Thermal Behavior of Naturally Ventilated Buildings and their Energy Consumption

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Abstract—**Human behavior towards energy consuming devices is guided by the thermal comfort of the built environment. Many studies have shown that thermal discomfort leads to higher energy consumption of a building. Achieving thermal comfort is a challenging task especially in naturally ventilated buildings. In this paper, field survey of exiting naturally ventilated buildings was performed to analyze their thermal behavior as per the adaptive model of thermal comfort by ASHRAE. The key findings hint that measures are required to improve the thermal comfort of the existing naturally ventilated buildings and thereby improving the energy consumption.**

Keywords— ***Thermal Comfor; Energy Efficienc; Building Envelope; Adaptive Comfort Standard***

I. THERMAL BEHAVIOUR AND ENERGY USE OF BUILDINGS

Thermal comfort is a subjective sensation which is defined as "that condition of mind which expresses satisfaction with the thermal environment" [i]. Under optimum thermal environment a person can maintain a body heat balance at normal body temperature and without perceptible sweating. The requirements of thermal comfort vary based upon the climate [ii]. Thermal discomfort has been known to lead to sick building syndrome. Therefore, thermal comfort has been inferred as an important parameter which need not be neglected or compromised while designing a building and thereafter improving the energy efficiency of any building as a large part of the total energy is expended on making the indoor thermal environment comfortable, using space heating/cooling, in a domestic building [iii,iv,v].

To achieve desired thermal comfort in a naturally ventilated building, many take retort of the air-conditioning systems which not only increase the energy consumption but also leads to the building syndrome [vi]. It otherwise becomes a challenge to achieve desired level of comfort in a naturally ventilated environment while keeping the energy usage under control. An adaptive thermal comfort model may play a major role in the same.

ANSI/ASHRAE Standard 55 defines the zone of thermal comfort as the span of conditions where 80% of sedentary or slightly active person find the environment thermally acceptable [vii]. There are a number of adaptive and static models developed to measure the thermal comfort in a scientific way e.g. Effective temperature, New effective temperature, Operative temperature, Tropical summer index, PMV-PPD index, Fanger comfort model, Pierce two node model, KSU two node model, Auliciems adaptive model, Humphreys adaptive model and Adaptive comfort standard [viii,ix,x,xi,xii,xiii]. Adaptive comfort standard by ANSI/ASHRAE Standard 55-2004 (ACS) is based on a theory that humans can adapt and tolerate different temperatures during different times of the year [xiv]. ACS is an optional method for determining acceptable thermal conditions in naturally ventilated spaces where occupants have a flexible control on the thermal comfort parameters and takes into account the mean outdoor air temperature [xv].

This quantitative investigation with the help of case studies, field survey, on-spot measurements using data loggers, building simulation tools and statistical analysis techniques for model validation and calibration, reviews the thermal performance of existing naturally ventilated academics buildings as per ACS and investigates any need of retrofits to improve the buildings thermal comfort hence the energy efficiency.

II. CASE STUDIES, FIELD SURVEY, SIMULATION ARRANGEMENT AND MODEL VALIDATION

A field survey of 14 naturally ventilated academic buildings was conducted at the Indian Institute of Technology Roorkee. Roorkee with geographical coordinates 29.52N 77.53E, is located in the state of Uttarakhand, India in the close proximity to the Himalayas and the river Ganges and experiences composite climate (or a humid sub-tropical type of climate).

For easy comprehension of the buildings dynamic interactions with the external environment, sophisticated computer based tools and software is required wherein a simulated environment is created by integrating the thermal properties of the building envelope, internal loads, weather conditions and most importantly the operation schedules of various appliances and the occupancy [xvi]. U.S Department of energy has enlisted 416 building energy software tools for evaluating energy efficiency of the buildings [xvii]. In this particular study, Design Builder's (DB) v.3.0.0.105 is used to evaluate the thermal behavior of the surveyed buildings. DB is a user-friendly modelling environment where one can work with virtual building models and provides varied graphical outputs including electricity consumption, comfort data, internal gains, system loads, heating and cooling design data, etc [xviii]. Simulation models were created to conduct the thermal analysis of the surveyed buildings by representing the existing conditions into the building simulation tool. A wide range of information of the 14 naturally ventilated academic department building was collected which falls under six heads namely weather data, building layout, construction details, fenestration data, equipment details and the occupancy & equipment schedules (TABLE I.). The method for baseline building data collection included historical records, on-site measurements, direct observations, unstructured interviews with the occupants etc. The documented data has been referred throughout the investigation process.

TABLE I. METHOD OF COLLECTION OF BASELINE INPUT DATA

S.no.	Type of baseline input data	Method of data collection
1.	Weather Data	Weather data file was selected after carefully analyzing the case study locations measured weather data records of past three years and weather records from the in-built weather files of three nearby locations
2.	Building Layout	Building model was recreated in the simulation software by keeping as-built plans as a reference
3.	Construction Details	Construction details were fed in the simulation software after performing a comprehensive analysis using well researched and published data from CBRI.
4.	Fenestration Data	Fenestration details entered in the simulation software were kept in line with the ECBC and ISO 15099 norms and pre-checked using WINDOW software.
5.	Equipment Details	A careful inventory of equipments types, their loads and numbers was prepared manually by conducting structured site-visits to the case-study buildings.
6.	Building Schedules	Building schedules were prepared by conducting interviews with the occupants and site visits at varying time periods.

In building simulation, the question of model validity arises because differences between the simulated and measured data are observed [xix,xx]. These differences have been accepted by the researchers as the inherited uncertainties, which should be within the acceptable statistical tolerances as recommended by the international performance measurement and verification protocol (IPMVP, 2010), ASHRAE guideline 14, 2002 and Federal Energy Management Program (FEMP) [xxi]. Averill M. Law in his book Simulation Modelling and Analysis has suggested that a model is just an approximation to a system and there is no such thing as absolute model validity, therefore a simulation modeller must decide that at what level the model is detailed [xxii]. Also, D. Coakley et al. has mentioned that the calibration criteria necessary for BES model validations have not been widely accepted [xxiii]. Therefore, in order to establish the validity of the baseline models for the purpose of use i.e. measurement of thermal comfort as per ACS, the spot measurements at varying times of the year were made to record the indoor environmental variables (air temperature, Ta; globe temperature, Tg; relative humidity, RH & air velocity, Av) of the case study buildings. These measurements helped in validating the comfort data of the simulation software with the measured data. Model validation using Percentage (%) Error, Coefficient of variance of the root mean squared error (CV RMSE) and Mean Bias Error (MBE) of the simulated models is crucial in order to ascertain that the existing thermal environment of the simulated buildings is a true representation of the surveyed buildings. TABLE II. outlines the acceptable tolerances defined by the various guideline standards.

For the brevity and clarity the authors presents only the valid model outputs which contributed to the thermal comfort analysis as per ACS in the upcoming section.

TABLE II. ACCEPTABLE TOLERANCES DEFINED BY GUIDELINE STANDARDS

Index	***ASHRAE 14 (%)***	***IPMVP (%)***	***FEMP (%)***
CV(RMSE)	± 15	***± 20***	***±10***
MBE	± 5		

III. SIMULATION RESULTS AND ANAYLSIS

Acceptable operative temperature ranges for naturally ventilated spaces as listed by ACS are reproduced in Fig. 1. Fig. 2 presents the lower and upper indoor operative temperature range for the case study location as per the ACS at 80% acceptability. It can be seen from Fig. 2 that the indoor operative temperature of a naturally ventilated building at the studied location shall be within 18.75 °C to 25.75 °C in the month of January. In this way, optimum range of indoor operative temperature for each month can be established. In addition to monthly variations, thermal acceptability also varies as per the floor and the cardinal direction. Therefore, operative temperatures of each case study is also studied for north, south, east and west cardinal directions on the three floors i.e ground, intermediate and top floor. Fig. 3 to Fig. 14 presents the simulated operative temperatures of the case studies with respect to the upper acceptability limit and lower acceptability limit of operative temperature of ACS.

The key findings of the operative temperature analysis are:

i. Top floor's baseline operative temperature falls above the upper acceptability limit in summers and below the lower acceptability limits in winters.

ii. Intermediate floor's baseline operative temperature touches or falls below the upper acceptability limit in summers and in winters it falls below the lower acceptability limits.

iii. Ground floor's baseline operative temperature touches the lower acceptability limits in summers and in winter's operative temperature falls below the lower acceptability limits.

iv. The operative temperature in the north zone reduces from top floor to ground floor in summers but it is almost uniform in winters for three floors. On all the three floors operative temperature in winters fall below the lower acceptability limits. However for summers operative temperature falls above the upper acceptability limit on top floor, falls below the upper acceptability limit on first floor and touches the lower acceptability limits on ground floor.

v. The operative temperature in the south zone reduces from top floor to ground floor in summers and winters. In summers operative temperature fall above the upper acceptability limit on top floor, fall below the upper acceptability limit on first floor and touches the lower acceptability limits on ground floor. But in winters, operative temperature touches the lower acceptability limits on top and first floor and falls below the lower acceptability limit on ground floor.

vi. The operative temperature in the east zone reduces from top floor to ground floor in all the months. On all the three floors operative temperature in winters fall below the lower acceptability limits. In summers operative temperature fall above the upper acceptability limit on top floor, fall below the upper acceptability limit on first floor and touches the lower acceptability limits on ground floor.

vii. The operative temperature in the west zone reduces from top floor to ground floor in all the months. In summers operative temperature fall above the upper acceptability limit on top floor, fall below the upper acceptability limit on first floor and touches the lower acceptability limits on ground floor. On all the three floors operative temperature in winters fall below the lower acceptability limits.

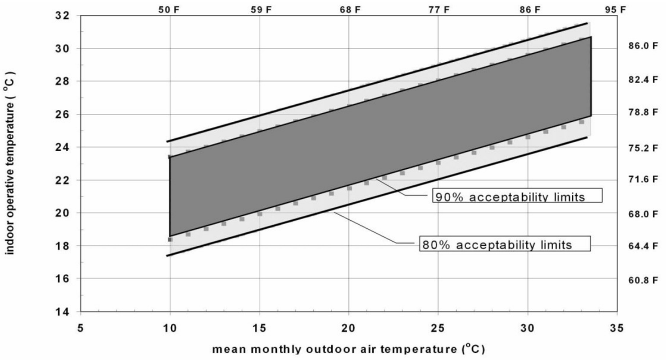

Fig. 1. Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces (From ANSI/ ASHRAE Standard 55-2004 Figure 5.3)

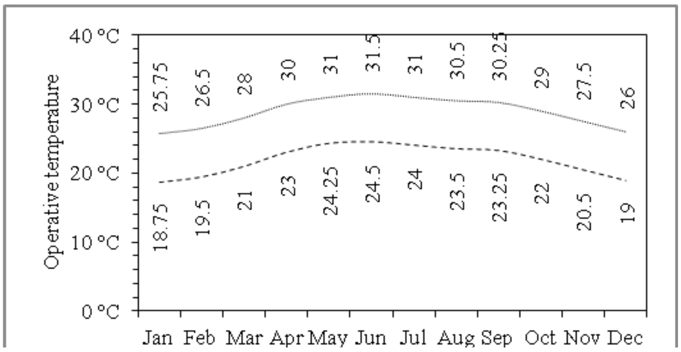

Fig. 2. Lower and Upper Operative Temperature Range for the Composite Climate as per ACS at 80% Acceptability

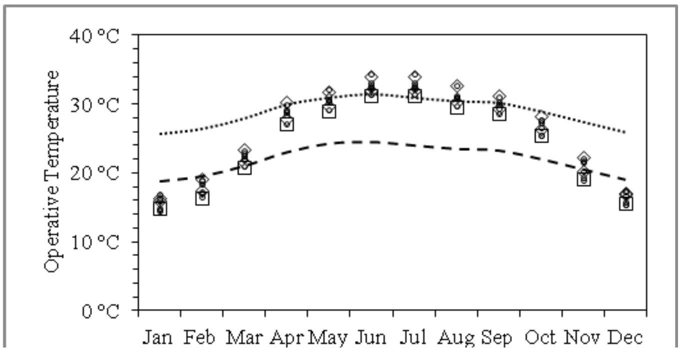

Fig. 3. Second Floor Analysis - North Zone

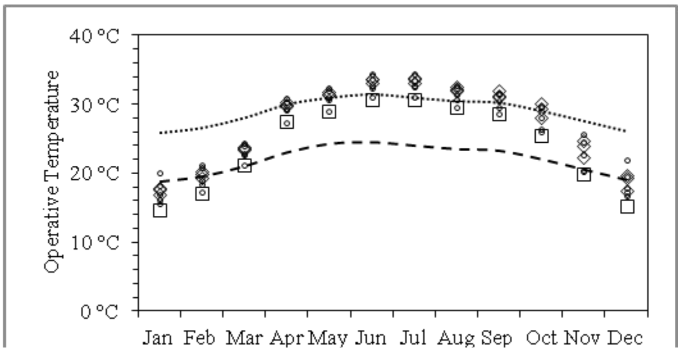

Fig. 4. Second Floor Analysis - South Zone

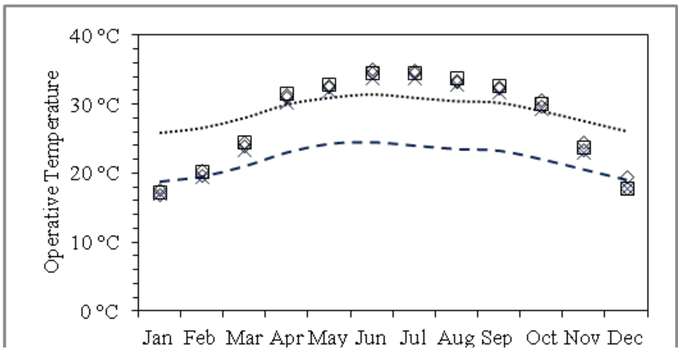

Fig. 5. Second Floor Analysis - East Zone

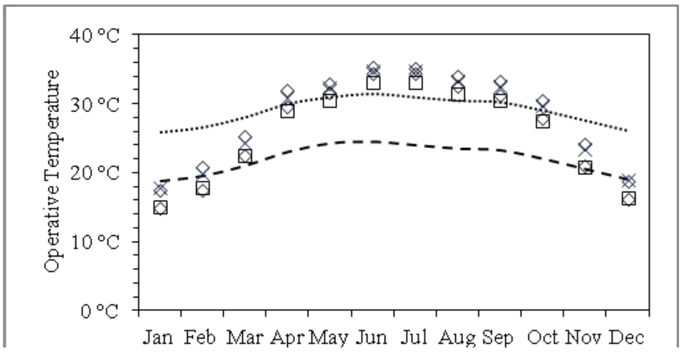

Fig. 6. Second Floor Analysis - West Zone

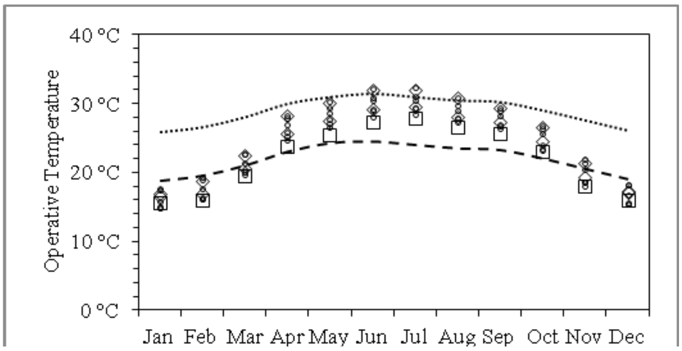

Fig. 7. First Floor Analysis – North Zone

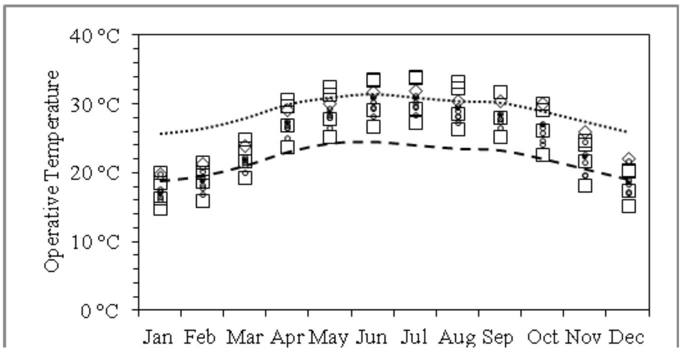

Fig. 8. First Floor Analysis – South Zone

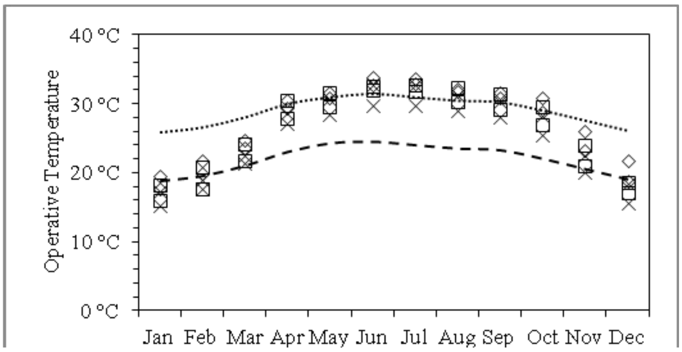

Fig. 9. First Floor Analysis – East Zone

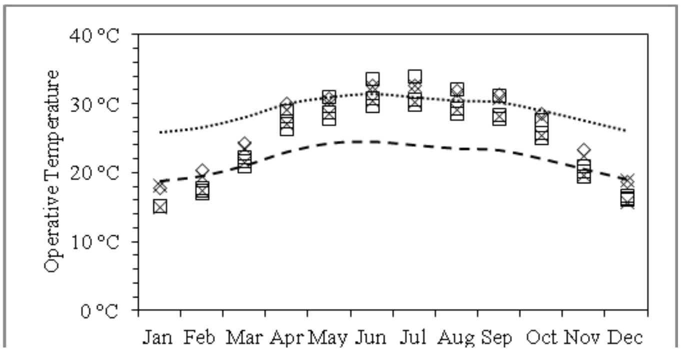

Fig. 10. First Floor Analysis – West Zone

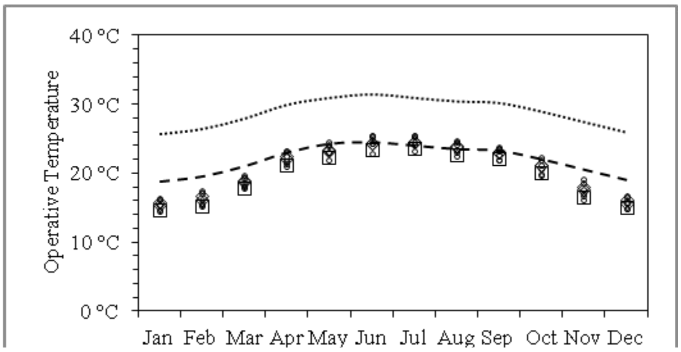

Fig. 11. Ground Floor Analysis – North Zone

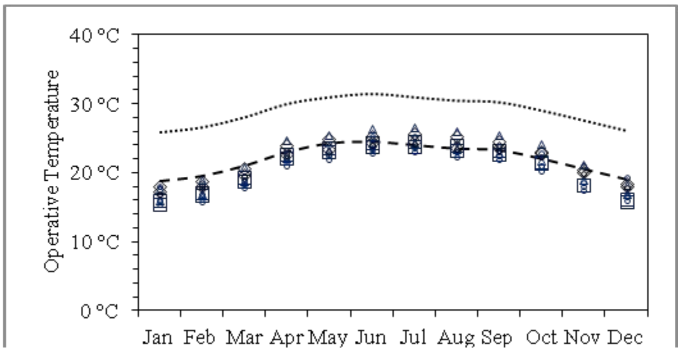

Fig. 12. Ground Floor Analysis – South Zone

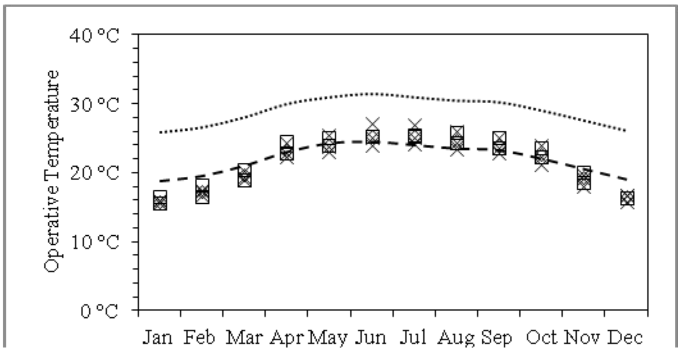

Fig. 13. Ground Floor Analysis – East Zone

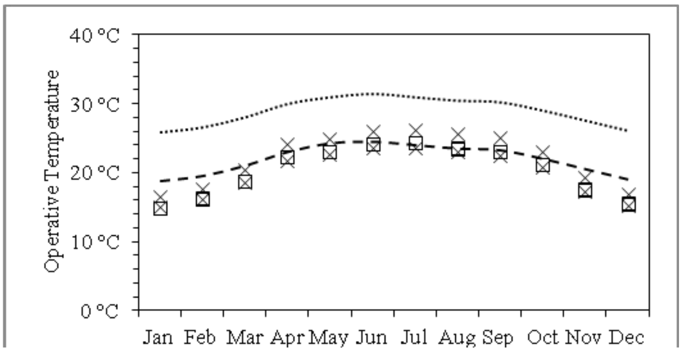

Fig. 14. Ground Floor Analysis – West Zone

IV. CONCLUSIONS & RECOMENDATIONS

Thermal comfort is a subjective sensation which depends upon the environmental and personal factors associated with a user. Since thermal discomfort has a huge implication on the energy consumption of any building it is important to achieve desired levels of the same. Field experiments conducted by ASHRAE has concluded that occupants' thermal responses in naturally ventilated spaces depends in part on the outdoor climate and may differ from thermal response in buildings with centralized HVAC systems. ACS is applicable primarily for the naturally ventilated buildings which takes into account the mean outdoor air temperature. A field survey of 14 naturally ventilated buildings was conducted, where after simulation arrangement was established in order to understand their thermal comfort behavior as per ACS. Interesting findings have been established from the validated simulation models of the 14 case studies. Operative temperature in twelve zones for various buildings follows a uniform profiles. Operative temperature in a particular zone reduces from top floor to ground floor in summers and in winters. It is evident that, only in the summers on first floors operative temperature falls under the acceptability zone of upper and lower limits. The adaptive comfort range for the studied climate is not met in certain cases during the peak summers and winters. Therefore, for the studied climate, architectural measures shall be taken for buildings design so that the operative temperature in summers reduces and in winters increases for acceptable thermal comfort and thence lesser reliability of energy intensive devices.

This simulated study is a snap shot of a naturally ventilated buildings thermal response which is validated using the on-spot measurements of thermal comfort parameters. It now levies onus on the building designers, specifically in the composite climate context of Indian subcontinent, which boasts of numerous passive design techniques and a plethora of naturally ventilated buildings.

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