

Indoor environmental quality and building energy efficiency

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Elements of Comfort

Buildings are an expression of our need for shelter which is driven by a host of factors including the need for comfort and security (Carlucci 2013). Our perceptions of, and responses to, our buildings are inseparable from the ways in which our buildings respond to the environments and climates in which they are built. Where occupants of buildings find the indoor environment to be uncomfortable, their default response is to employ mechanisms to achieve improved comfort levels (ASHRAE 2013). These responses include either voluntary or involuntary mechanisms. Involuntary mechanisms are generally physiological while voluntary mechanisms involve some effort to change the local environment either by modifying it directly (adjusting the thermostat or opening a window), modifying our state (clothing or activity levels) or relocating to an environment more comfortable.



Figure 1

Figure 1 shows the elements of indoor comfort (CIBSE 2006). A significant proportion of energy consumption in many non-industrial buildings relates to the management of thermal comfort levels through heating and cooling of indoor spaces (Lam 2000; Pérez-Lombard, L., Ortiz, J. & Pout, C. 2008). Therefore, this article focuses on those elements which harbour a significant potential to impact on the energy consumption of our buildings by driving behaviours, such as opening or closing windows and changing temperature control set-points, in the pursuit of improved comfort.. The elements considered to be important in this regard are:

- Thermal comfort
- Aural comfort (Acoustic)
- Visual comfort (Lighting)

Secondary aspects which may serve as confounding or compounding factors include:

- Air movement
- Air quality

Thermal Comfort

A comprehensive international body of work has been developed over the past 100 years to obtain a measure of understanding of the seemingly elusive parameters that determine thermal comfort. A list of more than 70

different models and indices for predicting human thermal comfort has been compiled as a useful summary by Carlucci in his book, *Thermal Comfort Assessment of Buildings*. These indices can be categorised as percentages, cumulative values, risk or averaging indices; and are determined from combinations of the heat balance of the body, physiological strain and physical environmental parameters (Carlucci 2013). What most of these models agree on is that it is impossible to achieve consensus amongst occupants of a room as to which conditions constitute a comfortable indoor environment.

The 6 principal factors that contribute to the sensation of thermal comfort are:

- Air temperature
- Radiant temperature¹
- Humidity
- Air movement
- Metabolic rate
- Clothing levels/insulation

Uniformity of sensation can also play a role in perceived levels of comfort (CIBSE 2006). This refers to instances where differences in skin temperature for different parts of the body are extreme but individually within the accepted comfort band. Also, where the indoor air temperature is above the radiant temperature, spaces tend to feel stuffy. This can occur with convective heating systems, such as warm air heating. Ideally, the radiant temperature should be slightly above the indoor air temperature. In order to avoid further discomfort however, the two temperatures should not be too far apart (CIBSE 2006). Mean radiant temperature can most easily be determined using a black-globe thermometer.

It has proven to be impossible to target a condition where everyone will feel comfortable all the time (Carlucci 2013; ASHRAE 2004; CIBSE 2006). For this reason, when designing for thermal comfort, a model using static comfort equations developed by Fanger since 1967 is used. This model is based on the six main factors listed above to create a predictive comfort index on a thermal sensation scale referred to as the predicted mean vote (PMV) and percentage persons dissatisfied (PPD) (Ole Fanger 1970; Fanger, P.O., Hojbjerre, J. & Thomsen, J.O., 1974; ASHRAE 2013). This allows designers to develop indoor conditions where the majority of occupants are thermally comfortable for the majority of the time.

Field studies, designed to validate the PMV-PPD model, have provided strong evidence that this model is not applicable to free running indoor conditions as found in naturally ventilated spaces (de Dear & Brager 1998). The PMV-PPD model assumes an environmental steady-state, and makes no allowance for adaptation or acclimatisation (De Dear & Auliciems 1985; de Dear & Brager 1998). What this implies is that these early models are inappropriate for predicating thermal comfort levels in naturally ventilated indoor spaces that will not have closely controlled conditions. In effect, this then excludes those buildings that employ passive comfort control measures from reliable assessment.

Adaptive Thermal Comfort

¹ Mean radiant temperature is the uniform theoretical temperature of a radiantly black enclosure within which an occupant would have the equivalent radiant heat exchange as in the actual, non-uniform space. For derivation refer ISO 7726

While the prevalence of electric heating and cooling continues to escalate in South Africa (Barnes, B., Mathee, A., Thomas. & Bruce, N. 2009), it is becoming increasingly important to consider ways to expand the comfort envelope for all types of buildings, in order to reduce the energy demanded of indoor comfort control.

The reason the PMV-PPD often fails is that the sensation of thermal comfort is not limited to empirical measures but is also influenced by physiological and psychological adaptation (Gonzalez, R.R., Nishi, Y. & Gagge, A P., 1974). The effectiveness of the modes by which our bodies exchange heat changes with the environment. Similarly our capacity for thermo-regulation varies between different types of buildings and environments.

The newer revisions of the ASHRAE 55 have adopted the recommendations of the likes of de Dear & Brager in that a thermal comfort model is required which addresses the issues of adaptation and acclimatisation (Brager & de Dear 2001; de Dear & Brager 2002; de Dear & Brager 1998). This standard was developed together, and is in close agreement with the standard ISO 7730:2005 (ASHRAE 2013)

“The adaptive hypothesis predicts that contextual factors and past thermal history modify building occupants' thermal expectations and preferences” -(de Dear & Brager 1998)

It has occurred to the author that over the previous 40 years, building designers and engineers may have been chasing an elusive theoretical sweet spot of satisfying the PMV-PPD model and lower energy consumption by developing increasingly complex HVAC systems; and all the while, the art of creating free running buildings, which can adapt to the environment and can also be adapted to, is being lost. The level perceived comfort in free running buildings can be further improved when occupants are given some level of control over their environment. Studies indicate that people fare much better physiologically when afforded the ability to control aspects of their indoor environment, even if when the control is merely over aesthetic elements (Rodin & Langer 1977). Simple control over openable windows, blinds, dress code and location within internal spaces are very effective in this regard (CIBSE 2006). The challenge is to design spaces which are not restrictive in these aspects but still remain efficient and functional.

As an example, a study conducted in Libya is one of many similar which found that the PVM model theoretically predicted that a sample of older, naturally ventilated buildings with courtyards and verandas would exhibit high levels of occupant thermal stress. The actual mean vote (AMV) found that those buildings resulted in a similarly high level of thermal comfort to a sample of modern, insulated and air-conditioned buildings. What was surprising was that the occupants of the older style buildings were generally more satisfied with their indoor environment (Ealiwa, M. Ealiwa, M.A., Taki, A.H., Howarth, A.T & Seden, M.R., 2001; Emmerich, S.J., Polidoro, B. & Axley, J.W., 2011).

It is unfortunately rare that climatic conditions would allow a completely free running building to achieve year-round adaptive comfort. For this reason most commercial buildings would require, as a minimum, some form of seasonal mixed-mode comfort control. The mechanical portion of these systems would then provide comfort cooling or heating only when the climatic conditions would

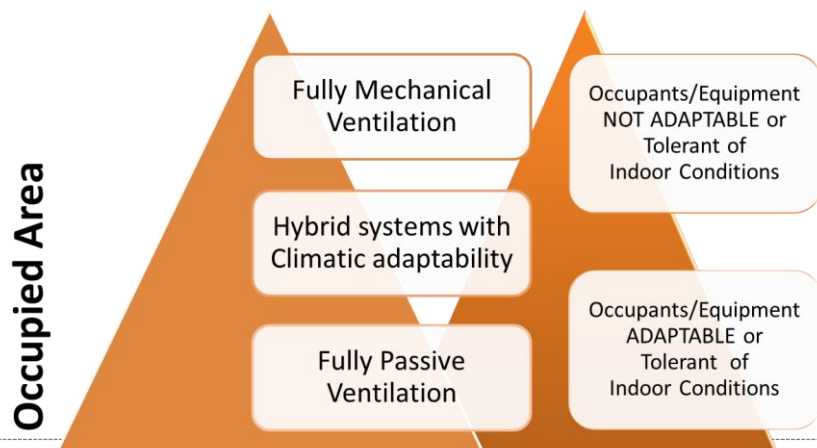


Figure 2 Hierarchy of Design Solutions

drive the indoor conditions beyond the limits of adaptive thermal comfort. Zonal mixed-mode systems could be employed where portions of a building have occupancies which cannot adapt to fluctuating conditions. Figure 2 demonstrates this principle and indicates that the proportions of occupied areas that have very restrictive requirements are relatively low.

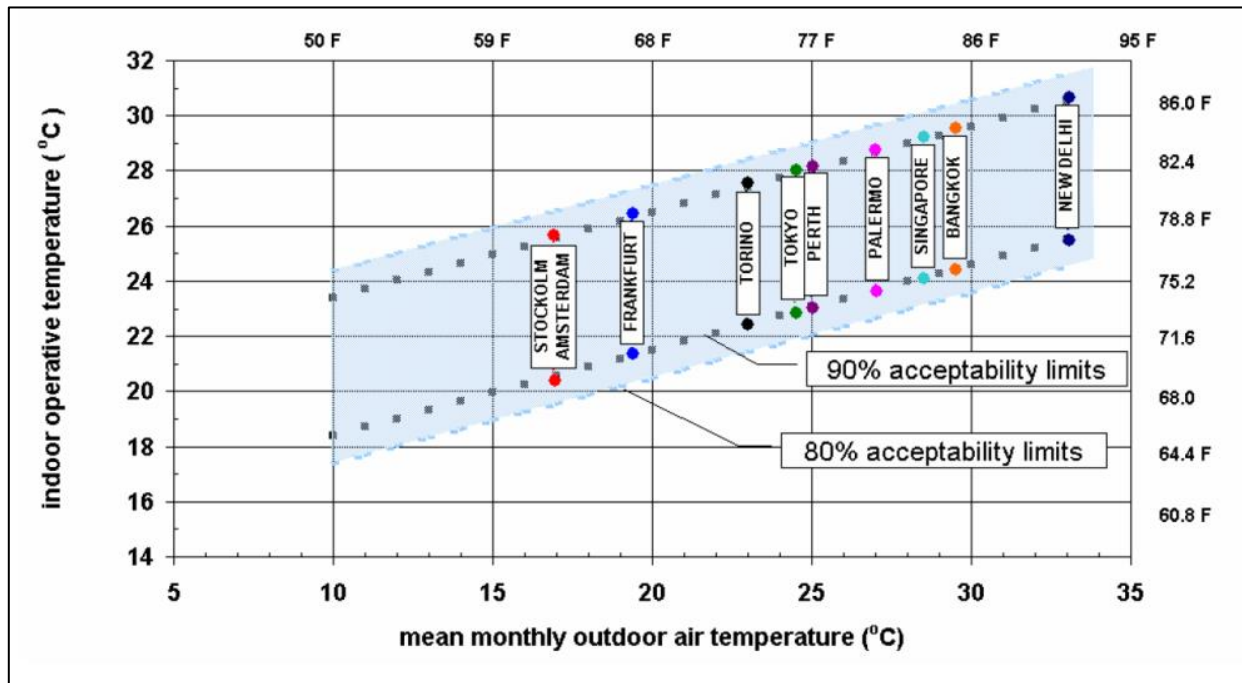


Figure 3: Acceptable operative temperature ranges for naturally conditioned spaces according to ASHRAE 55rev.-2003. Ranges shown for different climatic areas (Olesen 2004).

In order to promote the adoption of a hierarchy of design solutions, with passive ventilation and comfort control being prioritised over mechanical systems where feasible, CIBSE have presented flow charts or decision trees in the CIBSE Guide for Natural Ventilation in Non-Domestic Buildings (CIBSE 2005) and the CIBSE Application Manual AM13: Mixed Mode Ventilation (CIBSE 2000). An adaption after these diagrams, which expands on this diagram’s natural ventilation and mixed mode solutions, is available from the CSIR, on request.

Air movement

Studies indicate that most building occupants would prefer more air movement than is generally available (Arens, E., Turner, S., Zhang, H. & Paliaga, G., 2009). Air movement can contribute to the ability of people to lose heat to the environment and keep cool under conditions that would be considered too warm in air-still environments (Arens et al. 2009). Comfortable air velocities in the occupied zone are generally in the range of 0.1-1.0 m/s (reference). Velocities below 0.3 m/s would be barely perceptible while velocities approaching 1.0m/s would be considered “breezy” (ASHRAE 2013). At around 0.8 m/s air movement would start to disturb papers and indoor plants (CIBSE 2005; CIBSE 2006). The two parts of the body most susceptible to drafts are the back of the neck and the ankles and these are the two parts most exposed to high level and low level air inlets (CIBSE 2006). Special consideration should be given to inlet air speeds within occupied zones when designing for displacement ventilation.

Airborne Contamination

There are reasons for providing ventilation beyond the obvious of simply providing oxygen for occupants to breathe (CIBSE 2006). Ventilation is provided to:

- Provide oxygen to occupants (0.2 l/s per person)
- Dilute CO₂ from respiration (1.0 l/s pp)
- Dilute odours and contaminants (5-10 l/s pp)

It becomes apparent that we can require up to 50 times more air to control indoor air quality than what is required to replenish oxygen. The ASHRAE 62.1 guide adopts the additive method for selecting fresh air ventilation rates. This method is a more nuanced approach than the prescriptive method of simply demanding blind ventilation rates for different types of buildings. The demand based method considers factors such as activity levels, buildings materials and finishes and occupancy rates.

The mechanical ventilation rates required by building regulations are criticised as being too low. This is to be expected as these values are described as minimum allowable values. Therefore, if you want the absolutely worst permissible air quality, the values prescribed by the regulation should be used. Research has shown that by increasing the indoor air quality by 2-7 times over that offered by regulatory values, productivity in schools and offices is “significantly” improved. In order to make indoor air acceptable to even the most sensitive persons an increase of orders of magnitude is required (Fanger 2006).

Studies have described how indoor pathogenic microbiological ecosystems are created by sealing up our buildings and controlling indoor comfort using mechanical ventilation and cooling systems (Kembel, S.W., Jones, E., Kline, J., Northcutt, D., Stenson, J., Womack, A.M., Bohannan, B., Brown, G.Z. & Green, J.L. 2012). Kembel’s study showed how naturally ventilated buildings have a greater diversity of microbes but that their microbiological biomes resembles the outdoors and is less pathogenic for humans. Therefore, it is argued that highly sealed energy efficient buildings in the drive for increasing energy efficiency, could increase the prevalence of sick buildings.

Acoustic Comfort

Essentially, any unwanted sounds in buildings can be classified as noise. The four main problems encountered in buildings which relate to acoustic comfort or noises are annoyance, privacy, masking and hearing damage (Everest & Shaw 2001; CIBSE 2006). Annoyance and privacy are related problems as they both involve the transmission of unwanted sounds or conversations to parties who should not or do not need to hear them. Masking describes the effect where unwanted sounds interfere with any wanted sound reducing speak intelligibility. Masking can also be deliberately and carefully used to offer some measure of acoustic privacy (CIBSE 2006)

Natural ventilated building designs can inadvertently promote the acoustic problems identified above. This is because natural ventilation relies on the very small pressure differentials available from the wind and thermal stack effect drivers, and therefore requires large ventilation openings throughout the building. Where the usage profile of a building may be particularly sensitive to these effects, the potential for problems need to be mitigated either through employing a zonal mixed mode strategy or acoustic quality improvements. These improvements include careful design of ventilation openings, acoustic damping, frequency clipping or the generation of deliberately masking sounds such as white noise generation or even music (Bibby & Hodgson 2013).

Responding with informed design and intelligent design tools

As building simulation and modelling software, together with capable hardware, are becoming more affordable, prevalent and user friendly, access to these tools is improving. While this has released the potential for intelligent IEQ solutions across a wider range of building types, a very real risk lurks in the detail.

It is important to remember the adage that “a tool is not a solution”. This is nowhere more relevant in the complex field of simulation software. Figure 4 demonstrates what is commonly referred to as the “DIKW Pyramid” and it should be stressed that building simulation and modelling software can only occupy the **Information** tier of this hierarchy. These software tools invariably rely on the quality of the data fed from below and the skills of competent designers to extract knowledge from the information they provide, and apply it with wisdom.

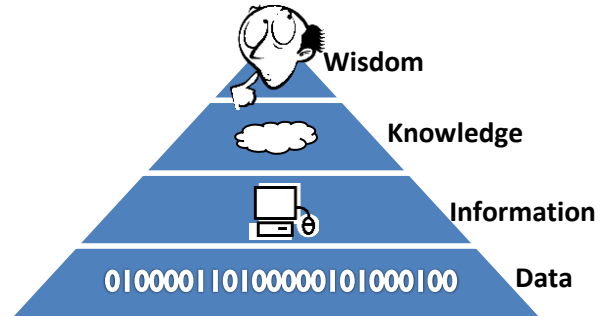


Figure 3 DIKW Pyramid

Conclusion

As we move towards a greater prevalence of buildings which adopt passive systems to meet the occupants’ functional requirements it is important to understand how the occupants’ acceptance criteria or expectations can be modified or accommodated. Essentially the comfort requirements of indoor occupants can be considerably less stringent when the occupant has

While the principles described above may be self-evident and appear simple, the integrated nature of any design for effective natural ventilation (as a supplement to HVAC) requires extensive knowledge of an array of technical fields. It is for this reason that experienced and competent practitioners in the field of natural ventilation are rare.

Building designers are encouraged to form multidisciplinary teams, including ventilation and acoustic experts, in order to ensure an integrated, optimised and functional solution.

The decision tree presented in the CIBSE Guide for Natural Ventilation in Non-Domestic Buildings (CIBSE 2005) and the diagram proposed in Figure 2 above describe how we should only be implementing conventional mechanical comfort control and ventilation systems in spaces where they are absolutely needed. For the majority of spaces and for a large portion of the year in South Africa, the opportunity exists to review the IEQ requirements in terms of the adaptive models of comfort identified above, and design for mixed mode comfort control systems accordingly.

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