकते हैं और जलवायु परिवर्तन से निपटने में मदद कर सकते हैं।

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Nomenclature

A	contact area (m^2)
A^*	ideal solution
A^-	anti-ideal solution
C_1^*	closeness degree of the ideal solution
$C_{p,(s)}$	specific heat in solid state [$kJ\ kg^{-1}\ K^{-1}$]
$C_{p,(l)}$	specific heat in liquid state [$kJ\ kg^{-1}\ K^{-1}$]
CI	consistency index
CV_i	consistency value
CR	consistency ratio
D	evaluation objective
$D_{(s)}$	density in solid state [$kg\ m^{-3}$]
$D_{(l)}$	density in liquid state [$kg\ m^{-3}$]
GM_i	geometric means of rows in the comparison matrix
H	height of the fins (m)
$K_{(s)}$	thermal conductivity in solid-state [$W\ m^{-1}\ K^{-1}$]
$K_{(l)}$	thermal conductivity in liquid state [$W\ m^{-1}\ K^{-1}$]
L	latent heat of fusion [$kJ\ kg^{-1}$]
N	total number of fins
N_i^+	proximity index of the ideal solution
Pr	Prandtl number of air

Q	total amount of heat extracted in the phase change process [J]
RI	random inconsistency
S^{-}	distance between the objective and anti-ideal solution A^{-}
T	temperature [°C]
W_i	relative normalized weight
X	evaluation index
a_{ij}	relative importance of criterion i with respect to criterion j
e_j	entropy of index j
h	enthalpy [kJ/kg]
m	mass [kg]
$\dot{m}$	mass flow rate [kg/s]
p	pressure [Pa]
p_{ij}	proportion of the index value of project i under index j
r_{ij}	normalized vector
v	volume [m^3]
v_{ij}	standardized value of weight
v_j^{*}	distance between index j and the most optimal objective
v_j^{-}	distance between index j and the worst objective
w_j	entropy weight of index j

Greek letters

α	thermal diffusivity of material [m^2 s^{-1}]
β	suitability score

ρ	density of PCM [kg m^{-3}]
λ_{max}	eigenvalues
λ	melt fraction
υ	kinematic viscosity [m^2 s^{-1}]
η	efficiency
ΔP	pressure drop [Pa]
τ	dimensionless time

Subscript

a	ambient
av	average
bp	base plate
comp	compressor
f	friction factor
fin	number of N fins
film	exposed (unfinned) surface of the baseplate
mix	mixed air, i.e., ambient and recirculated air
n	number of rows
ref	refrigerant
s	supply air
$\dot{s}$	entropy generation rate (J/K)

Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers

DSC	Differential scanning calorimeter
$\mathrm{GM_i}$	Geometric means of rows in the comparison matrix
HTF	Heat transfer fluid
HVAC	Heating, Ventilation, and Air-Conditioning
ISHRAE	Indian Society of Heating, Refrigerating and Air Conditioning Engineers
LHESS:	Latent Heat Energy Storage System
PCT	Phase Change Temperature [°C]
PCM	Phase Change Material
TR	Tons of refrigeration