Energy Conservation in Buildings – a Review

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***Abstract*-The primary function of a building is to provide thermally comfortable environment to its occupants. A good indoor climate is important for the success of any building, not only because it will make its occupants comfortable, but also because it will decide its energy consumption, and thus influences its sustainability. A literature review of over 100 research papers, in four areas in the field of Energy Conservation in Buildings, i.e. (i) Climate Responsive Buildings, (ii) Analysis, Simulation and Modelling, (iii) Zero Energy Buildings and (iv) Thermal Comfort, were conducted in order to obtain a valid research topic. The findings of the literature survey is presented in this paper which include issue wise discussion, solution approaches used by various researchers, strengths, weaknesses and future scope of work in the four issues pertaining to energy conservation in buildings. Out of the several identified lag, it was felt that there was a dearth of field studies based thermal comfort research in India, which is essential for the correct definition of building codes. Proper building codes are required not only for providing comfort condition but also to conserve energy. Hence field studies based thermal comfort study was considered for further research study. Thus, this paper summarizes the researches about Climate Responsive Buildings, Analysis, Simulation and Modelling, Zero Energy Buildings and Thermal Comfort. It also concludes the methodology of these researches in above four fields, and gives further work suggestions.**

Keywords- Climate Responsive Buildings; Thermal Modelling; Zero Energy Buildings; Predicted Mean Vote; Thermal Comfort

I. INTRODUCTION

The major use of energy in a building includes lighting, heating, cooling, ventilation, etc. Energy is also consumed for the production of materials used to construct the building which is known as embodied energy and also the energy required to transport the construction materials from where they are produced to where they are used. With the increase in the global concern for energy and environmental issues, the building sector holds a tremendous potential for energy savings. Hence, energy conservation in buildings is the decrease in the use of energy for its construction, for its running and maintenance, by proper design and orientation, use of climatic conditions including passive and active features, use of more efficient equipments, inclusion of renewable and optimization of thermal comfort condition.

A literature survey of over 100 research papers in the four field of Energy Conservation in Buildings i.e., (i) Climate Responsive Buildings, (ii) Thermal Load Modeling in Buildings, (iii) Zero Energy Buildings and (iv) Thermal Comfort were conducted in order to obtain a valid research topic. The issue of Thermal Comfort was further sub divided into three sub issues – Climate Chamber Based Heat Balance Studies, Adaptive Thermal Comfort Based Field Studies and Other Models/ Control Systems for Thermal Comfort. The findings of the literature survey are presented in this paper. In Section II, we present the issue wise discussions on these four issues. Section III is based upon the solution approaches or methodologies used by various researchers on the above four issues. In section IV, we discuss the issue wise findings, and further scope of work in these four areas as found out from the literature survey work are presented in section V.

During the literature review, the issue wise solution approaches used by various researchers were studied, followed by the strengths and weaknesses in each solution approach was identified. The weakness provided the gaps in research in the above issues pertaining to Energy Conservation in Buildings. Out of the various identified lag, it was felt that there was a dearth of field studies based thermal comfort research in India, which is essential for the correct definition of building codes, required not only for providing comfort condition but also to conserve energy. Thus field survey based thermal comfort study was considered for further research work. The research is currently at the stage of field survey using ASHRAE class II protocols and aims to study the thermal comfort in the free running buildings of the Darjeeling Himalayan Region and to correlate the thermal comfort with altitude of the place. However, the findings of the research are not presented in this paper but shall follow.

II. ISSUE WISE DISCUSSION

A. Climate Responsive Buildings

Knowledge of the climate at a given place can help the designer build a house that filters out its adverse effects, while simultaneously allowing those which are beneficial [1]. The idea of climatically responsive energy efficient design is to modulate the conditions such that they are always within or as close as possible to comfort zone. The ambient conditions over twenty-four hours are usually outside the comfort zone for the majority of the time.

Depending upon the climatic requirements, solar energy can be used to provide space heating and/ or cooling in a building, with or without the use of a thermal storage medium.

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Space heating is of particular relevance in colder countries where a significant amount of energy is required.

For cooling, apart from proper orientation of the building, proper design of the shading devices like the overhangs specific features can be incorporated through a variety of methods depending upon the climatic conditions prevailing in a particular place.

B. Thermal Load Modeling in Buildings

Thermal load is the heat to be supplied or to be extracted from the interior of any building in order to maintain the desired comfort conditions. Thermal load in any building does not have any fixed value; and changes with variation in any of the many variables such as solar radiation outside, occupancy level, equipment being used inside, etc. The most vital thing that governs thermal load is the indoor conditions that one wants to maintain inside the building.

Several methods of load calculations available are classified as:

1) Approximate Methods:

These methods find out the average energy requirements of a building, and are helpful during the planning stage [2], like the degree day method, bin method, steady state method, Howdy Plot, etc.

2) Correlation Methods:

In this case, the thermal relationship of a building is expressed in terms of a correlation coefficient, expressing the solar energy fraction with the heating requirements [2] like the solar load ratio, load collector ratio, etc.

3) Simulation Models:

Various simulation models (software) based on finite element methods for solving heat conduction equation with appropriate boundary conditions [2] are available such as the Energy Plus, Trnsys, RetScreen, Hot2000, etc.

C. Zero Energy Buildings

A *zero energy building (ZEB*) is self reliant in the energy which it requires both for providing thermal comfort to the occupants and powering the various utilities within the building, thus it produces as much energy as it consumes yearly by renewable means (either onsite or offsite) [3]. However, due to mismatch in the timings of energy generation and utilization, energy is needed to be stored which is done usually in the form of chemical energy in batteries. The energy may also be stored as thermal energy which may be either sensible in the case of fluids like water, thermic fluid, air, etc. or latent in case of phase change material (PCM) like wax, hydrated salts, etc.

However, in a *net zero energy building (NZEB)* the storage both the electrical and thermal is eliminated, by connecting the renewable energy generated in the house with the two way grid system, where the grid acts as the electrical energy storage. In case of grid connection, when the production is excess of the demand, electricity is sent to the grid and when the demand is higher than production, electricity is drawn from the grid. In case of thermal energy (in cold countries) connection is made to a district heating grid.

D. Thermal Comfort

Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment” [4]. Thermal comfort standards are required to help building designers to provide an indoor climate that building occupants will find thermally comfortable. The definition of a good indoor climate is important for the success of a building, because it will not only make its occupants comfortable, but also decide its energy consumption, and thus influence its sustainability.

To analyze thermal comfort, various indices have been developed, such as Effective Temperature (ET), Resultant Temperature (RT), Wet-bulb globe temperature (WBGT), Equatorial Comfort Index (ECI), Heat Stress Index (HSI), Index of thermal stress (ITS), Predicted 4 hour sweat rate (P_4SR), Tropical Summer Index (TSI), Predicted Mean Value (PMV), Wind Chill Equivalent Temperature (WCET) and humidex [2].

1) Climate Chamber Based Studies:

Several Climate Chamber experiments were conducted on American and European subjects by P. O. Fanger in the early 1970s, and gave a thermal index which made it possible to predict the thermal sensation for any given combination of activity level, clothing, air temperature, mean radiant temperature, air velocity and humidity.

Subjects were laid in a controlled condition inside a climate chamber with provisions for the measurement of temperature of different parts of their body. Activity level and clothing level of these subjects were observed, and their thermal sensation votes noted. The measurement of the thermal sensation were done by using the seven points of the psycho-physical scale ranging from -3 (Cold) to +3 (Hot) with 0 as neutral, and hence, it is known as the *predicted mean vote (PMV)* [5]. Many of the international standards were based on the Fanger PMV like the ISO 7730.

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However, the limitations of PMV model are:

a. unnatural way of judging the thermal sensation through unnatural laboratory-type research, or the so-called ‘chamber methodology’;

b. non inclusion of cultural, climate and social contextual dimension of comfort in the engineering approach;

c. high level of dissatisfaction in air-conditioned office buildings which was more related to the expectation ‘culture and clothing norms’ and less on ‘current research methods’ of comfort standards.

2) Adaptive Thermal Comfort:

The climate chamber based heat balance model discussed above is unable to take care of various adaptive approaches the occupants take in order to make themselves thermally comfortable, and hence frequently either underestimates the thermal sensation in cold regions or overestimates the thermal sensation in warm region. Thereby, advocating for an often more higher set point temperature during heating in winters and often more lower temperatures during air conditioning in summer would be otherwise required by the occupants for achieving thermal comfort. This leads to a more consumption of energy.

The adaptive comfort theory was first proposed in the 1970s due to oil-shocks. The adaptive principle is explained as: if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort [6]. In real environment, people utilize various adaptive approaches freely according to their own thermal preference to achieve thermal comfort. Adaptation is defined as lessening of the human response to repeated environmental stimulation, and can be behavioral (clothing, windows, ventilators), physiological (acclimatization) as well as psychological (expectation).

Adaptive Opportunities are broadly classified as under:

Behavioral Adaptation: Behavioral adjustments include all actions taken by a person consciously or unconsciously, which in turn affects the heat and mass fluxes of the governing body [7]. Behavioral adjustment acts on three levels:

a. *Personal level:* These are actions taken by people on personal variables, like changing clothing level, changing activity level, changing posture, eating, drinking or moving to different locations. Some of the actions like changing clothing level, posture change the surface area of the body exposed to the ambient air, change in relative velocity of the air with respect to the exposed body surface, while some actions like eating, drinking or changing activity level changes the metabolic rate.

b. *Technological Level:* In this case, the surrounding environments are modified by opening/closing of windows, doors, switching on/off of fans, etc.

c. *Cultural adjustments:* It includes scheduling activity according to socio-cultural and traditional setup, including adaptation of various clothing as per social norms.

Physiological adaptation: It is the change that would result from long-term exposure to thermal environment factor which makes the occupant habituated [7]. They are either (i) generic, slow process and extends beyond the life of individual; or (ii) acclimatization, short period of time other than the occupants are habituated to.

Psychological adaptation: The effects of cognitive and cultural variable on the thermal sensation of the individual and the extent to which one’s perception and expectations are altered towards a thermal environment [7]. They are habituation, expectation and preferences.

In the adaptive approach to thermal comfort indoor comfort temperature is expressed as a function of outdoor temperature,

$$T_{comf} = A\ T_{a,\,out} + B \tag{1}$$

where T_{comf} = comfort temperature, $T_{a,\,out}$ = monthly mean outdoor air temperature; A, B = constants. This regression equation is formed by noting the comfort votes of the occupants during a field survey and measuring the corresponding temperatures, and the values of the coefficients are thus obtained.

3) Other Models & Indices for Thermal Comfort:

In addition to the two methodologies described above for studying thermal comfort, several other thermal comfort indices are used depending upon the climatic conditions and requirements, like Effective Temperature (ET), Wet Bulb Globe Temperature (WBGT), Equatorial Comfort Index (ECI), Heat Stress Index (HSI), Index of Thermal Stress (ITS), Predicted 4 hour sweat rate (P_4SR), Tropical Summer Index (TSI), Wind Chill Index (WCI) and Humidex.

III. ISSUE WISE SOLUTION APPROACHES USED

A. Solution Approaches in Climate Responsive Buildings

Raman et al proposed 2 solar designs, which can provide both heating during winter and evaporation based cooling during summer by incorporating a solar chimney for the necessary draft [10]. The model, however, is applicable only in dry climates

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where the evaporation based cooling is feasible, and is applicable only for a single storey building due to roof top air heater based ventilation system as well. Also, the evaporation based cooling is lesser efficient in maintaining comfort than refrigeration based cooling. He et al designed an experimental house with multi functional system that provide heated air during the winter, induced ventilation effect during summer day time by incorporating an exhaust stack and cooled dry air during night besides hot water and PV based electricity [11]. This method though devised for a hot and humid climate, passive cooling techniques as discussed may not guarantee thermal comfort in extreme hot and humid summer.

Serag-Eldin discussed the feasibility of using foldable roof top PV modules that remain horizontal to cover and shade the roof during the day, while unfolds to become vertical so as to expose the roof to lose heat by radiation during night [12, 13]. In extreme desert conditions, only shading the roof may not provide complete comfort, in addition the insulation on the roof, if of fixed type will not allow the roof to lose heat during night.

Guruprakash Sastry discussed radiant cooling/ chilled beam technology used in the Infosys Building in Hyderabad [14]. Radiant Cooling is an emerging technology where chilled water runs in the pipes embedded in the beams and slabs, which reduces the mean radiant temperature the occupants are subjected to, thus providing comfortable condition without the need for refrigeration. This will considerably reduce the energy required in cooling, however, the quality and quantity of water in the region need to be studied in detail. Beghi et al used MATAB/ Simulink to develop a model-based approach to design efficient control architecture called “Comforstat” for radiant heating/cooling systems coupled with fan-coil units with the main objective of increasing both thermal comfort for building occupants and energy saving [15]. Fong et al made a comparison of energy savings potential between the Hybrid Renewable Cooling System (HRCS) with either chilled ceiling (CC) or passive chilled beams (PCB) and Solar Absorption Cooling System (SACS), Ground Source Heat Pump System (GHPS) with the conventional Water cooled Vapour Compression Chiller System (VCCS) in a hot and humid climate of Hong Kong [16]. Though HRCS is more energy efficient than VCCS, it involves higher complexity and greater initial cost.

Thanu et al discussed the findings of an experimental study of the earth-air-pipe system in Gurgaon, India [17]. The constant temperature of earth throughout the year at 4-6 meters depth and its large thermal mass is used to provide cooled air during summer and heated air during winter by passing air through a buried pipe of certain length before its entry in the building.

Srikonda et al discussed the thermal behavior of integration of natural ventilation by thermal buoyancy in a building with inlet and outlet openings of different sizes and at different vertical levels at opposite walls in a non-air-conditioned building using Fourier Heat Conduction Equation [18]. Guiping et al presented the simulation of air flow with temperature distribution in a double skin façade of a building to enhance ventilation effect [19].

Tarigh et al presented the review work of various solar passive buildings [20]. Passive designs alone, however may not guarantee complete thermal comfort, especially in extreme weather conditions. Mohammad Arif Kamal reviewed various Passive Cooling Techniques - Solar Shading, Insulations, Induced Ventilation techniques, Radiative Cooling, Evaporative Cooling, Earth Coupling, Desiccant Cooling, and enumerated the importance of improving quality aspects, developing advanced passive and hybrid cooling systems, and finally, developing advanced materials for the building envelope [21]. Soni et al reviewed various Thermal Comfort Factors, Passive strategies - orientation, shading devices, thermal mass; active strategies - earth pipe heat exchanger, heat pump and found that Combinations of active and passive building control strategies are useful to conserve significant energy [22].

Niachou et al made experimental measurements of temperature of the roof and interior in buildings with and without green roofs, and did the thermal simulation for calculating yearly load calculations to quantify the thermal properties and yearly savings [23]. Castleton et al presented a literature review on Green Roofs, highlighting the situations in which the greatest building energy savings can be made [24]. Nwakonobi et al made an evaluation of a Modified Passive Solar Housing System for poultry brooding and found that the thermal energy required for chicken brooding could be supplied during the sunless hours by the thermal energy stored in locally made brick walls, which could not only save energy but also decrease mortality rate by improving hygienic conditions as compared to fossil fuel based systems [25]. Mithraratne et al made a Mathematical Modeling of Temperature and Solar Radiation in two models of house with different thermal mass location and different solar gains using Fourier series, and discretisation using finite difference method [26]. As in the case of any periodic signal, diurnal temperature fluctuation as it passes through a thermal capacitance, i.e. the thermal mass the output signal gets attenuated by a factor of $\sqrt{\{1 + (\omega RC)^2\}}$ and will be out of phase from the input by $\tan^{-1}(\omega RC)$. The thermal mass may be a poor insulator during night and its effect needs to be studied separately. Briga-Sa et al discussed the influence of the massive wall thickness, the existence of the ventilation system and the introduction of the external shutters in the thermal performance of a Trombe wall and found that the heat gains by transfer represents 20.89% of the global heat gains, resulting 14.49% from conduction, convection and radiation through the wall and 6.40 % from air convection due to the existence of ventilation system [27]. Morris et al made a field based experimental study of insulated roof and insulated ceiling for naturally ventilated buildings in Malaysia and found that both the pitch insulation and ceiling insulation lowers the daytime indoor temperature up to 0.8 ℃ and 0.6 ℃ respectively [28]. However, both have adverse impact at night. Li et al investigated the thermal performance in winter of thermal insulation composite walls in Beijing area by using response factor method and finite difference method and found that

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composite wall had a good energy saving effect for the heating of building in winter - by building 50 mm thick EPS board on the outside surface of the wall, the hourly heat transfer was reduced by 67.5% [29].

Zhong et al made a simulation study using EnergyPlus to obtain an optimum melting temperature and phase transition zone of the PCM for attenuating the indoor air temperature in a solar passive house located in Lhasa, Tibet [30]. The drawback is that, only those PCMs whose melting temperature is within the temperature range of the passive solar house can be used. Also, the difficulties involved with the installation and heat transfer is also a separate field of study. Castell et al made experimental cubicles set-up to test phase change materials with two typical construction materials (conventional and alveolar brick) for Mediterranean construction in real conditions and found that the PCM can reduce the peak temperatures up to 1˚C and smooth out the daily fluctuations [31].

B. Solution Approaches in Analysis, Simulation & Modelling

Kolokotroni et al made the simulations for urban heat island effect taking the east-west transect in the Great London using Energy Plus [32]. CCWeather Generation tool was used to obtain 2050 climate data for each site and simulations were done. He found that the heating load decreased as the office location moved from the rural area to urban area due to temperature rise caused by Urban Heat Island effect and in future years due to temperature rise caused by global warming, whereas there was an increase in the cooling load, overheating hours, CO_2 emissions for both the cases. Lisa Guann portrayed the implication of global warming on air conditioned office building in the Australian cities using statistical analysis methods, including the descriptive statistics, Pearson Product Moment Correlation (called Pearson’s correlation for short). Also, regression analysis was used to analyze the climatic database and to illustrate the characteristic of weather variables [33]. Based on the current and projected future climate data, the building computer simulation technique was used to simulate the interactions between buildings and surrounding weather conditions, in order to provide quantitative analysis of the building thermal and energy behavior in face of global warming and climate change and found that with the increase of annual average outdoor temperature exceeding 2˚C, the risk of overheating will increase. In this work, lighting energy requirement were not taken into account. A. Lilly Rose made analysis of climatic change pattern and related thermal comfort in the typical climatic pattern and recent years and found that the recent climate of the Chennai Metropolitan Area has turned out to be uncomfortable all through the year due to the effect of rapid urbanization [34].

Bruelisauer et al made experimental evaluation of the stack effect induced by the heat rejected from split type air-conditioners in a high rise building, with sensors located at specific heights and by using CFD simulations [35]. Though his work clearly showed the decrease in COP due to stack effect, however it needed to incorporate more dynamic conditions to evaluate the effects under different operational and environmental conditions. Also it was not clear how stuck and stack effect influence each other.

Davies et al conducted a UK based statistical study for unintended consequences, both known and presently unknown arising due to refurbishment and various energy conservation measures [36]. He found that rapid and large scale refurbishment programme had the potential to result in many unintended consequences both known but lesser understood due to their complexities and presently unknown.

White et al discussed a method to predict monthly building energy use from average monthly temperatures using Howdy Plot [37]. It is based on the fact that a straight line results when the difference between monthly heating and cooling loads are plotted as a function of average monthly temperature. In addition, the slope of this line is equal to the building’s conduction UA and infiltration heat loss coefficients of the building when normalized on per unit of conditioned floor area basis. Once, this line is made for a building, the monthly heating/ cooling load can be directly read out from the figure using desired temperature difference. However, it requires an initial input from a conventional simulation program to estimate the value of UA. Paul Littlefair reviewed a range of tools to predict solar access in obstructed situation like, simple angular criteria, angular zones, sun path diagrams, sunlight availability and solar gain diagrams, shadowing studies, model studies, solar envelopes and computer based methods like SHADOWPACK, TOWNSCOPE and GOSOL [38]. Veeraboina et al discussed the way to estimate solar radiation at a place from the monthly maximum and minimum temperatures using Hargreaves Equation, though the predicted solar radiation may vary due to variable weather conditions [39]. Boukhris et al discussed a numerical method to calculate Sunspot position and area inside a building [40]. However, it requires training in FORTRAN to develop such model that can run in time dependent manner. A.K. Singh, et al gave equations for determination of psychrometric properties, with any given two psychrometric properties of an air–water mixture by using perfect gas relationships [41].

Bakar et al simulated various thermal parameters using ECOTECT software and made comparison with measured values in two storey office building of University of Tun Hussein Onn Malaysia, Batu Pahat, Johor and found that the simulated indoor temperature were a litter higher than the measured temperatures [42]. Bhattacharya et al conducted simulation of Thermal parameters using ECOTECT for different windows location and size in a hot and humid climate and found that in order to increase natural ventilation, floor height of a building must be increased without being confined within the minimum restriction and increase number of window at different levels in the wall of the room [43]. Karmacharya et al used MATLAB/ Simulink to model HVAC system which could predict the temperature variation within the building and estimate the amount of energy required to get the comfort [44]. He also found that pattern of air temperature obtained from Matlab/ Simulink for the

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bedroom resembled that obtained from the Design Builder with difference of 1˚C at few points. However, Simulink model consistently under predicted the temperature of living room which was due to the heat coming from ground. Vaˇsak et al used model predictive control to fully take into account the current thermal conditions in the house and the 24-hours-ahead weather forecast and found that if the outside temperature was within the given temperature limits, there was no need to heat or cool the rooms as the temperature satisfy the wishes of the tenant [45].

C. Solution Approaches in Zero Energy Buildings

Hernandez et al discussed the Life Cycle Cost in Zero Energy Buildings taking Annualized Embodied Energy (AEE) and Annual Energy Used (AEU) expressed in terms of primary energy units [3]. For a Life Cycle Zero Energy Building (LC-ZEB), annualized Life Cycle Energy (ALCE),

$$ALCE = AEU + AEE = 0. \quad (2)$$

However, the technique requires both AEE and AEU to be converted in terms of primary energy units, which may not always reflect the true picture. Also the concept of LC-ZEB does not take into account aspects of the decision and policy making processes, such as the integration of other environmental and socio-economic aspects of building construction. Marszal et al made a comparison of various methodologies along with their pros and cons for use of metric balance, balancing period, and type of energy to be balanced, grid interaction in the calculation of Zero Energy Buildings [46]. However, neither Embodied Energy (EBE) nor economics of ZEB are considered in most of the demonstration projects. Satyen Mukherjee integrated several energy savings technologies with the building design to a single controllable system. He proposed two types of control loops controlling the LEDs and window blinds for day lighting and DC grid in buildings and made energy simulations to verify it with ZEB standards using Energy Plus [47].

Bansal et al discussed the embodied energy and construction costs for one, two, three and four storied houses of a particular typology, with different construction materials [48]. Bill of quantities required for foundation, masonry with cement plaster/rendering, and RCC roofing with earth insulation, parapet, plinth/ lintels bands, cement concrete flooring & skirting and earthquake resistant features were prepared. Total amount of EBE of the house were obtained by summing up the product of quantity of materials and their embodied energy values. Though, the cost and Embodied Energy based optimization of different design and construction material is provided, aesthetic value of the different constructions is a separate issue and needs to be incorporated.

D. Solution Approaches in Thermal Comfort

A good indoor climate is essential for a building, not only because it will make its occupants comfortable, but also because it will decide the energy consumption and thus the sustainability of the building, as it affects the amount of energy required to achieve comfort which might be in the form of cooling, heating, ventilating or even lighting. Indoor operative temperature, T_o or the set point temperature T_s is the temperature usually maintained with the help of these heating or cooling devices which consumes energy. Hence, proper thermal comfort standards as necessary for specific conditions are required to help building designers to provide an optimum indoor climate. This will not only keep the occupants in a comfortable condition, but also minimizes the use of energy required to achieve the comfort condition by avoiding overheating or overcooling than as required. In this regard, research papers on the issue of thermal comfort; both climate chamber based studies like the Fanger's Heat Balance Method and field studies based Adaptive Thermal Comfort were also reviewed. The following sub section discusses the solution approaches used by various researchers in this field.

1) Solution Approach in the sub issue of Climate Chamber Based Studies:

Bartal et al reviewed the experiments performed by Fanger to obtain the thermal comfort equation [49]. The experiments performed by Fanger were climate chamber experiments where no consideration of real time occupancy or adaptations of the occupants were undertaken. Fanger et al extended his PMV model to include expectancy factor, e, whose value range from 0.5 (for a naturally ventilated building) to 1 (for a fully air conditioned building) for use in non-air-conditioned buildings in warm climates, so as to decrease the overestimation which it made in comparison to the field survey methods [50]. He also accepted that the second factor responsible for his thermal balance method to fail was the adjustment the occupants made in their metabolism in uncomfortable environments in order to make them self comfortable, whereas his PMV model was based on a fixed metabolic rate.

Fanger et al conducted a Climate Chamber based study to determine the limits of asymmetric radiation to which man can be exposed without feeling discomfort and found that a radiant temperature asymmetry of 10˚C was found permissible at a cool wall, 23˚C at warm wall and 14˚C under a cool ceiling [51]. Sharma & Ali made a Climate Chamber based study and developed an equation for index of thermal comfort, called 'Tropical Summer Index' based on multiple regression analysis expressing the thermal sensation in terms of the environmental variables and obtained Tropical Summer Index (TSI),

$$\theta = 0.308T_w + 0.745T_g - 2.06V^{1/2} + 0.841 \quad (3)$$

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T_w is the wet bulb temperature, T_s the globe temperature and V the air velocity [9]. It was also found that the total incidences of discomfort was minimum between 27˚C and 28˚C and that two out of three assessments were likely to be comfortable at this level of TSI. Rina Maiti made a Laboratory experiment on 40 Indian male college students in Bangalore, for evaluating the effect of indoor thermal environment on occupants' response and thermal comfort [52]. She found that with -0.5≤Thermal Sensation Vote TSV≤+0.5, the comfort temperature range was 23.25 – 26.32˚C and neutral temperature, T_n of 24.83˚C. For 0.5≤Predicted Mean Vote, PMV≤+0.5 it was 22.46 – 25.41˚C and T_n 23.91˚C. For -1≤TSV≤+1, the comfort zone was 21.73 – 27.92˚C. Pasut et al conducted a Climate Chamber study on human subject tests for examining the cooling effect of a low-wattage ceiling fan on occupants when air comes from different directions with different speeds, using questionnaires and statistical analysis software R and found that in contrast to the oscillating fan, the configurations with the fixed fan showed an improved thermal comfort and a cooler whole body thermal sensation [53]. In terms of perceived air quality, almost all the fan configurations performed better than the still-air reference configuration.

2) Solution Approach in the Sub Issue of Adaptive Thermal Comfort & Field Studies:

Halawa et al reviewed the works in adaptive thermal comfort of researchers like deDear, Brager and thermal heat balance model researchers like Fanger and made a critical evaluation of foundation and underlying assumptions of adaptive thermal comfort [54]. Nicol et al discussed the adaptive thermal comfort along with its difference with the rational indices by reviewing the work of adaptive thermal comfort researchers like deDear, Brager, Nicol, Humphreys, and came to the conclusion that for a free running building, comfort temperature T_c depends on the outdoor temperature T_o [6]. Kwong et al reviewed and discussed some of the major thermal comfort studies and noted the importance of thermal comfort evaluation towards energy conservation improvement in tropical buildings [55]. He found that the present amount of work for tropical buildings is still scanty, and more work is required for development of adaptive comfort models.

Nicol et al discussed the methods used to develop the equation relating the neutral temperature, T_n to the outdoor temperature, T_o of the European Standard EN15251 applicable to buildings in the free-running mode [56]. Neutral temperature is that temperature which most occupants indoor find neutral, i.e., neither warm nor cool in ASHRAE 7 point scale. Fergus Nicol advocated the reasons for the thermal parameters based PMV's unsuitability to define thermal comfort [57]. He extended the Humphrey's Adaptive Thermal Comfort equations to include the air velocity and relative humidity varying locally. Humphreys & Nicol used Statistical Regression Analysis to study the behaviour of PMV and its discrepancies when used for predicting subjective thermal comfort votes of people indoors in normal life [58]. They found a high statistical significance ($t = 11.5$, $p<0.001$). PMV based on Fanger's climate chamber method yields biased prediction for operative temperature T_{oper}, relative humidity RH, air movement, clothing insulation, metabolic rate, and also with respect to the outdoor ambient temperature T_{out}. deDear & Brager used the data of ASHRAE RP 884 to discuss the inclusion of adaptive comfort standards (ACS) in ASHRAE Standard 55 [59]. They found that in the HVAC buildings, PMV was successful at predicting comfort temperatures, however in naturally ventilated (NV) buildings the PMV model often overestimates or underestimates the thermal comfort.

Alfano et al discussed the Main Criteria for the design and assessment of thermal comfort in order to help building, and HVAC system designers and operators to navigate the complex and varied world of standards for improving indoor environmental quality and energy savings [60]. He found that measurement errors due to poor metrological performances of instruments, wrong measurement protocols can result in significant mistakes when PMV values are in the range between -0.20 and +0.20 and also the uncertainties due to the evaluation of the personal parameters metabolic rate and basic clothing insulation are very significant.

Raja et al conducted a field study of the thermal comfort of workers in naturally ventilated office buildings in Oxford and Aberdeen to understand the use of controls in NV buildings and found that in NV buildings, in summer the proportion of people recording discomfort is strongly correlated with the number of people using controls [61]. Sourbron et al simulated using TRNSYS and investigated whether, for a moderate climate and with the heating and cooling set points chosen according to the adaptive models, the building's energy use reduces or not and found that ASHRAE55 and the ISSO74 adaptive thermal comfort models do not result in energy savings, for a moderate climate and for office buildings with a cooling load throughout the year and it can be concluded that applying these adaptive thermal comfort models does not offer benefits compared to the basic non-adaptive thermal comfort model of ISO7730 [62]. Castilla et al presented a comparison among several predictive control approaches that allow for obtaining a high thermal comfort level optimizing the use of an HVAC system by means of different cost functions [63]. Mors et al [64] conducted a Field Survey and Statistical Analysis to investigate the thermal comfort and thermal comfort parameters for children in non-air-conditioned classrooms in three different primary school in Eindhoven, the Netherlands and found that PMV method underestimates thermal sensation for children, with an error largest in summer with underestimation ranging from 0.5 - 1.5 scale points at reference temperature, $\theta_{e, ref}$ of 15 - 25˚C.

Indraganti et al made field studies of actual thermal conditions and occupant responses in both naturally ventilated and air conditioned office buildings in Chennai (13˚04'N, 80˚17'E) and Hyderabad (17˚27'N, 78˚28'E), in order to develop custom made comfort standards, that was not possible by Fanger's predicted mean vote model [65]. However, such field studies require extensive monitoring in large scale over a long period of time encompassing seasonal changes. Inconsistencies in efficiencies of equipments & architectural and structural factors may affect the occupants' adaptive opportunities. Singh et al

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made a field survey to develop adaptive thermal model based Actual Mean Vote (AMV) and Thermal Balance Model based (PMV) for three different climatic zones of North-East India and developed an adaptive coefficient which could relate the survey based comfort votes and Fanger's PMV [7]. Again, in such field survey method it is necessary to carry out extensive experiments cross the different climate zones throughout the year, and only then it will be possible to calculate more accurate values of the adaptive coefficients. Singh et al reclassified the bio-climatic map of north-east India into warm and humid, cool and humid and cold and cloudy zones [66]. However, since, there were only 30 meteorological stations across the entire north-east India, and scarcely placed, it is quite obvious that there could be places with distinct microclimate. Singh et al made a field study at two different bioclimatic zones of North-East India, one at Tezpur, Assam - warm & humid and the other at Cherapunjee, Meghalaya cold & cloudy climate to study the thermal behavior of the vernacular houses in the region and developed formulas to predict indoor maximum temperature, average temperature, indoor minimum temperature from outdoor maximum, minimum, average, etc. for the two buildings that were monitored [67]. This methodology for generating the formulas used in the paper cannot be generalized. It is applicable for specific building that was monitored or similar set up only.

Yatim et al conducted a field survey and used statistical analysis of the thermal comfort in classrooms and lecture theatres of University Technology MARA, Puncak Alam, Malaysia and found that 76% individuals felt 'slightly warm', 'warm' and 'hot', while 66% individuals responded similar vote for lecture theatre, 2% voted for uncomfortable in both [68]. PMV was -0.05 & -0.62, PPD was 7.96% & 20.7% while TSV votes were -1.16 & -0.96 for the two types of buildings. Han et al conducted a Field Survey and regression analysis to study thermal comfort inside residences in the sub-tropical hot and humid region of Changsha, Guangzhou and Shenzhen, China [69]. His study indicates that the use of the house average operative temperature with the Fanger model over estimates the observed percentage of occupants who find their thermal environment unacceptable. Luo et al made a longitudinal field study and regression analysis in a mixed-mode (MM) building in Shenzhen, China where mechanical air conditioning and natural passive cooling coexist in the same case building [70]. Results of this study supported the idea that occupants' actual thermal sensation and acceptance of thermal conditions varied when the building changed from AC mode to NV mode, or vice versa. Indraganti et al conducted a Field survey and Statistical Analysis in four office buildings in Tokyo for three months in summer 2012 to study the relevance of prescribed set point temperature of not less than 28˚C in summer [71]. Harahap et al conducted a Field Study to understand the current condition of thermal comfort elements in urban low-cost apartment buildings in Shah Alam, Malaysia and found that the most comfortable indoor temperature was located at the lower floors whereas the most comfortable RH and air speed was found at the upper floors [72]. Bravo et al conducted field surveys for determination of thermal comfort in the Bioclimatic Prototype Dwelling (VBP - 1) in the middle of a slum in Maracaibo, Venezuela [73]. Hussein et al made a Field Study and Regression Analysis to study the environmental conditions and occupant comfort in air-conditioned buildings and non-air-conditioned buildings in Johor Baharu, Malaysia [74]. He showed that respondents in the tropical environment such as Malaysia may have a higher heat tolerance since they accepted the thermal conditions which exceeded the recommended standards. Ismail et al conducted a field survey and statistical analysis to study the thermal environment and investigated occupants' perception of the accepted level of thermal comfort in two natural ventilated pre-school building in Shah Alam, Malaysia [75].

Mishra et al conducted a field survey in an experimental laboratory at Kharagpur, India to assess how the occupants perceive their thermal environment in a free running building while carrying out their normally scheduled tasks and obtained a neutral temperature of 26.4˚C and comfort zone of 21 – 31.9˚C based on the TSV of the respondents, both of which are much higher than as prescribed by Indian Building Codes [76]. Hence opportunities for energy conservation exist. Shengxian et al conducted a 3 day field survey and regression analysis of indoor thermal environment taking two set of student flats in Qujing Normal University, Yunnan Province, China and developed thermal comfort correlations that were suitable to local climate [77].

Madhavi Indraganti made a thermal comfort survey in 45 apartments of Hyderabad (17˚27' N, 78˚28'E), India in 2008 and collected 3962 comfort responses and the use of controls of over 100 occupants in summer and monsoon months using ASHRAE Class II protocol [78]. She recommends that the local building codes may think of bringing in necessary additional provisions, in the form of structural controls and additional semi-outdoor spaces in roof exposed flats. This is to maintain thermal neutrality at high temperatures, which hinges on the adaptive use of various controls. Deuble et al made a field Survey and regression analysis to investigate how mixed-mode (MM) ventilation affects occupant comfort in Sydney, Australia and came to conclusion that adaptive comfort model was found to be applicable to the MM building, especially during times of natural ventilation, which will not only provide the appropriate conditions for thermal comfort but will also save energy [79].

Wei, et al made a field study and used genetic algorithm (GA) to find adaptive Predicted Mean Vote (aPMV) model and found out the adaptive coefficient for Beijing [80]. He found that the population size of genetic algorithm was 100, cross over rate of 0.8, and mutation rate of 0.2. The value of adaptive coefficient, λ obtained for Beijing climate were 0.285 for summer and -0.136 for winter conditions. Cao et al made a field study and regression analysis of human thermal comfort and thermal adaptability in summer and winter in Beijing, China [81]. He found the existence of "scissor difference" between the PMV and the TSV with different climatic conditions and obtained the neutral temperature. Luo et al conducted a field Study in Beijing and Shanghai, China and Regression to test the hypothesis that people with a higher degree of personal control tend to accept a wider range of indoor thermal environments [82]. His findings offered good support for the hypothesis in the adaptive model proposed by researchers like de Dear and Brager, Nicol and Humphreys that occupants with more opportunities of personal

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control tended to have closer match of indoor neutral temperatures with outdoor climates. Zhaojun Wang conducted a Field study and regression analysis during the winter months, in order to investigate the thermal environment and thermal comfort in residential buildings in Harbin, China [83]. The comfort temperature in all those field studies was close to the mean air temperature, which suggests that the subjects are good in adapting with the temperature of their surroundings. Junjie et al used Field Studies, Regression analysis, SPSS, ANN for studying relationship between thermal comfort and other environmental parameters in Chenghai District, Shantou City, China [84]. The results proved that modeling of indoor thermal sensation by neural network in natural ventilated houses of sub tropical region was possible and accurate.

Shen et al conducted a field survey and used statistical analysis to find correlation between comfort votes, i.e. THERMAL SENSATION VOTES (TSV), adaptive Predicted Mean vote (aPMV) and the Predicted Mean Vote (PMV) [85]. He established the adaptive thermal correlating equations for the Sichuan Province, China and calculated the adaptive coefficient value for the region, $\lambda = 0.334$ (summer) and -0.196 (winter). Wang Ye conducted a Field Study including thermal and environmental parameters thermal parameters of a big internet bar to know the Indoor Air Quality and thermal comfort of public entertainment place in Lanzhou, China [86].

Yao et al conducted a Field Survey, Regression Analysis, Least Square Method, Cybernetics Concept to study Theoretical adaptive model of thermal comfort based on the “Black Box” theory in Chongqing, China and explained the phenomena of discrepancy of the results between the field surveys and rational indices based on the cybernetics concept [87]. Yiyun et al conducted a Field Survey and Statistical Analysis to analyze the influential factors of indoor thermal environment of rural architecture in Yinchuan region, North Western China and found that 45% of the occupants felt uncomfortable [88].

Soebarto et al conducted a Field Survey & Statistical Analysis to investigate occupants’ thermal comfort and responses during summer period in a low to middle income housing development in Adelaide, South Australia and suggested that the current assumption in Australian Nation-wide Home Energy Rating Scheme – NatHERS which prescribes cooling at or above 25˚C for all spaces need to be revisited [89].

Al-Awainati et al. conducted a field study, parametric study on the thermal comfort and cooling performance of residential buildings in the hot arid climatic conditions in Doha, Qatar and showed a significant reduction in the total loads and the energy costs reduced by around 10.5% in the alternative design as compared with the case study [90]. Andersen et al conducted online survey and questionnaire in Danish dwellings and found that females opened the window more often when perceived illumination was dark, whereas the window opening behaviour of males was not affected by the perceived illumination [91]. Kariminia et al made a study on outdoor thermal comfort in a temperate and dry climate based field survey conducted in Esfahan, Iran and found that the percentage of people feeling neutral (TSV = 0) was highest (43%) with 84% of TSVs within the three central categories, preference was there for little more wind and higher humidity level [92].

3) Solution Approach in the Sub Issue of Other Models & Control Systems for Thermal Comfort:

Hoes et al discussed the User Behaviour and Building Robustness in Building performance assessment using USSU (user simulation of space utilisation) + SOCC (sub hourly occupancy control) + ESP-r (building energy simulation software) [93]. His work is an attempt to give guidance for an improved representation of user behavior in building performance assessment.

Liu et al quantified the physiological, behavioral and psychological portions of the adaptation process by using the analytic hierarchy process (AHP) based on the case studies conducted in the UK and China [94]. However the method requires respondents with adequate knowledge or relevant professional background.

Sicurella et al compared various thermal and visual comfort indicators using statistical approach for the combined evaluation of thermal and visual comfort in buildings [95]. The method requires hourly operative temperature and hourly average daylight illuminance to manage a visual and thermal comfort analysis. McCartney et al discussed the theory behind the adaptive control algorithm (ACA) and the findings from an EU-funded research project, smart controls and thermal comfort (SCATs) to develop control system based on ACA [96]. He found that ACA was a more representative (correlation 0.383) of the thermal comfort, than PMV (correlation 0.250).

Rana et al made a comparative study based on publicly available data spanning 7 different climate zones across 3 continents to ascertain suitability of using Humidex as an indoor thermal indicator [97]. In summer when humidity is high, humidex performs approximately 20% better than temperature, however, in winter season due to reduced humidity, humidex does not perform as good as temperature.

Spasokukotskiy et al made thermodynamic modelling using Finite Difference Method for measurement of a HVAC control, a new variable based upon model-based estimation of thermal comfort, which allows the determination of distributed and geometry related physical values like temperature, radiation, etc. without interfering the occupants [98].

Bin et al used Gaussian Process Regression based on Bayesian Method and MATLAB to determine PMV [99].

Zheng et al. conducted simulation using computational fluid dynamics (CFD) to determine the thermal comfort and indoor air quality of the task ambient air conditioning in a modern office and found that the temperature of the workplace with task conditioning was much lower (2 - 3˚C) than at other areas [100]. Chun-Cheng et al performed simulations using CFD, Airpak

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and modeling using neural network and found that the increased local airflow in the form of desk-side air outlets can considerably raise human thermal comfort level [101].

Li et al used neural network based on Fanger's PMV to develop a new type of air conditioning control mode, which takes thermal comfort index as the control parameter and achieved the desired goal and got a more accurate data [102]. Liu et al used experimental data and artificial neural network for study of human thermal comfort model that correlates the effects of pressure variation [103]. Songuppakarn et al used artificial neural network, NARX to model and to determine the thermal comfort level for an air conditioned space in an academic classroom and found that predicted values of the PMV (predicted by NARX) agreed well with the PMV values from Fanger's model and from the questionnaires [104]. Ferreirra et al showed experimentally that an artificial neural network (ANN) can estimate the PMV index with varying degrees of efficiency over the trade-off of accuracy versus computational speed-up [105].

Aoki et al used model of Bayesian networks and its experimental simulation to analyze the causal relationship between thermal comfort and the related factors and found that although the thermal sensation change and thermal sensation for face are important when the comfort evidence is GOOD, those for buttocks are important when the comfort evidence is BAD [106].

Cigler et al developed a computational tractable approach for solving PMV based predictive control optimization problem and found that further 10% energy can be saved compared to typical model predictive control (MPC), while keeping the comfort within the range defined by standards [107]. Zhu et al presented an intelligent control system based on artificial immune system architecture to maintain the thermal comfort while reducing energy consumption [108]. The experimental results show that by employing this intelligent system, the inside air temperature can be more stable and thus more comfortable than the two-position control and it consumes less energy than PI control.

Kon developed TY4700 thermal comfort sensor for indoor comfort control [109]. Min Wu developed an intelligent agent system based on personalized thermal comfort equation to co-ordinate thermal comfort and energy consumption using bodybugg arm band to monitor skin temperature and sweat secretion, sensors for occupancy, internal and external illumination, internal and external temperature, actuators of heating lighting and blinds and reliable means for identifying different users [110].

Cigler et al used simulations (TRNSYS-MATLAB) to optimize predicted mean vote (PMV) index which, opposed to the static temperature range, describes user comfort directly as against MPC [111]. It was seen that when using the same class of ISO norms, the proposed approach consumes 11% less energy than its alternative and at the same time satisfies thermal comfort at almost all instants. Prívara et al used model predictive controller (MPC) to control the temperature of real building and proved the supremacy of predictive controller over a well tuned weather compensated control, with the savings of 17 - 24% and the MPC discussed is able to track the desired temperature accurately [112].

Walek et al used adaptive fuzzy control based on IF-THEN expert system (knowledge base) for heating control in smart house [113]. Bermejo et al developed a system which is capable of adapting to the user's thermal preferences without any prior knowledge, and measuring his comfort level by aggregating several thermal parameters into one single thermal index using wireless sensor networks (WSN) and adaptive fuzzy logic [114]. Duan et al developed a fuzzy control strategy of the indoor temperature while maintaining the occupant's thermal comfort is presented using the concept of the predicted mean vote (PMV) index [115].

Lovin et al used Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) programming software for PMV and PPD calculations inside a vehicle [116]. Chaudhry et al used adaptive one step ahead and an adaptive weighted one step ahead controller for controlling the indoor air temperature of a building modeled by a bilinear system [117]. Donaisky et al proposed two predictive strategies proposed - first generating a temperature set-point signal that optimizes the building internal PMV value and second the controller prediction computations, generating a non linear PMV model having Wiener Structure [118]. Xie et al used numerical simulation and experiment investigation to predict air flow pattern and human thermal comfort environment [119]. He found that different air distributions had great effect on thermal comfort on the same air-supply rate, also would be dominantly influenced by location of inlet/ outlet.

Chu et al used least enthalpy estimator (LEE) which utilized the concept of thermal comfort and theory of enthalpy to provide a suitable setting on the effective temperature line for use by HVAC control system [120].

IV. ISSUE WISE FINDINGS

A. *Findings in Climate Responsive Buildings*

Different methodologies were used by researchers for improving thermal comfort or reducing energy consumption in a Building.

a. Solar Ventilation based heating and cooling;

b. Evaporative Cooling;

c. Roof top foldable PV modules;

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d. Radiant Cooling;
e. Earth-Air-Pipe System;
f. Absorption Cooling;
g. Enhancement of Natural Ventilation;
h. Green Roofs;
i. Phase Change Materials;
j. Thermal Mass;
k. Trombe Wall.

The solar ventilation and evaporative based system for composite climate of Delhi [10] helped in maintaining the winter temperature above 4˚C and the summer temperature below 2 - 3˚C than the reference room. The indoor temperature remained at about 30˚C even when the ambient temperature went up to 42˚C. The experimental house in warm & humid climate of south China [11], which used solar ventilation based exhaust combined with variety of other methods. Measurements showed that the rooms could be kept 4˚C cooler if windows were opened all day.

The foldable PV module that was used in a desert environment [12, 13], helped in reducing the roof temperature towards midnight, mainly due to the infra-red radiation exchange with the cooler sky after sunset and the electricity generated from the PV which was stored in batteries could provide the energy requirements, including the air conditioning load of 6 occupants and their activities.

The radiant cooling system used in the Infosys Campus, Hyderabad [14] lowered the cooling loads from 440000 units to 269000 units, thus with 33% of energy savings.

The earth-air-pipe system used in Gurgaon [17], cooled the air temperature by 8.3˚C in summer. The delivery temperature remained 30.1˚C even when the maximum ambient temperature reached 44.9˚C, while in winter the same system heated the air from 15.3 to 19.3˚C.

In comparison to the conventional vapour compression chiller system (VCCS), the hybrid renewable cooling system (HRCS) with chilled beams (CC) had year-round energy savings of 37%; the HRCS with passively chilled beams (PCB) had 52%; the solar absorption cooling system (SACS) had 31%; and the ground source heat pump system (GHPS) had 43% respectively [16].

Passive ventilation with slit above window was discussed [18]. It was found that the window area of 3 m^2 with 0.3 m^2 of slit/ ventilator area can decrease the temperature to 4.5˚C in summer season and contributes to thermal comfort conditions.

Researchers in green roofs [23, 24], found that in case of non insulated buildings, the indoor temperature was from 28 - 40˚C for buildings with green roofs while 42 - 48˚C without green roofs. It was deduced that the indoor comfort conditions in the building with green roof was improved by 2˚C, and the daily temperature fluctuation was only 4˚C for buildings with green roofs whereas 7˚C for buildings without green roofs.

The optimal value of melting point temperature of the PCM, i.e. T_m was found to be different for different month because the indoor temperature of different month was different [31]. PCM effectively saved the temperature swing and improve the indoor thermal comfort level.

B. Findings in Thermal Load Modelling in Buildings

It was seen that there existed a near linear correlation between the increase of average external air temperature arising due to urban heat island, global warming, and increase of building cooling load and total energy use [32]. This increase of cooling load is mainly due to the extended operation hours of air conditioning systems, which vary from 2% to 47% depending on the future climate scenario and location. In Chennai - the rate of temperature increase in the daytime is lesser in the rural station (0.002˚C/year) than in the city station (0.06˚C/ year) [34].

In case of study on effect of microclimate on split type condensers [35], the inlet temperature at the condensing units were seen to rise in a high rise building due to stack effect, and consequently the COP decreased. Unintended consequences, both known and presently unknown arises due to refurbishment and various energy conservation measures.

A non homogeneous temperature distribution is in the region of the first room where the sunspot fell was seen as against the conventional assumption of building software to assume a uniform temperature everywhere [111].

C. Findings in Zero Energy Buildings

Embodied energy was found to be highest for a single storied construction, irrespective of the construction materials used and lowest for two storied house [48]. The building construction with hollow cement concrete blocks had the least EBE and that by fire clay brick had the highest in all the four cased of housed considered (1, 2, 3 and 4 storied). Construction costs were significantly high for fired clay brick and HF fly ash constructions, and lowest for aerated autoclaved (AAC) blocks. No linear

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relationship was seen of embodied energy value, either with the construction cost per m2 plinth area or with the cost of construction.

The embodied energy of the houses can be reduced up to 40% than that for fired clay brick construction, by using appropriate building materials, and cost of construction can be reduced up to 20%.

D. Findings in Thermal Comfort

1) Findings in the Sub Issue of Climate Chamber Based Studies:

The mean skin temperature of thermal comfort declined as the activity level increased [51].

The expectancy factor, e whose value range from 1 to 0.5, 1 for air conditioned building and 0.5 to completely free running building, is multiplied with the PMV to get the corrected value of PMV [50].

Accepting that 5% of subjects may feel uncomfortable, a radiant temperature asymmetry of 10˚C was found permissible at a cool wall, 23˚C at warm wall and 14˚C under a cool ceiling [51].

Head was found more thermal sensitive, and hence the heat dissipation through head was significantly higher with the normalized body surface area than any other body region.

Under the tested conditions, a fixed-fan that directs air over a human body at a velocity between 0.8 and 0.9 m/s had a positive and statistically significant effect on users' thermal comfort and thermal sensation [53].

2) Findings in the Sub issue of Adaptive Thermal Comfort & Field Studies:

It was seen that the presence of air movement can be equivalent to a reduction in temperature of as much as 4˚C. In moist environment, people become uncomfortable with a smaller change in temperature than in dry environment.

In NV buildings, in summer the proportion of people recording discomfort is strongly correlated with the number of people who use the fans or windows, which implies that the controls are used in response to uncomfortable conditions [61]. Occupants with more personal control approaches had lower motivation to change their current thermal environment. It was seen that the females opened the window more often when perceiving the environment as bright as compared with dark, whereas the window opening behaviour of males was not affected by the perceived illumination.

The PMV model failed to predict thermal comfort when a mixed mode building run a NV mode. Adaptive comfort model was found to be applicable to the MM building, especially during times of natural ventilation [79].

The respondents in the tropic environment such as Malaysia [68] might have a higher heat tolerance since they accepted the thermal conditions which exceeded the standard.

Availability of controls and their appropriate use is the key to a better performance of the building and for improving occupant satisfaction. Fans being important and successful adaptation mechanism in both NV and AC offices, an opportunity to introduce higher air movement in Indian buildings [65] to improve both energy and comfort performance, exists.

3) Findings in the sub issue of Other Models & Control Systems for Thermal Comfort:

Humidex performed better than humidity in five climatic conditions, i.e., tropical savanna wet, humid subtropical summer, semi arid high altitude summer, west coast Marian summer and Mediterranean summer [97].

$$\text{Humidex} = T + 5/9\,(e - 10) \tag{4}$$

Where $e = 6.112 \times 10^{(7.5T/(237.7 + T))} \times H / 100$, T = temperature in degree Celsius, H = relative humidity.

The temperature of the workplace with task conditioning was much lower than those of other areas. Around the task air supplying region, the temperature were 2 - 3˚C lower than the surrounding [100]. The results of simulation and experiments indicated that the ventilation efficiency and human comfort would be dominantly influenced by location of inlet/ outlet. With different cases, occupants had a significant effect on the airflow, while the airflow in the room was highly influenced by persons and furniture present in the room space as well as inlet/ outlet configurations.

Compared with SVM and BP network model, the prediction mean absolute error and mean square error of Gaussian regression are smaller, and the dispersion degree between predicted value and real value were much smaller [99].

It was seen that a person feel uncomfortable if it was too warm in the buttocks. Also it was seen that the buttocks is usually cold and cannot be warmed easily [106].

V. FUTURE RESEARCH SCOPE

During the literature survey process, several gaps in the published research work were found, and based on those gaps future scope of research in the four field of energy conservation in buildings were identified.

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In Climate Responsive Buildings, further research can be done to design passive cooling concepts, which can provide a higher degree of thermal comfort in hot and humid climate and completely remove the need for air conditioning. Studies that can help to develop climate responsive buildings which are cost effective are also needed. Feasibility studies and design of different renewable energy use, like bio-energy for auxiliary heating of solar absorption cooling, can be taken up. Further experimental work can be done in Trombe wall, especially to determine the temperature fluctuations along the different layers, heat fluxes and delay in the return of heat. Research can be done to increase the range of melting point of the PCM to be used in a solar passive house which can improve the performance and utility of solar passive house. Studies can be undertaken for the development of passive designs including ventilation that is suitable for multi storey buildings. Development of less costly and lesser complex movable insulation and foldable PV designs that can be incorporated in roof tops of desert climatic is also needed. Study on applicability of radiant cooling, water quality and quantity in an area can be taken up. Studies can also be done for improvement of COP in absorption based cooling. Further studies can be done on the development of green roofs and the type of vegetation on it. Studies on integrative high-performance systems, such as heat rejection for high performance buildings through a centralized system like standard split-type condensing units being water cooled which plug into a centralized water based heat bus system that connects to an evaporative cooling tower can also be taken up as a research topic.

In the issue of Thermal Load Modelling in Buildings, simulation as well as experimental work can be done for prediction of energy consumption on the basis of UHI and global warming applied to other cities where data exists to generate weather files within the city and projections on future climate scenario. Inclusion of zoning method for the prediction of overheating risk and work performance in future energy modelling of a building can be of relevance. Further research can be done on ranking the viability of various potential mitigation and adaptation strategies on the face of climate change upon the possible impact on the energy use and indoor temperature, life cycle emission reduction, economic and social aspects. Studies can be taken up on the extent of microclimatic effects for the design of energy-efficient buildings. Studies on the development of methods that can provide more information about the resulting solar gains, particularly computer tools apart from solar access can be taken up. Projects are needed for the development of building energy simulation freeware that incorporate the features of embodied energy, life cycle energy, non quantifiable parameters like aesthetic value and which is user friendly too with lesser amount of technical details required as input from the user. Incorporation of embodied energy, life cycle energy cost, methods to weight different non quantifiable parameters like aesthetic value, cultural requirements in a single model may also be taken up as a research topic. A more detailed study can be done on unintended consequences of energy savings and methods to anticipate them. Studies taken to develop easier numerical ways of determining energy loads in a building with fewer input parameters can help building designers. Research is needed for the development of easier method to determine factors like sunspot inside a building from a façade and their effect.

In case of Zero Energy Buildings, further studies are needed for the development of calculation methodologies in embodied energy and zero energy buildings, which is compatible with a wider range of energy units. Studies can be done on the LC-ZEB, taking into account aspects of the decision and "policy making" processes such as the integration of other environmental and socio-economic aspects of building construction. Studies related to detailed data on life cycle of building products and systems to improve the accuracy and applicability of LC-ZEB is needed. Studies can be done for the development of commonly agreed ZEB definition framework and a robust 'zero' calculation methodology which can allow for a variety of solution sets and does not focus only on PV based solution sets, mainly for addressing small and new buildings. Studies can be done on the economics of zero energy buildings. Further studies can be done for development of easier way of grid connection of a zero energy building. Research can be done for the development of more efficient, robust and cheaper storage medium (batteries) for use in zero energy homes. Studies can be taken up, to develop ways for increasing the efficiencies while conversion of generated energy into DC and back to AC. Development of more detail but simpler methods to include the life cycle energy in assessment of zero energy buildings, can also be undertaken.

In the area of thermal comfort, research can be done for the development of inclusion of non climate chamber based thermal sensation measurements in the thermal parameters based PMV model. Research can be undertaken for decreasing the level of dissatisfaction in air-conditioned office buildings by the inclusion of expectation 'culture and clothing norms' and other adaptability. Development can be done in widening the range of applicability of the PMV model. A more detailed study can be done on the effect of relative air velocity and mean radiant temperature on the adaptive thermal comfort. Study is required for the development of experimental correlation between metabolic rate and clothing insulation to the outdoor temperature. Studies can also be done for the development of expression of the indoor comfort temperature as a function of the outdoor temperature by considering the conventional thermal comfort factors used in the heat balance approach. Studies aiming at the improvement of thermal comfort of zone in centralized air conditioned rooms such as hotels or office buildings can be undertaken, keeping purview of adaptability. Studies related to the inclusion of comfort parameters in the adaptive comfort charts of ANSI/ASHRAE standard-55 can be started. Studies are required for the development of thermal balance models that not only are easy to calculate, but also those which include adaptations of the occupants. Further development of Fanger's heat balance model to include adaptations of occupants, unlike the expectation factor which is again a measure from field surveys can be done. Studies for the inclusion of parameters like air velocity, humidity, etc. in the field survey based adaptive comfort equation in the thermal comfort equations may be initiated. Field Survey at various places can be undertaken to develop the regression based adaptive thermal comfort equations for the specific places incorporating parameters like microclimate, ethnicity, culture, etc. Studies can be undertaken to develop adaptive comfort equations that are more general or

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which can be applied to a wider spectrum. Studies can be also done for development of easier method to weigh the three different occupant adaptations, i.e. behavioural, psychological and physiological. A more robust and simpler mean to compare and improve thermal and visual comfort together is also needed.

VI. CONCLUSION

During the literature review process, the issue wise solution approaches used by various researchers were studied followed by the advantages and shortcomings of each solution approach was identified. Several gaps were identified in the published research after going through over 100 research papers in the four category of building energy conservation. It was felt that there was a dearth of field studies based thermal comfort research in India, which is essential for the correct definition of building codes. This is required for not only providing comfort condition but also conserving energy. It was also noted that, many thermal comfort based field study were conducted, mostly in China and a few in India by researchers like Madhavi Indraganthi, Manoj Kumar Singh, etc. However, Indian studies were confined to few cities of Hyderabad, Chennai and North East India, and there is a dearth of thermal comfort studies in India.

Hence, in order to study thermal comfort in the diverseness of socio-economic factors like culture, tradition and ethnicity, and also to understand the impact on thermal comfort of residents due to temperature differences arising out of change in altitude, a research is taken up to study the thermal comfort behaviour of residents in free running buildings in Darjeeling Himalayan Region using ASHRAE Class II protocols and is currently at the field survey stage. Though the outcomes of the research work is not presented in this paper but shall follow, the research aims to obtain the neutral temperature (T_n), adaptive coefficients and the comfort range for occupants living in a free running building in the region using ASHRAE class II protocols.

We anticipate the findings from our research shall be of use to building designers and architects in the region as well as in the similar regions elsewhere, for the design of thermally comfortable buildings within the passive norms for energy conservation.

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