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# Therma-Fuser™ Investigation into the Comparative Energy Performance of Therma-Fuser™ Systems in a Typical Commercial Building

**Automatic Control Company Pty Ltd**

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# Investigation into the Comparative Energy Performance of Therma-Fuser™ Systems in a Typical Commercial Building

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# Executive Summary

This report is an investigation into the comparative energy performance of three types of air conditioning systems – Therma-Fuser, Variable Air Volume and active chilled beams. Computer modelling of a hypothetical 10 storey office block was conducted in order to compare these three systems. This was done primarily for a Brisbane location. As a secondary exercise, Sydney and Melbourne simulations were also conducted with some simplifications to provide a comparison of performance across different climates.

The simulations all showed that all the systems provided comfortable environments, with temperatures within design conditions based on the assumptions adopted. This demonstrates that energy savings were not being made at the expense of occupant comfort.

The overall energy usage for each system in Brisbane, Sydney and Melbourne are outlined below in Table 1. More detailed analysis is given in Section 6.3 .

| Location | Therma-Fuser MWh | VAV MWh | Chilled Beam MWh |
|---|---|---|---|
| Brisbane | 489.4 | 535.5 | 470.7 |
| Sydney | 351.3 | 393.4 | 355.2 |
| Melbourne | 281.7 | 323.7 | 363.5 |

**Table 1: Energy results of building simulations**

The results of the simulation indicate that a well commissioned Therma-Fuser system can provide operational energy savings compared to a traditional VAV system for the same building. The simulation results demonstrated overall HVAC energy savings between 8.6% and 13.0% over the VAV system. The Therma-Fuser's improved energy efficiency is due to its lower minimum turn down rates and therefore lower fan power.

The chilled beam's relative performance varied depending on the location. For the chilled beam system that was used in the simulation, there were significant savings in cooling energy, but higher heating requirements. It is important to note that these results are dependant on the control strategy used. For this investigation, each floor had a preconditioning unit which ran an additional hour before the chilled beams started in order to ensure that humidity levels were low enough to prevent condensation.

Overall, the Therma-Fuser system had the best energy performance in Sydney and Melbourne and the chilled beam system performed marginally better than the Therma-Fusers in Brisbane. It is important to note that these figures are dependant on a number of factors relating to the building, the HVAC system design and the control algorithms used, and therefore should not be taken out of context or extrapolated to different types of buildings with different load profiles.

# 1.0 Introduction

This report outlines a thermal and energy simulation study of a notional commercial building in Brisbane utilising three different air side systems; a Therma-Fuser system, a traditional VAV system and a chilled beam installation. The aim of the study was to determine and compare the energy and performance benefits each system can provide.

Comparing the energy efficiency of different types of Heating, Ventilation and Air Conditioning (HVAC) systems can be complex. The energy used by cooling coils, heating coils and fans are interdependent. A system with reduced cooling energy may have increased fan energy, or result in lower occupant comfort. In addition, HVAC systems will perform differently in different climate zones, as higher or lower temperatures and humidity will affect the proportion of cooling versus heating, for example.

A Variable Air Volume (VAV) system works by using VAV boxes which can vary the airflow to different zones throughout a building. This allows high amounts of cooled air to go to areas that need it, while the airflow can be reduced in areas that do not have a high heat load at that time. For example, east and west zones both have high cooling load requirements, but only in the morning and late afternoon, respectively. Reducing the air outside these times saves fan energy and cooling energy, and prevents the spaces from being overcooled.

A Therma-Fuser system works on a similar principle to VAV boxes. A thermal VAV diffuser can reduce the amount of air being supplied based on the temperature in the space. The level of control is greater, because every individual diffuser is capable of reacting to its space, rather than a single VAV box controlling a number of diffusers. In addition, a Therma-Fuser is capable of reducing it's airflow to a lower level than a VAV system can.

An active chilled beam system works on different principles than either a VAV or Therma-Fuser system. Chilled water is passed through a beam which provides radiant cooling, and causes induced airflow as cool air drops and hot air rises. An active beam has air supplied through it, which affects the induced airflow further. The control and design of a chilled beam system needs to consider humidity and condensation. If incorrectly designed or operated, it is possible for condensation to occur at the beam, particularly in more humid climates such as Brisbane.

# 2.0 Approach

In this study the energy efficiency of a Therma-Fuser system has been compared against a conventional VAV system and an active chilled beam system. This has been done through the simulation of each of these systems serving a hypothetical ten storey commercial building. The system design is based on a typical system for a standard commercial building. The operation of these systems has considered in Brisbane, Sydney and Melbourne, to analyse how the performance varies across climates. It should be noted that the primary focus of this study has been for the Brisbane location. Some assumptions inherent in the modelling approach require further validation for their application to Sydney and Melbourne – these will become apparent in the report.

Where possible, details of the various plant systems are the same or similar, to provide a simpler comparison. For example, the total design static pressure of each system has been assumed to be equal for the Therma-Fuser, VAV and chilled beam systems. It is assumed that appropriate fans are selected for each system, with an efficiency of 55%. In addition, although an electric duct heater system would be common in Brisbane but unlikely in Melbourne, electric duct heaters have been used for all cities

This investigation is not intended to look at the effect of plant room sizing, and as such, plantrooms are not included in the model. However, for the purposes of the modelling a floor by floor approach to air handling plant has been assumed. This enables the model to maintain consistency across the systems.

No other external buildings have been included into the model to provide additional shading. The building fabric and shading have been incorporated in accordance with the requirements of the Building Code of Australia (BCA) – Section J Energy Efficiency [1]. This is a mandatory building regulation that is intended to provide a minimum level of energy efficiency. Brisbane lies within the BCA Climate Zone 2, and so the building complies with the requirements for Climate Zone 2.

As far as practical the mechanical systems designed for the building will comply with the requirements for "A" grade office space in accordance with the Property Council of Australia guidelines [2].

In order to reduce the amount of modelling required and reduce the simulation times, some steps to simplify the modelling process have been undertaken. Although all ten storeys are included in the model, only the ground floor, level 5 and the top floor are modelled in detail. The remaining floors are maintained between 21°C and 23°C during HVAC operation hours without a specific HVAC system. It is assumed that all middle floors will behave identically. On this basis, the energy use will be the total energy use of the top and bottom floors, and eight times the energy use of level 5.

The top and ground floor have been run together as one simulation, and the middle floor has been run separately as a different simulation for each HVAC system type and location. The chiller performance varies in accordance with how much load it serves at any one time. In order to account for this, the chiller running details have been modified for each simulation, assuming that all floors have similar peaks and behaviour, and that they are in the ratio of the maximum design heat loads for each floor. In this manner, the top and ground floors make up 21.2% of the total capacity, and an individual middle floor makes up 9.9%.

The ground floor and the top floor are open office areas. Level 5 contains a number of walled perimeter offices.

The internal heat loads and profiles for the building have been based on the Australian Building Greenhouse Rating Validation Protocol for Computer Simulations Version 2005-01 [3], which details typical office lighting, equipment and occupancy levels and daily variations. This allows for a realistic level of internal heat loads.

This study is not intended to investigate how airflow distribution or quantities affect occupant comfort. Occupant comfort is a separate issue and merits further consideration. Industry standard levels of minimum turndown have been used for VAV systems (40%) and Therma-Fuser systems (25%).

The temperature levels of the three types of system have been analysed in order to ensure that they are being fairly compared. If one type of system achieved low energy usage, but did so by providing inadequate cooling, it would not provide an equal comparison. An analysis has been conducted on the Brisbane results using Predicted Mean Vote (PMV) as a method of determining occupant comfort, which addresses more than just room temperature. This has not been done for the other cities as it is expected that the results would be similar, and again, this is not the main focus of the investigation.

# 3.0 Thermal Comfort – PMV

## 3.1 Background Information

Predicted Mean Vote (PMV) is used as a measure of occupant comfort. It takes into account air temperature, radiant temperature, relative humidity, air movement, clothing levels and metabolic levels. PMV is an index that predicts how the average occupant would feel in the space. It varies from -3 to 3, where positive values are hotter and negative values are colder, and 0 is a neutral temperature. A PMV between -1 and 1 would indicate that approximately 25% of the occupants are dissatisfied. A PMV between -0.5 and 0.5 would indicate that approximately 10% of the occupants are dissatisfied. The best PMV value of 0 still has 5% of occupants dissatisfied.

## 3.2 Comfort Parameters

For this analysis, the air temperature, radiant temperature and humidity levels are taken directly from simulation results, while the air movement, clothing levels and metabolic rates have been specified. The clothing levels are specified by CLO values. The metabolic rates are specified as MET values. 1.0 MET corresponds to 58.2 W/m$^2$, which is the energy used by an average person while sitting at rest.

For the purpose of the PMV analysis, some standard values have been used for clothing (CLO), metabolic rate (MET) and air velocity. This investigation has used the values suggested by the Green Star Office Design v2 tool [4]. These are appropriate for a typical office and are specified below:

For measuring warm conditions (PMV > 0.5)

| | |
|---|---|
| CLO | 0.6 |
| MET | 1.2 |
| Air velocity | 0.15 m/s |

For measuring cool conditions (PMV < -0.5)

| | |
|---|---|
| CLO | 0.95 |
| MET | 1.2 |
| Air velocity | 0.15 m/s |

# 4.0 Methodology

The study was carried out utilising Integrated Environmental Solutions' Virtual Environment software package incorporating the Apache Thermal software module. The software has passed the BESTEST validation test and complies with ASHRAE Standard 140-2001.

A 3-Dimensional computer model of the building was created and an analysis was carried out to ascertain the predicted building HVAC energy consumption. The facade solar performance and fabric thermal resistances were applied to the model along with occupant usage and plant operational profiles. A HVAC system was then applied to the model and a simulation undertaken using recorded weather data.

The model is also used to determine occupant comfort levels using a PMV analysis. The software is capable of determining the PMV levels from the room temperature, radiant temperature and humidity level, provided that metabolic rates, clothing levels and air speeds are entered manually.

In order to determine heat loads within the building and size plant capacities, the heat load estimation program Camel 5.00.7 by ACADS-BSG was used. For given building heat load data, the program determines the peak heating and cooling capacities, and required airflows.

# 5.0 Model Setup

## 5.1 Climate Data

The climate data used for the building simulations is:

| | |
|---|---|
| Weather File: | Brisbane Test Reference Year 1986 |
| Location: | Brisbane QLD |
| Ground Reflectance: | 0.2 |
| | |
| Weather File: | Sydney 1984 |
| Location: | Sydney NSW |
| Ground Reflectance: | 0.2 |
| | |
| Weather File: | Melbourne Test Reference Year 1971 |
| Location: | Melbourne VIC |
| Ground Reflectance: | 0.2 |

The Brisbane and Melbourne weather files are Test Reference Years (TRY) which have been selected as a year without unusual extremes in temperature, making them suitable for energy consumption modelling. It should be noted that the simulations for Sydney and Melbourne include 1 hour of daylight saving from November through March, while Brisbane has no daylight saving time.

## 5.2 Building Form

The hypothetical building is a 10 storey office tower. Each floorplate is identical with a GFA of 1,000m$^2$. It has a central core area of 140m$^2$ leaving NLA per floor of 860m$^2$. The floor to floor height has been set at 3.7m with an internal ceiling level set at 2.7m.

The building floorplate is square in shape with a façade length of 31.5m. The building is aligned to North. The floorplates, including HVAC zoning, are shown in Figure 1 and Figure 2 below. For all HVAC systems, the floorplate has been divided into four of 3 m deep perimeter zones and two internal zones.

The four perimeter zones and two internal zones (on the ground and top floors) are modelled as separate zones in the simulation. These are not further broken down into smaller VAV zones, as it is expected that there is no significant small scale differences in behaviour within these zones. Typically there may be more than one VAV box within each of these zones for a real system of this size, and there will be multiple independent thermafusers and chilled beams, it is expected that they will all react to the same conditions at the same times and essentially act identically within the zone. This assumption has been used in the modelling of the various HVAC systems. For the perimeter offices, every office is modelled as a different thermal zone.

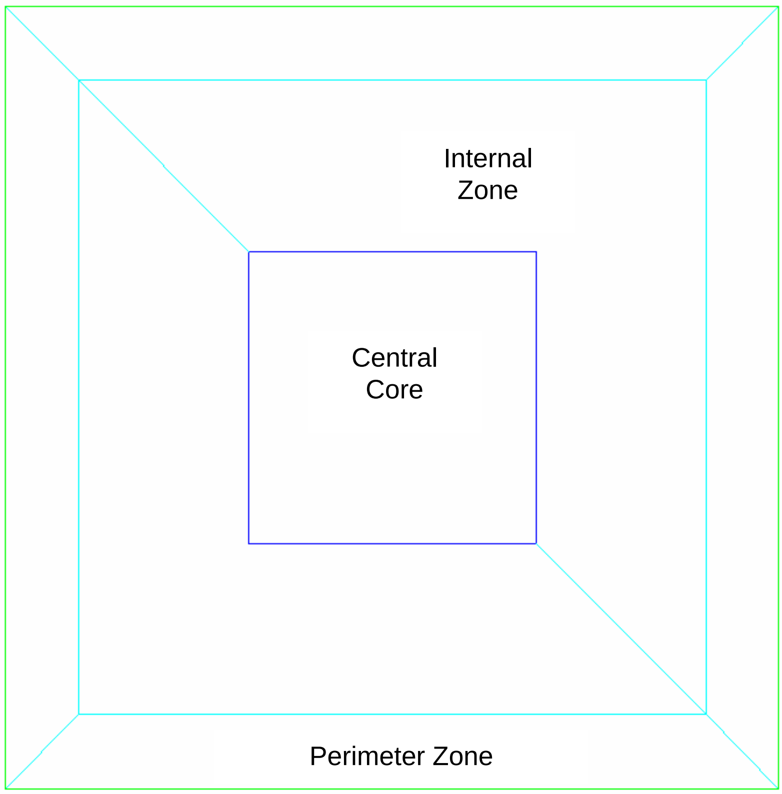


**Figure 1: Ground and top floor layout**

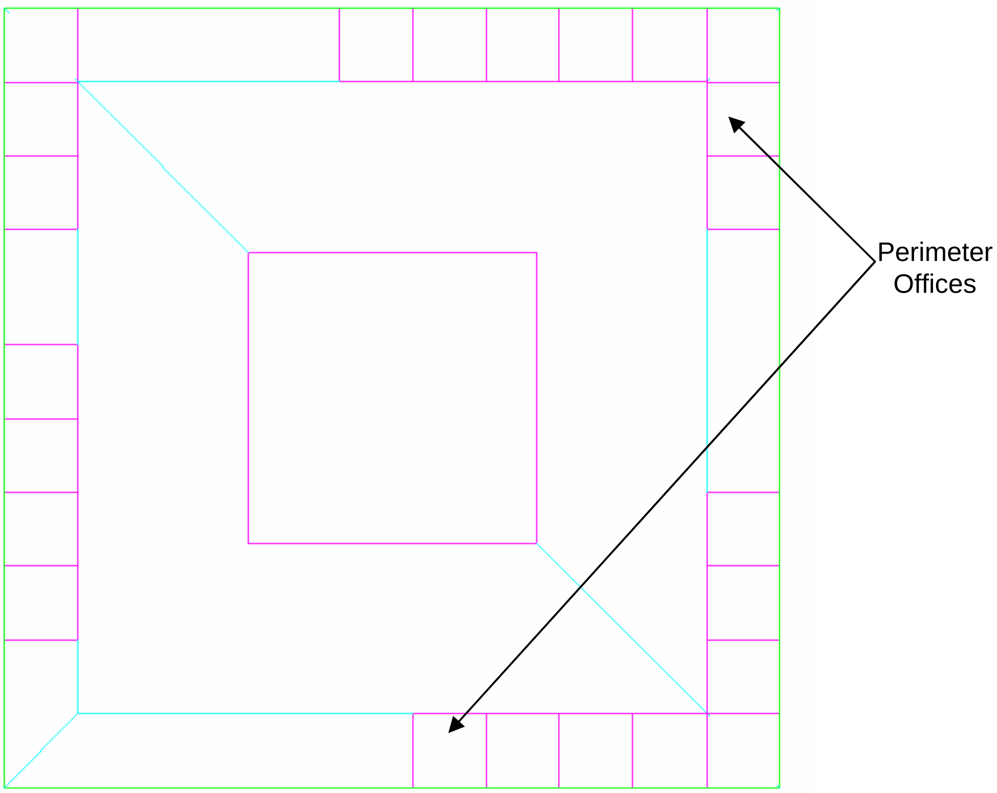


**Figure 2: Level 5 layout**

Plantrooms are not included in the model and do not affect the NLA of the conditioned space. However, for the purposes of the modelling a floor by floor approach to air handling plant has been assumed. This enables the model to maintain consistency across the systems.

No other external buildings have been included into the model, although some shading on the building has been considered as described in Section 5.3.

The building fabric and shading is be in accordance with the requirements of the Building Code of Australia (BCA) – Section J Energy Efficiency for Brisbane [1].

The proposed façade to the building is a curtain wall system with a glazing strip running from the sill height of 900mm to the underside of the ceiling. The glazing system used is a double glazed tinted unit. Further details of these constructions are outlined in section 6.0.

## 5.3 External Shading

External shading has been applied to the building to comply with the requirements for Climate Zone 2 of the Building Code of Australia – Section J Energy Efficiency for Brisbane (Climate zone 2) [1]. There is a 200 mm overhang over each floor's northern glazing, and a 400 mm overhang over each of the eastern floor's glazing. To ensure consistency across the models, the same shading is used for Brisbane, Sydney and Melbourne, regardless of what each city's individual requirements may be. The building, including shading, is shown below in Figure 3.

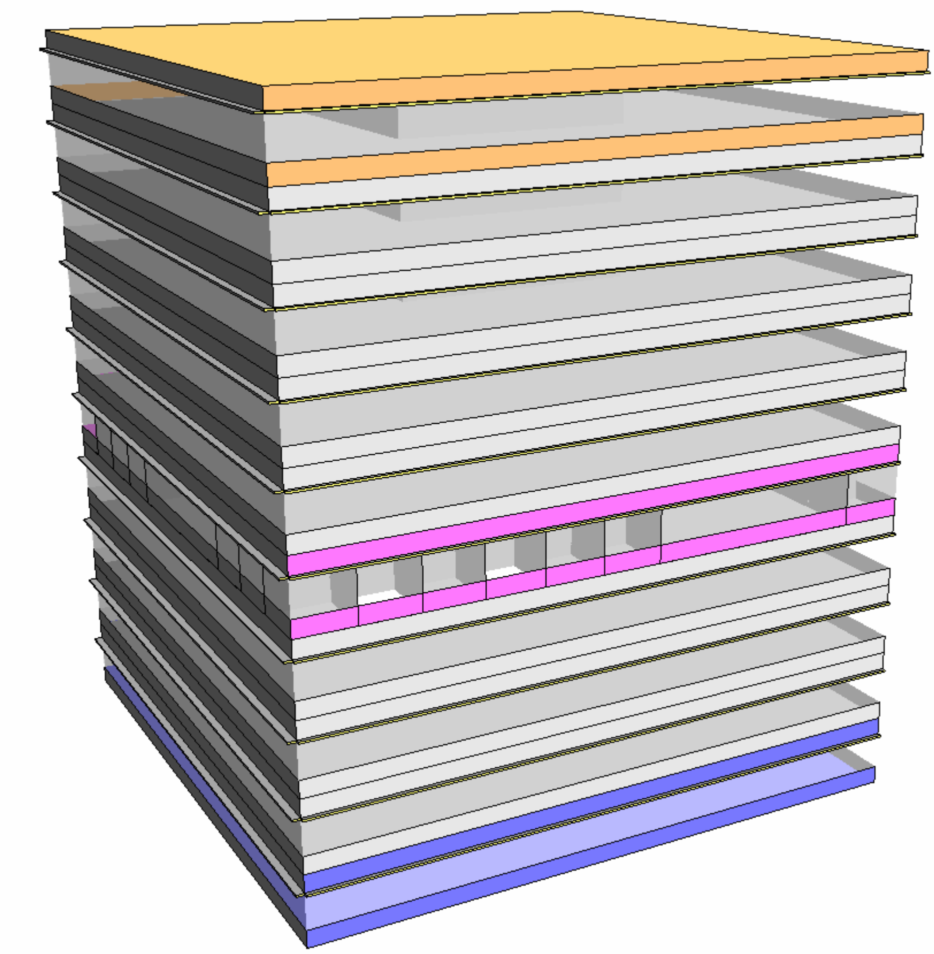

**Figure 3: Axionometric View of the Virtual Building including shading elements**

## 5.4 Glazing

The glazing is a double glazed unit based on the following G James unit: 6mm SC22 on green / 12 mm air / 6 mm LE80i on Clear glazing [5]. The thermal performance and light transmission properties for the glass are as follows:

**6mm SC22 on Green / 12 mm air / 6 mm LE80i on Clear**

| Overall U-value | 1.80 W/m$^2$K |
|---|---|
| External Pane | |
| Reflectance | 0.18 |
| Absorptance | 0.70 |
| Transmittance | 0.12 |
| Internal Pane | |
| Reflectance | 0.07 |
| Absorptance | 0.15 |
| Transmittance | 0.78 |

The glazing will include metal framing consisting of 5% of the area. This will bring the total U-value of the glazing to 1.99 W/m$^2$K.

This has been utilised for all external glazing on the building.

## 5.5 Wall Construction

All wall, roof, ceiling and floor types are proposed to be modelled as follows:

**External Walls**
The external walls are a curtain wall façade system, with the following properties:

| **External Wall 1** |
|---|
| Overall U-value of 0.41 |
| 6 mm glass spandrel |
| 80 mm glass fibre quilt (R2.0) |
| Air gap |
| 13 mm gypsum plasterboard |

**External Roof**
The external roof is modelled as per the construction shown below.

| **Roof 1** |
|---|
| Overall U-value of 0.34 |
| 1 mm steel |
| 100mm glass fibre quilt (R2.5) |
| 0.5 mm aluminium sheet (reflective foil) |
| Air gap |
| 13 mm gypsum plasterboard |

**Floor Slab**
The floor of the building was modelled as one of two constructions listed. Floor 1 is the typical floor finish throughout the office accommodation. Floor 2 is used in the toilets and core circulation areas. The ground floor has a 20°C temperature applied to it to model the thermal effects of the ground.

| **Floor 1** |
| --- |
| Overall U-value of 2.22 |
| 200 mm cast concrete<br>7 mm synthetic carpet |

| **Floor 2** |
| --- |
| Overall U-value of 2.94 |
| 200 mm cast concrete<br>5mm clay tiles |

**Internal Partitions**
The internal partitions are be modelled generally as Internal Partition 1. Internal partitions 2 has been used for party walls between core areas. Internal partition 1 is used between office spaces on level 5.

| **Internal partition 1** |
| --- |
| Overall U-value of 1.73 |
| 13mm gypsum plasterboard<br>Air gap<br>13mm gypsum plasterboard |

| **Internal partition 2** |
| --- |
| Overall U-value of 1.49 |
| 13mm gypsum plasterboard<br>140mm concrete block<br>13mm gypsum plasterboard |

## 5.6 Floor Area

The simulation model constituent areas are shown below in Table 2.

| Description | Area |
| --- | --- |
| Total NLA | 8,600 $m^2$ |
| Total Common Areas | 1,400 $m^2$ |
| Total Building Area | 10,000 $m^2$ |

**Table 2: Building area breakdown**

## 5.7 Facade Infiltration

An infiltration rate of 0.5 air changes per hour is incorporated into the simulation for zones with an external wall, including the roof void and ceiling spaces. Internal zones are assumed to have no infiltration.

## 5.8 Lighting Power Density

The lighting densities in the modelled tenancy areas are 12 $W/m^2$.

## 5.9 Lighting Hours

Lighting schedules have been taken from the ABGR default lighting schedule (limited control) [3]. The schedules for internal lighting proposed are shown in Table 3. The slight increase in lighting power on the weekend is intended to model a small number of people occasionally using the building on a weekend, although the air conditioning is still off.

| Time Period | Weekdays | Weekend |
|---|---|---|
| 0000-0700 | 15% | 15% |
| 0700-0800 | 40% | 15% |
| 0800-0900 | 90% | 25% |
| 0900-1700 | 100% | 25% |
| 1700-1800 | 80% | 15% |
| 1800-2000 | 60% | 15% |
| 2000-2100 | 50% | 15% |
| 2100-2400 | 15% | 15% |

**Table 3: Internal lighting schedules**

## 5.10 Tenant Equipment Density

The tenant equipment load (computers, other small power etc) used throughout the model are as prescribed by the ABGR Validation Protocol Procedures for an unknown tenant [3]. The equipment load is modelled as a diversified load with an average of 11 W/m$^2$. This is diversified as follows: 11 W/m$^2$ average over the full nett lettable area built up by the random distribution into zones of the following load figures; 5 W/m$^2$, 7 W/m$^2$, 11 W/m$^2$, 15 W/m$^2$, 19 W/m$^2$ in the following proportions 1:2:2:1:1. This is shown in Appendix B Equipment Loads.

## 5.11 Tenant Equipment Hours

Equipment schedules are taken from the ABGR default equipment schedule [3]. The schedules proposed for equipment are shown in Table 4. The slight increase in equipment power on the weekend is intended to model a small number of people occasionally using the building on a weekend, although the air conditioning is still off.

| Time Period | Weekdays | Weekend |
|---|---|---|
| 0000-0700 | 50% | 50% |
| 0700-0800 | 65% | 50% |
| 0800-0900 | 80% | 55% |
| 0900-1700 | 100% | 55% |
| 1700-1800 | 80% | 50% |
| 1800-1900 | 65% | 50% |
| 1900-2100 | 50% | 50% |
| 2100-2400 | 50% | 50% |

**Table 4: Tenant equipment schedules**

## 5.12 Occupancy

Occupancy density is modelled at 10m$^2$/person. Occupancy schedules have been taken from the ABGR default equipment schedule [3]. The occupancy schedules used are shown in Table 5. The occupancy on the weekend is intended to model a small number of people occasionally attending the building on a weekend, although the air conditioning is still off.

| Time Period | Weekdays | Weekend |
|---|---|---|
| 0000-0700 | 0% | 0% |
| 0700-0800 | 15% | 0% |
| 0800-0900 | 60% | 5% |
| 0900-1700 | 100% | 5% |
| 1700-1800 | 50% | 0% |
| 1800-1900 | 15% | 0% |
| 1900-2400 | 0% | 0% |

**Table 5: Occupancy schedules**

## 5.13 HVAC System – Water Side

The water side system is identical for each air side system modelled.

The water side system will comprise of two air cooled chillers sized at 60% of the total load. Each chiller will have an associated primary pump. A secondary pump will then distribute chilled water to the load around the building. The chillers are roof mounted.

The chillers are modelled using the RTAC140 Trane chiller information [6]. The part load data has been taken at constant condenser conditions. The performance of each of the two chillers is shown below in Table 6. It is assumed that below the minimum value of 20% capacity, the chiller uses a constant amount of electrical power. The staging of the chillers is that as the load increases, the first chiller ramps up to 20% load, then the second chiller comes online and both chillers share the load, both increasing until they are at 100% capacity. Distribution losses of 10% have been included in the simulation.

| Plant | Cooling Capacity (kW) | COP at % Capacity | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | 100% | 90% | 80% | 70% | 60% | 50% | 40% | 30% | 20% |
| Chiller | 480 | 2.96 | 3.02 | 3.02 | 2.94 | 2.49 | 2.40 | 2.98 | 2.78 | 2.12 |

**Table 6: Chiller performance**

The primary pumps each use 5.5 kW of power at full load. They do not have VSD operation and will therefore be off or on in association with their respective chiller. The secondary pump uses 11.0 kW of power at full load. It has VSD operation, with a minimum energy use of 50% and a conservatively assumed squared relation between flow and power.

A chiller will use a minimum amount of power at all times. For this investigation, it has been conservatively assumed that for any load less than the lowest published capacity of 20%, the chiller will use the same amount of electricity as if it were at that capacity. The smallest capacity in Table 7 (1.25%) is not manufacturer provided information, it is used to ensure this minimum energy use.

| Chillers Capacity (%) | Chillers Capacity (kW) | Combined Chillers COP | Primary Pump Power (kW) | Secondary Pump Power (kW) |
|---|---|---|---|---|
| 1.25 | 12 | 0.27 | 5.50 | 5.50 |
| 10 | 96 | 2.12 | 5.50 | 5.50 |
| 15 | 144 | 2.78 | 5.50 | 5.50 |
| 20 | 192 | 2.98 | 5.50 | 5.50 |
| 25 | 240 | 2.47 | 11.00 | 5.50 |
| 30 | 288 | 2.78 | 11.00 | 5.50 |
| 35 | 336 | 2.89 | 11.00 | 5.50 |
| 40 | 384 | 2.98 | 11.00 | 5.50 |
| 45 | 432 | 2.63 | 11.00 | 5.50 |
| 50 | 480 | 2.40 | 11.00 | 5.50 |
| 55 | 528 | 2.45 | 11.00 | 5.50 |
| 60 | 576 | 2.49 | 11.00 | 5.50 |
| 65 | 624 | 2.71 | 11.00 | 5.50 |
| 70 | 672 | 2.94 | 11.00 | 5.50 |
| 75 | 720 | 2.98 | 11.00 | 6.19 |
| 80 | 768 | 3.02 | 11.00 | 7.04 |
| 85 | 816 | 3.02 | 11.00 | 7.95 |
| 90 | 864 | 3.02 | 11.00 | 8.91 |
| 95 | 912 | 2.99 | 11.00 | 9.93 |
| 100 | 960 | 2.96 | 11.00 | 11.00 |

**Table 7: Water side system performance**

It should be noted that no increased pump power allocation has been made for the chilled beam application given the potential increased pressure drop through the system. In addition, a dedicated chiller for the chilled beam system separate to the preconditioning coils has not been incorporated which could yield energy benefits.

## 5.14 HVAC System – Air Side

Three separate systems have been modelled and these are outlined below.

### 5.14.1 Traditional VAV System

A single chilled water air handling unit is provided per floor. Each air handling unit serves a series of VAV boxes in each zone. Each VAV box is provided with electric reheat.

The fan within the air handling unit is provided with a variable speed drive to modulate to suit demand in the space.

Minimum turn down on the VAV boxes is provided to 40% of the maximum flow rate.

Fresh air is provided in accordance with AS1668.2 (1991) [7] and is at 10l/s per person. This is 865 L/s for each floor.

No economy cycle has been provided.

Details of plant capacities, airflow and other information can be found in Appendix B Equipment Loads.

### 5.14.2 Therma-Fuser System

A single chilled water air handling unit is provided per floor. Each air handling unit will serve a series of electric reheat boxes prior to distribution to the terminal Therma-Fuser variable volume diffuser units.

The fan within the air handling unit is provided with a variable speed drive to modulate to suit demand in the space.

Fresh air is provided in accordance with AS1668.2 (1991) [7] and is at 10l/s per person. This is 865 L/s for each floor.

No economy cycle has been provided.

Details of plant capacities, airflow and other information can be found in Appendix B Equipment Loads.

### 5.14.3 Chilled Beam

A single fresh air chilled water air handling unit is provided per floor. The air handling unit is a constant volume system. The air distribution system is zoned the same way as the VAV and Therma-Fuser systems. The fresh air system will provide 100% outside air. Each zone is provided with electric duct heaters in the same manner as for the VAV and Therma-Fuser systems.

The chilled beams are zoned as per the Therma-Fuser system. Details of the physical layout of the chilled beams have not been considered as part of the scope of this study.

Fresh air is provided to a level higher than is required by AS1668.2 (1991) [7]. Low levels of fresh air can lead to less effective induction rates. A flowrate of 20l/s per person is provided in order to ensure that the active chilled beam operates correctly. This is 1730 L/s for each floor.

Details of plant capacities, airflow and other information can be found in Appendix B Equipment Loads.

## 5.15 HVAC Hours

The plant operating hours is taken from the ABGR default equipment schedule [3]. The plant will run from 0700 until 1800 on weekdays only.

For the chilled beam system, the pre cooling Air Handling Unit (AHU) operates from 0600 until 1800 on weekdays. This has been done in order to prevent condensation occurring during startup of the chilled beams. By running the pre cooling system for an hour before the chilled beams operate, the humidity levels (which would have built up due to infiltration overnight and over weekends, particularly in Brisbane) are lowered, to prevent the dew point being higher than the temperature of the beams. It is acknowledged that this approach adversely affects the heating energy, particularly in Sydney and Melbourne. Some chilled beam systems have more sophisticated systems of ensuring that this does not occur, such as altering the minimum chilled water temperature at startup. This was difficult to implement in the model, and chilled beam control algorithms were not the focus of the study. It is therefore acknowledged that the chilled beam system used in this study is not controlled as well as is possible with current technology, and that better energy efficiency could be produced with further study.

## 5.16 HVAC Control

The HVAC system control strategy has been simulated as explained below. The control of the Therma-Fuser system is based on information provided in the Therma-Fuser design guide [8].

**<u>Chilled Water VAV AHUs</u>**

**AHU Cooling Operation:**

- AHU operation sensed off hottest zone.
- Off Coil temperature at 12°C when room temperature > 24°C.
- Off Coil temperature at 23°C when room temperature = 23°C.
- No cooling when room temperature < 23°C.
- Proportional cooling between 23°C and 24°C.

**Duct Heater Operation:**

- Heater providing 30°C at temperature < 21°C.
- Heater providing 22°C air when room temperature = 22°C.
- Heater off at temperature > 22°C.
- Proportional control of heat transfer between 21°C and 22°C.

**VAV Box Operation:**

- Maximum airflow at temperature > 23°C.
- Minimum airflow (40% of maximum) at temperature < 22°C.
- Proportional airflow between 22°C and 23°C.

**<u>Therma-Fuser Operation:</u>**

**AHU Cooling Operation:**

- AHU operation sensed off hottest zone.
- Off Coil temperature at 12°C when room temperature > 23.5°C.
- Off Coil temperature at 14°C when room temperature > 23°C.
- No cooling when room temperature < 23°C.

**Duct Heater Operation:**

- Heater supplies 30°C air when on.
- Heater operates at a setpoint of 22°C with a deadband of 1°C

**Therma-Fuser Operation:**

- Different operation in cooling or heating mode.
- Cooling/heating mode determined from duct supply air temperature.
- Setpoint of 23.25°C with a deadband of 2.5°C.
- In cooling mode,
    - Maximum airflow at temperature > 23.25°C.
    - Minimum airflow (25% of maximum) at temperature < 22.75°C.
    - Proportional airflow between 22.75°C and 23.25°C.
- In heating mode,
    - Maximum airflow at temperature > 21.75°C.
    - Minimum airflow (25% of maximum) at temperature < 22.25°C.
    - Proportional airflow between 21.75°C and 22.25°C.

**Chilled Beam Operation:**

The assumptions used to determine some of the control requirements for the chilled beam system operation are explained in Appendix A Plant Details.

**Fresh Air AHU Operation:**

- Constant supply air flow rate provided consisting of 100% fresh air.
- Supply air cooled to 16°C at all times

**Chilled Beam Cooling Operation:**

- Maximum airflow at temperature > 24°C.
- Off Coil temperature at 23°C when room temperature = 23°C.
- No cooling when room temperature < 23°C.
- Proportional cooling between 23°C and 24°C.

**Chilled Beam Induced Airflow Operation:**

- Maximum airflow when room temperature > 24°C.
- Maximum airflow is three times the fresh air flowrate.
- No airflow when room temperature < 23°C.
- Proportional cooling between 23°C and 24°C.

**Duct Heater Operation:**

- Heater providing 30°C at temperature < 21°C.
- Heater providing 22°C air when room temperature = 22°C.
- Heater off at temperature > 22°C.
- Proportional control of heat transfer between 21°C and 22°C.

# 6.0 Results

This study has utilised the Virtual Environment Software Suite incorporating the Apache 3D thermal simulation software to calculate the energy usage for each HVAC system in Brisbane, Sydney and Melbourne. The simulation package calculates building performance over a typical year of recorded data. In this project, a time step of one minute has been utilised for the energy modelling and a reporting interval of ten minutes has been used. This means that the program calculates the conditions in the model for every minute of simulated time, and the results file contains information about the state of the model in ten minute intervals for the entire simulated year.

## 6.1 Temperature

The building held design temperature for all system types. This is important, as it shows that the systems achieve energy efficiency without failing to adequately cool or heat the space. Some temperature graphs demonstrating temperature compliance on a typical day for the VAV, Therma-Fuser and chilled beam systems in Brisbane are shown in Figure 4, Figure 5, and Figure 6 respectively. Room temperature is shown in green, and room air supply is shown in orange (includes induced air for chilled beam system).

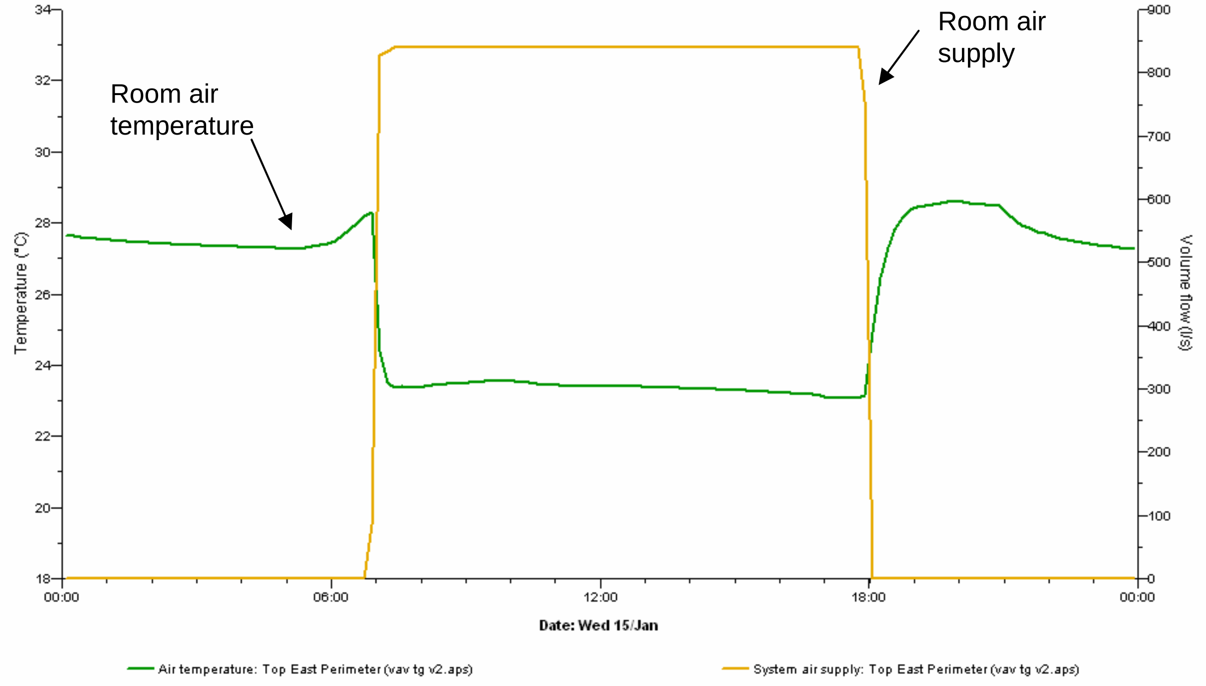


**Figure 4: Temperature in Top Floor East Zone for VAV System on January 15**

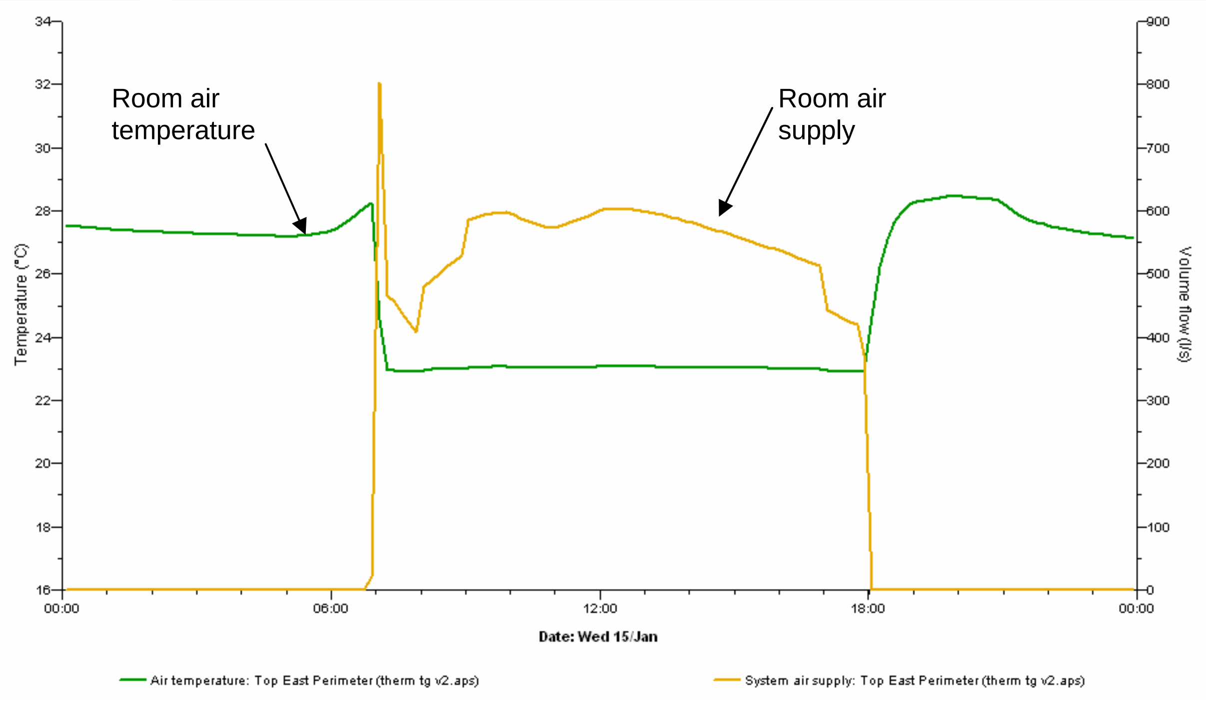


**Figure 5: Temperature in Top Floor East Zone for Therma-Fuser system on January 15**

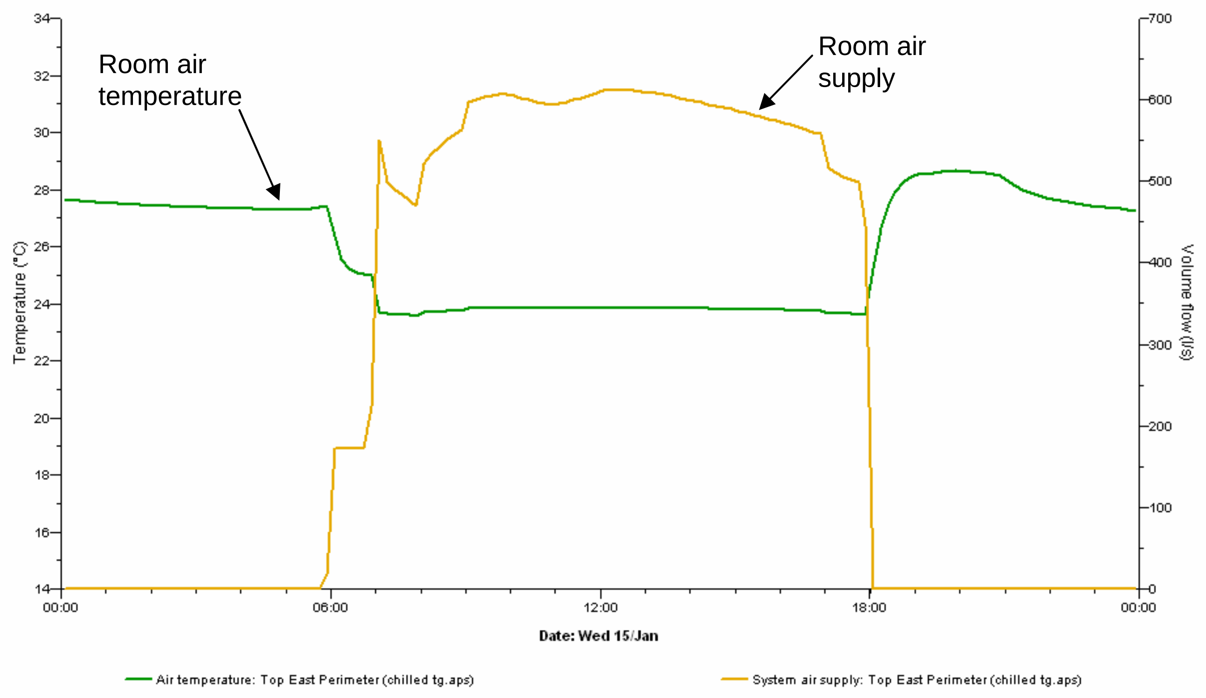


**Figure 6: Temperature in Top Floor East Zone for chilled beam system on January 15**

## 6.2 Comfort

In addition to ensuring that each system can hold design temperature, a PMV analysis has been conducted to determine the level of occupant comfort provided for each space. The number of hours that each space was outside certain PMV levels during office hours of 8:00 am to 6:00 pm was determined. The time from 7:00 am to 8:00 am is not considered as this includes plant start up time and is a low occupancy period. The full results can be seen in Appendix C Thermal Comfort Results.

The results have been summarised below in Table 8. The results between zones have been area weighted. It should be noted that level 5 has been given equal weighting with the ground and top levels, unlike in other sections of the report where the level 5 is considered to be representative of levels 1 through 4 and 6 through 8. This has not been done here as this would substantially exaggerate the effects of the results on level 5.

| HVAC Type | % Outside ± 0.5 PMV | % Outside ± 1.0 PMV |
|---|---|---|
| VAV System | 0.0003 | 0.0000 |
| Therma-Fuser System | 0.0005 | 0.0000 |
| Chilled beam System | 0.0124 | 0.0000 |

**Table 8: PMV result summary**

## 6.3 Energy

The energy results for Brisbane, Sydney and Melbourne are summarised in Table 9 through Table 11. The results break down the energy use into chiller, heater, fan and pump energy.

| Energy | Therma-Fuser MWh | VAV MWh | Chilled Beam MWh |
|---|---|---|---|
| Chillers | 421.5 | 412.1 | 377.2 |
| Heaters | 7.7 | 6.5 | 19.6 |
| Fans | 18.7 | 74.1 | 30.4 |
| Pumps | 41.5 | 42.9 | 43.3 |
| Total | 489.4 | 535.5 | 470.7 |

**Table 9: Brisbane Energy Results**

| Energy | Therma-Fuser MWh | VAV MWh | Chilled Beam MWh |
|---|---|---|---|
| Chillers | 275.4 | 267.6 | 223.0 |
| Heaters | 29.7 | 26.1 | 67.6 |
| Fans | 14.5 | 64.5 | 30.3 |
| Pumps | 31.7 | 35.3 | 34.4 |
| Total | 351.3 | 393.4 | 355.2 |

**Table 10: Sydney Energy Results**

| Energy | Therma-Fuser MWh | VAV MWh | Chilled Beam MWh |
|---|---|---|---|
| Chillers | 174.1 | 180.5 | 138.8 |
| Heaters | 72.5 | 65.6 | 169.0 |
| Fans | 14.0 | 51.8 | 30.4 |
| Pumps | 21.1 | 25.8 | 25.2 |
| Total | 281.7 | 323.7 | 363.5 |

**Table 11: Melbourne Energy Results**

It is noted that in all cities considered, the chiller energy is less with the chilled beam and this is due to the higher amount of outside air and separating the fresh air and return air conditioning. As the chilled beam system uses twice the outside air as the Therma-Fuser or VAV system, this allows it to benefit when external conditions permit, providing an element of "free cooling" from cooler outside air, as well as facilitating increased load removal through the higher exhaust rate as a result. This is evident as the chiller energy is noted to be worse for the chilled beam system during summer and performs better than Therma-Fuser and VAV systems during winter, spring and autumn.

The heaters for the chilled beam system utilise much more energy than for the Therma-Fuser and VAV systems. This is due to the increased fresh air load for the chilled beam system, as well as it being a constant volume system. As expected the heating load is greater for Sydney and Melbourne. It should also be noted that the early morning purge cycle employed in the chlled meam model contributes to the increased heating energy, particularly in Melbourne and Sydney during the winter months.

Fan energy is the least for the Therma-Fuser system which was to be expected due to the lower turndowns applied in the model. The chilled beam system utilises double the fan energy compared to the Therma-Fuser system which is expected given the system is constant volume.

Pumping energy is reasonably consistent across the three systems in each location. Although there is VSD operation on the secondary pump, the fact that the primary pumps are constant power and that the secondary pump uses a minimum amount of power up to 70.7% (see Table 7) mean that unless the chillers are running at high capacity, the pumping energy is relatively constant for much of the time. Although the VAV system uses less chiller energy than the Therma-Fuser system, the pumping energy is paradoxically higher. This is because the reductions in pumping energy at high capacity are smaller than the savings that the Therma-Fuser system gives when the pumps try to shut down due to the on/off nature of the cooling control.

# 7.0 Discussion

The simulation results for each system type show that they were all able to maintain design temperature. In addition to this, the PMV results indicate that all three HVAC systems were maintaining good levels of occupant comfort. Although the results indicate that the chilled beam system spent more time outside the PMV values of ± 0.5, it is still a very low proportion of time. Further to this, all three systems do not exceed the PMV values of ± 1.0. They can therefore all be considered to have achieved very good levels of occupant comfort and can be fairly compared on an energy basis.

The Therma-Fuser system uses less energy overall than the VAV system in all three climates. The Therma-Fuser and VAV systems are quite similar in terms of overall design, so comparisons can be easily made between the two. The Therma-Fuser system's energy savings come from its reduced fan usage. The Therm-Fuser system uses between 73.0% and 77.5% less fan energy than the VAV system in Brisbane, Sydney and Melbourne, due to its lower minimum turndown levels. Because of the cubic relation between airflow and fan power, large fan energy savings can be made from relatively small improvements in minimum fan turndown. The Therma-Fuser system used more cooling, and heating energy than the VAV system, but this was always more than offset by the fan savings. The Therma-Fusers require relatively constant duct air temperatures in order to operate correctly. This constant-off-coil-temperature control strategy causes it to use more cooling and heating energy than the VAV system, which adjusts its cooling and heating depending on room requirements. The extra cooling and heating energy is proportionally small, particularly compared to the fan energy savings. The pumping energy for the VAV system was higher than for the Therma-Fuser system, despite the VAV system using less chiller energy. Although the pump energy is related to the chiller operation, the staging of the chillers mean that savings between cases due to reduced chiller operation are largely seen at high capacities. The Therma-Fuser system's constant off-coil control strategy causes the chillers to switch on and off at some times, which causes the pumps to also switch on and off. The VAV system will tend to still provide cooling at many low demand times because it can increase the off-coil temperature to around 20°C which will stop the space overcooling. The Therma-Fuser system's behaviour generates some savings which are larger than the small savings caused by reduction in chiller energy. This pumping energy outcome is highly dependant on the selection and control strategy of the pumps and is not expected to occur for all applications in practice.

The chilled beam system used the smallest amount of chiller energy by a significant margin in each city. The chilled beam system uses twice the amount of outside air as the VAV or Therma-Fuser systems in order to give an appropriate minimum air supply. In cooler times such as winter and parts of autumn and spring, this allows for more "free cooling" from outside air as well as an increase in heat rejected through exhausted room air. The separation of fresh air and room cooling also provides some energy benefits. In each location, the chilled beam system has the largest heating use. This is because the chilled beam system is using twice the amount of outside air as the Therma-Fuser and VAV systems, resulting in an increase in the amount of heating during cold winter times. A large proportion of the chilled beam heating energy occurs at start up, however, this is true of the other types of systems as well. The chilled beam fan energy was less than that for the VAV system, but higher than that for the Therma-Fuser system. The chilled beam system's performance varied the most compared to the other systems across the different climate zones. It was the most efficient in Brisbane, second most efficient in Sydney and the worst in Melbourne. This performance seems to be due to the poor performance in heating mode. Brisbane has high cooling requirements and little need for heating in a commercial building, which suited the operation of the chilled beam system. In addition, the pre cooling AHU operates for an extra hour before the main system starts to prevent any possible condensation at start up. This consideration is more necessary for Brisbane with its higher humidity levels than for Melbourne and Sydney, but was applied to all for equitable comparison.

In Queensland, one kWh of electricity consumed causes 1.04 kg of carbon dioxide ($CO_2$) to be emitted [9]. The quantity of $CO_2$ emitted for each system type in Brisbane is 508,976, 556,920 and 489,528 kg CO2 for the Therma-Fuser, VAV and chilled beam systems respectively. When normalised according to net lettable area, this corrospondes to 59.2 $kgCO_2/m^2$ NLA, 64.8 $kgCO_2/m^2$ NLA, and 56.9 $kgCO_2/m^2$ NLA. In the ABGR system, for a base building rating in the Brisbane CBD for a building occupied 50 hours per week, a saving of 10 $kgCO_2/m^2$ NLA will give a ½ star improvement in building performance (assuming that the building is better than 0 stars). It should be noted that the figures given for $CO_2$ emission for each system only cover the building's HVAC energy, and further energy uses such as base building lighting and lifts would need to be accounted for in order to determine the building's estimated ABGR rating.

# 8.0 Conclusion

The results of the simulation indicate that a well commissioned Therma-Fuser system can provide operational energy savings compared to a traditional VAV system for the same building. The simulation results demonstrated overall HVAC energy savings between 8.6% and 13.0% over the VAV system for the hypothetical building. The chilled beam's relative performance varied depending on the location. Overall, the chilled beam system had the best energy performance in Brisbane, and the Therma-Fuser system had the best energy performance in Sydney and Melbourne. It is important to note that these performances are based on the assumptions listed throughout this report, and that actual performance will depend on the exact characteristics of the HVAC system and its controls methodology. It is important to be aware of the variations in HVAC system performance between different climates. The simulations showed that this did not appear to affect the Therma-Fuser's energy improvements over a VAV system, but it did have a great impact on the chilled beam system's performance compared to the Therma-Fuser and VAV systems.

# 9.0 Appendix A Plant Details

The cooling and heating capacities, airflows and zoning for each of the AHUs in the VAV system are shown in Table 12, Table 13, and Table 14 below for Brisbane, Sydney and Melbourne respectively.

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| VAV Ground | 84.1 | G North | 6.6 | 856 | 40 |
| | | G East | 6.3 | 794 | 40 |
| | | G West | 7.2 | 956 | 40 |
| | | G South | 4.1 | 467 | 40 |
| | | G Internal 1 | 5.6 | 953 | 40 |
| | | G Internal 2 | 5.6 | 953 | 40 |
| VAV L5 | 84.1 | L5 North Office 1 | 5.5 | 84 | 40 |
| | | L5 North Office 2 | | 84 | 40 |
| | | L5 North Office 3 | | 84 | 40 |
| | | L5 North Office 4 | | 84 | 40 |
| | | L5 North Office 5 | | 84 | 40 |
| | | L5 North Perimeter | | 300 | 40 |
| | | L5 East Office 1 | 6.9 | 77 | 40 |
| | | L5 East Office 2 | | 77 | 40 |
| | | L5 East Office 3 | | 77 | 40 |
| | | L5 East Office 4 | | 77 | 40 |
| | | L5 East Office 5 | | 77 | 40 |
| | | L5 East Perimeter | | 273 | 40 |
| | | L5 NE Corner Office | | 101 | 40 |
| | | L5 SE Corner Office | | 83 | 40 |
| | | L5 West Office 1 | 7.5 | 93 | 40 |
| | | L5 West Office 2 | | 93 | 40 |
| | | L5 West Office 3 | | 93 | 40 |
| | | L5 West Office 4 | | 93 | 40 |
| | | L5 West Office 5 | | 93 | 40 |
| | | L5 West Office 6 | | 93 | 40 |
| | | L5 West Perimeter 1 | | 146 | 40 |
| | | L5 West Perimeter 2 | | 170 | 40 |
| | | L5 NW Corner Office | | 120 | 40 |
| | | L5 South Office 1 | 3.8 | 47 | 40 |
| | | L5 South Office 2 | | 47 | 40 |
| | | L5 South Office 3 | | 47 | 40 |
| | | L5 South Office 4 | | 47 | 40 |
| | | L5 South Perimeter | | 247 | 40 |
| | | L5 Internal 1 | 5.6 | 953 | 40 |
| | | L5 Internal 2 | 5.6 | 953 | 40 |

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| VAV Top | 95.9 | T North | 6.6 | 913 | 40 |
| | | T East | 6.3 | 840 | 40 |
| | | T West | 7.2 | 1047 | 40 |
| | | T South | 4.1 | 561 | 40 |
| | | T Internal 1 | 5.6 | 1240 | 40 |
| | | T Internal 2 | 5.6 | 1240 | 40 |

**Table 12: Brisbane Chilled-Water Air Handling Unit Capacities**

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| VAV Ground | 79.1 | G North | 7.8 | 967 | 40 |
| | | G East | 7.2 | 858 | 40 |
| | | G West | 8.2 | 1064 | 40 |
| | | G South | 4.3 | 490 | 40 |
| | | G Internal 1 | 5.8 | 963.5 | 40 |
| | | G Internal 2 | 5.8 | 963.5 | 40 |
| VAV L5 | 79.1 | L5 North Office 1 | 6.0 | 95 | 40 |
| | | L5 North Office 2 | | 95 | 40 |
| | | L5 North Office 3 | | 95 | 40 |
| | | L5 North Office 4 | | 95 | 40 |
| | | L5 North Office 5 | | 95 | 40 |
| | | L5 North Perimeter | | 338 | 40 |
| | | L5 East Office 1 | 7.2 | 83 | 40 |
| | | L5 East Office 2 | | 83 | 40 |
| | | L5 East Office 3 | | 83 | 40 |
| | | L5 East Office 4 | | 83 | 40 |
| | | L5 East Office 5 | | 83 | 40 |
| | | L5 East Perimeter | | 295 | 40 |
| | | L5 NE Corner Office | | 114 | 40 |
| | | L5 SE Corner Office | | 91 | 40 |
| | | L5 West Office 1 | 8.0 | 101 | 40 |
| | | L5 West Office 2 | | 101 | 40 |
| | | L5 West Office 3 | | 101 | 40 |
| | | L5 West Office 4 | | 101 | 40 |
| | | L5 West Office 5 | | 101 | 40 |
| | | L5 West Office 6 | | 101 | 40 |
| | | L5 West Perimeter 1 | | 159 | 40 |
| | | L5 West Perimeter 2 | | 185 | 40 |
| | | L5 NW Corner Office | | 137 | 40 |
| | | L5 South Office 1 | 4.0 | 50 | 40 |
| | | L5 South Office 2 | | 50 | 40 |

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| | | L5 South Office 3 | | 50 | 40 |
| | | L5 South Office 4 | | 50 | 40 |
| | | L5 South Perimeter | | 259 | 40 |
| | | L5 Internal 1 | 5.6 | 963.5 | 40 |
| | | L5 Internal 2 | 5.6 | 963.5 | 40 |
| VAV Top | 89.0 | T North | 8.5 | 1026 | 40 |
| | | T East | 7.9 | 908 | 40 |
| | | T West | 9.1 | 1121 | 40 |
| | | T South | 5.2 | 590 | 40 |
| | | T Internal 1 | 8.8 | 1265.5 | 40 |
| | | T Internal 2 | 8.8 | 1265.5 | 40 |

**Table 13: Sydney Chilled-Water Air Handling Unit Capacities**

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| VAV Ground | 72.5 | G North | 8.6 | 1004 | 40 |
| | | G East | 7.9 | 899 | 40 |
| | | G West | 9.2 | 1100 | 40 |
| | | G South | 4.5 | 517 | 40 |
| | | G Internal 1 | 6.0 | 972.5 | 40 |
| | | G Internal 2 | 6.0 | 972.5 | 40 |
| VAV L5 | 72.5 | L5 North Office 1 | 7.2 | 98 | 40 |
| | | L5 North Office 2 | | 98 | 40 |
| | | L5 North Office 3 | | 98 | 40 |
| | | L5 North Office 4 | | 98 | 40 |
| | | L5 North Office 5 | | 98 | 40 |
| | | L5 North Perimeter | | 350 | 40 |
| | | L5 East Office 1 | 8.4 | 87 | 40 |
| | | L5 East Office 2 | | 87 | 40 |
| | | L5 East Office 3 | | 87 | 40 |
| | | L5 East Office 4 | | 87 | 40 |
| | | L5 East Office 5 | | 87 | 40 |
| | | L5 East Perimeter | | 309 | 40 |
| | | L5 NE Corner Office | | 122 | 40 |
| | | L5 SE Corner Office | | 96 | 40 |
| | | L5 West Office 1 | 9.6 | 106 | 40 |
| | | L5 West Office 2 | | 106 | 40 |
| | | L5 West Office 3 | | 106 | 40 |
| | | L5 West Office 4 | | 106 | 40 |
| | | L5 West Office 5 | | 106 | 40 |
| | | L5 West Office 6 | | 106 | 40 |

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| | | L5 West Perimeter 1 | | 166 | 40 |
| | | L5 West Perimeter 2 | | 194 | 40 |
| | | L5 NW Corner Office | | 144 | 40 |
| | | L5 South Office 1 | 4.2 | 52 | 40 |
| | | L5 South Office 2 | | 52 | 40 |
| | | L5 South Office 3 | | 52 | 40 |
| | | L5 South Office 4 | | 52 | 40 |
| | | L5 South Perimeter | | 273 | 40 |
| | | L5 Internal 1 | 6.0 | 972.5 | 40 |
| | | L5 Internal 2 | 6.0 | 972.5 | 40 |
| VAV Top | 82.0 | T North | 9.2 | 1049 | 40 |
| | | T East | 8.3 | 947 | 40 |
| | | T West | 10.1 | 1177 | 40 |
| | | T South | 4.1 | 614 | 40 |
| | | T Internal 1 | 5.4 | 1266 | 40 |
| | | T Internal 2 | 5.4 | 1266 | 40 |

**Table 14: Melbourne Chilled-Water Air Handling Unit Capacities**

The cooling and heating capacities, airflows and zoning for each of the AHUs in the Therma-Fuser system are shown in Table 12, Table 13, and Table 14 below for Brisbane, Sydney and Melbourne respectively.

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| Therma-Fuser Ground | 84.1 | G North | 6.6 | 856 | 25 |
| | | G East | 6.3 | 794 | 25 |
| | | G West | 7.2 | 956 | 25 |
| | | G South | 4.1 | 467 | 25 |
| | | G Internal 1 | 5.6 | 953 | 25 |
| | | G Internal 2 | 5.6 | 953 | 25 |
| Therma-Fuser L5 | 84.1 | L5 North Office 1 | 5.5 | 84 | 25 |
| | | L5 North Office 2 | | 84 | 25 |
| | | L5 North Office 3 | | 84 | 25 |
| | | L5 North Office 4 | | 84 | 25 |
| | | L5 North Office 5 | | 84 | 25 |
| | | L5 North Perimeter | | 300 | 25 |
| | | L5 East Office 1 | 6.9 | 78 | 25 |
| | | L5 East Office 2 | | 78 | 25 |
| | | L5 East Office 3 | | 78 | 25 |
| | | L5 East Office 4 | | 78 | 25 |
| | | L5 East Office 5 | | 78 | 25 |
| | | L5 East Perimeter | | 279 | 25 |

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| | | L5 NE Corner Office | | 103 | 25 |
| | | L5 SE Corner Office | | 84 | 25 |
| | | L5 West Office 1 | 7.6 | 95 | 25 |
| | | L5 West Office 2 | | 95 | 25 |
| | | L5 West Office 3 | | 95 | 25 |
| | | L5 West Office 4 | | 95 | 25 |
| | | L5 West Office 5 | | 95 | 25 |
| | | L5 West Office 6 | | 95 | 25 |
| | | L5 West Perimeter 1 | | 148 | 25 |
| | | L5 West Perimeter 2 | | 173 | 25 |
| | | L5 NW Corner Office | | 120 | 25 |
| | | L5 South Office 1 | 3.8 | 47 | 25 |
| | | L5 South Office 2 | | 47 | 25 |
| | | L5 South Office 3 | | 47 | 25 |
| | | L5 South Office 4 | | 47 | 25 |
| | | L5 South Perimeter | | 247 | 25 |
| | | L5 Internal 1 | 5.6 | 953 | 25 |
| | | L5 Internal 2 | 5.6 | 953 | 25 |
| VAV Therma-Fuser | 95.9 | T North | 6.6 | 913 | 25 |
| | | T East | 6.3 | 840 | 25 |
| | | T West | 7.2 | 1047 | 25 |
| | | T South | 4.1 | 561 | 25 |
| | | T Internal 1 | 5.6 | 1240 | 25 |
| | | T Internal 2 | 5.6 | 1240 | 25 |

**Table 15: Brisbane Chilled-Water Therma-Fuser Air Handling Unit Capacities**

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| Therma-Fuser Ground | 79.1 | G North | 7.8 | 967 | 25 |
| | | G East | 7.2 | 858 | 25 |
| | | G West | 8.2 | 1064 | 25 |
| | | G South | 4.3 | 490 | 25 |
| | | G Internal 1 | 5.8 | 963.5 | 25 |
| | | G Internal 2 | 5.8 | 963.5 | 25 |
| Therma-Fuser L5 | 79.1 | L5 North Office 1 | 6.5 | 95 | 25 |
| | | L5 North Office 2 | | 95 | 25 |
| | | L5 North Office 3 | | 95 | 25 |
| | | L5 North Office 4 | | 95 | 25 |
| | | L5 North Office 5 | | 95 | 25 |
| | | L5 North Perimeter | | 338 | 25 |
| | | L5 East Office 1 | 8.0 | 84 | 25 |

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| | | L5 East Office 2 | | 84 | 25 |
| | | L5 East Office 3 | | 84 | 25 |
| | | L5 East Office 4 | | 84 | 25 |
| | | L5 East Office 5 | | 84 | 25 |
| | | L5 East Perimeter | | 301 | 25 |
| | | L5 NE Corner Office | | 116 | 25 |
| | | L5 SE Corner Office | | 93 | 25 |
| | | L5 West Office 1 | 8.7 | 102 | 25 |
| | | L5 West Office 2 | | 102 | 25 |
| | | L5 West Office 3 | | 102 | 25 |
| | | L5 West Office 4 | | 102 | 25 |
| | | L5 West Office 5 | | 102 | 25 |
| | | L5 West Office 6 | | 102 | 25 |
| | | L5 West Perimeter 1 | | 160 | 25 |
| | | L5 West Perimeter 2 | | 187 | 25 |
| | | L5 NW Corner Office | | 138 | 25 |
| | | L5 South Office 1 | 4.0 | 50 | 25 |
| | | L5 South Office 2 | | 50 | 25 |
| | | L5 South Office 3 | | 50 | 25 |
| | | L5 South Office 4 | | 50 | 25 |
| | | L5 South Perimeter | | 259 | 25 |
| | | L5 Internal 1 | 5.8 | 963.5 | 25 |
| | | L5 Internal 2 | 5.8 | 963.5 | 25 |
| Therma-Fuser Top | 89.0 | T North | 8.5 | 1026 | 25 |
| | | T East | 7.9 | 908 | 25 |
| | | T West | 9.1 | 1121 | 25 |
| | | T South | 5.2 | 590 | 25 |
| | | T Internal 1 | 8.8 | 1265.5 | 25 |
| | | T Internal 2 | 8.8 | 1265.5 | 25 |

**Table 16: Sydney Therma-Fuser Chilled-Water Air Handling Unit Capacities**

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| Therma-Fuser Ground | 72.5 | G North | 8.6 | 1004 | 25 |
| | | G East | 7.9 | 899 | 25 |
| | | G West | 9.2 | 1100 | 25 |
| | | G South | 4.5 | 517 | 25 |
| | | G Internal 1 | 6.0 | 972.5 | 25 |
| | | G Internal 2 | 6.0 | 972.5 | 25 |
| Therma-Fuser L5 | 72.5 | L5 North Office 1 | 7.2 | 98 | 25 |
| | | L5 North Office 2 | | 98 | 25 |

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Maximum Air Quantity (L/s) | Minimum Air Quantity (%) |
|---|---|---|---|---|---|
| | | L5 North Office 3 | | 98 | 25 |
| | | L5 North Office 4 | | 98 | 25 |
| | | L5 North Office 5 | | 98 | 25 |
| | | L5 North Perimeter | | 350 | 25 |
| | | L5 East Office 1 | 8.5 | 88 | 25 |
| | | L5 East Office 2 | | 88 | 25 |
| | | L5 East Office 3 | | 88 | 25 |
| | | L5 East Office 4 | | 88 | 25 |
| | | L5 East Office 5 | | 88 | 25 |
| | | L5 East Perimeter | | 315 | 25 |
| | | L5 NE Corner Office | | 124 | 25 |
| | | L5 SE Corner Office | | 98 | 25 |
| | | L5 West Office 1 | 9.7 | 107 | 25 |
| | | L5 West Office 2 | | 107 | 25 |
| | | L5 West Office 3 | | 107 | 25 |
| | | L5 West Office 4 | | 107 | 25 |
| | | L5 West Office 5 | | 107 | 25 |
| | | L5 West Office 6 | | 107 | 25 |
| | | L5 West Perimeter 1 | | 168 | 25 |
| | | L5 West Perimeter 2 | | 197 | 25 |
| | | L5 NW Corner Office | | 146 | 25 |
| | | L5 South Office 1 | 4.2 | 52 | 25 |
| | | L5 South Office 2 | | 52 | 25 |
| | | L5 South Office 3 | | 52 | 25 |
| | | L5 South Office 4 | | 52 | 25 |
| | | L5 South Perimeter | | 273 | 25 |
| | | L5 Internal 1 | 6.0 | 972.5 | 25 |
| | | L5 Internal 2 | 6.0 | 972.5 | 25 |
| Therma-Fuser Top | 82.0 | T North | 9.2 | 1049 | 25 |
| | | T East | 8.3 | 947 | 25 |
| | | T West | 10.1 | 1177 | 25 |
| | | T South | 4.1 | 614 | 25 |
| | | T Internal 1 | 5.4 | 1266 | 25 |
| | | T Internal 2 | 5.4 | 1266 | 25 |

**Table 17: Melbourne Therma-Fuser Chilled-Water Air Handling Unit Capacities**

The cooling and heating capacities, outside (primary) and induced (secondary) airflows and zoning for each of the AHUs in the chilled beam system are shown in Table 12, Table 13, and Table 14 below for Brisbane, Sydney and Melbourne respectively. The fresh air AHU for each system has an oversized cooling capacity of 100 kW. The maximum induced airflow is three times the outside air supplied through the active chilled beam. This is based on a Dadanco information booklet [9] which claimed induction ratios of 2.7:1 to 3.2:1, and an article Cool Runnings in BSJ Building Services Journal [11], in which it was claimed that for standard active chilled beams a 4:1 ratio of induced to primary air was typically achieved. A 3:1 ratio has been conservatively assumed for the modelling of the chilled beams. It has been assumed that the induced airflow varies from 0 when no cooling occurs, to three times the induced airflow at full cooling, in a linear relationship. The cooling capacity of any individual chilled beam is a multiple of 1.045 kW. This is based on a 2.4 m chilled beam with 35 L/s primary airflow and an 8°C temperature difference, as described in the FläktWoods product catalogue [12].

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Outside Air Quantity (L/s) | Maximum Induced Airflow (L/s) |
|---|---|---|---|---|---|
| Chilled Beams Ground | 11.5 | G North | 6.6 | 172.1 | 516.3 |
| | 10.5 | G East | 6.3 | 172.1 | 516.3 |
| | 13.6 | G West | 7.2 | 172.1 | 516.3 |
| | 7.3 | G South | 4.1 | 172.1 | 516.3 |
| | 13.6 | G Internal 1 | 5.6 | 520.8 | 1562.4 |
| | 13.6 | G Internal 2 | 5.6 | 520.8 | 1562.4 |
| Chilled Beams L5 | 2.1 | L5 North Office 1 | 5.5 | 18 | 54 |
| | 2.1 | L5 North Office 2 | | 18 | 54 |
| | 2.1 | L5 North Office 3 | | 18 | 54 |
| | 2.1 | L5 North Office 4 | | 18 | 54 |
| | 2.1 | L5 North Office 5 | | 18 | 54 |
| | 4.2 | L5 North Perimeter | | 63.9 | 191.7 |
| | 1.05 | L5 East Office 1 | 6.9 | 18 | 54 |
| | 1.05 | L5 East Office 2 | | 18 | 54 |
| | 1.05 | L5 East Office 3 | | 18 | 54 |
| | 1.05 | L5 East Office 4 | | 18 | 54 |
| | 1.05 | L5 East Office 5 | | 18 | 54 |
| | 4.2 | L5 East Perimeter | | 64.1 | 192.3 |
| | 2.1 | L5 NE Corner Office | | 18.2 | 54.6 |
| | 2.1 | L5 SE Corner Office | | 18.2 | 54.6 |
| | 2.1 | L5 West Office 1 | 7.6 | 18 | 54 |
| | 2.1 | L5 West Office 2 | | 18 | 54 |
| | 2.1 | L5 West Office 3 | | 18 | 54 |
| | 2.1 | L5 West Office 4 | | 18 | 54 |
| | 2.1 | L5 West Office 5 | | 18 | 54 |
| | 2.1 | L5 West Office 6 | | 18 | 54 |
| | 2.1 | L5 West Perimeter 1 | | 28.2 | 84.6 |
| | 3.1 | L5 West Perimeter 2 | | 27 | 81 |
| | 2.1 | L5 NW Corner Office | | 18.2 | 54.6 |
| | 1.05 | L5 South Office 1 | 3.8 | 18 | 54 |
| | 1.05 | L5 South Office 2 | | 18 | 54 |
| | 1.05 | L5 South Office 3 | | 18 | 54 |
| | 1.05 | L5 South Office 4 | | 18 | 54 |
| | 3.1 | L5 South Perimeter | | 91.1 | 273.3 |
| | 13.6 | L5 Internal 1 | 5.6 | 520.7 | 1562.1 |
| | 13.6 | L5 Internal 2 | 5.6 | 520.7 | 1562.1 |

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Outside Air Quantity (L/s) | Maximum Induced Airflow (L/s) |
|---|---|---|---|---|---|
| Chilled Beams Top | 12.5 | T North | 7.2 | 172.1 | 516.3 |
| | 11.5 | T East | 6.9 | 172.1 | 516.3 |
| | 13.6 | T West | 8.0 | 172.1 | 516.3 |
| | 8.4 | T South | 4.9 | 172.1 | 516.3 |
| | 16.7 | T Internal 1 | 8.2 | 520.8 | 1562.4 |
| | 16.7 | T Internal 2 | 8.2 | 520.8 | 1562.4 |

**Table 18: Brisbane Chilled Beam Air Handling Unit Capacities**

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Outside Air Quantity (L/s) | Maximum Induced Airflow (L/s) |
|---|---|---|---|---|---|
| Chilled Beams Ground | 12.5 | G North | 7.8 | 172.1 | 516.3 |
| | 11.5 | G East | 7.2 | 172.1 | 516.3 |
| | 13.6 | G West | 8.2 | 172.1 | 516.3 |
| | 7.3 | G South | 4.3 | 172.1 | 516.3 |
| | 13.6 | G Internal 1 | 5.8 | 520.8 | 1562.4 |
| | 13.6 | G Internal 2 | 5.8 | 520.8 | 1562.4 |
| Chilled Beams L5 | 2.1 | L5 North Office 1 | 6.5 | 18 | 54 |
| | 2.1 | L5 North Office 2 | | 18 | 54 |
| | 2.1 | L5 North Office 3 | | 18 | 54 |
| | 2.1 | L5 North Office 4 | | 18 | 54 |
| | 2.1 | L5 North Office 5 | | 18 | 54 |
| | 4.2 | L5 North Perimeter | | 63.9 | 191.7 |
| | 1.05 | L5 East Office 1 | 8.0 | 18 | 54 |
| | 1.05 | L5 East Office 2 | | 18 | 54 |
| | 1.05 | L5 East Office 3 | | 18 | 54 |
| | 1.05 | L5 East Office 4 | | 18 | 54 |
| | 1.05 | L5 East Office 5 | | 18 | 54 |
| | 4.2 | L5 East Perimeter | | 64.1 | 192.3 |
| | 2.1 | L5 NE Corner Office | | 18.2 | 54.6 |
| | 2.1 | L5 SE Corner Office | | 18.2 | 54.6 |
| | 2.1 | L5 West Office 1 | 8.7 | 18 | 54 |
| | 2.1 | L5 West Office 2 | | 18 | 54 |
| | 2.1 | L5 West Office 3 | | 18 | 54 |
| | 2.1 | L5 West Office 4 | | 18 | 54 |
| | 2.1 | L5 West Office 5 | | 18 | 54 |
| | 2.1 | L5 West Office 6 | | 18 | 54 |
| | 2.1 | L5 West Perimeter 1 | | 28.2 | 84.6 |
| | 3.1 | L5 West Perimeter 2 | | 27 | 81 |
| | 2.1 | L5 NW Corner Office | | 18.2 | 54.6 |
| | 1.05 | L5 South Office 1 | 4.0 | 18 | 54 |
| | 1.05 | L5 South Office 2 | | 18 | 54 |

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Outside Air Quantity (L/s) | Maximum Induced Airflow (L/s) |
|---|---|---|---|---|---|
| | 1.05 | L5 South Office 3 | | 18 | 54 |
| | 1.05 | L5 South Office 4 | | 18 | 54 |
| | 4.2 | L5 South Perimeter | | 91.1 | 273.3 |
| | 13.6 | L5 Internal 1 | 5.8 | 520.7 | 1562.1 |
| | 13.6 | L5 Internal 2 | 5.8 | 520.7 | 1562.1 |
| Chilled Beams Top | 13.6 | T North | 8.5 | 172.1 | 516.3 |
| | 11.5 | T East | 7.9 | 172.1 | 516.3 |
| | 14.6 | T West | 9.1 | 172.1 | 516.3 |
| | 8.4 | T South | 5.2 | 172.1 | 516.3 |
| | 16.7 | T Internal 1 | 8.8 | 520.8 | 1562.4 |
| | 16.7 | T Internal 2 | 8.8 | 520.8 | 1562.4 |

**Table 19: Sydney Chilled Beam Air Handling Unit Capacities**

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Outside Air Quantity (L/s) | Maximum Induced Airflow (L/s) |
|---|---|---|---|---|---|
| Chilled Beams Ground | 12.5 | G North | 8.6 | 172.1 | 516.3 |
| | 11.5 | G East | 7.9 | 172.1 | 516.3 |
| | 13.6 | G West | 9.2 | 172.1 | 516.3 |
| | 7.3 | G South | 4.5 | 172.1 | 516.3 |
| | 13.6 | G Internal 1 | 6.0 | 520.8 | 1562.4 |
| | 13.6 | G Internal 2 | 6.0 | 520.8 | 1562.4 |
| Chilled Beams L5 | 2.1 | L5 North Office 1 | 7.2 | 18 | 54 |
| | 2.1 | L5 North Office 2 | | 18 | 54 |
| | 2.1 | L5 North Office 3 | | 18 | 54 |
| | 2.1 | L5 North Office 4 | | 18 | 54 |
| | 2.1 | L5 North Office 5 | | 18 | 54 |
| | 5.2 | L5 North Perimeter | | 63.9 | 191.7 |
| | 1.05 | L5 East Office 1 | 8.5 | 18 | 54 |
| | 1.05 | L5 East Office 2 | | 18 | 54 |
| | 1.05 | L5 East Office 3 | | 18 | 54 |
| | 1.05 | L5 East Office 4 | | 18 | 54 |
| | 1.05 | L5 East Office 5 | | 18 | 54 |
| | 4.2 | L5 East Perimeter | | 64.1 | 192.3 |
| | 2.1 | L5 NE Corner Office | | 18.2 | 54.6 |
| | 2.1 | L5 SE Corner Office | | 18.2 | 54.6 |
| | 2.1 | L5 West Office 1 | 7.6 | 18 | 54 |
| | 2.1 | L5 West Office 2 | | 18 | 54 |
| | 2.1 | L5 West Office 3 | | 18 | 54 |
| | 2.1 | L5 West Office 4 | | 18 | 54 |
| | 2.1 | L5 West Office 5 | | 18 | 54 |
| | 2.1 | L5 West Office 6 | | 18 | 54 |

| Plant | Total Cooling Capacity (kW) | Zone | Heating Capacity (kW) | Outside Air Quantity (L/s) | Maximum Induced Airflow (L/s) |
|---|---|---|---|---|---|
| | 2.1 | L5 West Perimeter 1 | | 28.2 | 84.6 |
| | 3.1 | L5 West Perimeter 2 | | 27 | 81 |
| | 2.1 | L5 NW Corner Office | | 18.2 | 54.6 |
| | 1.05 | L5 South Office 1 | 3.8 | 18 | 54 |
| | 1.05 | L5 South Office 2 | | 18 | 54 |
| | 1.05 | L5 South Office 3 | | 18 | 54 |
| | 1.05 | L5 South Office 4 | | 18 | 54 |
| | 4.2 | L5 South Perimeter | | 91.1 | 273.3 |
| | 13.6 | L5 Internal 1 | 5.6 | 520.7 | 1562.1 |
| | 13.6 | L5 Internal 2 | 5.6 | 520.7 | 1562.1 |
| Chilled Beams Top | 12.5 | T North | 9.2 | 172.1 | 516.3 |
| | 11.5 | T East | 8.3 | 172.1 | 516.3 |
| | 14.6 | T West | 10.1 | 172.1 | 516.3 |
| | 8.4 | T South | 5.4 | 172.1 | 516.3 |
| | 16.7 | T Internal 1 | 9.3 | 520.8 | 1562.4 |
| | 16.7 | T Internal 2 | 9.3 | 520.8 | 1562.4 |

**Table 20: Melbourne Chilled Beam Air Handling Unit Capacities**

The fan energy information for the AHUs is shown in Table 21 through Table 39. The pressure and therefore energy use follows a cubic relation with airflow. All fans have an assumed efficiency of 55.0%. Because every zone will have peak cooling at different times, the design airflow for the AHU is less than the sum of the design airflows for each zone. The model may predict times that the required airflow is higher than the design airflow for the AHU, either for a very brief period at startup or on days that are hotter than the design day used to calculate the airflows. For this reason, the expected behaviour of the fan at airflows above 100% of design airflow have been included. The program will not accept pressures of less than 10 Pa and so any values less than this have been rounded up to 10 Pa.

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 40.0 | 1700.4 | 19.2 |
| 60.0 | 2550.6 | 64.8 |
| 80.0 | 3400.8 | 153.6 |
| 100.0 | 4251.0 | 300.0 |
| 117.4 | 4990.0 | 485.2 |

**Table 21: Brisbane VAV Ground Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 40.0 | 1700.8 | 19.2 |
| 60.0 | 2551.2 | 64.8 |
| 80.0 | 3401.6 | 153.6 |
| 100.0 | 4252.0 | 300.0 |
| 115.2 | 4900.0 | 459.1 |

**Table 22: Brisbane VAV L5 Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 40.0 | 2079.2 | 19.2 |
| 60.0 | 3118.8 | 64.8 |
| 80.0 | 4158.4 | 153.6 |
| 100.0 | 5198.0 | 300.0 |
| 112.4 | 5841.0 | 425.7 |

**Table 23: Brisbane VAV Top Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 40.0 | 1870.0 | 19.2 |
| 60.0 | 2805.0 | 64.8 |
| 80.0 | 3740.0 | 153.6 |
| 100.0 | 4675.0 | 300.0 |
| 113.1 | 5288.0 | 434.2 |

**Table 24: Sydney VAV Ground Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 40.0 | 1870.8 | 19.2 |
| 60.0 | 2806.2 | 64.8 |
| 80.0 | 3741.6 | 153.6 |
| 100.0 | 4677.0 | 300.0 |
| 111.2 | 5201.0 | 412.6 |

**Table 25: Sydney VAV L5 Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 40.0 | 2191.6 | 19.2 |
| 60.0 | 3287.4 | 64.8 |
| 80.0 | 4383.2 | 153.6 |
| 100.0 | 5479.0 | 300.0 |
| 112.7 | 6176.0 | 429.7 |

**Table 26: Sydney VAV Top Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 40.0 | 1948.4 | 19.2 |
| 60.0 | 2922.6 | 64.8 |
| 80.0 | 3896.8 | 153.6 |
| 100.0 | 4871.0 | 300.0 |
| 112.0 | 5455.0 | 421.4 |

**Table 27: Melbourne VAV Ground Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 40.0 | 1949.2 | 19.2 |

| | | |
|---|---|---|
| 60.0 | 2923.8 | 64.8 |
| 80.0 | 3898.4 | 153.6 |
| 100.0 | 4873.0 | 300.0 |
| 110.2 | 5368.0 | 401.0 |

**Table 28: Melbourne VAV L5 Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 40.0 | 2263.2 | 19.2 |
| 60.0 | 3394.8 | 64.8 |
| 80.0 | 4526.4 | 153.6 |
| 100.0 | 5658.0 | 300.0 |
| 111.7 | 6319.0 | 417.9 |

**Table 29: Melbourne VAV Top Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 25.0 | 1062.8 | 10.0 |
| 50.0 | 2125.5 | 37.5 |
| 75.0 | 3188.3 | 126.6 |
| 100.0 | 4251.0 | 300.0 |
| 117.4 | 4990.0 | 485.2 |

**Table 30: Brisbane Therma-Fuser Ground Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 25.0 | 1063.0 | 10.0 |
| 50.0 | 2126.0 | 37.5 |
| 75.0 | 3189.0 | 126.6 |
| 100.0 | 4252.0 | 300.0 |
| 115.9 | 4928.0 | 467.0 |

**Table 31: Brisbane Therma-Fuser L5 Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 25.0 | 1299.5 | 10.0 |
| 50.0 | 2599.0 | 37.5 |
| 75.0 | 3898.5 | 126.6 |
| 100.0 | 5198.0 | 300.0 |
| 112.4 | 5841.0 | 425.7 |

**Table 32: Brisbane Therma-Fuser Top Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 25.0 | 1168.8 | 10.0 |
| 50.0 | 2337.5 | 37.5 |
| 75.0 | 3506.3 | 126.6 |
| 100.0 | 4675.0 | 300.0 |
| 113.1 | 5288.0 | 434.2 |

**Table 33: Sydney Therma-Fuser Ground Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 25.0 | 1169.3 | 10.0 |
| 50.0 | 2338.5 | 37.5 |
| 75.0 | 3507.8 | 126.6 |
| 100.0 | 4677.0 | 300.0 |
| 111.7 | 5226.0 | 418.5 |

**Table 34: Sydney Therma-Fuser L5 Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 25.0 | 1369.8 | 10.0 |
| 50.0 | 2739.5 | 37.5 |
| 75.0 | 4109.3 | 126.6 |
| 100.0 | 5479.0 | 300.0 |
| 112.7 | 6176.0 | 429.7 |

**Table 35: Sydney Therma-Fuser Top Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 25.0 | 1217.8 | 10.0 |
| 50.0 | 2435.5 | 37.5 |
| 75.0 | 3653.3 | 126.6 |
| 100.0 | 4871.0 | 300.0 |
| 112.2 | 5465.0 | 423.7 |

**Table 36: Melbourne Therma-Fuser Ground Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 25.0 | 1218.3 | 10.0 |
| 50.0 | 2436.5 | 37.5 |
| 75.0 | 3654.8 | 126.6 |
| 100.0 | 4873.0 | 300.0 |
| 110.7 | 5396.0 | 407.3 |

**Table 37: Melbourne Therma-Fuser L5 Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 25.0 | 1414.5 | 10.0 |
| 50.0 | 2829.0 | 37.5 |
| 75.0 | 4243.5 | 126.6 |
| 100.0 | 5658.0 | 300.0 |
| 111.7 | 6319.0 | 417.9 |

**Table 38: Melbourne Therma-Fuser Top Floor AHU Fan Data**

| % of Design Airflow | Airflow (L/s) | Pressure (Pa) |
|---|---|---|
| 100.0 | 1730.0 | 300.0 |

**Table 39: Chilled Beam AHU Fan Data**

# 10.0 Appendix B Equipment Loads

The equipment loads throughout the building are shown below in Table 40. The level 5 equipment loads are assumed to be replicated across the other middle floors for the purpose of ensuring the correct ratios of equipment loads are achieved. The average equipment load across the entire NLA of the building is 10.73 $W/m^2$.

| Room | Area | Equipment (W/m$^2$) |
|---|---|---|
| G North Perimeter | 86.1 | 11 |
| G East Perimeter | 86.1 | 15 |
| G West Perimeter | 86.1 | 5 |
| G South Perimeter | 86.1 | 11 |
| G Internal | 260.6 | 7 |
| G Internal | 260.6 | 11 |
| L5 East Office 1 | 9 | 5 |
| L5 East Office 2 | 9 | 19 |
| L5 East Office 3 | 9 | 15 |
| L5 East Office 4 | 9 | 5 |
| L5 East Office 5 | 9 | 19 |
| L5 East Perimeter | 32.1 | 5 |
| L5 Internal | 260.6 | 11 |
| L5 Internal | 260.6 | 7 |
| L5 NE Corner Office | 9.1 | 15 |
| L5 North Office 1 | 9 | 19 |
| L5 North Office 2 | 9 | 5 |
| L5 North Office 3 | 9 | 15 |
| L5 North Office 4 | 9 | 5 |
| L5 North Office 5 | 9 | 19 |
| L5 North Perimeter | 32 | 15 |
| L5 NW Corner Office | 9.1 | 15 |
| L5 SE Corner Office | 9.1 | 5 |
| L5 South Office 1 | 9 | 19 |
| L5 South Office 2 | 9 | 5 |
| L5 South Office 3 | 9 | 19 |
| L5 South Office 4 | 9 | 15 |
| L5 South Perimeter | 45.6 | 19 |
| L5 West Office 1 | 9 | 5 |
| L5 West Office 2 | 9 | 15 |
| L5 West Office 3 | 9 | 19 |
| L5 West Office 4 | 9 | 15 |
| L5 West Office 5 | 9 | 19 |
| L5 West Office 6 | 9 | 15 |
| L5 West Perimeter 1 | 14.1 | 5 |
| L5 West Perimeter 2 | 13.5 | 19 |
| Top North Perimeter | 86.1 | 15 |
| Top East Perimeter | 86.1 | 5 |
| Top West Perimeter | 86.1 | 15 |
| Top South Perimeter | 86.1 | 5 |
| Top Internal | 260.6 | 19 |
| Top Internal | 260.6 | 7 |

**Table 40: Tenant equipment loads**

# 11.0 Appendix C Thermal Comfort Results

The thermal comfort results for the three systems are detailed in Table 41 through Table 43. The number of hours between 8:00 am and 5:00 pm that are outside PMV limits over the year of simulation data are listed.

| Location | Area ($m^2$) | PMV > 0.50 (hrs) | PMV > 1.00 (hrs) | PMV < -1.00 (hrs) | PMV < -0.50 (hrs) |
|---|---|---|---|---|---|
| L5 East Office 1 | 9 | 0 | 0 | 0 | 0 |
| L5 East Office 2 | 9 | 0 | 0 | 0 | 0 |
| L5 East Office 3 | 9 | 0 | 0 | 0 | 0 |
| L5 East Office 4 | 9 | 0 | 0 | 0 | 0 |
| L5 East Office 5 | 9 | 0 | 0 | 0 | 0 |
| L5 East Perimeter | 32.1 | 0 | 0 | 0 | 0 |
| L5 Internal | 260.6 | 0 | 0 | 0 | 0 |
| L5 Internal | 260.6 | 0 | 0 | 0 | 0 |
| L5 NE Corner Office | 9.1 | 0 | 0 | 0 | 0 |
| L5 North Office 1 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 2 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 3 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 4 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 5 | 9 | 0 | 0 | 0 | 0 |
| L5 North Perimeter | 32 | 0 | 0 | 0 | 0 |
| L5 NW Corner Office | 9.1 | 0 | 0 | 0 | 0 |
| L5 SE Corner Office | 9.1 | 0 | 0 | 0 | 1.2 |
| L5 South Office 1 | 9 | 0 | 0 | 0 | 0 |
| L5 South Office 2 | 9 | 0 | 0 | 0 | 0.8 |
| L5 South Office 3 | 9 | 0 | 0 | 0 | 0 |
| L5 South Office 4 | 9 | 0 | 0 | 0 | 0 |
| L5 South Perimeter | 45.6 | 0 | 0 | 0 | 0 |
| L5 West Office 1 | 9 | 0 | 0 | 0 | 0 |
| L5 West Office 2 | 9 | 0 | 0 | 0 | 0 |
| L5 West Office 3 | 9 | 0 | 0 | 0 | 0 |
| L5 West Office 4 | 9 | 0 | 0 | 0 | 0 |
| L5 West Office 5 | 9 | 0 | 0 | 0 | 0 |
| L5 West Office 6 | 9 | 0 | 0 | 0 | 0 |
| L5 West Perimeter 1 | 14.1 | 0 | 0 | 0 | 0 |
| L5 West Perimeter 2 | 13.5 | 0 | 0 | 0 | 0 |
| G East Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| G Internal | 260.6 | 0 | 0 | 0 | 0 |
| G Internal | 260.6 | 0 | 0 | 0 | 0 |
| G North Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| G South Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| G West Perimeter | 86.1 | 0 | 0 | 0 | 0 |

| Location | Area ($m^2$) | PMV > 0.50 (hrs) | PMV > 1.00 (hrs) | PMV < -1.00 (hrs) | PMV < -0.50 (hrs) |
|---|---|---|---|---|---|
| Top East Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| Top Internal | 260.6 | 0 | 0 | 0 | 0 |
| Top Internal | 260.6 | 0 | 0 | 0 | 0 |
| Top North Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| Top South Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| Top West Perimeter | 86.1 | 0 | 0 | 0 | 0 |

**Table 41: VAV system PMV results**

| Location | Area ($m^2$) | PMV > 0.50 (hrs) | PMV > 1.00 (hrs) | PMV < -1.00 (hrs) | PMV < -0.50 (hrs) |
|---|---|---|---|---|---|
| L5 East Office 1 | 9 | 0 | 0 | 0 | 0 |
| L5 East Office 2 | 9 | 0 | 0 | 0 | 0 |
| L5 East Office 3 | 9 | 0 | 0 | 0 | 0 |
| L5 East Office 4 | 9 | 0 | 0 | 0 | 0 |
| L5 East Office 5 | 9 | 0 | 0 | 0 | 0 |
| L5 East Perimeter | 32.1 | 0 | 0 | 0 | 0 |
| L5 Internal | 260.6 | 0 | 0 | 0 | 0 |
| L5 Internal | 260.6 | 0 | 0 | 0 | 0 |
| L5 NE Corner Office | 9.1 | 0 | 0 | 0 | 0 |
| L5 North Office 1 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 2 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 3 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 4 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 5 | 9 | 0 | 0 | 0 | 0 |
| L5 North Perimeter | 32 | 0 | 0 | 0 | 0 |
| L5 NW Corner Office | 9.1 | 0 | 0 | 0 | 0 |
| L5 SE Corner Office | 9.1 | 0 | 0 | 0 | 4.2 |
| L5 South Office 1 | 9 | 0 | 0 | 0 | 0 |
| L5 South Office 2 | 9 | 0 | 0 | 0 | 0 |
| L5 South Office 3 | 9 | 0 | 0 | 0 | 0 |
| L5 South Office 4 | 9 | 0 | 0 | 0 | 0 |
| L5 South Perimeter | 45.6 | 0 | 0 | 0 | 0 |
| L5 West Office 1 | 9 | 0 | 0 | 0 | 0 |
| L5 West Office 2 | 9 | 0 | 0 | 0 | 0 |
| L5 West Office 3 | 9 | 0 | 0 | 0 | 0 |
| L5 West Office 4 | 9 | 0 | 0 | 0 | 0 |
| L5 West Office 5 | 9 | 0 | 0 | 0 | 0 |
| L5 West Office 6 | 9 | 0 | 0 | 0 | 0 |
| L5 West Perimeter 1 | 14.1 | 0 | 0 | 0 | 0 |
| L5 West Perimeter 2 | 13.5 | 0 | 0 | 0 | 0 |
| G East Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| G Internal | 260.6 | 0 | 0 | 0 | 0 |

| Location | Area ($m^2$) | PMV > 0.50 (hrs) | PMV > 1.00 (hrs) | PMV < -1.00 (hrs) | PMV < -0.50 (hrs) |
|---|---|---|---|---|---|
| G Internal | 260.6 | 0 | 0 | 0 | 0 |
| G North Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| G South Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| G West Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| Top East Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| Top Internal | 260.6 | 0 | 0 | 0 | 0 |
| Top Internal | 260.6 | 0 | 0 | 0 | 0 |
| Top North Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| Top South Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| Top West Perimeter | 86.1 | 0 | 0 | 0 | 0 |

**Table 42: Therma-Fuser system PMV results**

| Location | Area ($m^2$) | PMV > 0.50 (hrs) | PMV > 1.00 (hrs) | PMV < -1.00 (hrs) | PMV < -0.50 (hrs) |
|---|---|---|---|---|---|
| L5 East Office 1 | 9 | 0 | 0 | 0 | 0 |
| L5 East Office 2 | 9 | 2 | 0 | 0 | 0 |
| L5 East Office 3 | 9 | 1.7 | 0 | 0 | 0 |
| L5 East Office 4 | 9 | 0 | 0 | 0 | 0 |
| L5 East Office 5 | 9 | 2 | 0 | 0 | 0 |
| L5 East Perimeter | 32.1 | 0 | 0 | 0 | 0 |
| L5 Internal | 260.6 | 0 | 0 | 0 | 0 |
| L5 Internal | 260.6 | 0 | 0 | 0 | 0 |
| L5 NE Corner Office | 9.1 | 4.7 | 0 | 0 | 0 |
| L5 North Office 1 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 2 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 3 | 9 | 0 | 0 | 0 | 0 |
| L5 North Office 4 | 9 | 0 | 0 | 0 | 0.2 |
| L5 North Office 5 | 9 | 0 | 0 | 0 | 0 |
| L5 North Perimeter | 32 | 0 | 0 | 0 | 0 |
| L5 NW Corner Office | 9.1 | 19.7 | 0 | 0 | 0.2 |
| L5 SE Corner Office | 9.1 | 2.3 | 0 | 0 | 5.5 |
| L5 South Office 1 | 9 | 0 | 0 | 0 | 0.2 |
| L5 South Office 2 | 9 | 0 | 0 | 0 | 3.5 |
| L5 South Office 3 | 9 | 0 | 0 | 0 | 0.2 |
| L5 South Office 4 | 9 | 0 | 0 | 0 | 0.7 |
| L5 South Perimeter | 45.6 | 0 | 0 | 0 | 0 |
| L5 West Office 1 | 9 | 0 | 0 | 0 | 1.5 |
| L5 West Office 2 | 9 | 0.5 | 0 | 0 | 0.2 |
| L5 West Office 3 | 9 | 2.3 | 0 | 0 | 0 |
| L5 West Office 4 | 9 | 1.2 | 0 | 0 | 0.2 |
| L5 West Office 5 | 9 | 3 | 0 | 0 | 0 |
| L5 West Office 6 | 9 | 1 | 0 | 0 | 0.2 |

| Location | Area ($m^2$) | PMV > 0.50 (hrs) | PMV > 1.00 (hrs) | PMV < -1.00 (hrs) | PMV < -0.50 (hrs) |
|---|---|---|---|---|---|
| L5 West Perimeter 1 | 14.1 | 0 | 0 | 0 | 0 |
| L5 West Perimeter 2 | 13.5 | 0 | 0 | 0 | 0 |
| G East Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| G Internal | 260.6 | 0 | 0 | 0 | 0 |
| G Internal | 260.6 | 0 | 0 | 0 | 0 |
| G North Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| G South Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| G West Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| Top East Perimeter | 86.1 | 2.2 | 0 | 0 | 0 |
| Top Internal | 260.6 | 0 | 0 | 0 | 0 |
| Top Internal | 260.6 | 0 | 0 | 0 | 0.2 |
| Top North Perimeter | 86.1 | 0 | 0 | 0 | 0 |
| Top South Perimeter | 86.1 | 0 | 0 | 0 | 0.7 |
| Top West Perimeter | 86.1 | 0.5 | 0 | 0 | 0.2 |

**Table 43: Chilled beam system PMV results**

# 12.0 References


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