BUILDING DESIGN FOR HOT AND HUMID CLIMATES – IMPLICATIONS ON THERMAL COMFORT AND ENERGY EFFICIENCY

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ABSTRACT

The paper discusses the concept of an adaptive thermal comfort design methodology and its impact on the selection, design and performance of climate control systems for large public spaces with transient occupancy in hot and humid climates. It outlines the design methodology which is based on providing localised comfort conditions to zones within a building based on its occupancy patterns, activity of occupants and acceptable thermal comfort criteria.

The methodology focuses on quantifying the collective impact of space operating parameters on the thermal comfort of its occupants. By using thermal comfort analysis a range of values for those parameters can be identified, resulting in an acceptable level of thermal comfort. This analysis informs the mechanical system selection and design for maximum energy efficiency within the specified envelope of operating parameters.

Finally, the paper outlines the use of building modelling software in exploring the link between the selection of an air conditioning system, its design and controls on the thermal comfort and the building energy efficiency.

KEY WORDS

Thermal comfort, energy efficiency, air conditioning, building simulation

INTRODUCTION

The selection of space operating parameter, such as air and radiant temperatures, relative humidity and air velocity impacts both occupant comfort and building energy consumption (Simmonds 1993, Olesen 2000). It is desirable to select those parameters such that the difference between the space condition and the outside environment is minimised. In particular this is significant with respect to the design space temperature and relative humidity (Tanabe and Kimura, 1994). In large public spaces with transient occupancy the outside air cooling load both sensible and latent, always represents a significant overall cooling load item. This can lead to substantial energy consumption of the air conditioning plant, often not justified.

The paper presents a case study of a climate control system selection for an airport terminal building located in a tropical region. The architectural design brief calls for a light and open space with strong visual connection with the outside. For airport operational reasons, the use of any external shading devices is not possible.

The sensation of thermal comfort is a complex function of environmental variables and adaptation to the indoor environment (de Dear and Brager 1998). The quantification method of the effect of environmental variables on thermal comfort is described in thermal comfort standards ISO 7730 and ASHRAE 55-2004. The adaptation to the indoor thermal environment is expressed in terms of behavioral, physiological and psychological adaptation.

It is becoming increasingly obvious that energy efficiency of buildings can not be resolved exclusively by mechanistic approach to thermal comfort. The design of buildings and their climate control systems should reflect all the above aspects, rather than designing the indoor conditions for an arbitrary set of numbers describing thermal comfort, irrespective of the climatic, functional, social and cultural context.

Airports are characteristic for their large and open spaces with diverse and transient population. Clearly, this functional diversity has to be reflected in the respective definition of thermal comfort and corresponding selection of the climate control system with its design set points.

In such an approach, the overall building energy efficiency will depend more on defining the space comfort requirements and appropriate selection of the climate control system rather than the mechanical and thermal efficiency of the plant itself.

RESEARCH METHODS

This paper analyses a case study of a design approach which was aimed at minimizing energy use by the climate control system while providing acceptable thermal comfort in an airport terminal building. The case study outlined in this paper describes the following design process:

Define thermal comfort envelope(s) for the building indoor spaces considering their function and pattern of use;

Select climate control system(s) requiring least energy input in order to maintain space conditions identified for the thermal comfort envelope(s);

Use energy simulation software and CFD technique to gain insight into the predicted operation of the climate control system thus allowing for the optimization of the mechanical design.

Analysis of building location and function

The proposed building is an international airport terminal located in a tropical climate in northern Australia. The building's function is to provide a holding space for passengers awaiting departure, usually for a period of up to two hours. Some minor, mainly self serve retail outlets are provided in designated areas. An upper level provides a link for arriving passengers to the main terminal building.

As can be seen in Figure 1 the building has an extensive curtain wall to the West. The orientation of the building is dictated by the existing layout of the airport and can not be altered. Further, the operational requirements of the airport preclude the use of external shading devices. The west facing curtain wall is an IGU with an overall heat transfer coefficient U=1.6 W/m2K and shading coefficient SC=0.24. Figure 1 depicts the departure area of the terminal which is made of two spaces; one 10m high and extending 10 m from the perimeter while the other is 3m high directly under the upper level arrivals link.

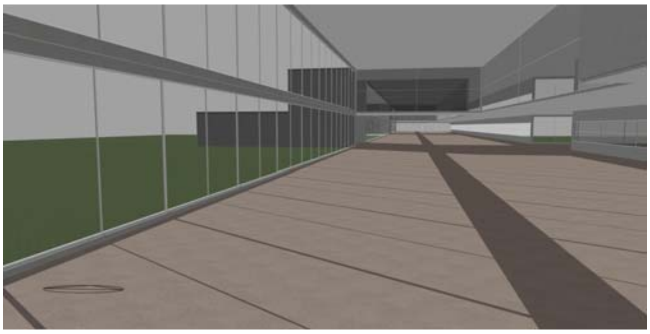

Figure 1 View of the terminal's interior

Determining thermal comfort envelope

Thermal comfort standards (ISO 773, ASHRAE 55-2004) provide methodology and formulas to quantify thermal comfort sensation as a function of four environmental variables, which can be controlled by the building climate control system, and two other variables which are subject and context dependent, i.e. clothing and metabolic rate.

The above standards define thermal comfort envelope in terms of Predicted Percentage Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV). For office spaces the thermal comfort envelope is defined by PPD≤10%. It is also assumed that 60%RH is the upper limit for the comfort space relative humidity. It has been demonstrated (Tanabe and Kimura, 1994) that higher relative humidity, up to 80%, can be acceptable provided there is adequate air movement to compensate for the increased air temperature and humidity. The above authors and others (Prianto and Depecker, 2003) have also demonstrated that prediction of thermal comfort using the standard method overestimates the thermal sensation of subjects in hot and humid environments.

Determination of space thermal comfort conditions is dictated by the environmental and contextual factors. It is reasonable to assume that in a tropical location the traveling public is expecting higher air temperature and humidity and adjust their comfort expectations accordingly. From the HVAC design and energy efficiency points of view it is desirable to provide space conditions as close to the ambient as possible without sacrificing the thermal comfort requirements.

Figure 2 demonstrates how a PPD surface can be plotted as a function of the air velocity and temperature for fixed values of the remaining four comfort variables. The figure was plotted assuming CLO=0.5, MET=1.0, radiant temperature TR=23˚C and the space relative humidity RH=70%, reflecting hot and humid environment. A higher than usual relative humidity set point results in the reduced energy requirement for dehumidification while providing control over the radiant temperature allows for greater flexibility in selecting the combination of air temperature and velocity.

As can be seen there exist a range of air flow velocities between 0.2-0.6m/s and air temperatures between 25-28˚C satisfying the condition PPD≤10%. In some areas with transient and short occupancy periods, such as transfer links, it may be reasonable to relax this condition in order to achieve greater energy efficiency without sacrificing the overall thermal comfort experience.

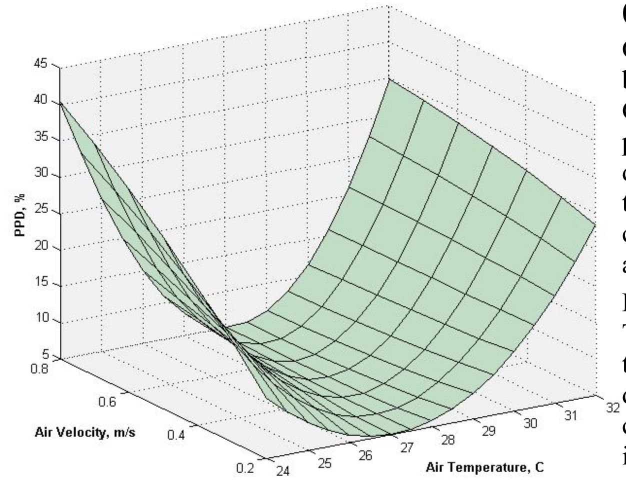

Figure 2 PPD as a function of air velocity and air temperature.

Selection of climate control system

The terminal building is characterized by large volume, high ceilings and extensive west facing façade which poses a number of challenges. These include the afternoon solar gain penetrating deep into the space, large volume of air to cool and dehumidify and organisation of the supply air flow pattern.

A climate control system based on radiant cooling and displacement ventilation is proposed for the main terminal area. The arrivals transfer link is air conditioned using a traditional overhead HVAC system.

The rationale behind this selection is that only small part of the entire volume, the occupied zone up to 2m above the floor, is required to be maintained at the required comfort conditions. The air is supplied, at 23-24˚C, directly to the occupied zone at low velocity, i.e. 0.2m/s, providing good ventilation and air movement. Cool floor at 23˚C, 1.5˚C above the space dew point, provides radiant heat sink for the occupants thus reducing the need for higher air velocities. Another important feature of the floor cooling is the ability to remove the solar gain absorbed by the floor, before it is re-emitted to the space thereby increasing the supply air quantity and consequently the fan power.

Radiant cooling systems require good quality condensation prevention control and air tight building fabric, particularly in hot and humid climates. It is assumed that a modern, good quality airport building provides for adequate infiltration control.

Thermal and Computational Fluid Dynamics (CFD) modeling

One of the challenges facing designers of complex buildings is the fact that none of the thermal and CFD modeling software packages on their own can provide answers to questions posed during the design process. From the end user point of view, the most important of those relate to the thermal comfort and operational efficiency of the building and its systems, i.e. energy efficiency among others.

Façade simulation software, such as Window5 and Therm, can help resolving specific questions related to the thermal adequacy of the proposed façade design for a specific set of environmental conditions. They do not however evaluate its impact on the thermal comfort of a person standing right next to it, nor do they quantify its impact on the annual energy consumption of an HVAC system. Energy simulation software such as EnergyPlus, with its DesignBuilder front end, is a very powerful and versatile tool for evaluating combined thermal performance of the building fabric and the associated climate control system. Although it uses detailed energy balance algorithms for both the building fabric and climate control system it can only provide high level indication of thermal comfort within the conditioned spaces. This level of detail is usually not acceptable for large open spaces. A more detailed spatial distribution of indoor conditions is required to ascertain the adequacy of the propose climate control scheme.

This is where a CFD package can prove an invaluable design tool. In this study AirPak2.06/Fluent software package has been used.

The use of CFD package in this case provided for a user perspective. It helps to quantify the combined effect of the various components of the design on the predicted thermal comfort sensation of users located at various points within the terminal building.

Although AirPak is a very powerful fluid dynamics computational tool it lacks the detailed description of the building fabric heat transfer processes offered by Window5, Therm and EnergyPlus combination.

The output from the above software packages provided boundary conditions for CFD performance simulation of the proposed climate control system. The simulation included calculation of space air temperature and velocity distribution as well as calculation of PMV and PPD thermal comfort indices.

With relatively limited computational capability of standard PC's, and the demands of the design development timelines, it is important to strike the right balance between the accuracy of the calculations and the time required for carrying out those calculations. This is particularly significant when dealing with large computational domains and tight design development timelines.

A detailed sensitivity analysis has been carried out, prior the simulation, in order to establish the maximum mesh size resulting in the required accuracy of calculations. This proved particularly important at boundaries with heat sources.

Figure 3 illustrates relationship between the grid height in the direction perpendicular to the boundary and the calculated surface temperatures.

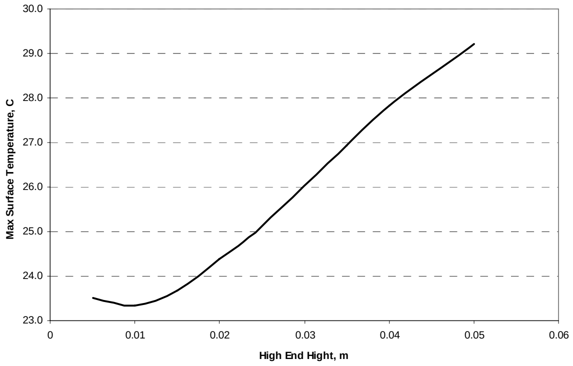

Figure 3 Results of sensitivity analysis for a radiant heat source

Additional mesh refinement was carried out at the supply air diffusers.

Figure 4 presents schematic diagram of the terminal building together with the input data for the CFD analysis.

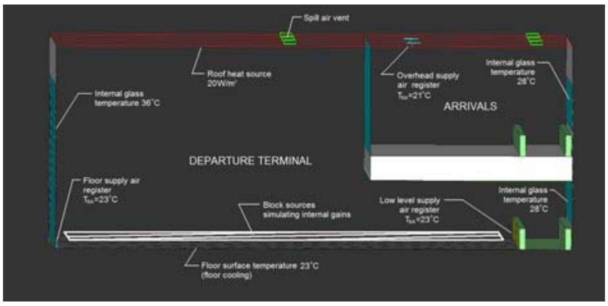

Figure 4 Schematic diagram for the CFD model

The analysis was carried out for the following design conditions:

Design Outdoor Conditions:

Summer 32.8˚C DB, 26.8˚C WB

Design Indoor Conditions:

Summer: 26.0˚C DB, 70%RH

The calculated design cooling space load, excluding outside air, is 97W/m2. Computer modeling of floor cooling established that 34W/m2 of the zone cooling load is absorbed by the floor coils. The remaining 63W/m2 is removed by displacement ventilation system. This internal load is simulated by means of blocks with a constant heat emission rates, distributed uniformly throughout the domain.

The floor cooling was simulated assuming constant floor temperature of 23˚C (indoor air dew point temperature is 21.5˚C). In practice this is achieved by modulating chilled water flow rate to the floor coils in response to the temperature of the slab measured by sensors embedded in the concrete.

RESULTS

The following figures present results of the simulation. Figure 5 shows PMV distribution. The space temperature distribution is shown in Figure 6 while the air flow pattern and velocities are depicted in Figure 7. As can be seen the proposed climate control system provides acceptable thermal comfort in the occupied zone.

Figure 4 indicates slight overcooling of the area directly adjacent to the low level supply air grille. This is despite the relatively low supply air velocity of 0.25m/s and high supply air temperature of 23˚C. For the selected Clo and Met values the results indicate slightly cold sensation for a sited person. This obviously can be avoided by not placing any sitting within 2m from the air outlet. The same combination of supply air parameters will also result in different level of the thermal comfort for a walking person or a person wearing heavier clothing.

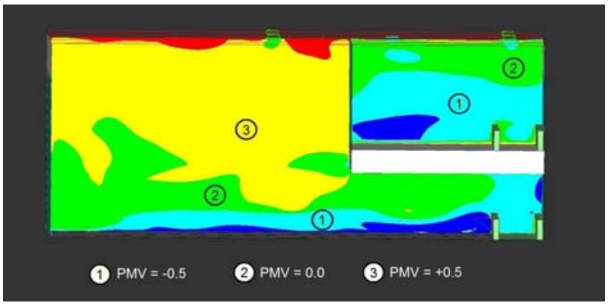

Figure 5 PMV distribution

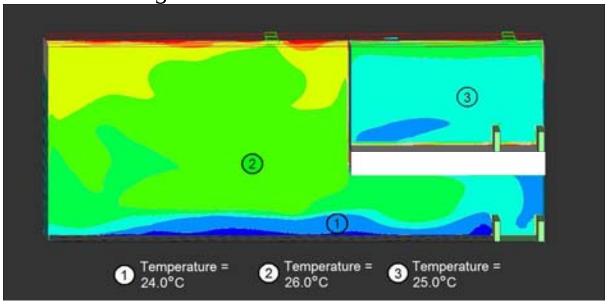

Figure 6 Temperature distribution

Figure 6 demonstrates the effect of thermal stratification within the occupied zone. It also illustrates the effect of cooled floor on the extended supply air throw, penetrating deep into the occupied zone.

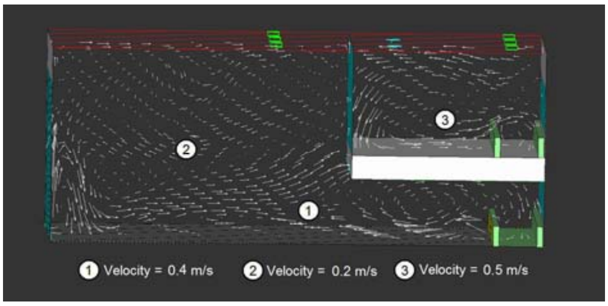

Figure 7 Air flow distribution

Figure 6 illustrates the air flow pattern and local air velocity within the terminal building. It shows an increased air flow velocity of approximately 0.4m/s within the occupied zone decreasing to approximately 0.2m/s above the occupied zone.

DISCUSSION

Traditional tropical architecture relies on natural ventilation and minimization of thermal mass. This may not always be achievable in large airports especially where the use of natural ventilation may be restricted due to security requirements and the need to maintain the relative humidity within a specific range.

Modern airports are characteristic for their large, open spaces with abundant natural light. Large glazed facades and concrete structure contribute to the increase of the Mean Radiant Temperature of the space which in turn may have a negative impact on thermal comfort.

The proposed system outlined in the above-mentioned case study provides good climate control in the occupied zone. Results of the analysis point out to aspects of the design which require careful consideration and attention by the design team. They are thermal stratification and the selection of the right combination of the supply air temperature and quantity (velocity).

Thermal stratification is one of the key objectives of the adopted design strategy. However it can potentially decrease thermal comfort if it results in an unacceptable vertical temperature distribution between the floor level and head height.

The other potential problem area is the selection of the right combination of the supply air temperature and quantity (velocity). Additionally, the supply of air directly to the occupied zone requires the supply air temperature to be close to the zone temperature in order to avoid draughts, yet low enough in order to reduce the volume of the supplied air. This optimization will inform the architectural design by specifying the required number and size of the low level supply air registers, to be incorporated in joinery or other architectural features.

CONCLUSIONS

Energy efficient design of large buildings with diverse and transient population in tropics poses a number of challenges. In order to arrive at the right solution the HVAC design should respond to local climatic conditions and functional requirements, rather than adopt generic set of operating conditions.

This approach requires close cooperation of the design team which should be initiated at the concept design development stage. Initial stages of the concept development also require full participation of all the stakeholders, including the end user and their operations representatives.

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