Validated Model and Study of a Rammed Earth Wall Building

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Abstract

A 2100 m² (GFA) two-storey rammed earth building was built on the Thurgoona campus of Charles Sturt University in 1999. The building is novel both in the use of materials and equipment for heating and cooling. The climate at Wodonga can be characterised as hot and dry, so the challenge of providing comfortable working conditions with minimal energy consumption is considerable. This paper describes a thermal model of one of the second-storey offices on the west-end of the building. The simulation software, TRNSYS, has been used to predict office temperatures and comparisons are made between these and measurements made over a typical week in summer. Reasonable agreement has been achieved under most conditions. The model has been used to investigate key building parameters and strategies, including night flushing, to improve the thermal comfort in the office.

1. INTRODUCTION

In recent years, some progress has been made worldwide in the design of commercial office buildings to minimise energy consumption, yet still provide acceptable levels of comfort. Such buildings are often referred to as environmentally sustainable, green or even 'deep green', when they display a range of sound environmental characteristics (Johnson, 2001). These buildings may include low operational and embodied energy, reduced water use and on-site wastewater management. The Thurgoona campus of Charles Sturt University (CSU) in the Riverina district of New South Wales has been designed in accordance with these principles. The buildings demonstrate solar active and passive design strategies, and include features such as composting toilets and rainwater collection. There are teaching buildings, an earth covered lecture theatre, student residences and an office building for staff.

This office building is constructed from rammed earth. This material is generally believed to be environmentally benign and an appropriate construction choice in certain circumstances and climates. Few studies of its use, however, appear in the research literature. In all of these studies, the material has been used in residential buildings built overseas (Kleespies, 2000; Goodhew et al., 2000). If this material is to be more widely used by designers of commercial buildings in Australia, its thermal performance in our climate needs to be better understood. The paper describes a simulation model of one of the offices in the rammed earth building on the CSU campus. The validation of the model and its use to investigate some of the key parameters and strategies to operate the building are presented.

2. THE CSU BUILDING

The CSU office building is a two-storey building with 300-mm thick load-bearing rammed earth external and internal walls. The building is curved and orientated as shown in Figures 1. There is a central corridor running the length of the building on both levels of the building with offices located on either side. Each office has a typical floor area of 10.5 m².

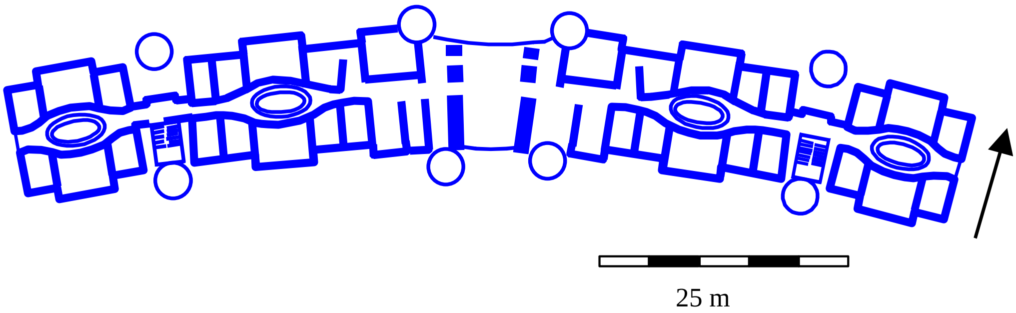

Figure 1 Orientation of CSU building

Ventilation is achieved during the daytime by opening the windows. The windows use single 6 mm glass mounted in wooden frames. The offices have double-hung vertically-sliding sash windows with weather strip sealing. In the stair wells and at the end of the corridors upstairs there are manually operated louvre windows. Window shading has been carefully designed to exclude all direct beam sunlight during the summer months. There are light and ventilation wells between the ground floor and upper storey. Ventilation towers or stacks are situated above these wells to increase ventilation. Each office has a variable speed sweep fan controlled by the occupier to assist air movement.

A hydronic system, controlled by a building management system (BMS), is used for heating and cooling. Heat is provided by a gas-fired boiler or solar panels and the initial design sourced cooling water via on-site dams or from water chilled by circulation through the solar panels at night. However the main method of cooling in summer was to be controlled ventilation at night, lowering the temperature of the rammed earth, which would then act as a store of “coolth” during the day. Since a hydronic system is used there is no need for a suspended ceiling to conceal duct work, and the concrete ceilings (on both storeys) remain exposed. In some places a corrugated profile has been cast into the ceiling to increase its surface area to enhance the heat transfer. The floors are carpeted, wool insulation has been used underneath the roof sheeting and foam insulation has been installed around the edge of the concrete slab. The external doors at CSU all close automatically and seal against a wooden frame.

3. MEASUREMENTS

The office on the north-western end of the building on Level 2 was chosen for this study because it is likely to experience the highest internal temperatures in summer because of its location (Figure 2).

Figure 2 Westerly and northerly views respectively of the office studied

During the later part of the 2001 summer data logging equipment was installed to record various temperatures (wall surface, mid-wall, ceiling, floor, air and globe at 1.1 m height). The opening of the window and operation of the ceiling sweep fan were also recorded at 15 minute intervals (Figure 3). Climatic variables (solar radiation, dry bulb temperature, wind speed and relative humidity) were recorded at a nearby weather station.

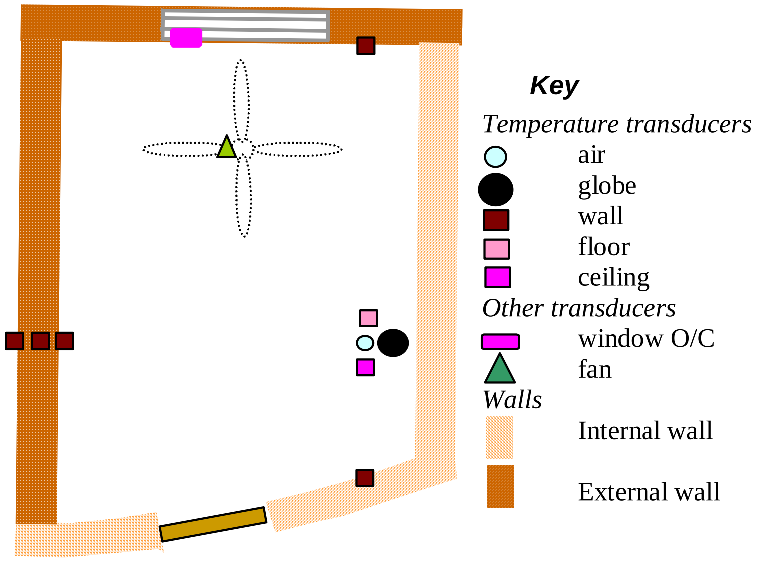

Figure 3 Position of temperature and other sensors within office

4. DESCRIPTION OF SIMULATION MODEL

The software used to simulate the thermal performance of the CSU building was TRNSYS (Transient System Simulation Program) developed by the University of Wisconsin in the mid-1970s (TRNSYS, 2000). TRNSYS treats the various spaces within the building as zones and in these simulations the office and the roof space were considered as two separate zones, whose boundary conditions were defined as follows. The temperatures of adjacent offices on Level 2 were taken to be at the same temperature as the studied office. An actual measured temperature was used as the boundary condition for the office below the studied office. TRNSYS itself generated the temperature of the roof zone. The external air temperature was measured by the weather station. Radiation falling on the roof and external walls was calculated by TRNSYS through the use of the radiation and wingwall subroutines, which allows for shading by eaves and adjacent walls.

The dimensions and construction materials of each zone are given in Table 1 and the material parameters used in the simulations are given in Table 2.

Table 1 Office dimensions and construction details

Building Zones	**Description**	**Area (m^2)**	**Vol (m^3)**
Office	Level 2, azimuth 22.5^0	10.5	28.4
Roof zone	Azimuth 22.5^0, slopes 7.5^0 & 37.5^0	188.0	179.4
Structural Element	**Construction**		
Roof	Corrugated steel + wool insulation		
Ceiling	150 mm thick concrete		
Floor	150 mm thick concrete + carpet		
Walls (int & ext)	300 mm rammed earth		
Glazing	6 mm single layer standard window glass		
Internal Loads	**Description**	**Schedule**	
People:	150 W	'on' between 8am and 6 pm	
Equipment:	140 W	'on' between 8am and 6 pm	
Lighting:	80 W	'on' between 8am and 6 pm	
Ventilation / Infiltration	**Value**	**Schedule**	
Ventilation (office)	1 x *vent*[1]	On when ambient + 2^0C = average inside temp Off when ambient = average inside temp	
Infiltration (office)	4 x *window* + 0.5	At all times	
Infiltration (roof)	2	At all times	

Table 2 Material Parameters

Parameter	**Value**	**Unit**
Internal air film conductance	8.3	$W/m^2 K$
External air film conductance[2] (wind vel m/s)	3.9 x wind vel + 5.62	$W/m^2 K$
Wall surface solar absorptance	0.5	n.a.
Density of rammed earth	2050	kg/m^3
Rammed earth conductivity	1.1	W/m K
Specific heat of rammed earth	600	J/kg K
Carpet R-value	0.22	$m^2 K/W$
Wool insulation R-value	3.6	$m^2 K/W$

5. MODEL VALIDATION

A five-day weekday period during late summer (February 19-24, 2002) was used to validate the model. In the week chosen, the weather was typical for Albury-Wodonga in summer with predominantly clear skies and warm-to-hot daytime ambient temperatures[3] (Figure 4). The maximum temperature reached was 36^0C late in the week, while the minimum of 15^0C occurred early in the week on the Monday. The total horizontal radiation peaked at 1100 W/m^2. Since the ambient conditions are within the expected range for this time of year, this period can be used to examine the performance of the building and comfort levels in summer conditions.

[1] The two variables, *window* and *vent* can take values of 0 or 1. The latter indicates that the window is open or the night purging is taking place, while a zero implies the contrary. Ventilation of the office occurred when the external air temperature fell 2^0C below the average internal building air temperature, and ceased when the two temperatures became equal.

[2] ASHRAE (1997) -Table 6, section IV, page 3.14

[3] During the summer period the maximum daily temperature is expected to rise above 30^oC on 52 days and be above 35^oC on 17 days.

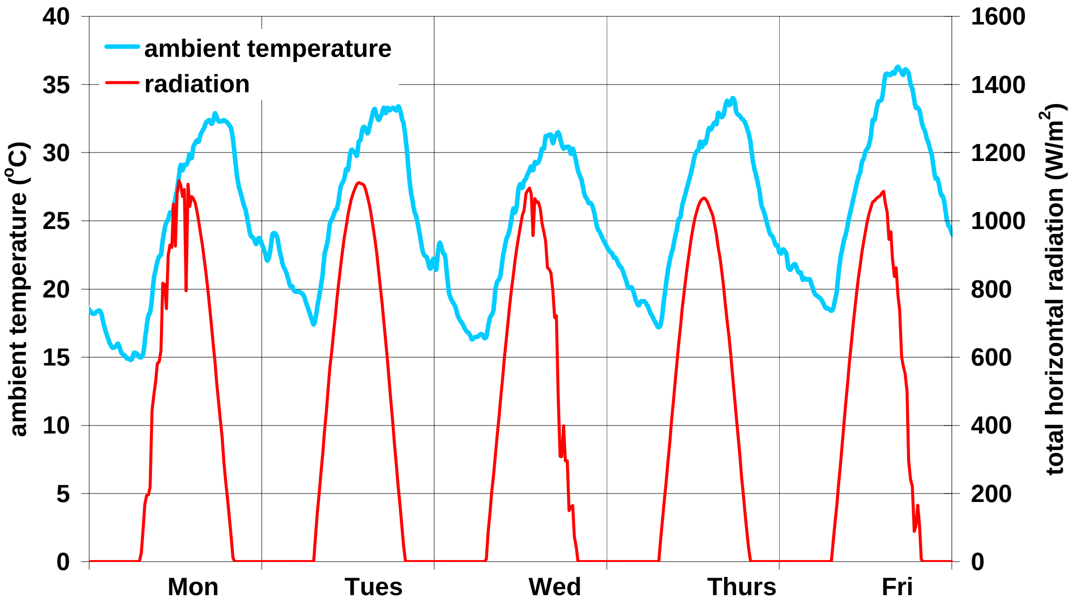

Figure 4 Solar radiation and ambient dry bulb temperatures used as input data

The air temperature within the office depends on heat transferred through the building envelope, the infiltration and ventilation rates, the internal heat gains and the effects of the thermal mass within the building. A comparison of measured and predicted office internal air temperatures, using the model parameters and schedules described above, is shown in Figure 5.

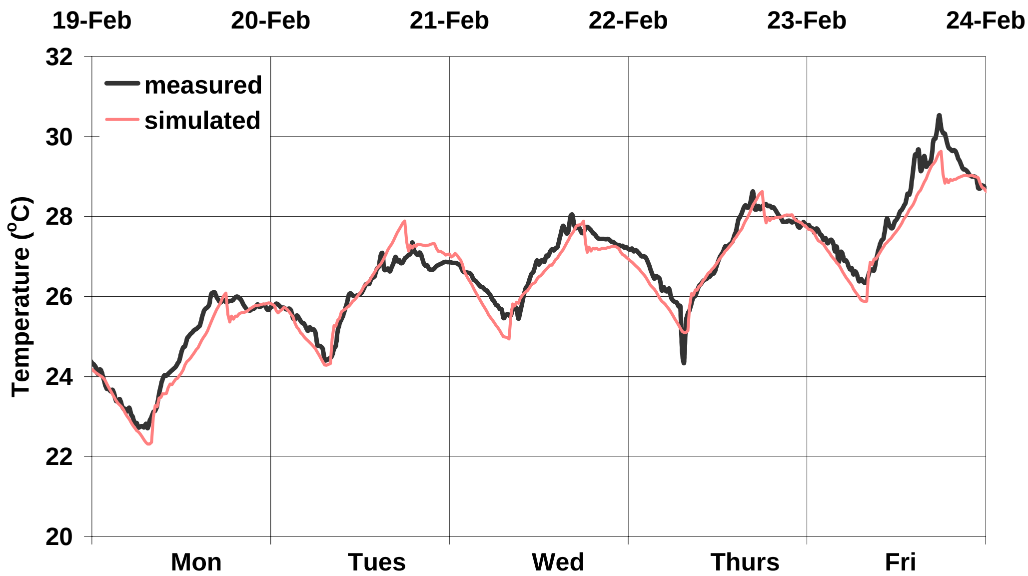

Figure 5 Simulated and measured office air temperatures

The temperature graph shows a diurnal variation in temperature with an overall temperature increase during the week. The office temperatures (measured and predicted), as well as the operative temperature, for the week between 8am to 6pm are shown in Table 3. The operative temperature was calculated by TRNSYS using the air velocity measured by the fan transducer. The measured and predicted office temperatures show close agreement and indicate that the model can be used to examine ways to improve performance and/or comfort levels.

Table 3 Measured, predicted and operative office temperatures

Statistic	Measured (^{0}C)	Predicted (^{0}C)	Operative (^{0}C)
minimum	23.0	22.4	22.5
25% percentile	25.8	25.8	25.5
median	26.7	26.7	26.4
75% percentile	27.7	27.6	27.2
maximum	30.5	29.6	29.3

ASHRAE 55 recommends that the acceptable range of summer operative temperatures is bounded by the 23 ^{0}C and 26 ^{0}C ET* lines (ASHRAE, 1992). The psychrometric chart gives corresponding operative temperatures at the 3pm humidity (typically 30%) to be 23.5 to 26.8^{0}C. Clothing level is taken as 0.5 clo, activity as 1.2 met and air movement up to 0.15 m/s. The ASHRAE 55 recommended comfort zone temperatures are higher than those frequently found in Australian buildings during the summer[4]. It is interesting to note that even if a building meets the ASHRAE criteria it may well be perceived to be too hot by occupants accustomed to other offices or dwellings chilled to a lower temperature. The results indicate that for well over 25% of the working week the temperature in the CSU office is well outside the ASHRAE comfort zone, and by common Australian standards would be judged very high even though the weather is not extreme for the summer period. The model was therefore used to examine some strategies to improve the comfort conditions in the office.

6. PARAMETRIC STUDY

Three strategies were investigated to reduce the office temperatures and hopefully improve the operative temperature. The strategies were a) increasing the night ventilation rate, b) adding insulation to the external walls and ceiling, and finally c) using a hydronic cooling system. Their effect was not investigated separately, rather the cumulative effect of the strategies was predicted, beginning with the simplest strategy i.e. increasing the night ventilation rate. This was followed by the adding insulation because this is a passive strategy involving a one-off expense and little or no on-going expenditure. The hydronic cooling system was the last strategy to employ because of the on-going cost and complexity to provide chilled water and energy for pumping.

6.3 Increasing the Night Ventilation Rate

The primary source of cooling in the CSU building is considered to be night ventilation. When validating the model, the air exchange rate during the night was 1.5 air changes per hour (ACH). This rate is low for night purging and may have resulted from the nature of the building or because the hand operated louvres above the door in the office were closed during the day and not opened at night. Three changes were made for this simulation. The air movement in the office for comfort calculations was set at 0.15 m/s. The boundary temperature for the floor was set to be identical to the zone temperature. Night ventilation rate was increased to a net value of 20 ACH between the midnight and 8am (Figure 6 and Table 4).

[4] A recent study in a climatically similar region suggested a preferred operative temperature of 22.3 ^{0}C in office buildings. Cena, K. and R. de Dear (1998) .

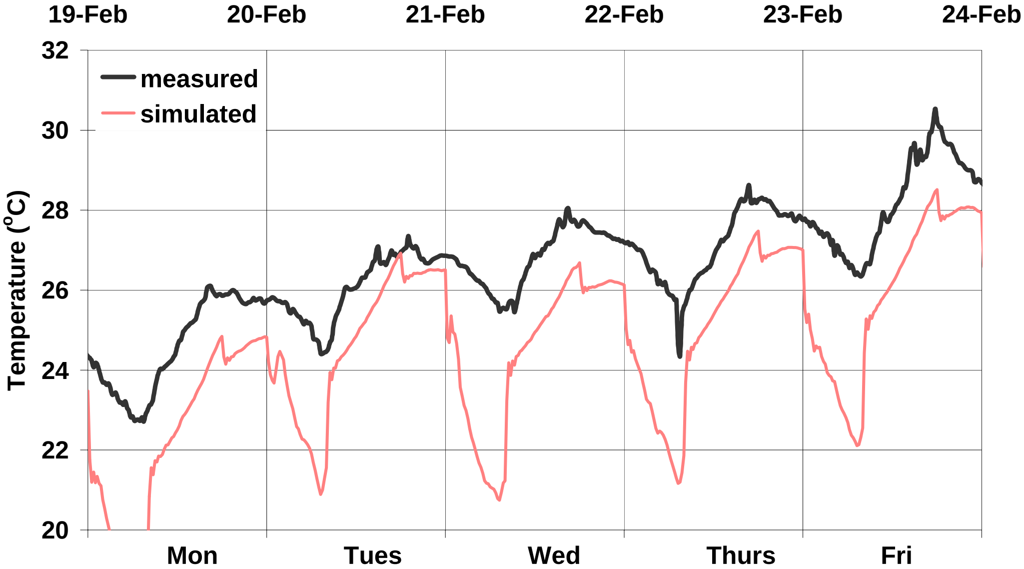

Figure 6 Measured and predicted office air temperatures with 20 ACH from midnight to 8am

Table 4 Measured, predicted and operative office temperatures with 20 ACH night ventilation

Statistic	Measured (°C)	Predicted (°C)	Operative (°C)
minimum	23.0	19.2	19.8
25% percentile	25.8	24.3	24.0
median	26.7	25.3	24.9
75% percentile	27.7	26.3	25.9
maximum	30.5	28.5	28.1

At midnight when the night cooling starts there is an immediate drop in air temperature. This continues through the night until 8am when there is a sharp rise of 3°C. This rise is in part due to the heat loads but also due to the wall temperatures remaining above that of the cooling air temperature. The office air temperature rises steadily by 2.5°C during the working day until 6pm when the absence of the daytime heat loads leads to a 0.5°C temperature drop. There is an improvement in comfort conditions but towards the end of the week the steady build-up of heat in the building results in temperatures for most of the working day being above 26°C. Now, however, with the increased night ventilation rate, the office operative temperature lies within the ASHRAE comfort zone for more than 75% of the time.

6.3 Adding Insulation

Earth walls, while adding good levels of thermal mass to a building, are a poor form of insulation. The effect of adding 50 mm of polystyrene insulation to the outside surface of the external walls and above the ceiling was therefore investigated[5]. The high ventilation used in the previous section was maintained. Figure 7 and Table 5 show the results of these simulations.

[5] The R-value for the earth material alone for a 300-mm thick wall is in the order of 0.27 m^2K/W. The insulation added has an R-value of 1.8 m^2K/W giving a total of 2.07 m^2K/W.

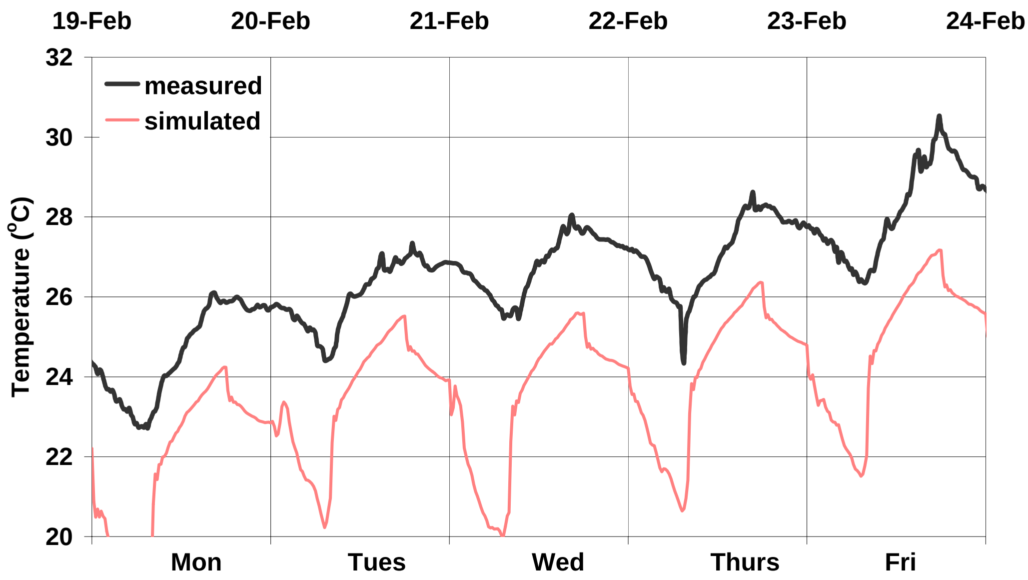

Figure 7 Measured and predicted office air temperatures with increased night ventilation and added insulation

Table 5 Measured and predicted office air temperatures with increased night ventilation and added insulation

Statistic	**Measured (^{0}C)**	**Predicted (^{0}C)**	**Operative (^{0}C)**
minimum	23.0	19.2	19.7
25% percentile	25.8	23.7	23.4
median	26.7	24.7	24.4
75% percentile	27.7	25.5	25.2
maximum	30.5	27.2	26.8

Table 5 shows that the maximum operative temperature predicted by the simulation is now at the uppermost end of the ASHRAE comfort zone and occurs at 6pm of Friday when the ambient temperature is over 35^{o}C. For over 75% of the time the operative temperature is below 26^{o}C.

6.3 Improving the Hydronic Cooling System

A network of plastic pipes (25-mm OD 4-mm wall) at 150-mm centres was embedded during construction in the ceiling and floor of the offices. The design aim was to use the hydronic system for both heating and cooling. At the time of monitoring this system had not been used for cooling. The effect of using the hydronic cooling system was therefore investigated by simulation. The inlet water temperature to the system was assumed to be 18^{0}C with a flow rate of 12 kg/s per m^2 of element area. (For a second storey office both floor and ceiling would be chilled so that cooling is also provided for the ground floor). The system was operated from midday until 4 pm during the peak cooling demand period. The same level of night ventilation, insulated walls and ceiling was maintained while operating the hydronic system. Figure 8 and Table 6 show the results of these simulations.

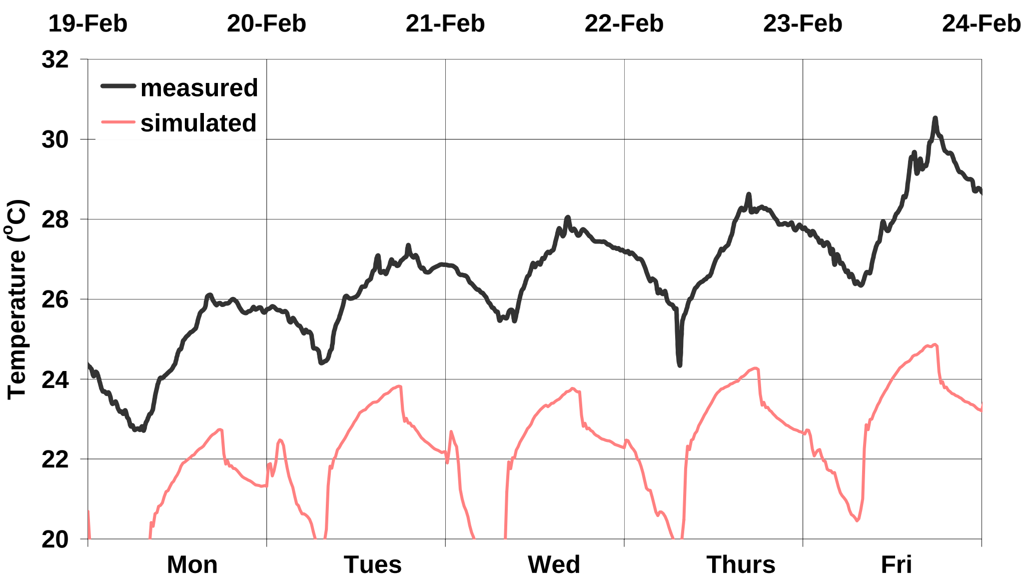

Figure 8 Measured and predicted office air temperatures with water circulation added

Table 6 Measured and predicted office air temperatures with water circulation added

Statistic	Measured (^{0}C)	Predicted (^{0}C)	Operative (^{0}C)
minimum	23.0	18.5	18.8
25% percentile	25.8	22.3	22.0
median	26.7	23.2	22.9
75% percentile	27.7	23.8	23.4
maximum	30.5	24.9	24.4

Table 6 shows that the operative temperature is now below the lower limit of the ASHRAE comfort zone for 75% of the time, although it would probably be very acceptable by Australian standards.

7. CONCLUSIONS

The modeling has demonstrated that the strategies of night purging, external insulation when combined with high thermal mass and a small amount of hydronic cooling produce significant benefit in achieving comfortable temperatures in the office studied. This office has a larger exposure to summer solar radiation than other offices since it is situated on the top west corner of the building. Hence it would be reasonable to assume that the entire building could be cooled successfully using the above strategies.

8. REFERENCES

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