CHAPTER 1

Introduction

1.1 Building energy usage and the future

We live in times when terms like global warming, energy crisis, and fossil fuel depletion have infiltrated from academic domain into common parlance. Energy usage and conservation have come out as issues of paramount concern. Buildings are responsible for about 40% of world primary energy consumption and about one third of world CO_2 emissions (du Can and Price, 2008; Eicker, 2009). Looking at future predictions, by 2030, CO_2 emissions from buildings are expected to rise by nearly 37% (Levermore, 2008). In India, residential and commercial buildings together account for around one-third of the total electricity consumption (CSO, 2012). Over the past decade, gross built up area in India has been consistently rising at 10% per annum (Mills et al., 2012) and correspondingly, estimates from TERI show energy requirements of buildings in India increasing by 5.4 billion units every year (TERI, 2010). A complete switch to renewable energy sources is unlikely to take place any time soon and hence, energy savings will form a critical part of any future oriented energy policy. The good news for building sector is that as per the Intergovernmental Panel on Climate Change (IPCC), among all sectors, the buildings sector affords opportunity for highest cost effective reduction in emissions (Levermore, 2008). And since these estimates do not consider non-technical options (like changes to building usage) for emission reduction, the actual potential is likely to be higher.

1.1.1 Thermal comfort and building energy use

Since the industrial revolution, human beings have been spending progressively larger proportions of their day indoors and today's buildings often try to guarantee comfort by isolating the indoor environment from the surroundings. They end up consuming huge amounts of energy in the process. According to an estimate by International Institute of Refrigeration, about 10-20% of electricity produced worldwide is consumed by refrigeration and air-conditioning (AC) machines of some nature or the other (Lucas, 1998). An affectation of ease and invincibility is associated with AC. Over the past 30 years, home owners in the USA have been progressively over-cooling their residences during summer and over-heating them in winter (Barkenbus, 2013). The ability to control indoor climates has also led to a globalisation of office work attire. Corporates in hot-humid tropics impose dress codes whose clothing insulation value could only be deemed appropriate for temperate or subarctic climates (Morgan and de Dear, 2003).

Commercial buildings in India use 32% and residential buildings use 7% of their electricity consumption for space conditioning (Gupta and Chandiwala, 2009). India's proximity to equator means that the aforesaid amount of energy is primarily used for cooling. Between 2009 and 2010, AC sales in India went up by slightly more than a million units (Jayswal, 2012). Projections show India beating both USA and China by 2055 to become the world leader in energy consumption for AC (Isaac and Van Vuuren, 2009). In 2011-12, Indian electric grid had a 8.5% deficit in meeting total energy demand and a 10.6% deficit in meeting peak energy demand (CEA, 2012). Every summer, India faces the double pronged problem of reduced electricity production due to reduced water levels in hydroelectric installations and increased demand in agricultural sector for irrigation and building sector for AC. The confluence of all these factors may make grid collapses similar to that of 2012 summer (BBC News, 2012) more commonplace.

1.1.2 Role of comfort standards

Comfort standards followed in designing a building define the acceptable indoor environmental conditions — temperature, humidity, air velocity etc. Thus energy used in space conditioning depends on the comfort standard. The need of the hour is buildings that are energy efficient and sustainable but do not sacrifice thermal comfort in the bargain. And as Humphreys and Nicol (1998) put it, if done in a well thought out manner with well defined guidelines to building design, the reduction in energy consumption need not be a miserable experience for the occupant. Appropriate thermal comfort standard in building codes can accelerate the drive towards high performing buildings and aid in achieving the so called *zero energy* buildings.

1.2 Human thermal comfort

ASHRAE defines thermal comfort as *'that condition of mind which expresses satisfaction with the thermal environment'* (ASHRAE, 2013). This definition is all encompassing and at the same time, rather vague due to its subjective nature. The human body has a delicate and efficient mechanism — armed with such defences as vasoconstriction, vasodilation, shivering, piloerection, sweating etc. — for maintaining body core temperature close to 37 ℃. Apart from physiological defences, we frequently take behavioural thermoregulatory measures at our body's behest. Chatonnet and Cabanac (1965) observe "Behavioral thermoregulation, ... is well developed in man and becomes preponderant and tends to supplant other forms of thermoregulation". Physiological thermoregulation is brought into play when behavioural measures like moving to shade, drinking cold water, putting on extra clothes, moving near a fire etc. fail or cannot be used (Romanovsky, 2007). Physiological and behavioural thermoregulatory measures together help to ensure thermal comfort of human body over quite wide ranges of ambient temperature. At the same time, a tertiary line of defence is provided by our shelter, i.e., the buildings.

1.2.1 Whole body human thermal models

Most authors accept that the first thermal model of the human body was proposed by A. C. Burton in 1934 (Stolwijk and Hardy, 1966; Wissler, 2012). Burton considered a single cylinder with uniform properties to represent the human body in its thermal exchanges with the environment. Some of the historically important thermal models developed for the human body are: Fanger's model (Fanger, 1972), the Two-Node model (Gagge, 1971), Wissler model (Wissler, 1964), and Stolwijk model (Stolwijk and Hardy, 1966). These models traditionally followed a heat balance approach involving the body's thermoregulatory physiology and heat transfer physics and hence they have been called *'rational models'*. The gradual increase in number of nodes of human thermal models is partly attributable to the growing computational power available to researchers and to our growing understanding of the human body. It is expected that multinode models, coupled with high-resolution CFD models of indoor environments, will have a greater role to play in future of thermal comfort research (de Dear et al., 2013).

1.2.2 Fanger's model

Through most of the last four decades global thermal comfort standards were primarily based on the works of Fanger (Fanger, 1973; 1972). It had been known for sometime that thermal comfort is affected by four environmental variables (air temperature, humidity, air velocity, and mean radiant temperature) and two variables personal to the occupant (clothing insulation and activity level). Fanger proposed an index that combined all these six variables and called it the Predicted Mean Vote (PMV). He modelled the body as a passive system that exchanges heat with its environment through convection, radiation, sweating, and heat loss through expiration.

Fanger's proposed index was based on comfort surveys carried out in climate chambers. In these surveys, occupants assessed their thermal perception on the ASHRAE seven point scale (Figure 1.1). On this scale, the mid point i.e. 0 is called the neutral point and anyone recording their thermal sensation at the neutral point are deemed to be comfortable. Since individual differences would make it impossible for a particular thermal environment to be neutral to everyone, a wider comfort band is considered between ±1. Any occupant voting within the comfort band is deemed to be reasonably comfortable and not stressed by her/his thermal environment.

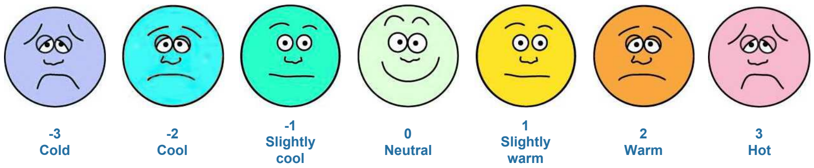

Figure 1.1: ASHRAE thermal sensation scale

Fanger's PMV index could be used to find a Predicted Percentage Dissatisfied (PPD) amongst occupants using Equation 1.1.

$$PPD = 100 - 95 \cdot \exp[-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2] \tag{1.1}$$

As is apparent from Equation 1.1, whatever be the conditions, we can not expect to have a 100% satisfaction amongst occupants. For most buildings, satisfied percentage between 80 to 90 is considered adequate (ASHRAE, 2009). Widely accepted comfort standards like the ASHRAE Standard 55 (ASHRAE, 2013) or ISO 7730 (ISO, 2005) primarily rely on the PMV model for determining comfort conditions. Recently, these standards have been giving an increased importance to enhanced air velocity in calculating PMV. Air speeds up to 0.8 m/s are now allowed in occupied zone and this value may be further enhanced to 1.2 m/s when occupants have direct control over air speed (ASHRAE, 2013). These allowances can push upper limit of summer thermal comfort zones to near 30 °C.

1.2.3 Changing face of thermal comfort

To quote Brager et al. (2015), in recent years, thermal comfort standards have seen "shifts from centralized to personal control, from still to breezy air movement, from thermal neutrality to delight, from active to passive design, and from system disengagement to improved feedback loops".

One of the issues taken with PMV is that the surveys used to determine its empirical form were conducted in controlled climatic chambers and they do not necessarily extrapolate well to real life occupants who adjust to their surroundings or adjust their surroundings to themselves (Nicol and Humphreys, 2002). At the same time, the so called rational models are hard pressed to take into account effect of occupant acclimatization on thermoregulatory responses (Hwang and Konz, 1977), individual differences in thermoregulatory responses (Takada et al., 2009), and behavioural thermoregulation by occupants. As human physiology and behaviour, both are likely to adapt to circumstances, standards relying solely on physics may prove to be inadequate (Stoops, 2006). Or, as Humphreys puts it: "...if thermal comfort does prove to be context-dependent, then no heat exchange equation can be entirely successful as a basis for thermal comfort standards." (Humphreys, 1996).

The PMV model, by accounting for changes of clothing, wind velocity, and metabolic rates, does account for certain behavioural changes. More recently, Fanger's model was modified to account for the expectation ('e') of people living in warm climates (Fanger and Toftum, 2002). This has been referred to as the extended PMV model or ePMV for short. Lack of agreement on how to quantify the expectation of different occupants has meant that this modification has not seen much use.

Arens et al. (2010) showed that indoors with narrowly controlled temperature do not provide better occupant aceptability over indoors that have a slightly broader temperature variation. Corroboratory evidence was also found by Zhang et al. (2011) in their studies showing occupant acceptability is indistinguishable over a certain broad range of temperatures and use of ceiling fans and personal control over the environment can serve to further broaden this said range. Hence, it is not logical to maintain spaces at an 'optimal' temperature by incurring significantly more energy costs.

1.2.4 Adaptive comfort standards

Thermal comfort research in recent years has been driven by a need for energy efficiency in building sector without compromising long term health and well being of occupants. In this regard, great promise has been shown by the so called *adaptive comfort standards (ACS)*. Human beings have a natural tendency to adapt to their environments and at some level, probably this even rewards us with some level of pleasure. At the heart of adaptive comfort standards is the idea that "if a change occurs in the surroundings that causes discomfort, then people will react so as to restore their feeling of comfort" (Humphreys and Nicol, 1998). These reactions can be adapting to the environment (drinking cool water, changing clothes etc.) or adapting the environment (opening windows, switching on fans etc.). Three types of adaptation have been identified that allow occupants to adjust to a broader comfort zone: *physiological, behavioural, and psychological* (de Dear and Brager, 1998; Brager and de Dear, 1998). These develop depending upon individual's climatic and cultural experience, apart from other minor contributors. While individual effects of each adaptive step might be negligible, the cumulative effect of all the measures that the body puts into play, both at the conscious and the subconscious levels, can be enough to change thermal perception (Baker and Standeven, 1996). Baker and Standeven also proposed that the discrepancy between rational and adaptive models was due to the 'adaptive errors' from behavioural adjustment of occupant, adjustments that rational models may not account.

Quite early on, Nicol and Humphreys (1973) had suggested in one of their works that building design should pay more attention to how people react to their surroundings. Field studies have shown that in naturally ventilated (NV) buildings, through adaptive actions, an acceptable degree of comfort is possible over a range of air temperatures from about 17 to 31 ℃ (ASHRAE, 2009). In face of mounting evidence from field studies, ASHRAE commissioned project RP 884, headed by Prof. de Dear and Prof. Brager amongst others, to create a consolidated database of field survey results and analyse them. A database of 21,000 responses was formed. This lead to a seminal work in the field of adaptive thermal comfort which established that NV spaces had wider comfort zones than conditioned spaces, occupants in conditioned spaces were far more sensitive to temperature variations, and the comfort temperature in an NV space bore a strong correlation with the prevailing outdoor air temperature (de Dear and Brager, 1998). The relation between comfort temperature (t_c) and outdoor temperature (t_{out}) for naturally ventilated buildings is given in terms of adaptive comfort equations (ACE). These equations have the following generic form: $t_c = a + b \cdot t_{out}$. In the past two decades, certain pioneering works (Humphreys and Nicol, 1998; de Dear and Brager, 1998) and major international comfort standards — like ASHRAE Standard 55 (ASHRAE, 2013) and EN15251 (CEN, 2007) — have brought ACS to mainstream comfort research. When introduced in the 2004 version of ASHRAE Standard 55, adaptive comfort standards were put forth as suggested alternative method for determining comfort levels in NV buildings. By the 2010 version though, several changes were introduced including removal of the word 'Optional' from the section heading of adaptive comfort, use of PMOAT, inclusion of effect of enhanced air velocity on limits of comfort etc. These trends show adaptive comfort standards gaining greater acceptability in the international community.

There is at least one reported work on the use of adaptive comfort algorithms in actual building comfort systems. Using the adaptive comfort equations determined through the European project on Smart Controls and Thermal Comfort (SCATs), TAC Controls in Sweden modified the TAC Xenta® range of air-conditioners (McCartney and Nicol, 2002). These controllers saved up to 30% of the cooling load vis-a-vis a fixed set point system and reduced annual carbon dioxide emissions by 200 tonnes for the test case buildings (McCartney and Nicol, 2002).

1.2.4.1 Why does the adaptive comfort model work?

de Dear (2010) explains why a certain indoor environment may be comfortable in

NV buildings, while at the same time being unacceptable in AC buildings, using the concept of alliesthesia of the occupants. The other issue that is sometimes raised about ACEs is how can indoor comfort be formulated just in terms of the outdoor temperature. In long term, climate of location influences behaviour, acclimatization, and adaptive attitude of people. In short term, clothing patterns depend on outdoor temperature as do — to a certain extent — posture and metabolic rate of people. Thus, this feedback between climate and adaptive actions of occupants, means that only the outdoor temperature need be considered in real situations and real buildings (Nicol and Humphreys, 2002). For a detailed discussion on why adaptive thermal comfort works the way it does and how thermal comfort is part of a self regulating system of the occupant, and not just a property of the environment, one may refer to work of Humphreys and Nicol (1998).

1.2.4.2 Adaptive comfort and energy efficient buildings

With changing climate, concerns regarding CO_2 emissions, and fossil fuel depletion, there is an increased drive towards energy economy. Many of the ‘greener’ building designs rely on greater variability of indoors in making the building’s design green (Deuble and de Dear, 2012). Under these conditions, it is not a far fetched idea that in the near future, natural ventilation and low energy cooling systems would be the norm instead of the fringe. The imperative would be to have the right standards and design methods for the new systems so that we can effect energy economy without sacrificing comfort. Buildings employing passive cooling measures or operating in mixed mode conditions often cannot meet standards based on Fanger’s model (Fanger, 1970), while they may meet standards based on adaptive approach. The same is true for vernacular building designs which provided comfort to so many past generations. Including the adaptive comfort model into building codes and comfort standards is certain to encourage and foster energy efficient, climate-friendly building designs (Humphreys et al., 2007).

1.3 Thermal comfort for Indian classrooms

In India, the demographic eligible for attending institutes of higher education, i.e. 18 to 23 year old, makes up 11-12% of the national population (UGC, 2008). While actual enrolment is nowhere near 100% of this age group, still, with 14.6 million enrolled students, higher education system of India is one of the largest globally (PCI, 2012). For perspective, that number is larger than the population of most European nations. Over the past years, number of higher education institutes in India have seen compounded annual growth rate of 11% while student enrolment CAGR was 6% (PCI, 2012). This will mean significant growth in the sheer number of classrooms. Ensuring thermal comfort in the large number of classrooms of these educational institutes is in national interest and a matter of urgency. With recent economic development of India, the desire for AC has made a gross and unjustifiable jump from the category of 'luxury' items to that of 'necessary' items. Educational institutes have started proffering AC in a bid to stay attractive to prospective students. While AC may be seen as an easy way out for providing thermal comfort, in terms of energy demand, the idea is hardly sustainable. Also, classrooms are ideal locations for what Indraganti has called *"thermal indulgence"* (Indraganti, 2011) since users never face a utility bill. India's energy scenario, as discussed in Section 1.1.1, forebodes a grim future if an unfettered rise in building energy consumption continues.

It is rather obvious that indoor environment would affect occupants' physiology. Along the same lines, several studies and meta-analysis of studies confirm the important role indoor environmental quality (IEQ) plays in performance and productivity of occupants, in particular, the teaching-learning process (Mendell and Heath, 2005; Hancock and Vasmatzidis, 2003; Wyon et al., 1979; Lee et al., 2012). Unfortunately, there do not exist many studies on influence of classroom environment on classroom performance, particularly university classrooms.

For long, Indian classrooms relied on climate suitable design, natural ventilation, and ample use of fans to ensure student comfort. Conscientious design of classroom thermal environment is necessary both because of the high occupant densities classrooms have and the adverse impact deficient thermal settings can have on the teaching-learning process. Judicious comfort standards will be an essential part of designing thermally comfortable and energy efficient classrooms. Supplementing current Indian building codes with judicious adaptive comfort standards would come as a succour to Indian energy scenario and pave the way towards sustainable future development. Development of such standard would be immensely aided by the results of thermal comfort field studies.

1.4 Research hypothesis

With this background on the importance of thermal comfort standards, effect of comfort on teaching-learning process, and the implications of energy security, we formulate the research questions and hypothesis.

1.4.1 Research questions

Research question: In naturally ventilated classrooms in hot–humid regions of India, what is the range of thermal conditions with which students can adapt and still be comfortable?

Sub-question: What would be a suitable correlation to relate indoor comfort temperature in naturally ventilated classrooms and outdoor thermal conditions?

Sub-question: Can a distinct difference in student performance be identified between classrooms with mechanical conditioning and natural ventilation?

1.4.2 Research hypothesis

For naturally ventilated classrooms in the hot-humid climatic zones of India, an adaptive thermal comfort model may be used to identify suitable comfort standards and thermally comfortable zones which would help to have energy efficient buildings without compromising comfort and performance.

Context and domain of the work

- **Context:** The work will be restricted to hot-humid climates of India. We regard regions with Type A Köppen climate to have a hot-humid climate for the purpose of this work. Nearly a fifth of world land area comes under Type A Köppen climate and about 28% of the world population live in these areas (Kummu and Varis, 2011). In context of India, nearly 40% of India's land area comes under Type A Köppen climate (estimated from the high resolution Köppen climate of the world provided by Peel et al. (2007), using ImageJ® version 1.46r). Five of India's ten largest urban agglomerations have Type A climate (Mumbai, Bangalore, Chennai, Surat, and Kolkata) while two other in the top ten just border upon Type A climatic regions (Hyderabad and Pune) (Census, 2012).

- **Domain:** The domain of exploration would be classrooms in the said context.

Study limitations

- The analysis will consider classrooms at college/university levels, i.e., students in their late teens or beyond. Research shows comfort requirement of young children to be very different (Humphreys, 1977) and hence, it will not be considered in the current work.

- Our analysis would be of comfort requirements of classroom occupants. So, the subjects of study would be sedentary or near sedentary in their activity level.

Following the hypothesis, the research work would be focusing on the thermal environments and cooling needs of college/university level classrooms in the hot-humid climatic regions of India.

1.5 Thesis structure

Chapter 1 presents an introduction to the issues of building energy use, role of thermal comfort standards, and the importance of appropriate thermal comfort standards for

Indian classrooms. Following the research hypothesis extended in Chapter 1, the rest of the thesis structure is as follows.

Chapter 2 presents an extensive literature review covering adaptive comfort models, field studies on thermal comfort, current Indian building codes, impact of indoor environment on occupant performance, and an overview of passive cooling measures.

Chapter 3 presents the results from thermal comfort field studies conducted in naturally ventilated (NV) classrooms and laboratories in Indian Institute of Technology Kharagpur.

Chapter 4 presents a comparison between student performances for courses taught in classrooms with and without AC.

In recent years, a few adaptive comfort equations have been proposed for hot-humid climates apart from the equations in international standards. Chapter 5 uses results from thermal comfort field studies done in hot-humid climatic regions of India to identify the most suitable adaptive comfort model for hot-humid regions of India among the aforesaid equations.

Chapter 6, using the basis of findings from our studies, tries to outline remedial strategies that could be used to improve classroom comfort levels. Though these measures are discussed particularly in the context of Kharagpur, they may easily be extended to classrooms in other hot-humid regions.

The thesis ends with major conclusions drawn and thoughts on possible directions of future work in Chapter 7.