

**INVESTIGATION OF THERMAL RETROFITTING
OPTIONS FOR IMPROVING BUILDING ENERGY
PERFORMANCE**

PRANAYNIL SAIKIA



DEPARTMENT OF ENERGY SCIENCE AND ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2021

© Indian Institute of Technology Delhi (IITD), New Delhi, 2021

**INVESTIGATION OF THERMAL RETROFITTING
OPTIONS FOR IMPROVING BUILDING ENERGY
PERFORMANCE**

by

PRANAYNIL SAIKIA

Department of Energy Science and Engineering

Submitted

**in fulfilment of the requirements of the degree of Doctor of Philosophy
to the**



INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2021

Certificate

This is to certify that the thesis entitled “**Investigation of Thermal Retrofitting Options for Improving Building Energy Performance**” being submitted by Mr. Pranaynil Saikia to the Indian Institute of Technology Delhi in fulfilment of the requirements for the award of the degree of ‘Doctor of Philosophy’ 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 full to any other University or Institute for the award of any degree or diploma.

(Prof. Dibakar Rakshit)

Associate Professor

Department of Energy Science and Engineering

Indian Institute of Technology Delhi

Hauz Khas, New Delhi - 110016

ACKNOWLEDGEMENTS

I wholeheartedly thank my supervisor, Prof. Dibakar Rakshit for his insights, support and freedom endowed to me during my doctoral research. All these elements were vital to successfully achieve the milestones in my doctoral journey. I had the opportunity to grow in my professional as well as personal life through the precious knowledge received from him, for which I will be forever grateful.

The SRC panel members for my thesis have been very supportive during my research progress. Prof. Vamsi Krishna Komarala and Prof. Anil Verma continuously motivated me with their positive feedbacks and thoughtful advices whereas Prof. K. Ravi Kumar helped me enrich the quality of my research through his numerous questions and insights to improve my work during every interaction I had with him.

My fellow research colleagues have been helpful in every possible way I could imagine. I learned many precious lessons in day-to-day research life from my seniors Dr. Abdus Salam Azad, Dr. Rajat Saxena, and Dr. Rupinder Pal Singh. I particularly thank Mr. Sai Saran Yagnamurthy for his indomitable positive spirit in all circumstances which has been a life lesson for our entire research group. Ms. Sana Fatima Ali has been remarkable in her sincerity with which she scrutinized all the important works of our group including mine. The challenging experiments of my research could not have been completed without the assistance of Ms. Ashima Verma and Mr. Sagar Vashisht. I also thank Mr. Rahul Kumar Sharma, Mr. Alok Kumar Ray, Mr. Mohit Barthwal and Mr. Rahul Verma for all their support; they all have been integral parts of my doctoral journey.

For the research logistics, I thank Mr. Niraj Mahant, Mr. Trilochan Singh, Mr. Maninder Singh and Mr. Akhilesh for their timely help. The inputs received from Mr. Jonaq Niveer Sarma and my brother Mr. Tanmoy Saikia are highly appreciated. I am grateful to Head (DESE, IIT Delhi) and Prof. Kaushik Saha for assisting in setting up the appropriate laboratory

environment for my experiments. The glass blowing section of IIT Delhi has also played a major role in my experimental setup fabrication. For the computational resources, I thank HPC, IIT Delhi for their supercomputing facility. Vital inputs for my computational models were received from Prof. Ramesh Narayanaswamy (Curtin University, Australia), Prof. Fu-Jen Wang (National Chin-Yi University of Technology, Taiwan), and Prof. Udayraj (IIT Bhilai, India). A special note of gratitude is to be mentioned here for Prof. B. K. Panigrahi and Department of Science and Technology, Government of India for providing the necessary funds for the successful execution of the research work.

Finally, I thank my parents and the Almighty for everything, their blessings have been my source of faith throughout my life.

A big circle of supporters in addition to the names mentioned above has been pivotal in my research journey to whom I extend my sincere gratitude.

Pranaynil Saikia

Pranaynil Saikia

ABSTRACT

This thesis illustrates the research endeavours devoted to building energy conservation through thermal retrofitting strategies in the hot climate of India. The overall research efforts in this thesis are broadly categorized into two aspects. The first aspect concerns the understanding and improvement of popular building thermal retrofits (phase change materials and thermal insulation) in the Indian climatic context. The other aspect is a venture towards the discovery of a new class of thermal retrofit which is reported for the first time for passive building cooling application.

The thermal performance of a phase change material (PCM) embedded roof is initially examined for different climatic conditions of India. The varying weather parameters (eg. incident solar radiation, ambient temperature swing, etc.) for different climates act as independent determinants of PCM incorporated roof's thermal performance. To identify a suitable PCM for a given climate, the effects of different weather parameters are consolidated into a single parameter viz. heat gain through a base roof without retrofit. The evaluation of several combinations of weather parameters and different PCMs demonstrated that the rate of heat gain through a building roof without any retrofit can act as a marker to dictate the relative suitability of one PCM with respect to another in a given climatic condition. This consolidated parameter is easy to evaluate and it helps bypass the tedious route of one-to-one mapping of each influencing weather parameter with PCM retrofitted building roof performance.

In addition to the weather effects, the size and location of thermal retrofit in the building envelope can also impact the overall thermal performance of a building. This aspect is dealt with at a deeper level by developing a genetic algorithm framework for continuous and simultaneous variation of multiple envelope retrofits' sizes and locations. Diverse asymmetric results (in terms of optimum envelope configuration) are obtained for different retrofit material

combinations and different orientations of buildings. The energy savings with an optimally configured retrofitted envelope could be as high as 33.5% in hot Indian climate.

The outbreak of COVID-19 during the tenure of this research instigated a worldwide crisis of healthcare wards to accommodate a vast infected population. India has been one of the highest affected countries where COVID-19 spread rapidly throughout the nation. Considering the state of emergency, a major part of this thesis is devoted to energy and space conservative healthcare ward design to accommodate patients with airborne infection. Thermal retrofitting measures are tested in the ward envelope so that indoor thermal comfort could be retained with a minimum active HVAC power supply. The changes in the airflow within the ward are examined for different cases of retrofitting. An optimal design is finally suggested which could address the shortage of healthcare facilities while maintaining a conservative approach for the limited space, energy, and other construction resources for a large-scale infrastructure upgrade.

Finally, the thesis reports for the first time a new category of PCM which operates in the liquid-vapour phase transition regime. The existing PCMs deployed throughout the world for passive building cooling applications majorly operate in the solid-liquid phase transition. Such solid-liquid PCMs (SLPCMs) have certain limitations arising from their inherent material characteristics. The novel liquid-vapour PCM (LVPCM) demonstrated competitive performance with its SLPCM predecessors while overcoming the major SLPCM limitation of night-time heating. Furthermore, LVPCM system could be fabricated with common low-cost and environment-friendly materials. This new technology is therefore anticipated to launch a new paradigm of passive building conditioning research.

The design strategies and outcomes covered in the thesis can contribute to the global energy sustainability campaign whereas the new class of PCM discovered in this research could be the harbinger of major reforms in thermal retrofitting practices for building cooling.

यह शोध प्रबन्ध भारत के गर्म जलवायु में थर्मल रेट्रोफिटिंग प्रणालियों के माध्यम से इमारती ऊर्जा संरक्षण के निर्माण के लिए समर्पित अनुसंधान प्रयासों को दर्शाती है। इस शोध प्रबन्ध में समग्र अनुसंधान प्रयासों को मोटे तौर पर दो पहलुओं में वर्गीकृत किया गया है। पहला पहलू भारतीय जलवायु संदर्भ में प्रचलित इमारती थर्मल रेट्रोफिट्स (चरण परिवर्तन पदार्थ और थर्मल तपावरोधन) की समझ और सुधार से संबंधित है। दूसरा पहलू थर्मल रेट्रोफिट के एक नए वर्ग की खोज की दिशा में एक उद्यम है जो निष्क्रिय भवन शीतलन के लिए पहली बार सूचित किया गया है।

भारत की विभिन्न जलवायु स्थितियों के लिए शुरू में एक चरण परिवर्तन पदार्थ (पीसीएम) संयुक्त छत के थर्मल प्रदर्शन की जांच की गई है। विभिन्न प्रकार के जलवायु के लिए अलग-अलग मौसम मापदंड (सौर विकिरण, परिवेश तापमान परिवर्तन आदि) पीसीएम के स्वतंत्र निर्धारकों के रूप में कार्य करते हैं जो पीसीएम संयुक्त छत के थर्मल प्रदर्शन को नापते हैं। किसी दिए गए जलवायु के लिए उपयुक्त पीसीएम की पहचान करने के लिए विभिन्न मौसम मापदंडों के प्रभाव को एक पैरामीटर में समेकित किया गया है अर्थात् रेट्रोफिट के बिना बेस रूफ के माध्यम से ऊर्जा लाभ। मौसम मापदंडों और विभिन्न पीसीएम के कई संयोजनों के मूल्यांकन ने दिखा दिया कि बिना किसी रेट्रोफिट के इमारत की छत के माध्यम से गर्मी लाभ की दर एक मार्कर के रूप में कार्य कर सकती है ताकि एक पीसीएम की सापेक्ष उपयुक्तता को किसी दिए गए जलवायु स्थिति में दूसरे पीसीएम के संबंध में निर्देशित किया जा सके। यह समेकित पैरामीटर मूल्यांकन करना आसान है और यह पीसीएम रेट्रोफिट वाली छत के प्रदर्शन के साथ प्रत्येक प्रभावित मौसम पैरामीटर के वन-टू-वन मैपिंग के कठिन मार्ग को हटाने में मदद करता है।

मौसम प्रभाव के अलावा इमारती ढांचों में थर्मल रेट्रोफिट का आकार और स्थान भी इमारत के समग्र थर्मल प्रदर्शन को प्रभावित कर सकता है। इस पहलू में कई इमारती रेट्रोफिट ढांचे के आकार और स्थानों के निरंतर और समान भिन्नता के लिए एक जेनेटिक एल्गोरिदम ढांचे को विकसित करके प्रगाढ़ स्तर पर देखा गया है। विभिन्न रेट्रोफिट पदार्थ संयोजनों और इमारतों के विभिन्न अभिविन्यासों के लिए विविध असममित परिणाम (इष्टतम ढांचा विन्यास मामले में) प्राप्त किए गए हैं। एक इष्टतम विन्यास वाले इमारती रेट्रोफिट ढांचे के साथ गर्म भारतीय जलवायु में ऊर्जा बचत 33.5% तक अधिक हो सकती है।

इस शोध के कार्यकाल के दौरान COVID-19 के प्रकोप ने एक विशाल संक्रमित आबादी को समायोजित करने के लिए स्वास्थ्य देखभाल वार्डों के विश्वव्यापी संकट को उभारा। भारत सबसे अधिक प्रभावित देशों में से एक रहा है जहां COVID-19 पूरे देश में तेजी से फैल गया। आपातकालीन स्थिति को ध्यान में रखते हुए इस शोध प्रबन्ध का एक प्रमुख हिस्सा ऊर्जा और रूढ़िवादी स्वास्थ्य देखभाल वार्ड डिजाइन को समर्पित है जिसमें वायु संक्रमित रोगियों को रखा जा सके। थर्मल रेट्रोफिटिंग उपायों का परीक्षण वार्ड में किया गया है ताकि न्यूनतम सक्रिय एचवीएसी बिजली आपूर्ति के साथ भीतरी थर्मल आराम को बनाए रखा जा सके। वार्ड के भीतर वायु प्रवाह में बदलाव से रेट्रोफिटिंग के अलग-अलग मामलों की जांच की गयी है। एक

इष्टतम डिजाइन अंततः सुझाया गया है जो एक बड़े पैमाने पर बुनियादी ढांचे के उन्नयन के लिए सीमित स्थान ऊर्जा और अन्य निर्माण संसाधनों के लिए एक रूढ़िवादी दृष्टिकोण को बनाए रखते हुए स्वास्थ्य सुविधाओं की कमी को दूर कर सकता है।

अंत में यह शोध प्रबन्ध पहली बार पीसीएम की एक नई श्रेणी को दर्शाती है जो तरल-वाष्प चरण में संचालित होती है। निष्क्रिय भवन शीतलन अनुप्रयोगों के लिए दुनिया भर में प्रसिद्ध मौजूदा पीसीएम मुख्य रूप से ठोस-तरल चरण में काम करते हैं। इस तरह के ठोस-तरल पीसीएम (एसएलपीसीएम) की अंतर्निहित पदार्थ विशेषताओं से उत्पन्न होने वाली कुछ सीमाएं होती हैं। नवीन तरल-वाष्प पीसीएम (एलवीपीसीएम) ने रात के समय हीटिंग की प्रमुख एसएलपीसीएम सीमा पर काबू पाते हुए अपने एसएलपीसीएम पूर्ववर्तियों से अच्छा प्रदर्शन किया। इसके अलावा एलवीपीसीएम प्रणाली को कम लागत और पर्यावरण के अनुकूल पदार्थों के साथ गढ़ा जा सकता है। इसलिए इस नई तकनीक से निष्क्रिय भवन अनुकूलन अनुसंधान में एक नए प्रतिमान को प्रकट करने का अनुमान है।

शोध प्रबन्ध में शामिल डिजाइन प्रणालियाँ और परिणाम वैश्विक ऊर्जा स्थिरता अभियान में योगदान दे सकते हैं और इस शोध में खोजे गए पीसीएम का नया वर्ग भवन शीतलन के निर्माण के लिए थर्मल रेट्रोफिटिंग प्रथाओं में प्रमुख सुधारों का अग्रदूत हो सकता है।

CONTENTS

LIST OF FIGURES	xiii
LIST OF TABLES	xix
NOMENCLATURE	xxi
CHAPTER-1: INTRODUCTION.....	1
1.1 Building and global energy scenario.....	1
1.2 Passive building conditioning	4
1.3 Phase change materials – a general introduction	5
1.4 Organization of the thesis	7
1.5 List of publications	11
CHAPTER-2: LITERATURE REVIEW.....	13
2.1 Passive building conditioning with traditional and modern thermal retrofits.....	13
2.2 Research gaps.....	26
2.3 Research objectives.....	28
CHAPTER-3: NUMERICAL ANALYSIS OF PCM EMBEDDED ROOF’S THERMAL PERFORMANCE IN DIFFERENT CLIMATIC ZONES OF INDIA.....	31
3.1 Introduction.....	31
3.2 Numerical formulation.....	32
3.2.1 Model Geometry	32
3.2.2 Mathematical Model	33
3.2.3 Model validation	40
3.3 Results and discussion	41

3.3.1 Thermal performance of PCM roof in absence of wind.....	44
3.3.2 Thermal performance of PCM roof in presence of wind	45
3.4 Summary	49
CHAPTER-4: HOLISTIC OPTIMIZATION OF MULTI-RETROFIT BUILDING ENVELOPE FOR ENHANCED ENERGY PERFORMANCE	51
4.1 Introduction.....	51
4.2 Detailed understanding of the problem.....	52
4.3 Mathematical Modelling.....	56
4.3.1 Thermal modelling	57
4.3.2 Optimization Using Genetic Algorithm	67
4.4 Materials	75
4.5 Results and discussion	76
4.5.1 Optimizing the envelope configuration.....	76
4.5.2 Fixing the building orientation.....	85
4.6 Summary	89
CHAPTER-5: ENERGY AND SPACE CONSERVATIVE HEALTHCARE WARD DESIGN TO TACKLE MASSIVE OUTBREAK OF AIRBORNE PANDEMIC.....	91
5.1 Introduction.....	91
5.2 Model details and authentication	93
5.2.1 Validation with experimental data	102
5.2.2 Grid and timestep size independence study	106
5.3 Results and discussion	109

5.3.1 Thermal comfort of occupants	110
5.3.2 Cooling energy supplied and indoor heat gain.....	115
5.3.3 Airflow patterns.....	117
5.3.4 Mean Age of Air (MAA)	119
5.3.5 Optimal design selection	125
5.4 Summary	129
CHAPTER-6: INVESTIGATION OF LIQUID-VAPOUR PCM FOR PASSIVE THERMAL CONDITIONING OF BUILDING.....	131
6.1 Introduction.....	131
6.2 Method and Materials	132
6.2.1 Phase 1: Metallic vessel	134
6.2.2 Phase 2a: Glass apparatus with LVPCM.....	136
6.2.3 Phase 2b: Modified LVPCM glass vessel.....	139
6.2.4 Indoor experimental setup.....	140
6.3 Initial test without LVPCM	144
6.4 Boundary conditions	146
6.5 Results and discussion	149
6.6 Uncertainty Analysis.....	154
6.7 Benefits and limitations	155
6.8 Summary	157
CHAPTER-7: OVERALL CONCLUSIONS AND RECOMMENDATIONS.....	159
7.1 Overall conclusions.....	159

7.2 Recommendations for further research	161
APPENDIX.....	165
REFERENCES	167

LIST OF FIGURES

Fig. 1.1: Strategies to achieve energy and environmental sustainability	2
Fig. 1.2: Vegetative rooftop at the author's house as a traditional step towards sustainability .	3
Fig. 1.3: General classification of PCM for passive building conditioning.....	7
Fig. 1.4: Climatic zones of India.....	8
Fig. 2.2: PCM incorporated walls (image courtesy: Ref. [27])	17
Fig. 2.3: PCM filled in cylindrical holes inscribed on roof (image courtesy: Ref. [29]).....	17
Fig. 2.4: PCM incorporated bricks (image courtesy: Ref. [11])	18
Fig. 2.5: PCM based underfloor heating system (image courtesy: Ref. [41])	19
Fig. 2.6: PCM based heat exchanger for peak load shaving (image courtesy: Ref. [58])	23
Fig. 2.7: Cool roof with reflective white paint (image courtesy: Ref. [66])	25
Fig. 2.8: Semi-transparent PV windows (image courtesy: Ref. [73]).....	26
Fig. 3.1: Dimensions of the PCM-embedded roof.....	32
Fig. 3.2: Transient heat transfer along the thickness of the PCM-embedded roof	34
Fig. 3.3: Validation of the numerical model	41
Fig. 3.4: Net heat gain through the roof in presence of wind (Bikaner, June).....	42
Fig. 3.5: Net heat gain through the roof in absence of wind (Hyderabad, July).....	43
Fig. 3.6: Net heat gain through the roof in presence of wind (Chennai, May)	43
Fig. 4.1: Different configurations of a roof section depending upon the location and thickness of single retrofitting layer	52

Fig. 4.2: Different configurations of a roof section depending upon the location and thickness of two retrofitting layers	52
Fig. 4.3: PMAY house schematic (a) Top view (b) Side A view (c) Side B view	55
Fig. 4.4: An insulator layer can be inserted in two relative configurations (a) Concrete-PCM-Concrete-Insulator-Concrete or CPCIC (b) Concrete-Insulator-Concrete-PCM-Concrete or CICPC (c) Concrete-Insulator-Concrete subsection common in (a) & (b).....	58
Fig. 4.5: Hourly insolation and ambient temperature data for Delhi for the month of May....	61
Fig. 4.6: (a) Complete experimental setup (b) Layers of concrete slabs with thermocouples inserted at the interfaces.....	63
Fig. 4.7: (a),(b),(c),(d): Validation of numerical model with experimental data.....	65
Fig. 4.8: Effect of element thickness variation in temperature calculations.....	66
Fig. 4.9: Comparison of total indoor heat transfer (present model versus Li et al).....	67
Fig. 4.10: Flowchart of new elitist principle.....	72
Fig. 4.11: Mutation operation performed only in columns having all 0s or 1s.....	73
Fig. 4.12: Minimization of (a) Rastrigin function (b) Rosenbrock function with the new GA	74
Fig. 4.13: Sample temperature-time curves (a) Sample no. 4 of Table 5 (b) Sample no. 11 of Table 5.....	78
Fig. 4.14: Sample GA optimization curves (a) ZNH-PUF South CICPC (b) CCH-Polystyrene North CICPC (c) ZNH-PUF Roof CPCIC (d) CCH-Polystyrene East CPCIC.....	79
Fig. 4.15: Case with no operation of PCM in the latent heating regime (ZNH-Polystyrene CICPC-North wall).....	80

Fig. 4.16: Sample temperature-time plots of optimized CCH-Polystyrene CPCIC configuration	
(a) Roof (b) South wall.....	81
Fig. 5.1: Model details (a) Structural anatomy of envelope (b) Ward schematic	95
Fig. 5.2: Monthly average air temperature and incident solar radiation in Delhi for the month of May.....	97
Fig. 5.3: (a) Geometry of reference test room (b) Meshed geometry	102
Fig. 5.4: Velocity profiles on mid-plane A (present model versus reference literature)	104
Fig. 5.5: Temperature profiles on mid-plane A (present model versus reference literature).	105
Fig. 5.6: Visualization of Line 1, and Reference Points A, B, C.....	107
Fig. 5.7: Grid independence check for (a)Temperature (c)Velocity (e)MAA and Timestep size independence for (b)Temperature (d)Velocity (f)MAA.....	108
Fig. 5.8: Average (diurnal) deviation from operative temperature (°C).....	111
Fig. 5.9: Temperature distribution for (a) Case 7 at 12pm (b) Case 7 at 12am (c) Case 15 at 12pm (d) Case 15 at 12am (e) Case 23 at 12pm (f) Case 23 at 12am	113
Fig. 5.10: Diurnal average of pointwise temperature variations in the proximity of patient for different design cases.....	114
Fig. 5.11: Heat gain and cooling energy supplied for different design cases	116
Fig. 5.12: Streamline plots for (a) Case 7 at 12pm (b) Case 7 at 12am (c) Case 15 at 12pm (d) Case 15 at 12am (e) Case 23 at 12pm (f) Case 23 at 12am.....	118
Fig. 5.13: MAA variations for different design cases.....	120
Fig. 5.14: MAA distribution for (a) Case 7 at 12pm (b) Case 7 at 12am (c) Case 15 at 12pm (d) Case 15 at 12am (e) Case 23 at 12pm (f) Case 23 at 12am	122
Fig. 5.15: Average (diurnal) distance of max. MAA point from Reference Point A (m).....	124

Fig. 5.16: Diurnal average of pointwise MAA variations in the proximity of patient for different design cases	125
Fig. 6. 1: (a) Metallic vessel to carry LVPCM (b) LVPCM vessel carrying concrete exposed to sun and ambient temperature (c) Infrared image showing hot LVPCM vessel causing heating of concrete instead of cooling it.....	135
Fig. 6. 2: (a) Glass vessel carrying LVPCM (b) LVPCM glass vessel carrying concrete exposed to sun and ambient temperature (c) Infrared image showing colder LVPCM implanted concrete surface (d) LVPCM condensate accumulated on top part of LVPCM vessel	138
Fig. 6. 3: (a) LVPCM vessel made of transparent glass (b) LVPCM vessel dimensions...	140
Fig. 6. 4: (a) Concrete slabs – base concrete slab on left, concrete slab to carry LVPCM on right (b) Temperature sensors on bottom concrete surface (c) Ceramic fiber blanket insulation wrapped around lateral sides of the slabs (d) wooden planks placed over lateral insulation layer	142
Fig. 6. 5: Temperature measurement locations (a) Bare concrete slab top surface (b) LVPCM concrete slab top surface (c) Bare concrete slab bottom surface (d) LVPCM concrete slab bottom surface (All dimensions are in cm).....	142
Fig. 6. 6: (a) Inside view of lower wooden chamber (b) Top view of lower wooden chamber with LVPCM vessel implemented through slider opening on right side (c) Inside view of upper wooden chamber (d) Placement of heater and LVPCM vessel’s top portion within upper wooden chamber (e) Complete experimental setup	144
Fig. 6. 7: Temperature profiles of concrete slabs during initial test before implementing LVPCM	146
Fig. 6. 8: Weather station at IIT Delhi for recording the ambient conditions.....	147

Fig. 6. 9: Temperature profiles applied as boundary conditions..... 149

Fig. 6. 10: Bottom surface temperature of bare concrete and concrete with LVPCM 151

Fig. 6. 11: Bottom surface temperature of bare concrete and concrete with LVPCM
(Repeatability test)..... 152

Fig. 6. 12: Top surface temperature of bare concrete and concrete with LVPCM 153

Fig. 6. 13: Indoor heat gain reduction with LVPCM..... 154

LIST OF TABLES

Table 3.1: Monthly mean hourly global solar irradiance, ambient temperature and precipitable water for Bikaner location	36
Table 3.2: Monthly mean hourly global solar irradiance, ambient temperature and precipitable water for Chennai location	37
Table 3.3: Monthly mean hourly global solar irradiance, ambient temperature and precipitable water for Hyderabad location	38
Table 3.4: Material Properties.....	40
Table 3.5: Average daily heat gain in absence of wind (Bikaner).....	44
Table 3.6: Average daily heat gain in absence of wind (Chennai)	45
Table 3.7: Average daily heat gain in absence of wind (Hyderabad).....	45
Table 3.8: Average daily heat gain in presence of wind (Bikaner)	46
Table 3.9: Average daily heat gain in presence of wind (Chennai).....	46
Table 3.10: Average daily heat gain in presence of wind (Hyderabad).....	46
Table 3.11: Average daily heat gain in absence of wind (Bikaner) with 4 cm PCM thickness	48
Table 3.12: Average daily heat gain in absence of wind (Chennai) with 4 cm PCM thickness	49
Table 3.13: Average daily heat gain in absence of wind (Hyderabad) with 4 cm PCM thickness	49
Table 4.1: Stepwise decreasing Penalty parameters	72
Table 4.2: Key GA parameters values	74
Table 4.3: Results of standard function testing.....	75

Table 4.4 : Relevant material properties [77,88,98,99]	76
Table 4.5: Trial simulations performed on randomly selected envelope configurations.....	77
Table 4.6(a): Optimum configurations for CICPC arrangement	82
Table 4.7: Bare concrete envelope performance versus optimized envelope performance.....	84
Table 4.8: Effect of orientation on diurnal heat gain	87
Table 5.1: Envelope material properties [77,116,126]	96
Table 5.2: Boundary conditions.....	97
Table 5.3: Boundary conditions taken from reference study [136]	102
Table 5.4: Test matrix of different design cases investigated.....	110
Table 5.5: Summary of diurnal average/total values of key performance attributes for the design cases considered (Initial data matrix for TOPSIS)	127
Table 5.6: Weight normalized decision matrix and ranking of design cases using TOPSIS.	128
Table 6.1: Weather data for LVPCM testing	148
Table A.1: Hourly insolation and ambient temperature data for Delhi for the month of May	165
Table A. 2: Heat gain through envelope leakages	166

NOMENCLATURE

α : Thermal diffusivity (m^2/s)

abs : Solar radiation absorptivity of material

B_i : Biot number

c_p : Generalized specific heat ($\text{J}/\text{kg}\cdot\text{K}$)

c_{pa} : Specific heat of air ($\text{J}/\text{kg}\cdot\text{K}$)

c_{ps} : Specific heat of solid ($\text{J}/\text{kg}\cdot\text{K}$)

c_{pl} : Specific heat of liquid ($\text{J}/\text{kg}\cdot\text{K}$)

$C_{1\epsilon}$: Model constant (=1.44)

$C_{2\epsilon}$: Model constant (=1.92)

E : Total energy (J)

ems : Long wavelength emissivity of material

F_o : Fourier number

G_b : Buoyancy generated turbulent kinetic energy (W/m^3)

G_k : Generation of turbulent kinetic energy by mean velocity gradient (W/m^3)

g : Acceleration due to gravity (m/s^2)

H : Enthalpy (J)

h_o : Outdoor convective heat transfer co-efficient ($\text{W}/\text{m}^2\cdot\text{K}$)

I : Incident solar radiation (W/m^2)

k : Turbulent kinetic energy (J/kg)

k_{eff} : Effective thermal conductivity (W/m-K)

k_t : Thermal conductivity (W/m-K)

LH : Latent heat of fusion (J/kg)

m : Mass (kg)

\dot{m}_a : Mass flow rate of air supplied into the ward (kg/s)

p : Pressure (Pa)

q : Diurnal average of supplied cooling energy (W)

Q_{in} : Heat transferred to an element (W)

Q_{out} : Heat transferred from an element (W)

Q_{total} : Total diurnal cooling energy supplied (J)

ΔR : Long wavelength radiation exchange (=63 W/m²)

S : Volumetric heat source within fluid domain (W/m³)

S_k : Volumetric source terms for k (W/m³)

S_ϵ : Volumetric source terms for ϵ (W/m³-s)

T : Temperature (K)

T_a : Ambient temperature (K)

T_{inlet} : Inlet air temperature (°C)

T_L : Liquidus temperature (K)

$T_{mean\ outdoor}$: Mean outdoor temperature(°C)

T_o : Operating temperature for the Boussinesq approximation (K)

T_s : Solidus temperature (K)

T_{sol} : Sol-air temperature (K)

t : Time (s)

$\Delta t_{diurnal\ cycle}$: Duration of diurnal cycle (=86400 s)

u_i : Velocity component in i^{th} direction (m/s)

μ : Eddy viscosity (m^2/s)

v : Velocity (m/s)

Y_M : Contribution of fluctuating dilatation in compressible turbulence towards overall dissipation rate (W/m^3)

β : Thermal expansion co-efficient of air (K^{-1})

ε : Turbulent dissipation rate ($J/kg-s$)

ρ : Density (kg/m^3)

ρ_o : Reference density for the Boussinesq approximation (kg/m^3)

$\sigma_k, \sigma_\varepsilon$: Turbulent Prandtl number for k and ε respectively

$\bar{\tau}$: Stress tensor (Pa)

$\overline{\tau_{eff}}$: Deviatoric stress tensor (Pa)