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Thermal performance assessment of a retrofitted building using an integrated energy and computational fluid dynamics (IE - CFD) approach

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Abstract

The comfort of the occupant in the indoor thermal environment can be efficiently analysed using the principle of computational fluid dynamics (CFD) technique. This can be modelled as a difference of measure of a region equivalent to air circulation and diffusion in/out of the area. Other parameters influence the room operating condition and energy consumption by the building systems directly and indirectly over a period of time. This paper represents how to use comfort theory and CFD concepts to do a computational study of building comfort and improve the energy performance of the building during the summer and winter seasons in the subtropical climate. The occupants' overall comfort evaluation results in the chosen building are recorded, taking into account the suitable climate-responsive heating, ventilation and air conditioning approach and envelope systems. The thermal CFD simulation model used in this study incorporates the most current turbulence simulation methodology appropriate for airflow modelling in buildings. The numerical comfort analysis methodology is used to analyse the indoor thermal condition, considering the Cooled Beam cooling system and BioPCM as an envelope solution for possible retrofitting. The simulation findings show that the uniform temperature distributions observed during working hours are adequate and demonstrate improved energy performance by the building systems. Moreover, the results suggest that the use of advanced computational fluid dynamics techniques is a valuable method for the analysis of human comfort in indoor spaces.

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1. Introduction

Heating, ventilation, and air conditioning (HVAC) units are only a handful of the larger energy-intensive equipment in the building. According to the literature, many in the conventional building sector have a greater demand for human comfort, whilst the new building sector has better human comfort compared to the older buildings. A scientific study into human comfort by Peng [1] claimed that the temperature and conditions outside of the building deeply influence comfort within the building. Wang et al. [2] indicated that the comfort problems in buildings ought to be resolved as soon as possible due to the fact that an elevated level of discontentment among building tenants will have an immediate impact on their efficiency and overall well-being. Mansy [3] explained the process to determine the factors that explain comfort in an indoor space through a simulation of the human comfort and efficiency of the facility's occupants' energy use patterns. There are several measures that can be implemented to improve a facility's overall comfort. Additionally, many simulation-based study experiments explored human comfort and their behaviour to achieve and maintain a stable state in an occupied room. Thermal comfort is somewhat contextual and context-based. There is no one answer that can satisfy everyone's needs every time. Although it would be expensive, it is required to be maintained at the recommended temperature for 100% of the occupied time as well as in severe weather to ensure comfort for most of the occupied hours, as indicated by Yang et al. [4], Nag [5] and Song et al. [6]. While there has been an increase in an effort dedicated to recognising the compromise between human thermal comfort and energy usage discussed by Chowdhury et al. [7] and Han et al. [8], with this increased understanding comes an opportunity to optimise the cooling settings and temperature settings to one another. An approach to regulating temperature relies on thermally sensitive comfort models to fluctuate the setpoint. A case study analysis by Jindal [9] and Rijal et al. [10] revealed that a significant amount of electricity might be saved for both the workplace and the home. Several studies have investigated how non-residential facilities can reduce their energy use by strategies such as adaptive thermal gain under adjusted indoor conditions. Office building case studies by Draganova et al. [11] and Göçer et al. [12] demonstrated that comfortable large-scale indoor environments could be created by using current and future design ideas.

One of the current challenges for the heating, ventilation and air conditioning industry is the lack of realistic regulations that lower electricity consumption and increase the general wellbeing of occupants in institutional and industrial buildings. Many facilities incur significant costs to use power because of wide-ranging charges imposed by the power supply providers. The present energy market necessitates a reduction in Australia's energy consumption and emissions, but these conditions present many opportunities and difficulties. To keep people comfortable in a hot environment, buildings in tropical locations must be air-conditioned continuously using passive cooling provides comfort and increase the efficiency of the processes. A major portion of carbon pollution is thought to be attributable to energy consumption. Occupant comfort and building system efficiency can be improved with alternative HVAC systems. In the context of HVAC systems, alternative HVAC systems provide improved convenience and maximise the overall efficiency of the building systems. In addition to cutting carbon dioxide emissions and using less energy, the operational processes may help reduce carbon dioxide emissions and energy consumption. It is important to increase the mechanical HVAC system's efficiency in order to reduce the discharge of greenhouse gases. Understanding the best approaches for measuring the energy efficiency of buildings and assessing the occupants' comfort in that condition is crucial. Interior building thermal conditions can be impressively analysed using the computational fluid dynamics (CFD) method. This paper explained how to use comfort theories and CFD concepts to do a computational study of building comfort considering the Cooled Beam cooling system and BioPCM-based building envelop system.

2. Computational comfort analysis

Using CFD, it is possible to accurately predict the amount of air required for interior building spaces, as well as to simulate and measure the efficiency of building air-conditioning and ventilation. There are several studies examining the application of computational fluid dynamics (CFD) to indoor spaces with respect to the measurement of the effect of airflow inside and outside of buildings. Air dissemination methods for room air conditioning systems were analysed in detail by Sadrizadeh et al. [13]. Myhren and Holmberg [14] adopted computational fluid dynamics (CFD) based methodology to study indoor air quality and atmosphere management parameters. In an effort to better predict air temperature, airspeed, ventilation adequacy, and other properties, four diverse air dispersion systems with a cooling load were tested by Karimpanah et al. [15] and developed a specific computational fluid mechanics-based

research methodology. Zhai et al. [16] combined different building systems modelling programs and a CFD model resulting in a more substantial airflow prediction process. To improve CFD-based performance measurement process efficiency, Storås [17] tried to consolidate the CFD analysis approach with the building energy analysis. Ghosh et al. [18] conducted a research project that incorporated three different techniques: a $k-\varepsilon$ model, a low Reynolds model, and an RSM to discover and analyse the indoor airflow pattern in a home.

In order to simulate airflow patterns and thermal comfortability using standard CFD applications, a significant amount of time and resources must be spent to describe the structure, and boundary conditions and extract the possible outcomes. In this study, the CFD module of DesignBuilder was adopted to visualise the delivery of airflow and temperature in and around structures. DesignBuilder's CFD module is incredibly valuable since it greatly restructures the operation by logically assigning the geometry and limit parameters, which are dependent on the supplied building modelling details. Utilising EnergyPlus in estimating building energy performance evaluation is simple in the sense that it is quick and precise. DesignBuilder's CFD algorithm provides assessment built from sequentially generated default data of building performance simulation. In Designbuilder, the temperature and heat stream rate in the building spaces ensures that the distribution of pressure, the velocity of air, and temperature are thorough and complete. The application of these data can be used to measure the effectiveness of various ventilation and air conditioning configurations, as well as to gauge the comfort conditions in the indoor environment. In this study, 3D CFD matrices are created from geometry and limits that pertain to the arrangement assembly and can be modified to help with the assembly process. The CFD algorithm employs a SIMPLER calculation, which is among the most frequently used CFD algorithms. The turbulence is illustrated by using the $k-\varepsilon$ model. This study represents a model to demonstrate how comfortable the occupants are in the building by using the selected CFD method.

3. Modelled scenario and CFD simulation processes

The foundation of the modelled building is made of concrete. The computation comfort analysis was carried out using the base case model created with the current operating condition. In the base-case scenario, the majority of the key building details (Table 1) have remained largely unchanged. The outdoor wall is customised to accommodate the BioPCM envelope, which is comprised of BioPCM Q23 as well as gypsum plasterboard, XPS extruded polystyrene, and brickwork externally. Both sides of the internal wall are plasterboard with a timber structure. There are three levels in the building, and the air conditioning has been changed to a Cooled Beam system, which is one of the best solutions for the tropical environment. The model is updated using a BioPCM based envelope system and the low-emission cooling system that is suitable for a tropical climate. The specification of the limit conditions is a critical first step in the execution of CFD analyses. All the related variables in the formulas are provided with realistic values for the computations to be performed in the fluid domain, which is referred to as the boundary conditions in the problem statement. In order to conduct a CFD analysis, design settings of the indoor space that represent residents and HVAC systems, for instance, heat gains, supply diffusers, Zone surface temperatures, grilles etc., are defined in the developed model.

DesignBuilder program is being used to test people's level of comfort in an educational facility in Rockhampton, Australia. To assess the comfortability of people inside the building, the DesignBuilder (DB) Release 6.0.1.019 CFD package [19] was used. DesignBuilder generates a virtual environment in which the efficiency of a building's energy systems is measured, and people's thermal comfort is expected. The CFD technique considers the underlying differential equation (PDEs) based on momentum, energy and turbulence magnitudes. The DesignBuilder software's CFD approach considers both appropriate and useable yield patterns. The CFD grid is configured to correspond to the design of the model building's components. The accuracy and statistical symmetry of the model are determined by the grid. The mathematical technique used for the CFD module is referred to as a primitive variable system, and it contains equation sets that describe the conservation of mass and momentum. It is necessary to include three velocity profiles as well as temperature in the momentum equation (Navier–Stokes formulas). The study made use of the turbulence model as well as the turbulent kinetic energy theory to analyse the flow. The formulas are a collection of nonlinear partial differential equations of second order that are coupled together. According to the hypothesis, airflow in an air-conditioning is an incompressible and steady-state phenomenon.

In this analysis, the $k-\varepsilon$ model, an open and commonly used turbulence model derivative of the Reynolds Averaged Navier–Stokes (RANS), is used. The instantaneous rate in the energy equations is replaced with a mean and swaying element in this $k-\varepsilon$ model. Reynolds stresses and unpredictable heat flux elements are provided

Table 1. Base case modelled building.

Category	Value
External wall	Double brick plaster
Roof ceiling	Plasterboard and concrete
Floor surface	Concrete slab with carpet
Internal partition	Lightweight gypsum plasterboard with cavity
Metabolic	0.9
Winter and summer clothing insulation	1 clo and 0.5 clo
Glazing	Single glazed, clear float $\frac{1}{4}$ inch with blinds
Occupancy rate	1 person per 10 sq.m
Outside air intake	10 l/s/person
Shading	Overhang
Lighting type and power density	Fluorescent, 15 w/sq.m
Cooling type and power density	Air-cooled chiller, 40 w/sq.m
Ventilation type and power density	Standard, 5 w/sq.m
Plug load type and power density	Standard, 15 w/sq.m

by the derived methods. Reynolds stresses are modified in terminology, implying instantaneous speeds. For the energy calculations, a comparable alternative is used. The sum of turbulence viscosity obtained as a result of turbulent kinetic energy is referred to as the effective viscosity following the method explained in DesignBuilder Software [19].

The system of equations is solved using the finite volume method. The stability of the flow rate is analysed, and the velocity module for both inlet and outlet flow is inspected. A computer-based undifferentiated model grid surface is introduced, where an algorithmic mesh refinement is allowed to fine-tune the boundary conditions. Gradients in solution variables, such as air velocity, are measured by applying a grid to the equation. On the layer of heat sources, as well as in the suction and discharge areas, grid refining is added. In order to verify the airflow rates and conditions of the air source diffusers and jets, the airflow rates and parameters are set relative to their real values. The flow is intended to uniformly distribute across the streams by way of a continuous, constantly increasing vertical velocity. In the model, the parameters of the inner surface were stated. For example, heat fluxes were used to estimate the amount of heat produced by different forms of heat sources. Figs. 1 and 2 show the cooled beam system and BioPCM-based envelop system configuration considered in the study. Indoor temperature design conditions in CFD ranged from 22 °C to 24 °C, humidity between 45 and 50 per cent, and comfort index between −0.5 and 0.5. The outdoor temperature was 36.5 °C, the outdoor wet-bulb temperature was 24 °C, and global solar radiation was 950 W/m².

4. Findings from computational comfort analysis

Using average weather data, an estimate of cooling and heating load is made to determine the size of the air-conditioning equipment required to maintain the most common summer and winter conditions expected to occur in Rockhampton. Air temperature is blended and stable in thermal blocks which are considered in the EnergyPlus algorithm. In this case, it is assumed that the airflow temperature is totally uniform in the indoor space. Environmental information such as the dry-bulb temperature, clear and diffusive solar radiation, dew point temperature, wind direction and velocity, and air pressure, which change during the summer and winter months, are used. As can be shown in Fig. 3, the normal relative humidity and dry bulb temperature profile of the indoor space is obtained.

Fig. 4 represents the temperature distribution and PMV values in a typical thermal zone at the floor level. The room analysis demonstrates the temperature varies mostly from 22.31 °C to 22.97 °C with slightly higher temperature at the externally exposed surfaces and corridors where there is no dedicated air duct. From Fig. 5, we can see the direction and magnitude of velocity vectors situated from 0.01 m/s to 0.07 m/s, with just a minor variation in the inlet and outlet areas (doors and windows). Pressure differs in each thermal zone. When the air pressure moves towards the windows and doors, the air velocity changes gradually from turbulent to almost uniform. The results of the CFD

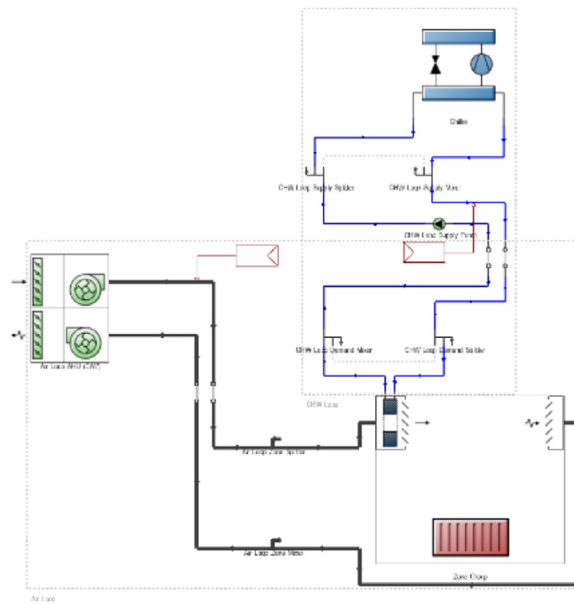


Fig. 1. Cooled beam system considered in the study.



Fig. 2. BioPCM Q23 based building envelop system.

simulation in Fig. 6 show the mean operating temperature and average radiant temperature, as well as their respective distributions. Determining the comfort level of the people was done by using the measurements of air velocity and temperature. The findings show that pressure-inlet boundary conditions are more beneficial for CFD simulations using a pressure source than for velocity-inlet boundary conditions. The gradients of simulated temperatures are shown in Fig. 7. The temperature vectors change to an almost equal flow as the flow goes through the zone. The air-conditioned rooms in the building have a temperature range of 23.33 °C to 24.33 °C. The example in Fig. 7 in which the thermal comfort threshold is particularly high in the roof space. Fig. 8 demonstrates that the PPD value fluctuated between 9.7 and 9.95% throughout winter and summer business hours, which is within the 10% PPD limit specified in the comfort zone. A converged solution in terms of thermal density, temperature and velocity is obtained on completion of 22000 iterations. Figs. 9 and 10 correspond to the normalised hourly energy consumption profiles of the building for typical summer and winter days. Fig. 11 represents a comparison of simulated and measured temperature profile which demonstrate consistency in the temperature in the airconditioned space. Throughout this study, significant facts about the building's internal environmental settings and user satisfaction levels have been examined. At the ideal level of comfort, the temperature and comfort index values are deemed steady and well-managed. In this research, the present operating strategies in the indoor space are examined, and the construction's

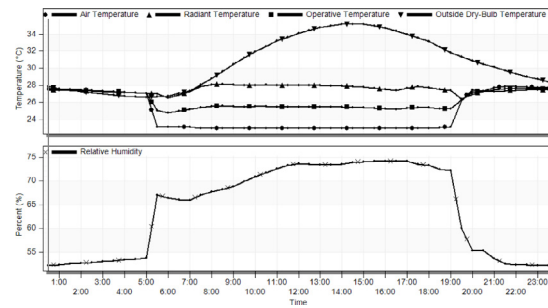


Fig. 3. The hourly distribution of indoor air, radiant, operative and outdoor dry-bulb temperature and indoor relative humidity in a typical day.

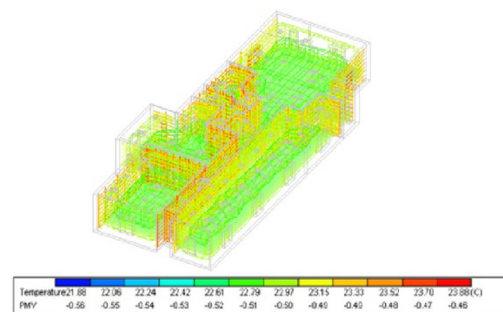


Fig. 4. Temperature and PMV distribution in a typical thermal zone at the floor level.

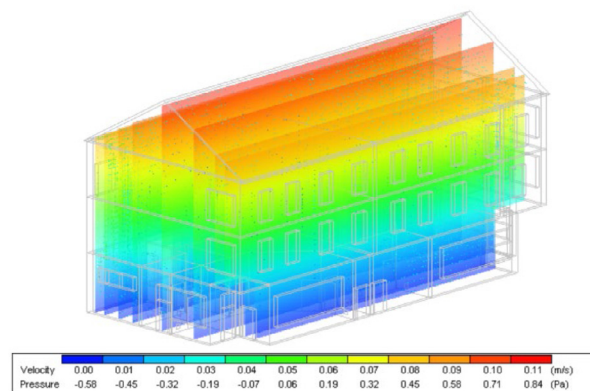


Fig. 5. Simulated representation of velocity profile and pressure values of the indoor space.

comfort potential is assessed using existing concepts. The comfort index (Fanger PMV) is simulated on a thermal point scale, with outcomes that are consistently within ± 0.5 throughout the simulation period. The CFD simulations also allowed an opportunity to reveal any flow conditions that were not expected. As shown in the results, the simulated flow fields confirm expected flows and reveal no anomalies in the airflow.

5. Conclusion

The model used in this study comprises the most up-to-date turbulence modelling approach suitable for modelling building airflow. The thermal state of a retrofitted building is examined using an Integrated Energy and

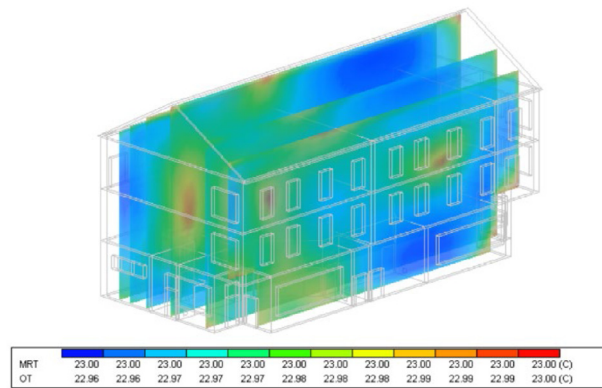


Fig. 6. Simulated representation of operative temperature and mean radiant temperature profile.

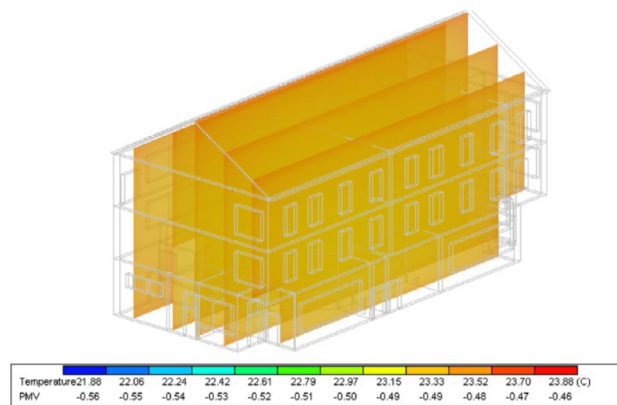


Fig. 7. Simulated representation of PMV values and temperature profile.

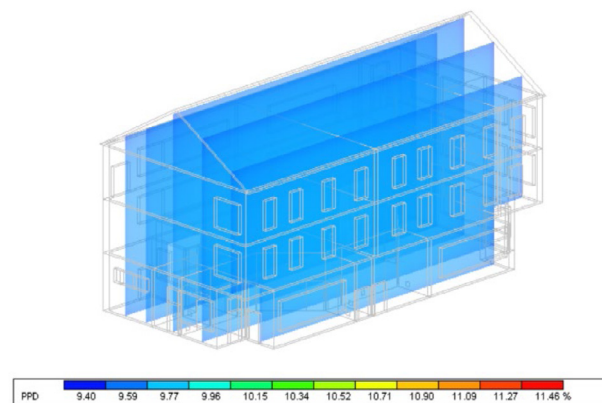


Fig. 8. Simulated representation of PPD profile .

Computational Fluid Dynamic Simulation (IE - CFD) Approach. The simulation's findings will give convincing and useful numerical information regarding the building's real thermal comfort. The numerical comfort analysis approach is used to estimate the interior thermal environment by assessing the performance of building systems utilising the Cooled Beam alternative low emission cooling process and the BioPCM alternative envelope. During working hours, the temperature distributions were consistent and appropriate, according to the simulation results. The modelling

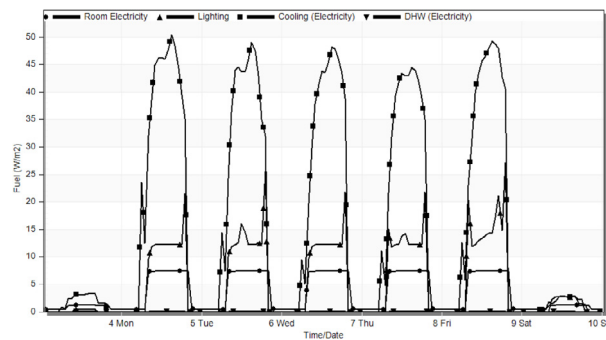


Fig. 9. Energy consumption profile in a summer week.

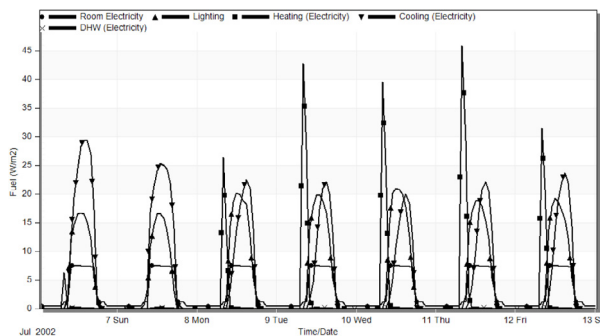


Fig. 10. Energy consumption profile in a winter week.

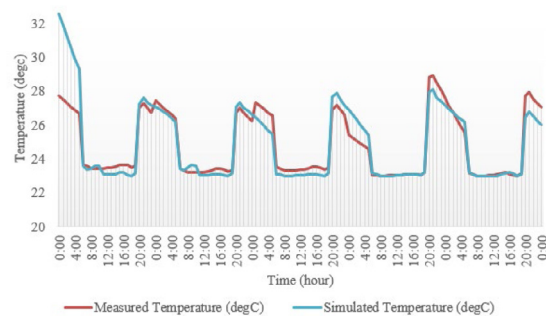


Fig. 11. Comparison of the simulated and measured temperature profile in a typical week.

findings also demonstrate that using sophisticated CFD methods to investigate human comfort in the interior area is a useful tool for assessing occupant comfortability. Choosing the right cooling system and external building envelope is critical to avoid wasting energy and ensuring people's comfort. The research revealed that it is viable to adopt resolutions that compete positively with cost-effective alternatives and can adapt to changing indoor comfort owing to emerging climate change phenomena. The study's findings will help engineers and other professionals and academics better understand the complex interconnections of climate-dependent variables on energy conservation and thermal efficacy of building systems in Australia's subtropical climates.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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