

INVESTIGATION OF PASSIVE BUILDING CONDITIONING METHODS FOR ENHANCING BUILDING ENERGY PERFORMANCE

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Investigation of Passive Building Conditioning Methods for Enhancing Building Energy Performance

by

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To Maa Saraswati!

Certificate

This is to certify that the thesis entitled “**Investigation of Passive Building Conditioning Methods for Enhancing Building Energy Performance**” being submitted by **Rahul Verma** 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 bonafide research work carried out by him under my 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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Declaration

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Abstract

This thesis presents thermal retrofitting strategies for different climatic zones in India, focusing on building energy savings while enhancing thermal comfort and indoor air quality. Developing new buildings or renovating existing ones is a critical challenge for the coming decades, as it involves building heat-resilient buildings and combating building energy inefficiencies. Maintaining a comfortable indoor environment with an inefficient building envelope has substantial implications for its occupants, particularly those with limited financial resources. In regions where extreme conditions are periodic, and building owners cannot afford air conditioning systems, passive retrofitting or the use of passive methods in new buildings should be considered to regulate indoor air temperature.

In the first phase of the thesis, a numerical model is developed using the DesignBuilder simulation tool to investigate the heat transfer barrier, comprising phase change material (PCM), insulation, reflective paint, and a shading system, with both individual and synergistic implementations in composite climatic conditions. The holistic analysis of multi-retrofit solutions, appropriately incorporated into the building envelope for different regions within the same climatic zones, is performed discreetly. Out of the different insulators, shading systems, PCMs, and reflective paint investigated in the present study, the combination of reflective paint and insulation provides the best thermal performance. Furthermore, the non-sorting genetic algorithm (NSGA)-II is applied in a practical context to optimally construct a multi-retrofit envelope using thermal insulator, glazing system, orientation, and window-to-wall ratios of a building across various climatic conditions in India. The existing design parameters of the building can be significantly optimized to assess its sustainability quotient. By modifying the building envelope's characteristics with reflective paint, insulation, and other passive strategies, total HVAC loads are reduced by 6–32 %, and the reflective coating offers lower thermal mass or resistance for similar energy performance.

Further research aimed to design and demonstrate material-based passive strategies that enhance occupants' thermal comfort in India's composite climate. Insulation, phase change material, and reflective paint strategies are tested with a test room model to enhance thermal efficiency. The thermal performance of the PCM room fluctuates considerably depending on external climate conditions. However, the performance of the reflective paint room is observed to be closely aligned and stable with the intensity of outdoor solar radiation. The reflective paint room offers a more productive and enhanced thermal environment at night, rendering it more effective for enhancing nighttime comfort in free-floating buildings than alternative roofing solutions. The research also validates the numerical model through experimental monitoring of the ceiling surface and indoor air temperature in four small-scale test rooms. A comprehensive comparative analysis has been conducted using temperature, energy, economic, life cycle assessment (LCA), and environmental-based indices to highlight the advantages of incorporating different passive strategies. The energy analysis based on the studied passive strategies yields substantial annual energy savings of 8 kWh/m² to 37.7 kWh/m², which can result in a carbon emission reduction of 2.5 to 8 kg CO₂eq/year/m². The cost-benefit analysis uncovers the minimal payback period of 0.9 to 4.4 years, except for PCM, and the minimal return period is highly dependent on building utilization time.

Furthermore, the thesis endeavored to accentuate a resource and energy-conservative indoor space wherein occupants' comfort could be effectively maintained in terms of thermal and air quality. The aim of the research is to enhance indoor air quality and control energy consumption by assessing mandatory ventilation requirements for different occupancy scenarios and outdoor CO₂ concentration. Implementing tailored ventilation strategies based on specific building scenarios can result in energy savings of up to 50 % in the building. Post-night occupancy, leveraging ambient CO₂ levels can also save further energy.

सारांश

यह शोध प्रबंध भारत के अलग-अलग जलवायु क्षेत्र के लिए उष्णता सम्बन्धी अनुरूपान्तर रणनीतियाँ बताती है, जो इमारत में ऊर्जा की बचत पर फोकस करती है, साथ ही तापीय आराम और भीतरी वायु गुणवत्ता को बेहतर बनाती है। आने वाले दशकों में नई इमारत बनाना या मौजूदा इमारत का नवीनीकरण करना एक बड़ी चुनौती है, क्योंकि इसमें गर्मी सहने वाली इमारतें बनाना और इमारत की ऊर्जा कमियों से निपटना शामिल है। जिन इलाकों में समय-समय पर बहुत खराब हालात रहते हैं, और इमारत मालिक वातानुकूलक व्यवस्था का खर्च नहीं उठा सकते, वहां घर के अंदर हवा का तापमान नियंत्रण करने के लिए निष्क्रिय रणनीतियाँ या इमारतों में निष्क्रिय तरीकों के इस्तेमाल पर विचार किया जाना चाहिए।

शोध प्रबंध के प्रथम चरण में, डिज़ाइनबिल्डर सतत अनुकरण का इस्तेमाल करके ऊष्मा स्थानान्तरण अवरोध की जांच करने के लिए एक संख्यात्मक मॉडल विकसित किया गया है, जिसमें चरण परिवर्तन पदार्थ (पीसीएम), तापावरोधन, परावर्तक लेप और एक छायांकन योजना शामिल है, जिसमें मिश्रित जलवायु परिस्थितियों में वैयक्तिक और सहक्रियात्मक दोनों तरह के कार्यान्वयन शामिल हैं। एक ही जलवायु क्षेत्र के अलग-अलग इलाकों के लिए भवन आवरण में सही तरीके से शामिल किए गए एकाधिक-नवीनीकरण समाधान का समग्र विश्लेषण सावधानी से किया जाता है। इस अध्ययन में जांचे गए अलग-अलग विसंवाहक, छायांकन योजना, पीसीएम और परावर्तक लेप में से, परावर्तक लेप और तापावरोधन का युग्म सबसे अच्छा तापीय प्रदर्शन देता है। इसके अलावा, नॉन-सॉर्टिंग जेनेटिक एल्गोरिदम (एनएसजीए)-II को प्रायोगिक तौर पर इस्तेमाल किया जाता है ताकि भारत में अलग-अलग जलवायु परिस्थितियों में किसी इमारत के तापीय विसंवाहक, ग्लेज़िंग प्रणाली, उन्मुखीकरण और दीवार-मे-खिड़की अनुपात का इस्तेमाल करके एक एकाधिक-नवीनीकरण आवरण को सबसे अच्छे तरीके से बनाया जा

सके। इमारत की मौजूदा बनावट मापदंडों को उसके सततता भागफल का पता लगाने के लिए काफी अनुकूलित किया जा सकता है। परावर्तक लेप, तापावरोधक और दूसरी निष्क्रिय रणनीतियों के साथ इमारत आवरण की खासियतों को बदलकर, कुल एचवीएसी भार 6–32% तक कम हो जाते हैं, और परावर्तक लेप समरूप ऊर्जा प्रदर्शन के लिए कम तापीय द्रव्यमान या प्रतिरोध लेती है।

अग्रगामी अनुसंधान का मकसद सामग्री-आधारित निष्क्रिय रणनीतियों को रचना और दिखाना था जो भारत के मिश्रित जलवायु में रहने वालों के तापीय आराम को बेहतर बनाती हैं। तापीय दक्षता बढ़ाने के लिए एक परीक्षण कक्ष नमूने के साथ तापावरोधक, चरण परिवर्तन पदार्थ और परावर्तक लेप रणनीतियों को टेस्ट किया जाता है। पीसीएम रूम का तापीय प्रदर्शन बाहरी जलवायु की स्थिति के आधार पर काफी ऊपर-नीचे होता है। हालांकि, परावर्तक लेप रूम का प्रदर्शन बाहरी सौर विकिरण की तीव्रता के साथ काफी हद तक संरेखित और स्थिर पाई गई है। परावर्तक लेप रूम रात में ज़्यादा लाभदायक और बेहतर तापीय माहौल देता है, जिससे यह दूसरे पाटन समाधान की तुलना में मुक्त रूप से प्रवाहित इमारत में रात के समय आराम बढ़ाने के लिए ज़्यादा असरदार हो जाता है। अनुसंधान चार छोटे परीक्षण कक्ष में भीतरी छत सतह और आभ्यन्तरिक वायु तापमान की प्रायोगिक निगरानी के ज़रिए संख्यात्मक मॉडल को विधिमान्य भी करती है। अलग-अलग पैसिव स्ट्रेटेजी को शामिल करने के फ़ायदों को बताने के लिए तापमान, ऊर्जा, आर्थिक, जीवन चक्र मूल्यांकन (एलसीए), और पर्यावरण-आधारित अनुक्रमणिका का इस्तेमाल करके एक व्यापक तुलनात्मक विश्लेषण किया गया है। अध्ययन की गई निष्क्रिय रणनीतियाँ पर आधारित ऊर्जा विश्लेषण से 8 kWh/m² से 37.7 kWh/m² तक सालाना एनर्जी बचत होती है, जिससे कार्बन उत्सर्जन में 2.5 kg CO₂eq/year/m² से 8 kg CO₂eq/year/m² की कमी हो सकती है। पीसीएम को छोड़कर लागत लाभ विश्लेषण से, 0.9 से 4.4 साल का न्यूनतम-भुगतान अवधि

पता चलता है, और न्यूनतम-भुगतान अवधि इमारत के इस्तेमाल के समय पर बहुत ज़्यादा निर्भर करता है।

इसके अलावा, शोध प्रबंध ने एक संसाधन और ऊर्जा-संरक्षण स्थान पर ज़ोर देने की कोशिश की, जिसमें इमारत में रहने वालों का तापीय और वायु गुणवत्ता के मामले में आराम अच्छे से बनाए रखा जा सके। इस अनुसंधान का मकसद अलग-अलग जन घनत्व परिदृश्यों और बाहरी CO₂ सांद्रता के लिए ज़रूरी वायु-संचार की ज़रूरतों का अंदाज़ा लगाकर भीतरी वायु गुणवत्ता को बेहतर बनाना और ऊर्जा की खपत को नियंत्रित करना है। खास निर्माण परिदृश्य के आधार पर खास वायु-संचालन रणनीति लागू करने से इमारत में 50% तक ऊर्जा की बचत हो सकती है। रात की जन घनत्व के बाद, वायुमंडलीय CO₂ लेवल का फ़ायदा उठाकर और भी ऊर्जा बचाई जा सकती है।

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Nomenclature

Abbreviations

ACH	Air change per Hour
CR	Cool Roof
Dbl	Double Layer
EPI	Energy Performance Index
EPS	Expanded polystyrene
In	Insulation
PCM	Phase Change Material
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PUF	Polyurethane foam
RR	Reflective Roof
RRW	Reflective Roof and Wall
Sh	Shading System

Greek Symbols

α	Thermal diffusivity of material (m^2/s)
Δ	Delta
σ	Stefan Boltzmann Constant ($\text{W}/\text{m}^2\text{K}^4$)

Symbols

c	Density of material
C_r	Rate of dry respiratory heat loss (W/m^2)
E_r	Rate of latent respiratory heat loss (W/m^2)
E_s	Total evaporative heat loss (W/m^2)

E_{rsw}	Rate of heat loss from evaporation of regulatory sweating (W/m ²)
f_{cl}	Ratio of clothed body
f_e	Fraction of surface effective for radiation
H	Internal heat production rate of an occupant per unit area (W/m ²)
h_c	Convective heat transfer coefficient (W/m ² °C)
i	Node being modelled
$i+1$	Adjacent node to interior of construction
$i-1$	Adjacent node to the exterior of the construction
K_e	Thermal conductivity for interface between i node and $i-1$ node
K_w	Thermal conductivity for interface between i node and $i+1$ node
L	All modes of energy loss from the body (W/m ²)
M	Metabolic rate per unit area (W/m ²)
n	New time step
o	Previous time step
P_a	Water vapour pressure in ambient air (Torr)
P_{sk}	Saturated water vapour pressure at required skin temperature (Torr)
Q_c	Rate of convective heat loss (W/m ²)
Q_d	Sensible heat flow from skin (W/m ²)
Q_r	Rate of radiative heat loss (W/m ²)
Q_{res}	Rate of respiratory heat loss (W/m ²)
t	Calculation time step
T_a	Air temperature (°C)
T_{skr}	Skin temperature required to achieve thermal comfort (°C)
W	Rate of heat loss due to performance of work (W/m ²)

x	Finite difference layer thickness (always less than construction layer thickness)
E_t	Experimental Recorded Indoor Air Temperature (°C)
C_t	Computational Indoor Air Temperature (°C)