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52, Chander Lane, Kaimari Road,
Hisar 125001, Haryana, India

PROFILE SUMMARY

Lead with more than nine years of experience in research & development, consultancy, and academia in engineering. Extensive experience in handling government consultancy and research projects with knowledge dissemination through research training and scientific publications.

EDUCATION

Ph. D. (Doctor of Philosophy) in Energy and Environment **Synopsis submitted (Jan 2021)**
Malaviya National Institute of Technology (MNIT), Jaipur, Rajasthan, India
Thesis: *Quantification of Occupant's Adaptive Actions for Improving Indoor Environmental Quality in Buildings*
Supervisors: Dr. Jyotirmay Mathur (Sr. Professor, Centre for Energy and Environment, MNIT Jaipur) and Dr. Sanjay Mathur (Professor and Head, Civil Engineering Department, MNIT Jaipur)

M. Tech. (Master of Technology) in Mechanical Engineering **Jun 2014**
Guru Jambheshwar University of Science and Technology (GJUS&T), Hisar, Haryana, India
Thesis: *Analysis of Ginger Drying Inside a Forced Convection Indirect Solar Dryer: An Experimental Study*
Supervisors: Dr. Mahesh Kumar (Associate Professor, Mechanical Engineering Department, GJUS&T Hisar) and Dr. Pankaj Khatak (Professor and Head, Mechanical Engineering Department, GJUS&T Hisar)
CGPA: 7.3 out of 10

B. E. (Bachelor of Engineering) in Mechanical Engineering **Jun 2010**
Maharshi Dayanand University, Rohtak, Haryana, India
Final year project: *Vehicle Differential Power Control System*
Percentage marks: 75.18% (Degree awarded with distinction)

RESEARCH EXPERIENCE (5.9 Years)

Senior Research Fellow **Jan 2018-till date**
Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur, India
Project: *Residential Building Energy Demand Reduction in India*
Funding Agency: *Department of Science and Technology (Government of India) and Engineering and Physical Sciences Research Council (United Kingdom)*
Job description: *Review of existing and available empirical data on thermal comfort and energy use in Indian dwellings. Field study of residential thermal comfort and energy use that involves physical measurements, procurement of instruments, statistical analysis, and development of scientific publications.*

Research Associate **Nov 2017-Jan 2018**
Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur, India
Project: *Indoor Environmental Quality Standard Implementation Methodology*

Funding Agency: *Indian Society of Heating, Refrigerating and Air Conditioning Engineers*
Job description: *Demonstration of the implementation methodology for India's first indoor environmental quality standard (IEQ) in actual buildings. Performed a field study that involves physical measurements of IEQ parameters, procurement of instruments, statistical analysis, and development of publication/ reports.*

Project Engineer **Jun 2016-Jun 2017**
Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur, India
Project: *Centre for Building Energy Research and Development*
Funding Agency: *India-United States Partnership to Advance Clean Energy*
Job description: *Operation and maintenance of solar thermal technologies particularly the Scheffler dish for steam cooking applications. Research activities including data refinement and analytics for improving the ISHRAE weather data and development of scientific publications or reports.*

Senior Research Fellow **Dec 2014-May 2016**
Thermochemical Conversion Division, SSS-National Institute of Bio-energy, Kapurthala, India
Project: National Bioenergy Promotion Fellowship
Funding Agency: *Ministry of New and Renewable Energy, Government of India*
Job description: *Operation and maintenance of downdraft* biomass gasification *unit. Research activities including r*esearch administration, scientific publications, and writing research proposals especially on thermochemical biomass conversion processes.

TEACHING EXPERIENCE (1.6 Years)

Teaching Associate **Sep 2011-May 2012**
Mechanical Engineering Department, Guru Jambheshwar University of Science & Technology, Hisar, India
Subjects taught: *Refrigeration and air-conditioning, thermodynamics, energy conversion*

Lecturer **Aug 2010-May 2011**
Mechanical Engineering Department, Kalpana Chawla Institute of Engineering & Technology, Hisar, India
Subjects taught: *Refrigeration and air-conditioning and thermodynamics*

CONSULTANCY EXPERIENCE (2.25 Years)

Technical Course Developer **May 2018-Dec 2018**
Environmental Design Solutions, New Delhi, India
Job description: *Development of e-learning academic courses on renewable energy technologies for graduate-level students. Two courses on 'A Primer to Solar Power' (https://www.udemy.com/course/a-primer-to-solar-energy/) and 'Introduction to Renewable Energy' (https://www.udemy.com/course/renewable-energy/) have been developed.*

Managed Network Expert **Sep 2012-Dec 2014**
Chegg India Private Limited, Visakhapatnam, India
Job description: To provide educational guidance and assistance to the students by providing them relevant academic solutions and courses of their interests.

COMPUTER PROFICIENCY

Computer Basics; Microsoft Word/Excel/Powerpoint; Design tool - AutoCAD (Basic); Statistical tool - SPSS (Basic) and Simulation tool - DesignBuilder (Basic).

AWARDS/ACHIEVEMENTS/RECOGNITIONS

- Awarded the prestigious BHAVAN Fellowship 2020 for carrying out research at the University of Texas at Austin, USA (Funded by Indo-U.S. Science and Technology Forum and DST, Govt. of India)
- Selected for the Indo-German Research and Academic Program and visited Technical University of Applied Sciences, Germany in 2019 (Funded by German Academic Exchange Service).
- Received recognition for authoring the most cited research paper published in the Renewable and Sustainable Energy Reviews Journal of Elsevier during 2017-18.
- Received outstanding reviewer recognitions by reputed journals of Elsevier such as Renewable Energy Focus, Solar Energy, and Energy Conversion & Management in 2018.
- Awarded National Bioenergy Promotion Fellowship at SSS-National Institute of Bioenergy under the Ministry of New & Renewable Energy, Government of India during 2014-16.
- Conferred with Silver Medal for outstanding academic accomplishments during Bachelor of Engineering in Mechanical Engineering in 2010.
- Meritorious award for securing distinction position in Secondary School Examinations conducted by the Board of School Education Haryana in 2004.
- Awarded rank 1 in Bhartiya Sanskriti Gyan Pariksha conducted by Shantikunj Gayatri Parivar (Haridwar) in 2004.
- Awarded rank 2 in Interschool Competition Exam conducted by Ideal Shiksha Samiti (Hisar) in 2002.

CONFERENCES/WORKSHOPS/TRAINING/COURSES ATTENDED

- One day industry and academia amalgamation named 2nd PAN India Research Network Meet jointly organized by National Institute of Wind Energy, Chennai, and CEE, MNIT Jaipur (06th Jan 2020).
- One day Industry-Academia Conclave on Energy Storage organized by Department of Science and Technology, Govt. of India at MNIT Jaipur (30th Nov 2019).
- Two days regional workshop on Energy Efficiency in Residential Buildings organized by Bureau of Energy Efficiency, Ministry of Power in association with RRECL at Jaipur (05-06th Nov 2019).
- One-week academic workshop on 'Energy Storage: The Future of Energy' under the AICTE Training and Learning (ATAL) scheme organized by MNIT, Jaipur, India (11-15th Mar 2019).
- South Asia's Largest Exhibition on Refrigeration & Cold Chain, Air Conditioning, Ventilation, and Intelligent Buildings organized by Indian Society of Heating, Refrigerating, and Air Conditioning Engineers at BEC, Mumbai, India (28th Feb to 2nd Mar 2019).
- One-week short-term course on Research Methods and Data Analysis Using SPSS organized by NIT Jalandhar, India (20-24th Jan 2019).
- E-course on Cities and Climate Change organized by UN Climate Change Learning Partnership 2019.
- Three days' workshop on Building Performance Evaluation (under the initiative of the UK-India Learn-BPE project) at Manipal University, Jaipur, India (11-13th Oct 2018).
- One DL program on ASHRAE 90.1 organized by ASHRAE Jaipur Section in association with ISHRAE Jaipur Chapter at Hotel Leisure Inn Grand Chanakya, Jaipur, India (23rd Aug 2018).
- One day SVAGRIHA Training Program organised by Green Rating for Integrated Habitat Assessment at MNIT, Jaipur, India (03rd Aug 2018).
- South Asia's Largest Exhibition on Refrigeration & Cold Chain, Air Conditioning, Ventilation, and Intelligent Buildings organized by Indian Society of Heating, Refrigerating, and Air Conditioning Engineers at BIEC, Bangalore, India (22-24th Feb 2018).
- One-week short-term course on Building Energy Simulation for ECBC 2017 organized by Indian Institute of Information Technology, Hyderabad, India (12-16th Feb 2018).
- One-day Thought-Provoking Workshop on Pertinent Issues Related to Air Quality in India, organized by Civil Engineering Department, MNIT, Jaipur, India (20th Jan 2018).

- One-week short-term course on Recent Advances in PCM-based Cooling Technology organized by IIT Bhubaneswar (India) under GIAN scheme (11-15th Dec 2017).
- Five days National Workshop on Performance Evaluation and O&M of Solar Thermal Systems organized by the National Institute of Solar Energy under MNRE, India (20-24th Apr 2017).
- One-day National Workshop on Concentrated Solar Technologies organized by Rajasthan Renewable Energy Corporation Limited at Bhiwadi, Rajasthan, India (2nd Mar 2017).
- International Conference on New and Renewable Energy Resources for Sustainable Future organized by SKIT, Jagatpura, Jaipur, India (2-4th Feb 2017).
- First and Second International Conference on Recent Advances on Bio-energy Research organized by SSS-NIBE, Kapurthala, India (14-17th Mar 2015 and 25-27th Feb 2016).
- International Conference & Exhibition on Cutting Edge Technological Challenges in Mechanical Engineering organized by NIET, Greater Noida, India (21-22nd Mar 2015).
- National Conference on Research Methodology and Advancement in Engineering and Science organized by Shanti Niketan College of Engineering, Hisar, India (24th Apr 2013).
- Three days National Workshop on Designing of Concentrated Solar Thermal & Solar Water Heating System organized by National Institute of Solar Energy, Gurgaon, India (08-10th Aug 2016).
- One-week National Training Program on Biofuel Production and Its Characterization organized by SSS-NIBE, India (30th Nov-04th Dec 2015).
- Three days National Training Program on Biofuel Production and Catalysis organized by SSS-NIBE, India (19-21st Jan 2015).

PUBLICATIONS

1. **Sansaniwal SK**, Mathur J and Mathur S. Quantifying occupant's adaptive actions for controlling indoor environment in naturally ventilated buildings under composite climate of India. Journal of Building Engineering 2021, Mar 12:102399 **(SCI)**.
2. **Sansaniwal SK,** Jain N, Mathur J and Mathur S. Towards implementing an indoor environmental quality (IEQ) standard in buildings: a pilot study. Building Services Engineering Research and Technology 2020. DOI: 10.1177/0143624421997989 **(SCI)**.
3. **Sansaniwal SK**, Tewari P, Kumar S, Mathur J and Mathur S. Impact assessment of air velocity on thermal comfort in composite climate of India. Science and Technology for the Built Environment 2020; 26:1301-1320 **(SCI)**.
4. **Sansaniwal SK,** Mathur J, Garg V and Gupta R. Review of studies on thermal comfort in Indian residential buildings. Science & Technology for Built Environment 2020;26(6):727-48 **(SCI)**.
5. **Sansaniwal SK,** Mathur J and Mathur S. Review of practices for human thermal comfort in buildings: Present and future perspectives. International Journal of Ambient Energy 2020. **(Scopus)**.
6. **Sansaniwal SK**. Advances and challenges in solar-powered wastewater treatment technologies for sustainable development: an overview. International Journal of Ambient Energy, 2019. DOI: 10.1080/01430750.2019.1682038 **(Scopus)**.
7. **Sansaniwal SK**, Sharma V, Mathur J. Energy and exergy analyses of various typical solar energy applications: a comprehensive review. Renewable and Sustainable Energy Reviews 2018; 82 (1):1576-1601 **(SCI)**.
8. **Sansaniwal SK** et al. Global challenges in the sustainable development of biomass gasification: an overview. Renewable and Sustainable Energy Reviews 2017;80:23-43 **(SCI)**.
9. **Sansaniwal SK** et al. Recent advances in the developments of biomass gasification technology: a comprehensive review. Renewable and Sustainable Energy Reviews 2017;72:363-84 **(SCI)**.
10. Kumar M, **Sansaniwal SK**, Khatak P. Progress in solar dryers for drying various commodities. Renewable and Sustainable Energy Reviews 2016; 55:346-60 **(SCI)**.

11. **Sansaniwal SK**, Kumar M. Analysis of ginger drying inside a natural convection indirect solar dryer: An experimental study. Journal of Mechanical Engineering & Sciences 2015; 9:1671-85 **(Scopus)**.
12. **Sansaniwal SK**, Kumar M, Kaushal R, Kumar V. Investigation of indirect solar drying of ginger rhizomes (Zingiber officinale): a comparative study. Journal of Engineering Science & Technology 2017; 12(7):1956-71 (**Scopus)**.
13. **Sansaniwal SK**, Bhutani V. Recent advances in the developments of pool boiling systems for food processing. Journal of Biofuel and Bioenergy 2016; 2(1):44-51.
14. Pal K, **Sansaniwal SK**, Gera P, Jha MK, Tyagi SK. An assessment to the biomass-based combustion systems. Journal of Biofuel and Bioenergy 2016; 2(2):102-21.
15. **Sansaniwal SK**, Kaushal R. Biomass pyrolysis for sustainable developments of bio-products. 1st International Conference on New Frontiers in Engineering, Science & Technology, New Delhi, India, Jan 8-12, 2018, 656-63.
16. **Sansaniwal SK**, Sahdev R and Kumar M. Towards natural convection solar drying of date palm fruits (Phoenix dactylifera L.): an experimental study. Submitted in Journal of Stored Products Research 2021 **(SCI)**.

STUDENT GUIDED /SUPERVISED

Guided final year students of B. Tech. (Mechanical Engineering) for their major project entitled 'Field Assessment of IEQ in Residential Buildings during Winter Season of Jaipur'.

PROFESSIONAL ACTIVITIES

1. Membership of professional bodies:
    - ASHRAE Technical Committee (T-TAC-TC01.01; T-TAC-TC02.01 and T-TAC-TRG4.IAQP)
    - Chartered Institution of Building Services Engineers (Member ID: 058034)
    - Indian Society of Heating, Refrigerating & Air Conditioning Engineers (Member ID: S00079280)
    - Institution of Mechanical Engineers (Member ID: 80181805)
    - International Association of Engineers (Member ID: 246519)
    - Society of Building Science Educators (Member ID: 56179992)
    - Teaching & Education Research Association (Member ID: M19101178)
    - The Asia Society of Researchers (Senior Member ID: R219042002)
2. Workshops, Conferences, and Research meeting organized:
    - Member, Organizing Committee for Industry-Academia Conclave on Energy Storage jointly organized by Department of Science and Technology (GOI) and MNIT, Jaipur (30th Nov 2019).
    - Member, Organizing Committee for International Conference & Exhibition on Green Buildings organized by the Confederation of Indian Industry (CII) at Jaipur (04-07th Oct 2017).
    - Member, Organizing Committee for First & Second International Conferences on Recent Advances on Bioenergy Research organized by SSS-National Institute of Bioenergy, Kapurthala (2015-16).
    - Member, Organizing Committee for the First Research Advisory Committee Meeting organized by SSS-National Institute of Bioenergy, Kapurthala (22nd Jun 2015).
3. Research projects, proposals, and reports prepared:
    - Prepared a report on Meta-study of Residential Energy and Comfort Datasets in India (Under Indo-UK Joint Research Project Funded by EPSRC, United Kingdom, and DST, Govt. of India).
    - Prepared two chapters on biomass gasification and pyrolysis for a consultancy project on Training Module for Trainees in Bioenergy (Under National Bioenergy Fellowship Program, Govt. of India).
    - Prepared a research project on Biomass Gasifier Testing, Certification, and R&D Centre at SSS-NIBE, Kapurthala (Under National Bioenergy Fellowship Program, Govt. of India).
    - Prepared a proposal for training of participants from government bodies and ASEAN member States on Bioenergy Technology (Under National Bioenergy Fellowship Program, Govt. of India).

4. Reviewer:
- Applied Energy (SCI)
- Applied Water Science (UGC-CARE)
- Bentham Science Publishers
- Energy (SCIE)
- Energy Conversion and Management (SCIE)
- Energy Sources, Part A: Recovery, Utilization & Environmental Effects (SCI)
- Heliyon (SCIE)
- Ingeniería-e-Investigación (SCIE)
- International Energy Journal (Scopus)
- International Journal of Ambient Energy (Scopus)
- International Journal of Energy Research (SCIE)
- Journal of Building Construction & Planning Research
- Journal of Engineering Science & Technology (Scopus)
- Journal of Thermal Analysis & Calorimetry (SCI)
- Lawrence Press
- Renewable & Sustainable Energy Reviews (SCI)
- Renewable Energy Focus (Scopus)
- Scientific Nature Reports (SCI)
- Solar Energy (SCIE)
- Sustainable Cities and Society (SCIE)

PERSONAL INFORMATION

- Date of Birth: 03.08.1989 (Bhiwani, Haryana, India)
- Linguistic Proficiency: Hindi, English, Haryanvi
- Special Interest/ Hobbies: Watching comedy shows and working out at the gym

INTERNATIONAL VISITS & TOURS

Technical University of Applied Science (Germany); Amsterdam (Netherland); Brussels (Belgium) and Paris (France)

REFEREES

1. Dr.-Ing. Jyotirmay Mathur
   Sr. Professor, Mechanical Engineering Department and Centre for Energy and Environment
   Head, MNIT Innovation and Incubation Centre
   Malaviya National Institute of Technology, J.L.N. Marg, Jaipur 302017, India
   E-mail: jmathur.mech@mnit.ac.in

2. Dr. Sanjay Mathur
   Professor and Head, Civil Engineering Department
   Malaviya National Institute of Technology, J.L.N. Marg, Jaipur 302017, India
   E-mail: smathur.ce@mnit.ac.in

3. Dr. Mahesh Kumar
   Associate Professor, Mechanical Engineering Department
   Guru Jambheshwar University of Science and Technology, Hisar 125001, India
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Quantifying occupant's adaptive actions for controlling indoor environment in naturally ventilated buildings under composite climate of India

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Centre for Energy and Environment, Malaviya National Institute of Technology, Jaipur, 302017, India

ARTICLE INFO

Keywords:
Window opening behaviour
Blind use behaviour
Fan use behaviour
Indoor environment
Naturally ventilated buildings

ABSTRACT

Occupant's adaptive actions (like windows opening, use of blinds and use of ceiling fan) have a strong effect on indoor environment. Only a few models of these actions exist and are solely based on indoor and outdoor thermal environments. This leads to large discrepancies between the actual and predicted indoor environment. There is no such study prevails in India and this highlights the need to investigate the occupant's local adaptive behaviour using the actual field data. The present study has developed adaptive behaviour models that relate window opening behaviour, blind use behaviour and fan use behaviour to the environment conditions in naturally ventilated buildings under the composite climate of India. Field measurements of adaptive behaviour actions and environmental conditions were conducted in thirty-one naturally ventilated buildings. The occupant's adaptive behaviour models were thus governed by various explanatory variables. In window opening behaviour model, the indoor and outdoor air temperatures, indoor air velocity, indoor lighting level and indoor CO_2 were important governing variables. In blind use behaviour model, the indoor lighting level, indoor air velocity and window state were significant governing variables and in fan use behaviour model, the indoor air temperature, indoor air velocity and window and blind states were the most influencing variables. The occupant's adaptive actions were mostly governed by the pursuit of comfort and primarily driven based on the change in indoor environment rather than outdoors. Occupant's behaviour patterns of adaptive controls use were consistent with the literature and can be used for simulating the built environment in naturally ventilated buildings.

1. Introduction

People spend most of their time inside buildings and therefore, the healthy and comfort indoor environment is essential for humans. The indoor environmental quality encompasses the four environment conditions (thermal, air quality, visual and acoustic) inside the building [1]. Humans have endeavoured to control their built environments in which they can feel comfortable. Occupant's use of adaptive actions such as window or door opening, blind use and fan use substantially influences the indoor environment. Naturally ventilated or free-running buildings provide many adaptive opportunities to the occupants' to improve their built environment by utilising the natural airflows [2]. Window opening aids comfort air ventilation, distribution of fresh air and extract overheated and contaminated air from the indoor space [3]. Window opening provides a dual role in controlling indoor air temperatures and regulating indoor air quality through increasing air flows. When natural airflow through windows is not strong enough, the use of ceiling fan is a reliable source to control ventilation through regulating air circulation and airflow. Increase in air movement has a direct impact on the subject's thermal comfort and building energy demand. The use of window blinds protects occupants from direct solar glare and also maximizes the use of daylight based on occupant's preference of daylighting [4]. Occupant's adaptive actions are not only governed by a single predictor but also by many other factors related to occupant, building and environment. Therefore, it is important to study various factors that can have an influence on occupant's adaptive behaviour. Fabi et al. [5] reviewed various factors influencing the occupant's window opening behaviour in residential and office buildings. Many studies emphasised on prevailing window states rather than transition of window state with time. Several influencing factors were identified of which some were more contributing than others.

The earlier researchers have quantified some of the occupant's

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Case Study

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Towards implementing an indoor environmental quality standard in buildings: A pilot study

Sunil Kumar Sansaniwal, Shailendra Kumar, Nikhil Jain, Jyotirmay Mathur and Sanjay Mathur

Abstract

This paper demonstrates the implementation methodology for India's first IEQ standard (ISHRAE Standard-10001:2016) in actual buildings. The IEQ standard encompasses the definitions of IEQ elements (i.e. thermal comfort, indoor air quality, visual comfort, and acoustic comfort), threshold values of IEQ parameters determining these elements, specifications of measuring instruments, and methodology to undertake IEQ assessments in buildings. The pilot study identified the preliminary findings to understand and evaluate the practical implementation of the IEQ standard through field measurements. The quantitative measurements of IEQ elements were carried out in two academic buildings in the Jaipur climate (warm and humid as well as hot and dry and cold). The occupant's subjective evaluation was made through a questionnaire survey administrated concurrently with physical measurements of IEQ parameters. This study provides the clarity of method for taking IEQ measurements and comments on the availability of instruments and their specifications as recommended by the standard.

Practical application: The present study is the practical implementation of the IEQ standard in buildings. This standard provides the threshold limits of IEQ parameters by classifying them into three classes covering international and local benchmarking. The standard also specifies the research methodology including field measurement protocol and specification of monitoring devices for IEQ assessment. This standard is useful for evolving IEQ rating of buildings in India where the majority of the building stocks are yet to be built.

Keywords

Thermal comfort, indoor air quality, visual comfort, acoustic comfort, academic buildings, occupant satisfaction survey

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Introduction

Buildings require significant aftercare during the operational stage which can even be cost higher than initial capital investment. Modern developers and occupiers have become more aware of

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Impact assessment of air velocity on thermal comfort in composite climate of India

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Thermal adaptation plays crucial role in energy efficient operation of buildings without compromising with human thermal comfort. Elevated air velocity is commonly desired to restore comfort requirements at higher temperatures especially in NV and MM buildings located in tropical countries like India. This article is the systematic field study comprising a total of 4872 responses (1874 from NV buildings and 2998 from MM buildings) collected over a period of six years (2011–2017) during summer and moderate seasons under composite climate of Jaipur (India). Subjects' responses and concurrent field measurements were utilized to investigate the impact of elevated air velocity on indoor thermal comfort. This research is a first attempt of its kind that deals with graphical quantification of air velocity required to offset increased temperature and follows similar approach as presented in ISO 7730. A redefined air velocity offset chart for Indian subjects working in office buildings has been proposed using the evidences (i.e. comfort expectations, preferences and local adaptation) collected from actual field observations. Thus, the offset in comfort operative temperature from 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 the elevated air velocity of 1.5 m/s.

1. Introduction

Thermal satisfaction in buildings has become the necessity for healthy survival of human being as people spend about 90% of their time indoors. In India, the building energy consumption is expected to be increased by more than twice of the global average increase or by the annual average increase of 2.7% till 2040 (U.S. Energy Information Administration 2017). About 48% of annual energy consumption in residential buildings and 31% in commercial buildings are used for satisfying thermal comfort requirements through HVAC systems (Rawal et al. 2012; BEE 2007). Thermal comfort not only affects the subject's health but also the building energy performance to great extents (Taylor, Fuller, and Luther 2008; Wagner et al. 2007). Global standards for thermal comfort including ASHRAE 55 (ASHRAE 2013) and ISO 7730 (ISO 2005) are based on heat balance approach and have specified comfort requirements of subjects for different building typologies. However, these standards have several systematic discrepancies and the range of thermal comfort (26 °C–32 °C) obtained for Indian contexts is way above the values (i.e. 23 °C–26 °C for summer and 21 °C–23 °C for winter) prescribed by these standards (Kumar et al. 2016a, 2016b, 2017; Tewari et al. 2019c; Dhaka et al. 2013, 2015; Sansaniwal et al. 2020a). This difference indicates the prominent role of socio-cultural setup and local adaptation in finding actual thermal comfort requirements.

More country specific field research that accounts socio-cultural aspects and local adaptive behavior are required which will benefit engineers and architects to quantify actual requirements of thermal comfort. Further, the contributing factors of thermal comfort are categorized in two types namely, the environmental factors (i.e. RAT, MRT, air velocity and RH) and personal factors (i.e. clothing insulation and activity levels) (Erlandson et al. 2003; Sansaniwal, Mathur, and Mathur 2020b). Air velocity is an important parameter that substantially influences thermal comfort in the prevailing environment. In hot and dry climate, the inhabitants closer to the equator line often stay in NV or semi-open spaces with electric fan operation. Rise in air velocity using ceiling fan and/or window opening during summer season is the noteworthy behavioral adaptation mechanism to combat high temperature conditions (Vijayalaxmi 2009). Feriadi and Wong (2004) reported the subject's tendency to modify the prevailing warm and humid

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Sunil Kumar Sansaniwal, PhD (Pursuing), is a Senior Research Fellow. **Priyam Tewari, PhD,** Student Member ASHRAE, is an Associate Fellow. **Shaildendra Kumar, M.Tech,** Student Member ASHRAE, is a Consultant. **Sanjay Mathur, PhD,** is a Professor. **Jyotirmay Mathur, PhD,** Member ASHRAE, is a Professor.
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Review of studies on thermal comfort in Indian residential buildings

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[2]*Centre for IT in Building Science, International Institute of Information Technology, Hyderabad, India*
[3]*Oxford Institute for Sustainable Development, Oxford Brookes University, Oxford, United Kingdom*

This article presents a systematic review of thermal comfort studies in Indian residential buildings, to identify the present research scenario, data gaps, and policy interventions. The majority of the studies were performed in a composite climate (10), followed by a warm humid climate (seven), and a very few from cold (two) and hot and dry (two) climates. None of these thermal comfort studies took place in a temperate climate. In addition, seven studies have considered multiple climates for assessment of thermal comfort in residential buildings. This illustrates that thermal comfort studies in Indian residential buildings are scarce, scattered, and unorganized. Further, due to differences in sociocultural setup and local adaptations, wide variations in occupant comfort requirements were reported. This review argues that there are dynamic modifications in individual behaviors due to changes in cost of building energy services and comfort requirements. Only four of the reviewed studies partially considered the occupant behavior regarding control of the indoor thermal environment. The results obtained from these studies indicate that there is pressing need for the localized thermal comfort models that will improve not only the comfort requirements but also building energy performance. Importantly, this review paves the way for harmonised thermal comfort research in India, where a large amount of residential building stock is yet to be built.

Introduction

Among the Asia Pacific Partnership countries, India has the highest residential building energy consumption, which is likely to be increased with the addition of new building stock (Bin and Evans 2008). In Indian dwellings, about 73% of total energy consumption is used for HVAC and lighting, to meet the requirements for thermal and visual comfort (ECBC 2007). India has diversified sociocultural setups and climatic conditions that provide opportunities to people to drive their livelihood and healthy lifestyle (Kumar et al. 2017). The Indian climate has an extraordinary variety, ranging from tropical in the south to temperate in the north. It is strongly influenced by the Himalayas in the north, the Thar Desert to the northwest, and the sea in the south (Rao and Patil 2016). India has five designated climatic zones, namely, hot–dry, warm–humid, composite, cold, and temperate (NBC 2005). The requirements for human thermal comfort vary greatly with climatic zones that have such a disparity in environmental conditions.

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An occupant's expectations for thermal comfort also vary considerably, and hence, so does the building energy consumption. In Indian residential buildings, about 45% of energy is used to meet the requirements of thermal comfort (ECBC 2007). With a high growth rate in modern infrastructure and residential building stock, the residential energy demand is likely to increase in the future. Thermal comfort is "the state of mind that expresses satisfaction within the thermal environment" and is generally assessed subjectively (ASHRAE 2004). It generally depends on six parameters: four environmental parameters (room air temperature [RAT], mean radiant temperature [MRT], air velocity, and relative humidity [RH]) and two personal parameters (clothing level and metabolic activity) (ISO 2005).

The adaptive model (amalgamation of physiological, psychological, and behavioral aspects) can significantly decrease the building space cooling requirements. It is based on the principle of adaptability, which states that if a person feels discomfort due to change of conditions, that person will react to restore the comfort level (Roaf et al. 2010). The adaptive model considers the dynamic variations of both internal and external environmental conditions, including the individual behavior, using field study data from real buildings (Fabbri 2015; Djongyang, Tchinda, and Njomo 2010). However, the sociocultural aspects, thermal history, income, and context are not comprehensively considered in the existing thermal comfort model. The adaptive thermal comfort model was also incorporated in ASHRAE 55 (ASHRAE 2004).

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REVIEW

Review of practices for human thermal comfort in buildings: present and future perspectives

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ABSTRACT
Thermal comfort markedly impacts our health, well-being and work productivity. This article is a review of practices generally adopted to quantify human thermal comfort in buildings. The review indicates that there is significant variation in comfort requirements due to diversified socio-cultural set-up and local adaptive behaviour. Thus, the localised thermal comfort models need to be developed to identify the actual comfort requirements helpful in drafting new local comfort standards. The study justifying the relationship between thermal comfort and indoor air quality are scant and need to be explored as such relationships are greatly dependent on occupant's adaptive behaviour. Further, the interdisciplinary research on thermal comfort which not only helps in real-time assessment but also covers other critical aspects like building architecture and energy consumption is lacking in the literature. Moreover, this review paves way for research on thermal comfort in countries where high building stock is expected in future.

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Human thermal comfort; thermoregulatory system; thermal comfort parameters and approaches; thermal comfort standards; office and residential buildings

Nomenclature

A_d:	DuBois area (m^2)
A_c:	Convection body area (m^2)
A_r:	Effective radiation area of body (m^2)
C_k:	Heat loss by thermal conduction (W/m^2)
D:	Globe diameter (mm)
F_{cl}:	Clothing area factor
F_{pcl}:	Clothing permeability factor
h_r:	Radiative heat transfer coefficient ($W/m^2.°C$)
h_c:	Convective heat transfer coefficient ($W/m^2.°C$)
h_e:	Evaporative heat transfer coefficient ($W/m^2.°C$)
H_{wv}:	Water vapour concentration (kg/kg air)
I_{cl}:	Thermal insulation of clothing (clo)
l:	Body height (m)
L:	Thermal load on body (W/m^2)
m:	Body mass (kg)
M:	Metabolic heat production (W/m^2)
M_b:	Basal metabolic heat (W)
M_p:	Metabolic heat of posture (W)
M_a:	Metabolic heat of activity (W)
P_a:	Partial air vapour pressure (Pa)
P_w:	Actual water vapour pressure (Pa)
P_{sat}:	Saturated vapour pressure of pure water (Pa)
P_{aH2O}:	Water vapour pressure in ambient air (Pa)
P_{skH2O}:	Water vapour pressure in saturated air (Pa)
R_{cl}:	Insulation of clothing (m^2K/W)
S_i:	Area of surface i (m^2)
T_g:	Globe temperature (°C)
T_a:	Air temperature / Ambient temperature (°C)
T_i:	Temperature of surface i (°C)
T_{db}:	Dry bulb temperature (°C)
T_{op}:	Operative temperature (°C)
T_d:	Dew point temperature (°C)
T_n:	Indoor neutral temperature (°C)
T_{sk}:	Skin temperature (°C)
T_{cl}:	Clothing surface temperature (°C)
T_b:	Body temperature (°C)
T_{com}:	Comfort temperature (°C)
T_{rm}:	Running mean of external temperature (°C)
$\overline{T_{sk}}$:	Mean skin temperature (°C)
$\overline{T_{mr}} = T_{mr}$:	Mean radiant temperature (°C)
V_a:	Air velocity (m/s)
V_{ar}:	Resultant air velocity (m/s)
w:	Skin wettedness

Greek symbol

ϵ:	Globe emissivity
α:	Coefficient depending on relative air velocity
σ:	Stefan Boltzmann Coefficient (5.67×10^8 $W/m^2\,K^4$)
ϵ_{sk}:	Emissivity of skin ($=0.97$)
γ:	Sensitivity coefficient

Abbreviation

EMR:	exit matter reservoir
TER:	thermal energy reservoir
MER:	mechanical energy reservoir
PMV:	predicted mean vote
AMV:	actual mean vote
PPD:	predicted percentage dissatisfied
aPMV:	adaptive predicted mean vote
ePMV:	extended predicted mean vote

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