ISHRAE WHITE PAPER ON THERMAL COMFORT

FOREWORD

ISHRAE, as a part of its objective to disseminate knowledge, has taken initiatives to publish Guidebooks, Standards, Data Books and Position Papers to address various HVAC&R requirements specifically in the Indian context. This White Paper is one of the many initiatives undertaken in the same direction to impart learning & knowledge in this all-important field of Thermal Comfort.

ISHRAE has a very active Technical committee well supported by nearly 30 technical groups addressing all possible aspects of the HVAC&R industry. We seek interested and knowledgeable professionals to come forward and volunteer to serve the society and industry and thus lead to technical excellence.

The document is an outcome of the dedication and passion of the THERMAL COMFORT technical group members and we thank each one of them.

Vishal Kapur

ISHRAE Technical Committee Chair

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ACKNOWLEDGEMENTS :

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PREFACE

The field of thermal comfort has attracted the attention of professionals and researchers right from the beginning of building system design practices. The dynamics of thermal comfort has been reviewed, revised, and contextualized by several organizations and individuals. Understanding of thermal comfort including occupant adaptation and behavior, it's bearing over air conditioning system sizing and energy consumption, and approaches for minimizing energy consumption without compromising thermal comfort has been visited in several ways. The purpose of this white paper is to collect and collate such work, especially in the Indian context for making readers of this white paper aware of the chronological progress of the evolution of this field starting with the basics of thermal comfort to identifying areas that require more attention for future work through presenting different strategies for addressing and achieving thermal comfort. The document suggests that thermal comfort research and studies on thermal adaptation started more than three decades back and now around two dozen organizations and institutes based in India alone, along with several international ones, are carrying it forward. Efforts have been made to include all such contributions, however, if any study has been missed out, it is purely unintentional or is due to its non-availability in the public domain. This document has been developed by 'ISHRAE Technical Group No. B-103: Thermal Comfort'. It expresses findings and opinions of the technical group as a whole, based on the documents and reports available in the public domain involving peer-reviewed scientific journals, conference proceedings, and publicly accessible available reports. Since a plethora of documents representing work done in different parts of the world is available, an attempt has been made to focus more on India-relevant work while presenting a glimpse of the international scenario.

'ISHRAE Technical Group No. B-103: Thermal Comfort'

1. OBJECTIVE

The objective of this paper is to provide a brief account of:

- Thermal comfort basics
- Strategies to improve thermal comfort while minimizing the environmental impacts
- National and international thermal comfort codes and standards
- Thermal comfort research in India with a focus on adaptive thermal comfort

The above shall facilitate the identification of research gaps on thermal comfort in India and help facilitate ISHRAE strategize its activities in the domain.

In the Indian context, due to the predominantly tropical climate, we mostly require space cooling to provide thermal comfort. While in the colder regions, space heating is also required to provide thermal comfort; this paper focuses on assessing thermal comfort as it applies to space cooling.

2. THERMAL COMFORT BASICS

"Thermal comfort is that condition of mind, which expresses satisfaction with the thermal environment, and it is assessed by subjective evaluation" as defined by ASHRAE Standard 55[1] . Six primary factors directly affect thermal comfort, and they are generally grouped in two categories:

- Personal factors: characteristics of the occupants (including clothing and metabolic rate)
- Environmental factors: conditions of the thermal environment (including indoor air temperature, mean radiant temperature, air-speed, and relative humidity)

Apart from the parameters indicated above, there are additional factors affecting thermal comfort and heat dissipation from the body, such as food and drink, acclimatization, body shape, body mass index, age and gender, and state of health.

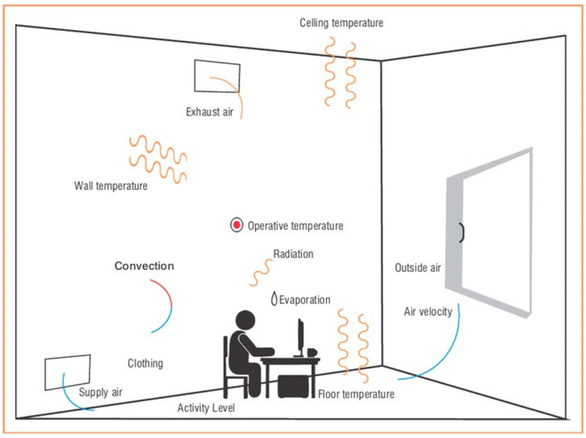


Figure 1: *Factors affecting thermal comfort in the indoor environment[2]*

[1] ANSI/ASHRAE Standard 55 (2020) Thermal Environmental Conditions for Human Occupancy

IMPACT OF THERMAL COMFORT ON OCCUPANT HEALTH AND WELLBEING

The thermal environment impacts our buildings' energy consumption and plays a crucial role in the thermal experience of building occupants at residence, workplaces, etc. Thermal comfort is linked to our health, wellbeing, and productivity and is ranked as the most significant factor to overall human satisfaction while indoor. Due to its linkages to integumentary, endocrine, and respiratory body systems, thermal comfort can impact multiple health outcomes. Research findings suggest that we perform 6% poorer when our office is overheated and 4% poorer if the office is cold.[3] Thus, the consideration of the prevailing thermal environment in the buildings is of utmost importance.

THERMAL COMFORT ASSESSMENT APPROACHES

The two main approaches for thermal comfort assessment are the "heat balance approach" and the "adaptive approach". "Climate chamber studies" are utilized to extract and predict thermal comfort related information in the "heat balance approach" while "field investigations" undertaken in actual buildings are the basis for comfort prediction and estimation in the "adaptive approach".

A. HEAT BALANCE APPROACH

The "heat balance approach" first proposed by P. O. Fanger[4] in 1982, applied a steady-state heat transfer model on the experimental results obtained during controlled climate chamber studies of 1296 young Danish students. This approach describes thermal comfort as "the imbalance between the actual heat flow from the body in a given thermal environment and the heat flow required for optimum (i.e., neutral) comfort for a particular activity". An imbalance between the constant core temperature of the human body and the outdoor thermal environment produces a state of thermal discomfort. The human body generates heat, exchanges heat with the surroundings, and loses heat by diffusion and evaporation from the body. Steady-state experiments showed that warmth discomfort is strongly related to the skin wettedness caused by sweat secretion, and cold discomfort is strongly associated with the mean skin temperature. The dissatisfaction may be caused by the body as a whole being too warm or cold; or by unwanted heating or cooling of a particular part of the body, i.e., local discomfort.

Two thermal comfort indices, "Predicted Mean Vote (PMV)" and "Percentage Predicted Dissatisfied (PPD)", were introduced through this approach for evaluating the thermal comfort conditions in the built environment. Figure 2 presents the comfort band prescribed by PMV/PPD model. Although physical and behavioural adaptations in the form of clothing were passively included in the model, more important factors such as psychological, physiological, and socio-cultural aspects of occupant comfort in different types of buildings and climates were not considered. In this light, the scientists began conducting field

[2] ISHRAE Standard 10001: 2019 Indoor Environmental Quality Standard
[3] D. Licina, Thermal Comfort WELLography Article 2017

research of thermal comfort in distinct settings to know the impact of local climate and thermal adaptation on human thermal comfort.

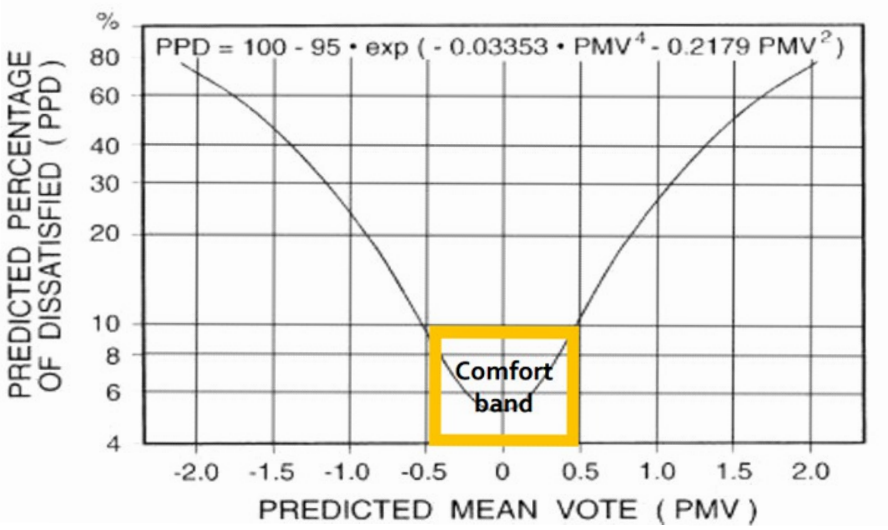


Figure 2: *PMV/PPD model of thermal comfort*

B. ADAPTIVE APPROACH

In 1998, Humphreys and Nicol[5] introduced the adaptive approach of thermal comfort, which states that "if a change occurs such as to produce discomfort, people react in ways that tend to restore their comfort". The "heat balance" approach views comfort as part of a deterministic sequence of cause and effect and ignores the adaptive role of occupants. The adaptive comfort approach finds its basis in field studies, which are performed to analyse the real acceptability of the thermal environment. For restoring their comfort in response to the outdoor environment, people undertake behavioural, physiological, and psychological adaptation. The subjectivity in thermal experience and the interpretations flowing from a very complex interaction between the occupants and their environment has been the research focus and provides the theoretical underpinning to the adaptive approach to thermal comfort studies. Adaptive thermal comfort research has disclosed a wider range of acceptable temperatures that are dependent on climate, construction type, behavioural controls, and other comparable variables through numerous field studies conducted around the globe over the previous decade.

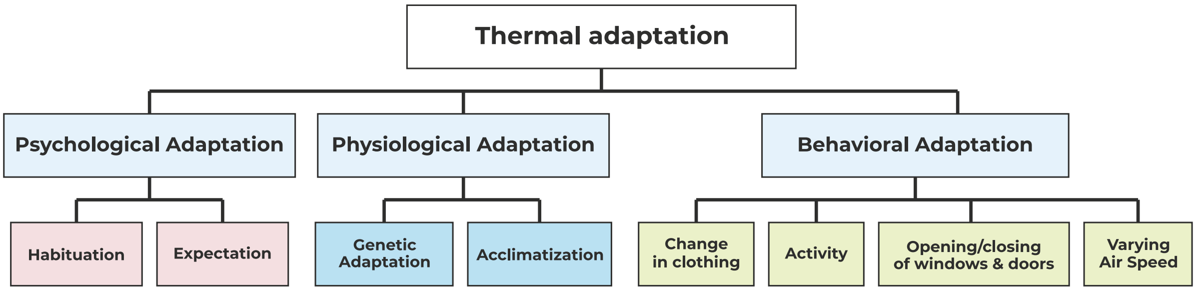


Figure 3: *Thermal adaptation schematic*

[4] P.O. Fanger, (1970). Thermal comfort. Analysis and applications in environmental engineering. Thermal comfort. Analysis and applications in environmental engineering.

3. STRATEGIES TO IMPROVE THERMAL COMFORT WHILE MINIMIZING THE ENVIRONMENTAL IMPACTS

The steady growth in cooling demand in India, especially residential and commercial buildings, poses huge stress on the electricity grids and the environment. This ever-increasing cooling demand in India should be dealt rationally while balancing active air-conditioning with passive measures to reduce the cooling demand in the first place. Thermal comfort and the resultant energy consumption have a direct relation with three interrelated factors 1) climate-responsive building design, 2) climate-responsive cooling system design, and 3) building occupants' adaptation.

i) Climate-responsive Building Design

Buildings with carefully controlled solar gains and good thermal inertia require much less intervention from active or passive cooling systems. Reduction in heat ingress during the day by assessment of **orientation, buffer spaces, shading, building envelope- thermal mass, cavity walls, reflective surface finish for walls and roof, green roof, and insulation** should be the first line of defence. Applicable natural ventilation strategies (such as **stack effect, wind-induced pressure differences, night purging, wind towers,** etc.) and passive cooling strategies (such as **nocturnal cooling, roof pond with movable insulation, courtyards,** etc.) as suggested by the National Building Code of India (NBC-2016) should be considered next to minimize the need for artificial cooling by lowering the space temperatures as well as eliminate/minimize the need for mechanical blowers. All the above building design strategies should be carefully assessed for the prevailing climatic conditions as per the climatic zone map of India, first referred in NBC-2005 and subsequently ECBC-2007[6] . Designers can use various building bioclimatic design charts or analytical tools for identifying appropriate passive design strategy for maximising thermal comfort without use of active air conditioning systems.

ii) Climate-responsive Cooling System Design

Active air conditioning cannot be considered as the only means to provide adequate thermal comfort for all. It is desirable to explore the possibility of using low-energy cooling techniques for indoor space as an alternative for compressor-driven energy-intensive conventional air-conditioning systems. Passive systems in combination with mechanical systems may also be suitably hybridized to offer systems that have significantly lower energy consumption in comparison to conventional HVAC systems. Feasible alternate technologies as suggested by NBC-2016 (such as **pre-cooling of ventilation air through heat/enthalpy recovery wheels and economizer cycles, single or two-stage evaporative cooling, desiccant dehumidification/cooling, geothermal cooling, earth air tunnel, radiant cooling or thermally active building systems,** etc.) may be considered while designing the cooling systems. The government's India Cooling Action Plan (ICAP)[7] also gives an overview of both not-in-kind technologies such as **solar vapour absorption,** etc.

[5] M.A. Humphreys and J.F. Nicol, Understanding the adaptive approach of thermal comfort, ASHRAE Transactions (1998) 991-1004.

(with future advancements) as well as alternate cooling technologies such as **thermal energy storage, personalised cooling/conditioning, trigeneration, and district cooling systems.** The designers can also use advanced analytical simulation tool "EvapCal" which is developed by ISHRAE and can help designer to simulate and analyse the possible indoor air conditions using hybrid and single stage evaporative cooling systems for entire year.

iii) Building Occupants' Adaptation

Climatically responsive buildings using low-energy cooling systems are more likely to result in better adaptation and more favourable occupant behaviour. Such buildings can have a higher level of adaptation through:

- Adjustment: through behavioural/technological changes
- Acclimatization: physiological changes including thermal history consideration
- Habituation: psychological adaptation (changing expectations, preferences, etc.)

Common adaptive actions include changing the activity, adjusting the openings, switching on fans, adjusting thermostat set points, etc. Extensive field studies carried out in naturally ventilated, mixed-mode, and air-conditioned buildings of the country have demonstrated that wide comfort bandwidths exist for Indian subjects than the comfort bandwidths found for subjects residing in cold countries. This is due to a higher degree of behavioural, physiological, and psychological adaptation to warm climates. The use of adaptive controls is affected by seasonal and climatic variations. It may be noted that several adaptive actions that primarily seem to be governed by climatic conditions, also have a barring due to other non-climatic factors such as outdoor noise and pollution governing use of windows, background noise governing use of elevated air speed and so on.

4. NATIONAL AND INTERNATIONAL THERMAL COMFORT CODES AND STANDARDS

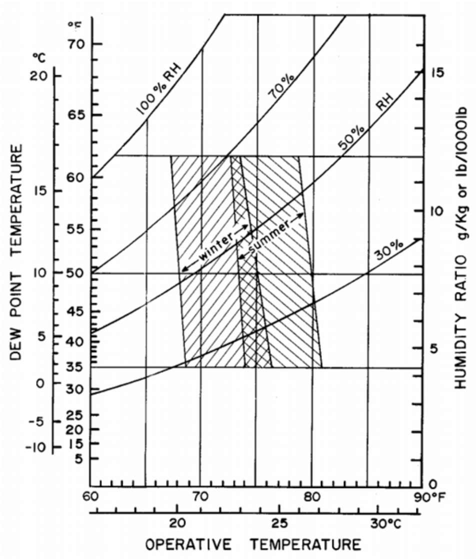
Multiple codes and standards have been published to outline the thermally acceptable environmental conditions for building occupants in different types of buildings.

ISO 7730:2005 standard presents methods for predicting the degree of general thermal sensation and discomfort (thermal dissatisfaction) of exposed people using the calculation of PMV (predicted mean vote) and PPD (predicted percentage of dissatisfied) indices and local thermal comfort criteria. **ISO 17772-1:2017** standard addresses the indoor environmental quality holistically while specifying the requirements for thermal comfort, air quality, lighting, and acoustics.

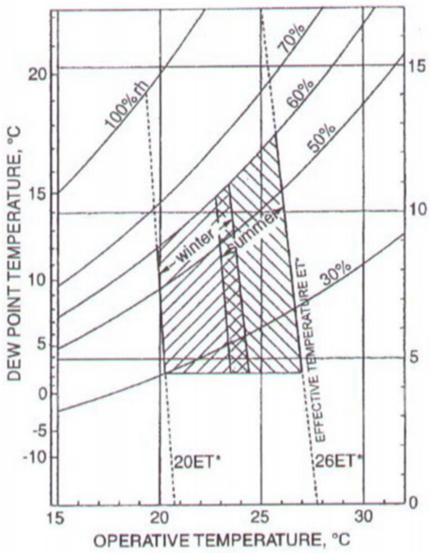
ANSI/ASHRAE Standard 55 (Thermal Environmental Conditions for Human Occupancy), first published in 1966, establishes the ranges of indoor environmental conditions for

[6] Energy Conservation Building Code (ECBC), first released in 2007 and subsequently revised in 2017
[7] Ozone Cell, Ministry of Environment, Forest & Climate Change. 2019. India Cooling Action Plan. [online] Available at: <http://ozonecell.nic.in/wp-content/uploads/2019/03/INDIA-COOLING-ACTION-PLAN-e-circulation-version080319.pdf>

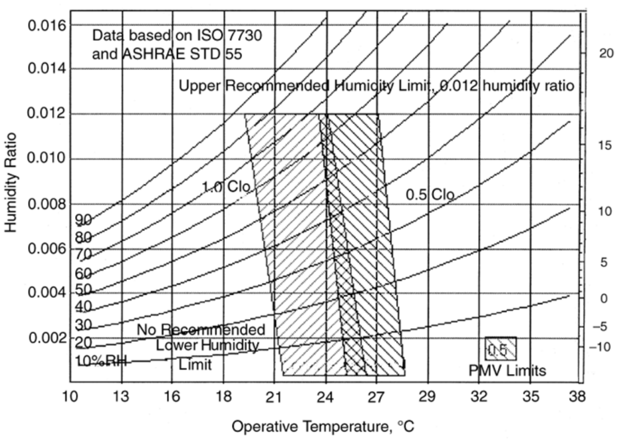
building occupants to achieve acceptable thermal comfort. The latest edition of ASHRAE's thermal comfort standard is ANSI/ASHRAE Standard 55-2020. It offers two methods for determining acceptable thermal environments in occupied spaces: an analytical comfort zone method and an elevated air speed comfort zone method. The standard covers requirements for addressing local thermal discomfort from radiant temperature asymmetry, ankle air speed, vertical air temperature gradient, and floor surface temperature. It also specifies requirements for allowable temperature variations with time. In addition, the standard has a separate method for determining acceptable thermal conditions in occupant-controlled naturally conditioned spaces i.e., the adaptive model. The ASHRAE comfort zone is usually drawn on a standard psychrometric chart defining the indoor operative temperature and humidity for a sedentary person at a defined clothing level.



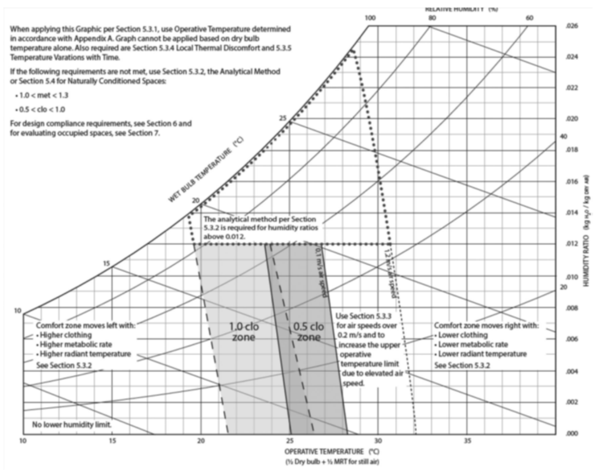
(a) 1981



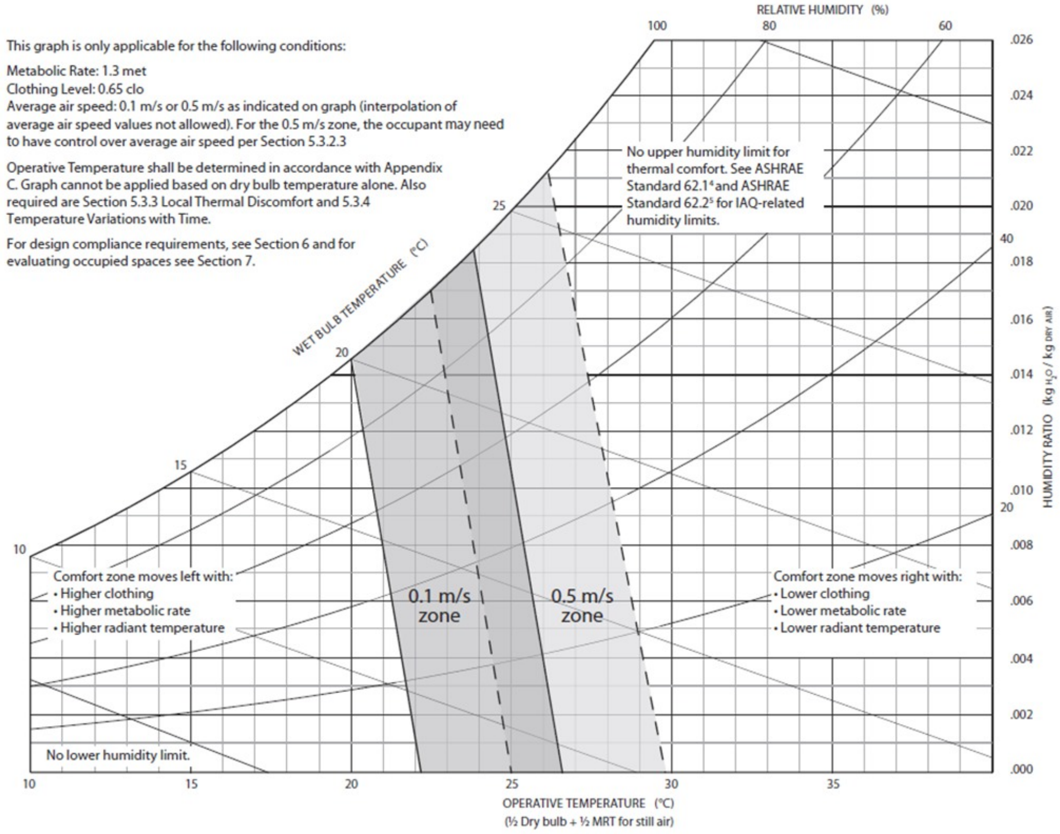
(b) 1992



(c) 2004



(d) 2010, 2013 and 2017



(e) 2020

Figure 4: *Evolution of the ASHRAE Standard 55 thermal comfort zone over years- (a) 1981, (b) 1992, (c) 2004 (d) 2010, 2013 and 2017, (e) 2020*

The shape of the ASHRAE 55 comfort zone on the standard psychrometric chart has evolved as the standard was revised at regular intervals in the years 1981, 1992, 2004, 2010 and 2020 (see Figure 4). The revisions also reflect the evolution of thermal comfort research and the acceptability of adaptive thermal comfort principles among the wider community.

The European Standardization Organization (CEN) developed **EN 15251** standard, which specifies indoor thermal comfort design values. EN 15251 recommends thermal comfort design criteria for four categories of buildings defined according to different levels of occupants' expectations. **EN 15251** was subsequently revised and is now replaced by **EN 16798-1:2019,** which specifies the requirements for the indoor environment standards for the thermal environment, indoor air quality, lighting, and acoustics and specifies how to set these standards for system design and building energy performance calculations. This revised European standard includes design criteria for local thermal discomfort factors, draft, radiant temperature asymmetry, vertical air temperature differences, and floor surface temperatures.

The Indian **National Building Code (NBC) 2016** defines three thermal indices for our climate: Standard Effective Temperature (SET), tropical summer index (TSI), and adaptive thermal comfort. Indoor design conditions as per adaptive thermal comfort are recommended for naturally ventilated (NV), mixed-mode (MM) buildings, and air-conditioned (AC) buildings. NBC recognizes that people's thermal comfort needs depend on their past and present context and that these needs vary with the outdoor environmental conditions of their location.

ISHRAE released the first-ever Indian standard on Indoor Environmental Quality (IEQ) in 2016, which was subsequently updated to **ISHRAE Standard 10001: 2019.** This standard identifies thermal comfort, indoor air quality, visual comfort, and acoustic comfort as four critical elements of IEQ. These elements have been covered by defining their respective threshold levels of IEQ parameters. The ISHRAE IEQ standard recognises the impact of air velocity on thermal comfort acceptability and defines operative temperature as a function of air velocity. This standard is applicable for both residential and commercial buildings of either naturally ventilated, mixed-mode or air-conditioned types. The standard also specifies IEQ testing methods, instrument specifications, and an occupant satisfaction survey.

5. COMPILATION OF THERMAL COMFORT RESEARCH IN INDIA

Thermal comfort related research work has been happening in India at various academic and other institutes independently and in collaboration with various international institutions. All thermal comfort related research work published in peer-reviewed journals and conference proceedings since the publication of The Tropical Summer Index in 1986 has been compiled.

Table 1: *Compilation of thermal comfort research in India*

S.No.	RESEARCH TITLE	INSTITUTIONS	PUB. YR. (DATA DURATION)	RESEARCH FOCUS
1	Tropical summer index-a study of thermal comfort of Indian subjects	Central Building Research Institute, Roorkee 247667, India	1986	Occupant Survey (Residential)
2	Passive options for thermal comfort in Building envelopes--an assessment	Central Building Research Institute, Roorkee 247 667, India	1991	Building Design (Residential)
3	A passive solar system for thermal comfort conditioning of buildings in composite climates	Tata Energy Research Institute, New Delhi	2001 (1998)	Cooling System Design
4	Evaluation of data for developing an adaptive model of thermal comfort and preference	Maulana Azad National Institute of Technology, Bhopal, India	2007 (2004-05)	Occupant Survey (Residential)
5	Different glazing systems and their impact on human thermal comfort-Indian scenario	Centre for Energy Studies, Indian Institute of Technology (Hauz Khas), New Delhi 110016, India	2008 (2006-07)	Building Material & Treatment
6	Bioclimatism and vernacular architecture of north-east India	Instrument Design and Development Centre, Indian Institute of Technology Delhi, New Delhi 110016, India	2009 (2008)	Building Design (Residential)

7	An approach towards development of PMV based thermal comfort smart sensor	Instrument Design and Development Centre, Indian Institute of Technology Delhi, New Delhi 110016, India	2009	Occupant Survey (Lab Building)
8	Analysis of thermal comfort in an office room by varying the dimensions of the windows on adjacent walls using CFD: A case study based on numerical simulation	Department of Mechanical Engineering, Jayaram Engineering College and Technology, Trichy, Tamil Nadu-621 014, India	2009	Building Design (Commercial Office)
9	Using the adaptive model of thermal comfort for obtaining indoor neutral temperature: Findings from a field study in Hyderabad, India	Architecture Department, Jawaharlal Nehru Architecture and Fine Arts University, Hyderabad, India	2010 (2008)	Occupant Survey (Residential)
10	Adaptive use of natural ventilation for thermal comfort in Indian apartments	Jawaharlal Nehru Architecture and Fine Arts University, Hyderabad	2010 (2008)	Occupant Survey (Residential)
11	Behavioural adaptation and the use of environmental controls in summer for thermal comfort in apartments in India	Architecture Department, Jawaharlal Nehru Architecture and Fine Arts University, Hyderabad, India	2010 (2008)	Occupant Survey (Residential)
12	Effect of age, gender, economic group and tenure on thermal comfort: A field study in residential buildings in hot and dry climate with seasonal variations	Architecture Department, Jawaharlal Nehru Architecture and Fine Arts University, Hyderabad, India	2010 (2008)	Occupant Survey (Residential)
13	Thermal performance study and evaluation of comfort temperatures in vernacular buildings of North-East India	Instrument Design and Development Centre, Indian Institute of Technology Delhi, New Delhi 110016, India	2010 (2008)	Occupant Survey (Residential), Building Design
14	Thermal monitoring and indoor temperature modeling in vernacular buildings of North-East India	Instrument Design and Development Centre, Indian Institute of Technology Delhi, New Delhi 110016, India	2010 (2008)	Building Design (Residential)
15	Evaluation of thermal comfort in a rail terminal location in India	Civil Engineering Department (BTCM Division), Indian Institute of Technology Madras, Chennai 600036, India	2010 (2009)	Occupant Survey (Commercial), Building Design
16	Thermal comfort study of Kerala traditional residential buildings based on questionnaire survey among occupants of traditional and modern buildings	Department of Architecture, TKM College of Engineering, Kollam, Kerala, India	2010 (2009)	Occupant Survey (Residential), Building Design

17	Adaptive comfort and thermal expectations - a subjective evaluation in hot humid climate	Building technology and construction management division, Department of Civil Engineering, IIT Madras, Chennai 600036, India	2010 (2009)	Occupant Survey (Residential), Building Design
18	The significance of Physiological Equivalent Temperature (PET) in outdoor thermal comfort studies	Civil Engineering Department, IIT Madras, Chennai, India	2010	Outdoor Thermal Comfort
19	Air Conditioning, Comfort and Energy in India's Commercial Building Sector	1 Faculty of Design, Architecture and Building, University of Technology, Sydney; 2 Faculty of Architecture, Design and Planning, The University of Sydney; 3 Faculty of Design, CEPT University, Ahmedabad; 4 Ashok B Lall Architects, New Delhi; 5 Team Catalyst, Sydney	2010	Occupant Survey (Commercial)
20	Impact of Urbanization on the Thermal Comfort Conditions in the Hot Humid City of Chennai, India	Sathyabama University, Chennai, India	2010	Urban Heat Island Impact on Thermal Comfort
21	Thermal comfort in apartments in India: Adaptive use of environmental controls and hindrances	Architecture Department, Jawaharlal Nehru Architecture and Fine Arts University, Hyderabad, India	2011 (2008)	Occupant Survey (Residential)
22	Adaptive thermal comfort model for different climatic zones of North-East India	Instrument Design and Development Centre, Indian Institute of Technology Delhi, New Delhi 110 016, India	2011 (2008)	Occupant Survey (Residential)
23	Combined effect of energy efficiency measures and thermal adaptation on air conditioned building in warm climatic conditions of India	Department of Mechanical Engineering, Malaviya National Institute of Technology, Jaipur, India	2012 (2011)	Building Material & Treatment (Residential Hostel)
24	Impacts of modern transitions on thermal comfort in vernacular dwellings in warm-humid climate of Sugganahalli (India)	Centre for Sustainable Technologies, Indian Institute of Science, Bangalore, India	2012 (2011)	Building Design, Occupant Survey (Residential)
25	Evaluation of thermal environmental conditions and thermal perception at naturally ventilated hostels of undergraduate students in composite climate	Malaviya National Institute of Technology (MNIT) Jaipur	2013 (2011)	Occupant Survey (Residential Hostel)

26	Experimental evaluation of insulation materials for walls and roofs and their impact on indoor thermal comfort under composite climate	CSIR-Central Building Research Institute, Roorkee, Uttarakhand, India	2013 (2011)	Lab Testing of Building Material
27	Field investigation of comfort temperature in Indian office buildings: A case of Chennai and Hyderabad	1 Department of Architecture, Center for the Built Environment (CBE), University of California, Berkeley, USA; 2 Department of Human and Social Systems, Institute of Industrial Science, The University of Tokyo, Japan; 3 Department of Restoration Ecology and Built Environment, Tokyo City University, Yokohama, Japan	2013 (2012)	Occupant Survey (Commercial Office)
28	Physiological and subjective thermal response from Indians	Human Engineering Research Laboratory (HERL), Centre for Product Design & Manufacturing (CPDM), Indian Institute of Science (IISc), Bangalore 560012, India	2013	Occupant Survey (Lab Building)
29	Study of thermal environment and energy savings considering adaptive thermostat control: A case study of an air conditioned office building in composite climate of India	1 Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, India; 2 Centre for IT in Building Science, International Institute of Information Technology, Hyderabad, India; 3 Building Science Group (fbta), Karlsurhe Institute of Technology (KIT), Germany	2013	Occupant Survey (Commercial Office)
30	Comfort and adaptation in mixed-mode buildings in a hot-dry climate	1 Center for the Built Environment, University of California Berkeley; 2 Center for Energy and Environment, Malaviya National Institute of Technology Jaipur	2014 (2011)	Occupant Survey (Commercial)
31	Assessment of Air Velocity Preferences and Satisfaction for Naturally Ventilated Office Buildings in India	1 CEPT University; 2 University of Technology, Sydney; 3 University of Sydney	2014 (2012)	Occupant Survey (Commercial Office)
32	Adaptive model of thermal comfort for offices in hot and humid climates of India	Center for the Built Environment (CBE), University of California, USA	2014 (2012-13)	Occupant Survey (Commercial Office)

33	Thermal comfort field study in undergraduate laboratories - An analysis of occupant perceptions	Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, India	2014 (2013)	Occupant Survey (Lab Building)
34	Thermal comfort in undergraduate laboratories - A field study in Kharagpur, India	Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, India	2014 (2013)	Occupant Survey (Lab Building)
35	Assessing Impact of Material Transition and Thermal Comfort Models on Embodied and Operational Energy in Vernacular Dwellings (India)	Department of Civil Engineering, Indian Institute of Science, Bangalore 560012, India	2014 (2013)	Building Material (Residential)
36	Performance assessment of a passive solar building for thermal comfort and energy saving in a hilly terrain of India	Centre for Energy and Environment, National Institute of Technology, Hamirpur 177005, Himachal Pradesh, India	2014 (2013-14)	Building Design (Lab Building)
37	Occupant Feedback in Energy-Conscious and' Business as Usual' Buildings in India	1 CBE, UC Berkeley; 2 CARBSE, CEPT University	2014	Occupant Survey (Commercial)
38	Development of thermal comfort models for various climatic zones of North-East India	Department of Energy, Tezpur University, Tezpur 784028, Assam, India	2015 (2009)	Occupant Survey (Residential)
39	Assessment of thermal environmental conditions and quantification of thermal adaptation in naturally ventilated buildings in composite climate of India	Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, India	2015 (2011)	Occupant Survey (Residential & Commercial)
40	A thermal comfort field study of naturally ventilated classrooms in Kharagpur, India	Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, India	2015 (2013-14)	Occupant Survey (Classroom)
41	Development of thermal comfort models for various climatic zones of North-East India	1 Faculté des Sciences Appliquées, Department ArGEnCo, Local Environment Management and Analysis (LEMA), Université de Liège Belgium; 2 Integrated Research and Action for Development (IRADe), New Delhi 110017, India; 3 Department of Energy, Tezpur University, Tezpur 784028, Assam, India	2015 (2014)	Occupant Survey (Residential)

42	An adaptive thermal comfort model for the tropical climatic regions of India (Köppen climate type A)	Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, India	2015	Occupant Survey (Residential & Commercial)
43	Role of building material in thermal comfort in tropical climates - A review	Sri Ramachandra University, Chennai	2015	Building Material
44	Quantification of thermal adaptation in air-conditioned buildings of composite climate, India	Malaviya National Institute of Technology (MNIT) Jaipur	2016 (2011 & 2013)	Occupant Survey (Commercial Office)
45	Thermal comfort assessment and characteristics of occupant's behaviour in naturally ventilated buildings in composite climate of India	Malaviya National Institute of Technology (MNIT) Jaipur	2016 (2011-15)	Occupant Survey (Residential & Commercial)
46	Field studies of thermal comfort across multiple climate zones for the subcontinent: India Model for Adaptive Comfort (IMAC)	Centre for Advanced Research in Building Science and Energy, CEPT University, Ahmedabad 380009, India	2016 (2012)	Occupant Survey (Commercial Office)
47	Occupant feedback in air conditioned and mixed-mode office buildings in India	1 CARBSE, CEPT University 2 CBE, UC Berkeley	2016	Occupant Survey (Commercial Office)
48	Development of mathematical correlations for indoor temperature from field observations of the performance of high thermal mass buildings in India	1 Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur, 302017, India; 2 Civil Engineering Department, Malaviya National Institute of Technology, Jaipur, 302017, India	2017 (2015 & 2016)	Occupant Survey (Residential), Building Material
49	Adaptive thermal comfort in the offices of North-East India in autumn season	Department of Human and Social Systems, Institute of Industrial Science, The University of Tokyo, 153-8505, Japan	2017 (2016)	Occupant Survey (Commercial Office)
50	Energy efficient building envelope & ventilation strategies for multi-storey residential buildings in India	Indo-Swiss Building Energy Efficiency Project (BEEP), Switzerland	2017	Building Design (Residential)
51	Passive Design Indices: Quantifying the Potential of Passive Design Strategies in a Climate	CEPT University	2017	Building Design

51	Passive Design Indices: Quantifying the Potential of Passive Design Strategies in a Climate	CEPT University	2017	Building Design
52	Thermal comfort in traditional buildings composed of local and modern construction materials	Indian Institute of Technology Madras, Chennai 600036, India	2017	Building Design & Material
53	Thermal comfort in naturally ventilated office buildings in cold and cloudy climate of Darjeeling, India - An adaptive approach	Jalpaiguri Govt. Engineering College, Jalpaiguri, W.B., India	2018 (2014-15)	Occupant Survey (Commercial Office)
54	Status of thermal comfort in naturally ventilated classrooms during the summer season in the composite climate of India	Department of Human and Social Systems, Institute of Industrial Science, The University of Tokyo, Tokyo 153-8505, Japan	2018 (2015)	Occupant Survey (Classroom)
55	Thermal comfort in urban open spaces: Objective assessment and subjective perception study in tropical city of Bhopal, India	Department of Ecosystem and Environment Management, Indian Institute of Forest Management, Bhopal, Madhya Pradesh 462003, India	2018 (2016)	Outdoor Thermal Comfort
56	Thermal performance prediction of office buildings using direct evaporative cooling systems in the composite climate of India	Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur, 302017, India	2019 (2016)	Cooling System Design
57	Advancing building bioclimatic design charts for the use of evaporative cooling in the composite climate of India	1 Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur 302017, India 2 School of Architecture, Carnegie Mellon University, Pittsburgh, PA 15213, USA	2019 (2016-17)	Occupant Survey, Cooling System Design
58	Field study on indoor thermal comfort of office buildings using evaporative cooling in the composite climate of India	1 Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur, Rajasthan 302017, India; 2 School of Architecture, Carnegie Mellon University, Pittsburgh, PA 15213, United States; 3 Mechanical Engineering Department, Dr. B R Ambedkar National Institute of Technology, Jalandhar, Punjab 144011, India	2019 (2016-17)	Occupant Survey (Commercial Office), Cooling System Design

59	Correlating room air conditioner energy consumption with thermostat setting to encourage occupant behavioural change towards enhanced energy efficiency and thermal comfort	Alliance for an Energy Efficient Economy, New Delhi, India	2019 (2018)	Lab Testing of RACs
60	Review of studies on thermal comfort in Indian residential buildings	Centre for Energy & Environment, Malaviya National Institute of Technology, Jaipur	2020	Residential thermal comfort in India (Review)
61	Review of practices for human thermal comfort in buildings: present and future perspectives	Centre for Energy & Environment, Malaviya National Institute of Technology, Jaipur	2020	Human thermal comfort (Review)
62	Impact assessment of air velocity on thermal comfort in composite climate of India	Centre for Energy & Environment, Malaviya National Institute of Technology, Jaipur	2020 (2011-17)	Occupant Survey (Commercial Office), Cooling System Design
63	Quantifying occupant's adaptive actions for controlling indoor environment in naturally ventilated buildings under composite climate of India	Centre for Energy & Environment, Malaviya National Institute of Technology, Jaipur	2021 (2011-17)	Occupant Survey, physical monitoring, adaptive controls
64	Towards implementing an indoor environmental quality standard in buildings: A pilot study	Centre for Energy & Environment, Malaviya National Institute of Technology, Jaipur	2021 (2017-18)	Occupant Survey, physical monitoring of IEQ parameters

Recently, an Indo-UK joint research project called 'Residential building energy demand reduction in India (RESIDE)' has also developed an online repository named REACT repository on residential energy and thermal comfort. The aim of this repository is to provide the accessible details of the meta-study on thermal comfort and energy use carried out in the residential buildings in India. This repository can be updated with the future studies happening in the area of residential thermal comfort and energy use in Indian context.

The thermal comfort related research in India revolves around the following three core themes:

1. survey of building occupants' thermal comfort perception
2. thermal comfort impact of building design and material selection
3. thermal comfort impact of cooling system design

The researchers have investigated these research strands in different combinations apart from a few additional focus areas. The research focus areas have been mapped for individual research papers in Table 1. A summary of the research focus areas is compiled in Table 2 below:

Table 2: *Summary of thermal comfort research focus*

S.No.	Research Focus	No. of Research Studies
1	Occupant Survey	34
2	Building Material & Design	12
3	Occupancy Survey and Building Material & Design	6
4	Occupant Survey and Cooling System Design	3
5	Cooling System Design	2
6	Outdoor Thermal Comfort	2
7	Lab Testing	2
8	Review	2
9	Urban Heat Island Effect	1

A closer look at the number of institutions reveals that 23 national and 9 international institutes have been active in thermal comfort research in India over the past 35 years. While occupant surveys for different building types have dominated the research focus, a limited number of researchers have looked into areas such as lab testing to validate the actual energy savings achieved through the adoption of adaptive thermal comfort standards. No research study has been conducted on in-situ monitoring of the energy performance impact of adaptive setpoint based AC operation.

ADAPTIVE THERMAL COMFORT IN THE INDIAN CONTEXT

The adaptive comfort concept has received remarkable interest within the Indian research and policy community in the recent past. Field studies carried out in tropical climates like India report that people tend to feel comfortable at a wider range of temperatures due to various acclimatization and adaptive measures. Increased indoor air movements and lowered clothing values can significantly improve the thermal comfort.

NBC-2016 defines separate indoor adaptive thermal comfort conditions depending upon the building operation, i.e., naturally ventilated (NV), mixed-mode (MM) or air-conditioned buildings (AC). NBC recommends operative temperature based adaptive thermal comfort model for NV and MM buildings. While for AC buildings, NBC recommends both air temperature and standard effective temperature (SET) based adaptive thermal comfort models. However, any description of the operation and design of buildings using evaporative cooling systems is not provided in the code.

The following adaptions and changes in the air conditioning system operation are worth noting in the Indian context:

1. Introducing the concept of an "adaptive setpoint" for operating air-conditioning systems by varying thermostat setting instead of fixed setpoints can result in reducing energy usage whilst maintaining the comfort, productivity, and well-being of the building occupants. This can be done by integrating the adaptive comfort model with the air conditioning system operation cycle.
2. Designing an occupant-centric building with greater emphasis on providing the occupant with controls such as operable windows, doors, fans can escalate the thermal comfort while reducing the building energy consumption. Offering improved visibility to building occupants on environmental conditions (indoor and outdoor), energy use by cooling/air-conditioning systems, and alarms for recommended actions can significantly enhance the conscious transition of people towards thermally comfortable and energy-efficient buildings.
3. Clothing adjustment is one of the first adaptive actions which people take in accordance with the changing outdoor environment. Generating awareness on clothing adjustments can significantly reduce the air conditioning requirements. Tailor-made programmes like the Cool Biz campaign in Japan have demonstrated remarkable energy savings by implementing clothing adjustments (liberal summer code) and by changing the air conditioner temperature setpoint to 28 °C in controlled office buildings.
4. Elevated air velocity is another common measure to restore comfort at higher temperatures, especially in NV and MM buildings in tropical countries like India. A redefined air velocity offset chart for Indian subjects working in office buildings has been proposed using the data (i.e., comfort expectations, preferences, and local adaptation) collected from actual field observations. This redefined chart, adapted from EN15251 and customised for the Indian context, has also been incorporated in the ISHRAE IEQ Standard 10001:2019. The offset in comfort operative temperature from the base value of 28.04°C and 26.93°C for NV and MM buildings were obtained to be 4.78°C and 4.24°C, respectively for an elevated air velocity of 1.5 m/s.

6. RESEARCH GAPS AND OTHER CHALLENGES

Based upon a review of thermal comfort research and its applications in India, the following gaps and challenges have been identified with respect to larger adoption of adaptive thermal comfort based building design and operation in India:

1. More India-specific research on quantifying the impact of adaptive thermal comfort on energy savings, occupant health, and wellbeing must be conducted for different building types, operation modes, and climate zones.
2. The interplay of building design and material selection with greater adoption of adaptive thermal comfort based cooling system selection, design, and operation should be further explored.
3. The India Cooling Action Plan (ICAP) underscores the importance of a shift in the

behavioural as well as psychological attitudes towards adaptive thermal comfort practices to reduce cooling requirements and promote a healthy living/working environment. More research on harnessing behaviour change for promoting greater adoption of adaptive thermal comfort based cooling system operation is required. In-depth research to understand the motivations, attitudes and behavioural tendencies of the AC/other cooling system users should be conducted in the Indian context.

4. Field studies on quantification of thermal comfort in buildings utilizing passive and low energy cooling strategies (evaporative cooling, thermal mass, night ventilation, etc.) require more focus and deliberation. Evidence-based research on the quantification of best comfort strategies for the design and operation of mixed-mode buildings is needed.

5. ISHRAE's "EvapCal" tool is based on building bioclimatic design chart for evaporative cooling in composite climate based on the field investigations carried out in India. On similar lines, more focus should be towards the development of pre-design tools based on the thermal acceptability limits drawn from India specific field studies that accommodate thermal adaptation of occupants.

6. Adaptive thermal comfort models have matured in the theoretical domain globally as well as in India. They have even been recognized in the National Building Code 2016. However, there has been limited adoption in actual practice during the building design and operational stages. The following reasons can be attributed to the lower adoption adaptive comfort model in real practice:

   i. One primary reason for the low adoption is the unique microclimate and operating characteristics, which results in the deviation of adaptive coefficients from the established adaptive comfort models. This is a consequence of differences in the source region and nature of raw field study data which was the initial basis of adaptive model development.

   ii. The input variable for adaptive comfort models, namely outdoor temperature reference, plays a crucial role. The outdoor conditions can be characterized as the running mean outdoor temperature or the prevailing mean of outdoor temperature. However, the selection of the exponentially decaying weighting factor (commonly denoted as α) remains ambiguous. Also, appropriate calculations of 7 sequential days weighted mean outdoor temperature need deliberation and clarity for common understanding.

   iii. Despite wide acceptance of outdoor temperature reference for adaptive model development, any guidance on the correct starting day and duration of calculation period (i.e., season) is unclear in the most referenced documents like building codes.

7. Standard Effective Temperature (SET) based approach that includes air temperature, mean radiant temperature (MRT), relative humidity, air velocity, clothing and activity level may be more comprehensive and suitable to evaluate thermal comfort in India over the prevailing operative temperature based approach which has its limitations.

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7. SUMMARY

Since, the building occupants play an active role in ensuring thermal comfort, the designers should follow the adaptive thermal comfort principles while designing buildings and cooling systems. Climate-responsive features in building and cooling system design shall ensure optimal thermal comfort while minimising the adverse environmental impacts of building construction and operation, as well as increasing the health and productivity of building occupants

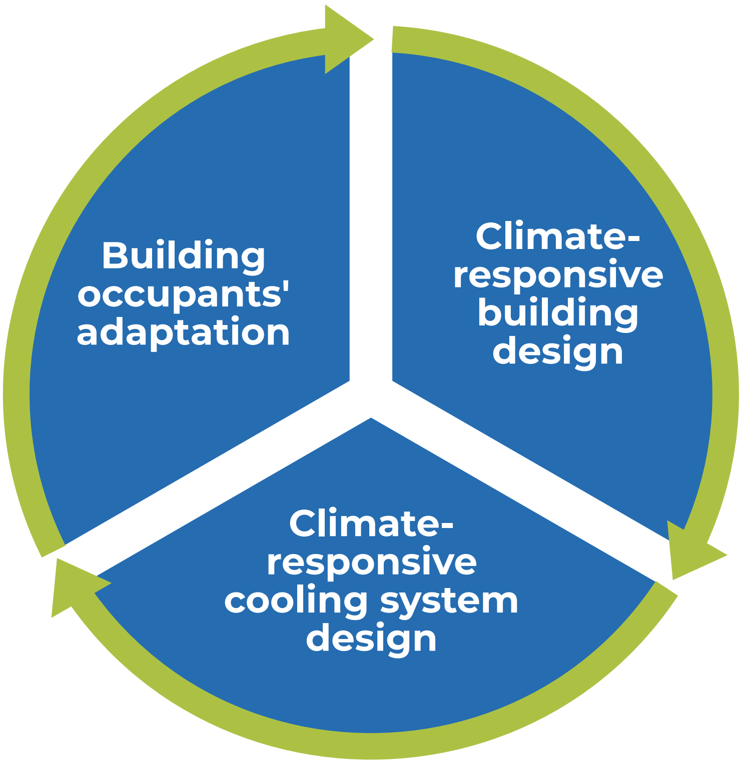

Figure 5: *Strategies to improve thermal comfort while minimizing the environmental impacts*

The ISHRAE research committee can prepare research proposals for selecting and supporting the identified research gaps as per the Research gaps and other challenges compiled above.

Additionally, ISHRAE can initiate large-scale awareness programmes and/or campaigns to change public perception of adaptive thermal comfort principles. ISHRAE regional Chapters and Sub-Chapters can organise seminars/workshops on various topics related to thermal comfort. The upcoming Acrex, Urjavaran and other ISHRAE flagship events can also have focussed discussions on the thermal comfort theme.

"One Degree Challenge"

The Bureau of Energy Efficiency (BEE) has mandated the default temperature setting of all ACs covered under the ambit of star-labelling program to be set at 24 degrees from 1st Jan 2020 onwards. [8]Prior to this, BEE had issued voluntary guidelines for all commercial building consumers to maintain the space temperatures between 24-25°C with appropriate humidity and airflow to conserve energy and for the health benefits of building occupants. [9] BEE guideline recognises that by increasing the setpoint temperature by every degree, an energy saving of up to 6% could be realised. Thus, by raising the setpoint temperature from 21°C (which is the typical setpoint operation) to 25°C, there exists an energy saving potential of up to 24%. BEE subsequently launched an awareness campaign on social and other media platforms to spread the message of energy (and cost) savings through raising the AC setpoint temperature.

[8] Bureau of Energy Efficiency (BEE). Room Air Conditioners S&L notification Amendment I: S.O. 3897(E) dated 30th October 2019. [online] Available at:

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[9] Bureau of Energy Efficiency (BEE). Advisory note-cum-Guidelines: "Energy conservation in building space cooling through recommended optimum temperature setting". 2018. [online] Available at:

<https://beeindia.gov.in/sites/default/files/press_releases/Recommended%20Guidelines.pdf>

Taking forward the BEE guidelines and awareness campaigns, ISHRAE launched "One Degree Challenge" which encourages building owners and end users to operate their air-conditioners at one degree higher than 24°C or their current standard operations. The challenge was supported and launched by all the members of Board of Governors of ISHRAE from more than 43 cities in 2019 that promotes users to save energy by adopting various strategies that are suggested to be implemented along with increase in setpoint temperature which can help the user to feel comfortable even after increasing the room temperature by one degree.

Effective awareness and implementation of the "One Degree Challenge" can help tremendous national energy savings due to the large base of air-conditioning system in use across India.

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