A COMPARISON STUDY FOR ACTIVE CHILLED BEAM AND VARIABLE AIR VOLUME SYSTEMS FOR AN OFFICE BUILDING

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FACULTY OF ENGINEERING
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KUALA LUMPUR

2018

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THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF MECHANICAL ENGINEERING

FACULTY OF ENGINEERING
UNIVERSITY OF MALAYA
KUALA LUMPUR

2018

UNIVERSITY OF MALAYA

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ABSTRACT

Comparison in terms of energy and cost is carried out between two different air distribution systems: variable air volume (VAV) and active chilled beam (ACB) based on a virtual building. Cooling load calculation was performed to determine the total load demand and system design was carried out to determine the system capacity. All design steps were presented in detail for both systems based on appropriate design requirement in accordance with ASHRAE's standards. Comparing to VAV, ACB is more complicated in terms of design as it involves specific design considerations such as room latent load shall not be too high, secondary chilled water temperature shall not be lower than the room dew point temperature and room shall have adequate ceiling space for the placement of chilled beam. Energy and cost analysis was done to determine which system gives better saving. From the results analysis, it shows that ACB is more energy-saving than VAV especially at full load and normal part-load conditions because of the reduced AHU fan's capacity. In terms of cost, ACB has higher initial cost than VAV where it is mainly contributed by the secondary chilled water pipe, heat exchanger and the beam itself. However, the operation cost is lower for ACB and for long term use, ACB is more cost-saving than VAV. Since the results discussed in this thesis is obtained by numerical method, for future work, it's recommended to perform energy audit on the actual building in order to verify the validity of the computed results.

ACKNOLEDGEMENTS

The author expresses his sincere appreciation to all who contributed to the success of this research. Special thanks to the research supervisor Professor Ir. Dr. Yau Yat Huang who had offered great assistance throughout this project. Without his knowledge and assistance this study would not have been successful.

Finally, sincere gratitude and acknowledgement dedicated towards the contribution of author's parents and friends who had been helpful and supportive throughout this research.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDICES

CHAPTER 1. INTRODUCTION

1.1 Background

Chilled water-based system is designed to provide cooling for large commercial buildings such as office, shopping mall, hotel and hospital. Due to the fact that more than 40% of the building's total energy comes from air-conditioning, equipment efficiency and system efficiency are often taken into serious consideration, be it at design stage, or during operation [1]. Not only they consume large amount of energy, resulting in high operating cost, they also represent a large amount of investment from the perspective of first cost, maintenance cost and physical space required.

A chiller plant (chilled water-based system) comprises of two parts: water side and air side where the former refers to chilled water distribution system and the latter refers to air distribution system. Chilled water distribution system involves major equipment like chillers, cooling towers and pumps whereas air distribution system involves air handling unit (AHU), dedicated outdoor air system (DOAS), fan coil unit (FCU) and exhaust fan. Equipment that consumes the most energy is chiller and most often, chiller efficiency is given top priority especially during equipment selection as wrong selection would end up high operating cost.

Typically, chiller efficiency is 0.56 kW/RT and the total plant efficiency is 0.9 kW/RT. The term kW refers to the energy consumed (electrical input) and RT refers to the equipment's capacity. The lower the kW/RT, the more efficient it is. To ensure the total plant efficiency is low in terms of kW/RT, it starts from the selection of individual equipment (chiller, cooling tower, pumps and ahu). The process is rather straight forward where the efficiency of equipment can be referred to the available technical specifications of the product itself. Unlike equipment efficiency, it involves more complicated system design, control and monitoring. to ensure high system efficiency.

For chilled water side, there are two common types of system design, namely constant primary/variable secondary flow (P/S) and variable primary flow (VPF). P/S consists of 2 loops where the primary loop is constant flow serving the chillers and the secondary loop is variable flow serving the AHUs. On the other hand, VPF consists of only 1 loop and the flow is variable throughout. Comparing between these two systems, VPF is more efficient as the chillers and pumps operate in response to the load demand. Unlike VPF, the primary pump for P/S operate at full load all the time regardless of the load demand.

For air side, there are many types of air distribution system such as constant air volume (CAV), variable air volume (VAV), underfloor air distribution (UFAD), stratum ventilation and active chilled beam system (ACB). CAV is the most conventional air distribution system and it's also the most inefficient system where the supply air flow is constant all the time regardless of the load demand. Meanwhile, VAV is the improved version of CAV where the supply air flow is varying in response to the load demand. This system is not new but it has been used for some time especially for office buildings.

Whereas, UFAD is an entirely different system where the air supply is from the ground (floor plenum) instead of from the top, as what is commonly seen in a normal overhead system. It is designed to supply cooled air up to human height rather than filling up the whole room [2]. For Stratum Ventilation, the air supply is from the side (wall plenum) that provides cooling directly to the occupants, which is claimed to be more efficient than UFAD [3]. Nevertheless, due to the fact that the difference in terms of design is significant for both UFAD and stratum ventilation when comparing to the conventional overhead system, the consideration of using such system is often turned down as it affects significantly on the building layout in order to fit in the system. ACB is another air distribution system, comparably more energy efficient but less common especially in Asia Pacific region [4]. Unlike UFAD and stratum ventilation, the design of ACB is not far different from the overhead system and in fact, the ceiling height required is lesser than the conventional CAV. Therefore, it is believed that ACB could be the better substitute of the conventional CAV or VAV in future compared to UFAD and stratum ventilation.

1.2 Problem Statement

Chilled water-based system consumes considerable amount of energy in a large building which results in high operation cost. There are many ways to reduce the total energy consumption of a chiller plant, one of which is by using efficient air distribution system. For office buildings, the most commonly-used air distribution system is variable air volume (VAV). VAV is claimed to be energy efficient as the capacity delivered by the system is based on the load demand. However, there is another type of air distribution system, Active Chilled Beam (ACB), claimed to be even more energy efficient than VAV where it helps remove room sensible load through secondary coil which consequently reduces the AHU capacity. As far as energy is concerned, efficiency of the air distribution system is of main priority. Some reports claim that VAV is more efficient than ACB in certain conditions. To determine which system is more efficient that could give better savings, proper analysis should be done based on appropriate design conditions.

1.3 Scope of study

A comprehensive literature review focusing on the comparison between VAV and ACB was performed. Review was based on the comparative study done by several authors. Design requirement used and design method proposed were taken into consideration in the analysis of this project in terms of system design, control and comparison method. Detailed comparison was performed based on virtual building and the best air distribution system in terms of efficiency and savings was proposed as the outcome of this project.

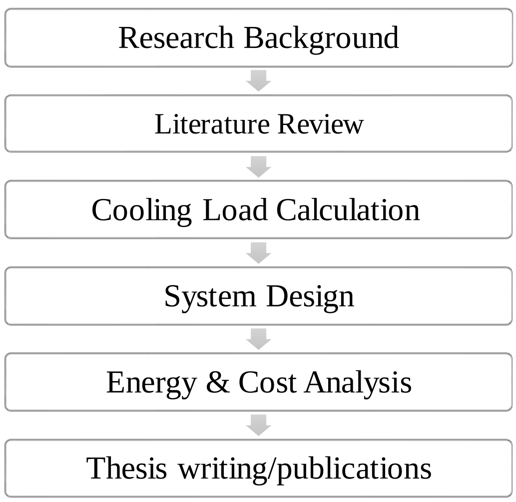
1.4 Objective

This research project is to propose a sustainable air distribution system that provides long term savings to the building's owner or consultant. The objectives are:

- To compare between two different systems: ACB and VAV in terms of design, control, efficiency and cost.
- To perform energy and cost analysis.
- To prove active chilled beam (ACB) is the better option.

1.5 Methodology

The research starts with a prior literature review on the comparison study between VAV and ACB done by others. The method of analysis used by the author is being analysed to understand how the comparison is done. Based on the method proposed where a fair comparison is made by the author, the same approach is being applied on the analysis for this project. The design calculations are based on appropriate calculation method as recommended in ASHRAE's handbook. System design for respective system is performed using validated design approach. Energy and cost analysis are carried out to determine the savings comparing between two systems. Finally, all processes are compiled and documented into a thesis.



1.6 Outline of Thesis

It consists of total six chapters as follows:

In **Chapter 1**, research background, problem statement, scope of study, objective, and methodology were discussed.

In **Chapter 2**, previous work done by others were reviewed. The design requirement used and methodology proposed for respective system: VAV and CAV were studied.

In **Chapter 3**, methodology of this project was elaborated from design calculations to results analysis.

In **Chapter 4**, the calculation results were presented for both systems.

In **Chapter 5**, results analysis and discussion were performed.

In **Chapter 6**, conclusion was made based on the results analysis and recommendations were given for future work.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

A prior literature review was carried out to attain a deep understanding in the field of study. This chapter divided into two sections which are namely system design and technical comparison. System design includes fundamental principle, design consideration and control design proposed by others. Technical comparison covers technical analysis done by others comparing between variable air volume (VAV) and active chilled beam (ACB). The outcome of this review created the need for detailed comparison between active chilled beam (ACB) and variable air volume (VAV) based on the virtual building.

2.2 System Design

Research have been performed on both VAV and ACB to determine the fundamental principle and design consideration as well as the control design of each system.

2.2.1 Active Chilled Beam (ACB)

Generally, chilled beams can be divided into two types: passive chilled beam (PCB) and active chilled beam (ACB). For PCB, heat exchange takes place between the coil and the entering air is by natural means where the air movement through the coil is caused by the difference in density between warm air and cold air. On the other hand, for ACB, the primary air is supplied by a mechanical device (air handler) where it induces the room air to pass through the secondary coil and mix with the primary air before entering the room as shown in **Figure 2.1**. Since it involves forced convection, ACB is better than PCB in terms of performance and efficiency. For that reason, in this project, the comparison is made between ACB and VAV.

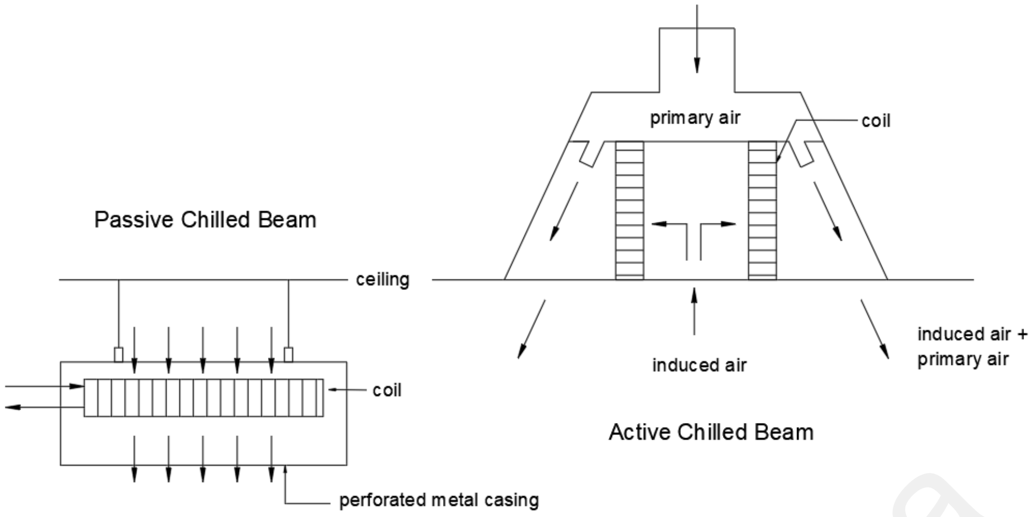


Figure 2.1 Passive Chilled Beam and Active Chilled Beam [5]

The processes of a typical active chilled beam system are explained as below:

Referring to **Figure 2.2** and **Figure 2.3**, the outdoor air at state 1 and the return air at state 2 are mixed at a certain percentage at state 3. The mixed air is then cooled and dehumidified by cooling coil from state 3 to state 4 where the air reaches its saturation point. As the air travels into the beam at state 5, the temperature is expected to increase slightly due to heat gains from the fan and ducts. The primary air at state 5 is then driven into the beam through number of nozzles which leads to entrainment effect, consequently causing the induction of air from the conditioned space to the secondary coil. The secondary coil removes only the room sensible heat. The secondary air is cooled from state 2 to state 6 by the secondary coil before being mixed with the primary air and released to the conditioned space at state 7.

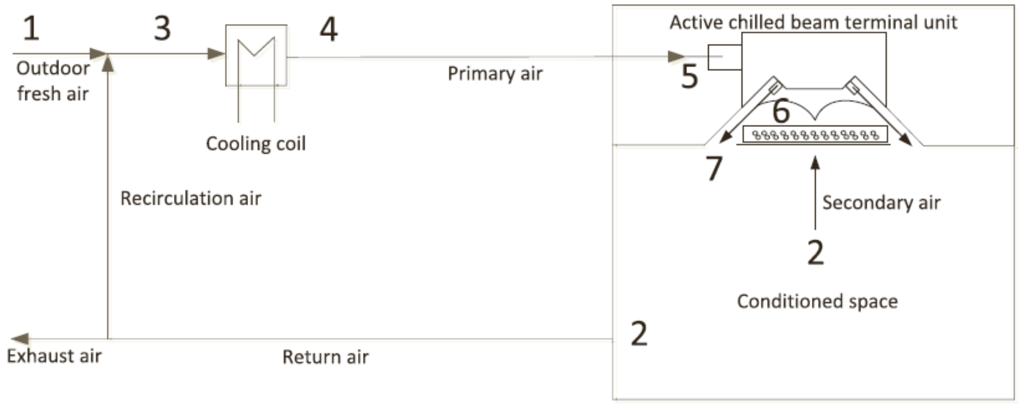


Figure 2.2 Schematic of An Active Chilled Beam System with Air Handling Unit [6]

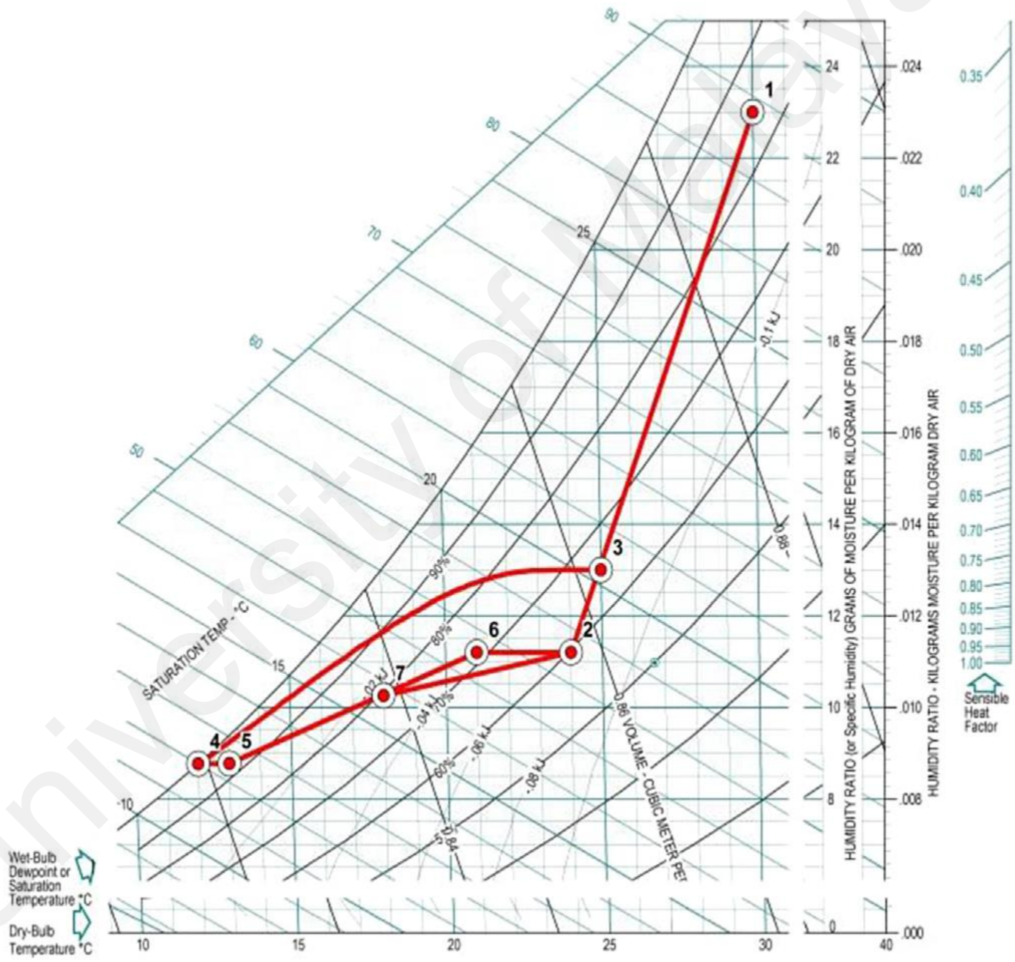


Figure 2.3 Psychrometric Chart of An Active Chilled Beam System with Air Handling Unit [6]

2.2.1.1 Air side

The advantage of using active chilled beam is the reduced airflow of the AHU/DOAS because of the secondary chilled water circuit in the beams that helps remove the room sensible load. The airflow of the primary air, however must be sufficient enough to remove the latent load in order to maintain specified room humidity levels and meet the minimum ventilation requirement [7]. **Figure 2.4** shows the relationship between primary air supply and space load conditions of a typical space. From the figure, the latent airflow factor (F_{LATENT}) is determined based on specified primary air dew point temperature and room relative humidity. With the ventilation rate assumed (in accordance with ASHRAE's standard), the primary airflow rate required can be calculated from the function as follows:

$$CFM_{LATENT} = F_{LATENT} \text{ x } CFM_{VENT}$$

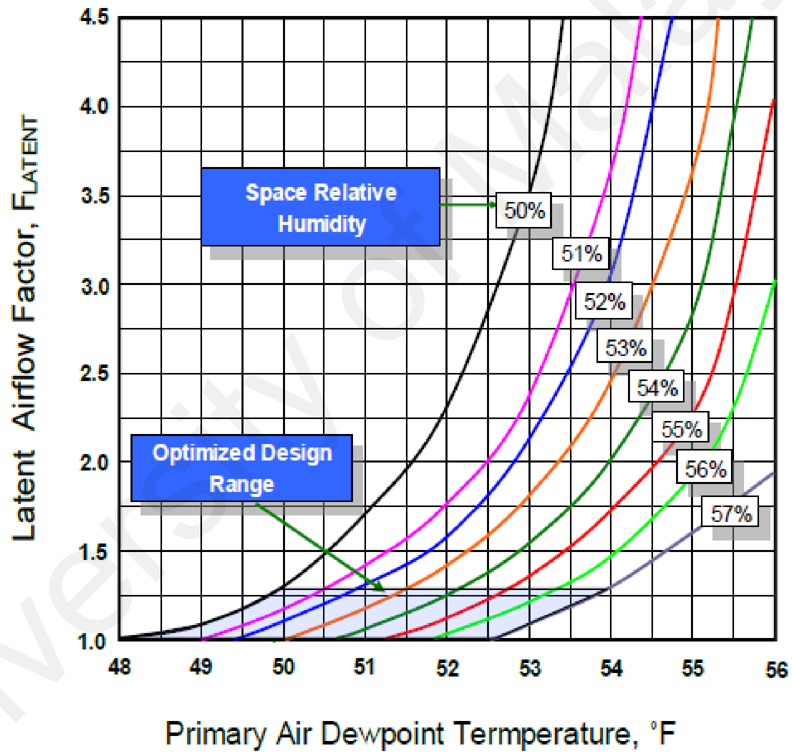
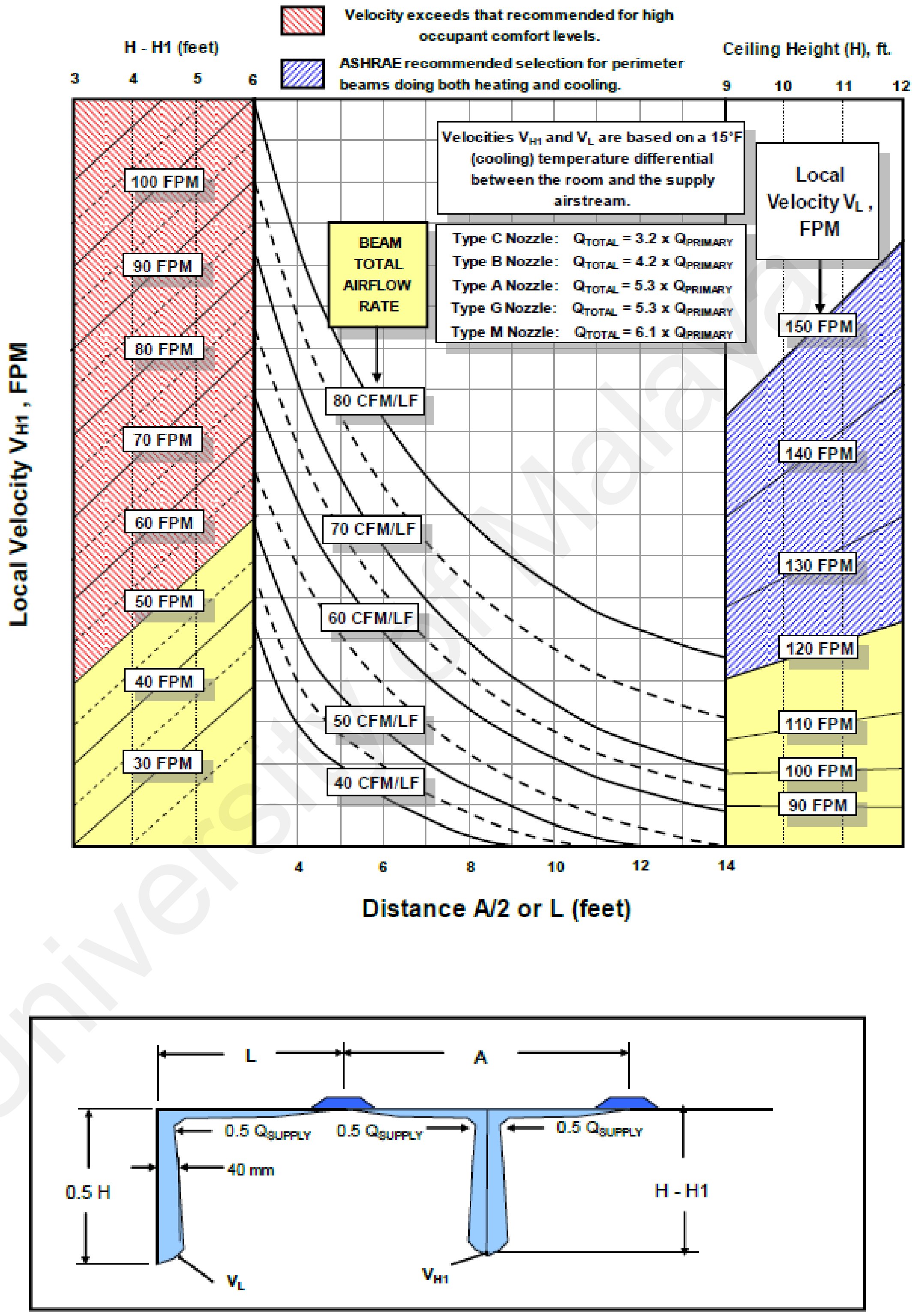


Figure 2.4 Psychrometric Relationship between Space and Primary Airflow [7]

As far as thermal comfort is concerned, beam placement should be optimized considering the air velocities. **Figure 2.5** shows the maximum occupied zone velocities in relation to the primary airflow rates and active chilled beam spacing. Assuming the ceiling height is 9 ft (2.74 m) and the distance L is set at 8 ft (2.44 m) the maximum airflow allowed is about 65 cfm/lf corresponding to the maximum local velocity, V_L of 120 fpm (0.61 m/s) and local velocity, V_{H1} of 30 fpm (0.15 m/s). As the distance increases, the maximum airflow allowed and local velocity increase as well. This consequently reduces the number of chilled beams required.



NOTES:

1) V_L values in chart are measured 6" from wall. Velocites 12" from wall will be 40% lower.

2) Selection and velocity recommendations are per 2007 ASHRAE Handbook (HVAC Applications) .

Figure 2.5 Relationship between Chilled Beams Placement, Airflow and Local Velocity [7]

2.2.1.2 Water side

The typical chilled water supply temperature to the air handlers or DOAS is 45 ^{o}F (7 ^{o}C). Whereas, the beam chilled water supply temperature ranges between 59 ^{o}F (15 ^{o}C) and 61 ^{o}F (16 ^{o}C) considering the space design condition and minimum ventilation rates. The space dewpoint temperature is about 51– 52 ^{o}F (10.5-11 ^{o}C) [8]. The air discharge temperature must be higher than the space dewpoint temperature to avoid condensation. There are two types of design configuration: the first one is where the chilled water supply for both the primary and secondary loop comes from the same source, or in other words, from the same chiller. However, this configuration requires a heat exchanger in the secondary loop to ensure the chilled water delivered is within the specified temperature range as to prevent condensation.

Another design configuration is the chilled water supply for the primary and secondary loops are not from the source where each loop has its own dedicated chiller serving the AHU and the beam respectively. In this case, heat exchanger is not required at the secondary side as the chilled water is directly supplied from the chiller itself where the chilled water will be set at higher temperature. This configuration is claimed to be more efficient in the sense that the chiller is designed based on higher supply temperature in which the energy consumed is lesser than chiller with low supply temperature. Besides, the temperature of the chilled water supply can be easily maintained at desired setpoint which makes the control easier for the prevention of condensation. **Figure 2.6** illustrates the chilled water schematics for system sharing the same chiller where a heat exchanger is used. The secondary loop consists of a pump, modulating valve and temperature sensor. The valve can be 2-way or 3-way depending on the pump type. If the pump is of constant speed, 3-way valve is used where a bypass is required to recirculate the water based on the supply temperature. If the pump is of variable speed, then 2-way valve is used where the pump speed will be adjusted accordingly when the valve is open/close.

Meanwhile, **Figure 2.7** shows the chilled water schematics for system with dedicated chiller. It consists of a pump, valve, storage vessel (expansion tank) and temperature sensor. The same thing for the valve where it can be 3-way or 2-way depending on the pump type (constant speed or variable speed). Storage vessel is required for the expansion of chilled water when the valve is close and during system shutdown when the chilled water becomes warm.

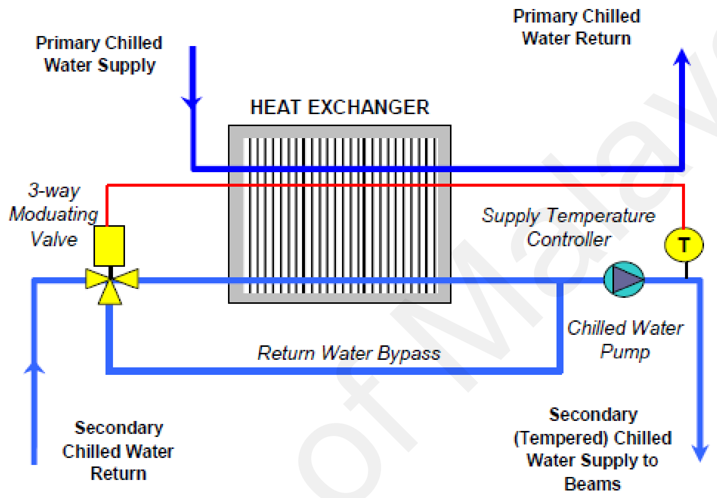


Figure 2.6 Schematics for System That Shares the Same Chiller [7]

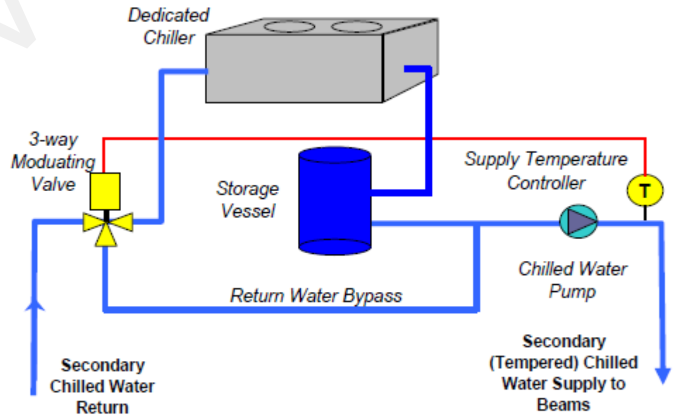


Figure 2.7 Schematics for System with Dedicated Chiller [7]

Condensation prevention strategy

Several methods to prevent condensation [7]:

1. Central monitoring and control
2. Zone monitoring with on/off control
3. Zone monitoring with modulating control

For **central monitoring and control**, the outdoor dew point temperature will be used to control the chilled water supply temperature. This method is used for applications where infiltration of outdoor air into the conditioned space is excessive. Another method is **zone monitoring with on/off control** where moisture sensors are used to control the zone on/off valve. The valve will be shut off until the moisture is evaporated. Meanwhile for **zone monitoring with modulating control**, temperature sensor and dew point sensor in the space will be used to modulate the zone chilled water supply temperature by recirculating the return water via a 3-way valve and a pump at the bypass line. Instead of using 3-way valve, another alternative is by using 2-way valve and a VSD pump.

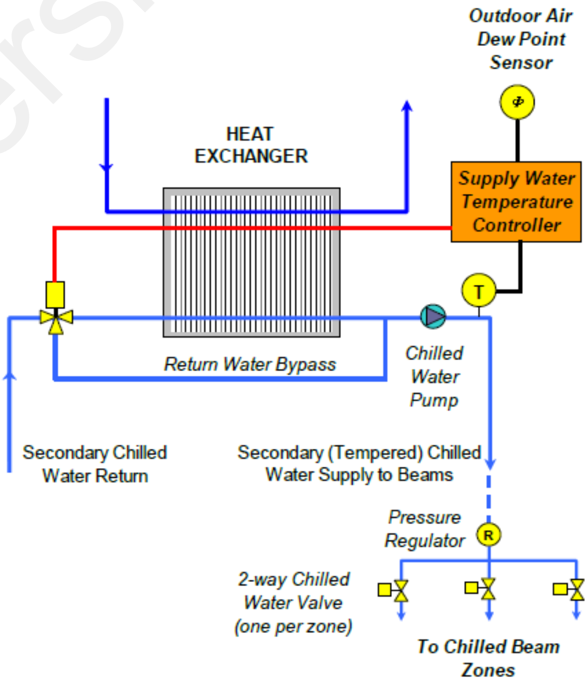


Figure 2.8 Chilled Water Temperature Reset based on Outdoor Air Dew Point [7]

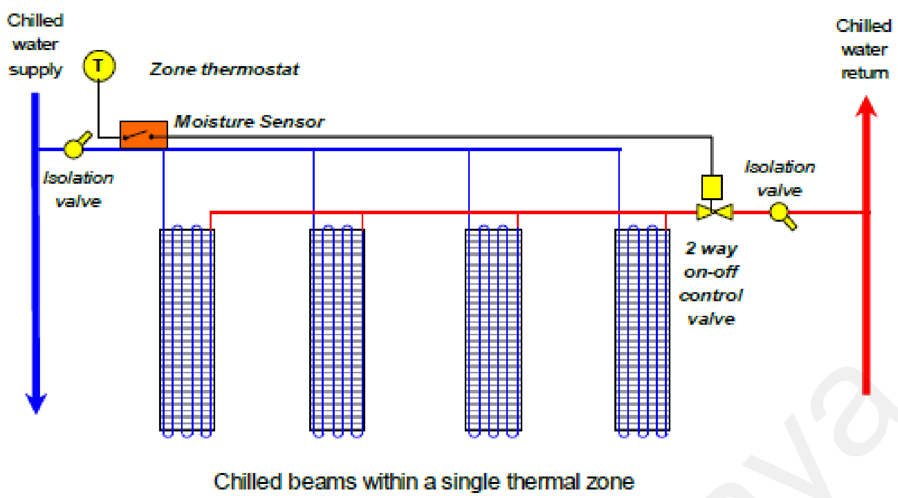


Figure 2.9 Zone Monitoring with On/off Control and Moisture Sensor [7]

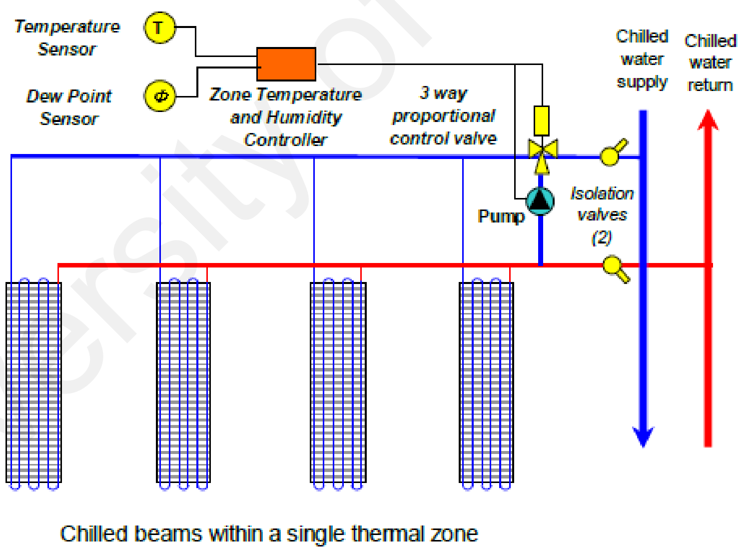


Figure 2.10 Zone Monitoring with Modulating Control [7]

2.2.2 Variable Air Volume (VAV)

VAV system is composed of multiple VAV boxes that control the air supply to respective zone by modulating the damper based on load demand. Temperature sensor or thermostat is used to determine the load demand where it will trigger the VAV damper to open/close and consequently the fan to ram up/down until the static pressure is maintained at its setpoint. The reheat coil is to ensure the supply air temperature is maintained at its setpoint during part load condition when the damper's position can no longer be adjusted as to meet the minimum ventilation rates [9].

There are two types of reheat: electric reheat and water reheat. Electric reheat uses electric element/coil to provide direct heating to the supply air whereas water reheat uses hot water from external source like boiler or cooling tower to heat the air passing through the coil. There are many different types of VAV controller depending on the brands. Each brand has its own control logic. **Figure 2.11** shows the example of system schematic of VAV controller with electric stages reheat. During cooling mode when the room temperature is above the cooling setpoint, the damper will open and the airflow will increase to maximum. Reheat will only take place during part load when the room temperature is below the heating setpoint. There are 3 stages of heating where the 1st stage will cut-in first, followed by 2nd stage and 3rd stage if the room temperature continues to fall at minimum constant airflow.

On the other hand, **Figure 2.12** shows the system schematic of VAV controller with modulating reheat. During cooling mode, the airflow will increase to maximum when the room temperature is above the cooling setpoint. However, during reheat mode, the heating takes place in such a way that the hot water supply is determined by the room temperature during part load. When the room temperature is lower than the heating setpoint, the valve will open to allow hot water to pass through the coil until the setpoint is met.

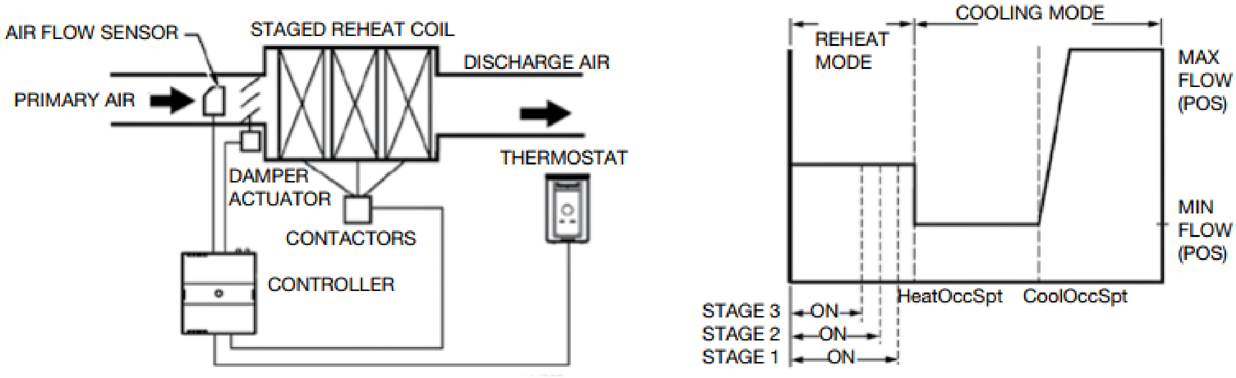


Figure 2.11 VAV Controller for Cooling with Electric Reheat [10]

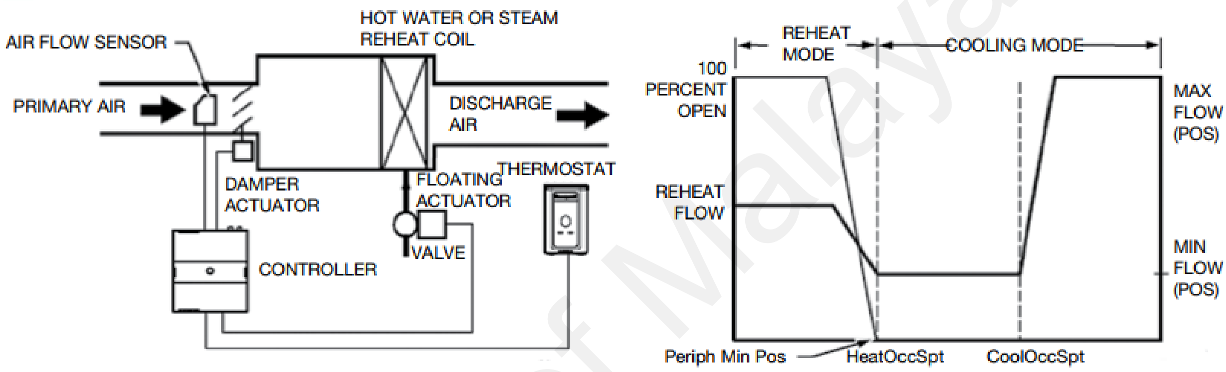


Figure 2.12 VAV Controller for Cooling with Modulating Reheat [10]

VAV system delivers a varying quantity of constant temperature air, typically between 45 ^{o}F and 55 ^{o}F dry-bulb temperature [11]. The load demand determines the airflow of the supply air required. **Figure 2.13** shows the processes of the system at different load conditions. For full load, the system is designed at peak outdoor air temperature that delivers 1,500 cfm of supply air, of which 450 cfm is outdoor air required for the space based on the maximum occupancy rate. Meanwhile, for part load, the system is designed at peak outdoor air dew point temperature that delivers a lower supply airflow due to reduced space sensible load in relation to solar load. In cases like rainy day, the supply airflow is further reduced as the outdoor air temperature is lower than usual. For all the conditions, the room air is maintained at 74 ^{o}F (23 ^{o}C) dry bulb and between 52% and 60% RH.

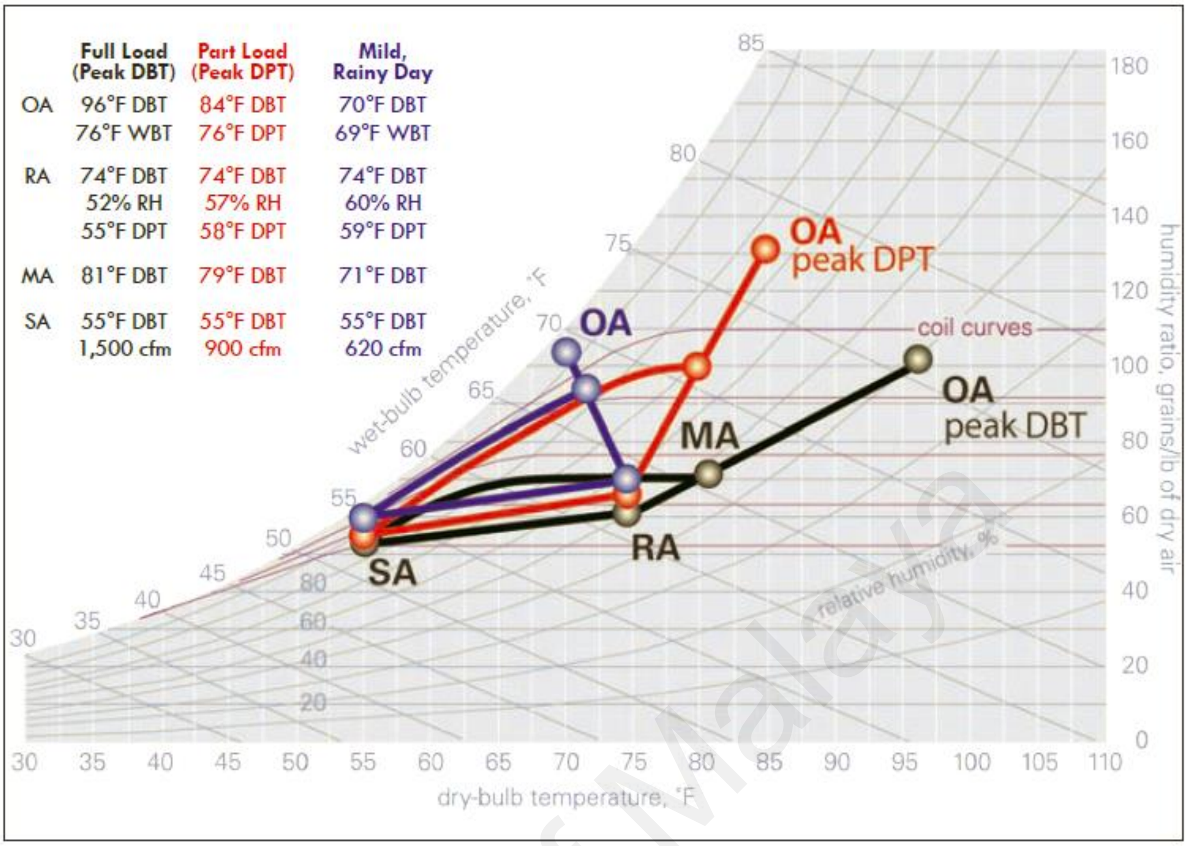


Figure 2.13 Cooling Processes of Basic VAV System [11]

2.2.2.1 Air side

Zoning and Thermostat

VAV system delivers air to conditioned space by zones where each zone has its own VAV box. The zoning is done based on the load characteristics and the function of the space. For example, office and conference room shall have separate zones as the load characteristic and function of the space are different. Unlike office, the occupancy load for conference room is not consistent and it only lasts for few hours. Temperature sensors or thermostats are used to determine the occupancy load which consequently modulate the VAV damper and the fan speed.

Demand Control Ventilation (DCV)

DCV controls ventilation air supply to the zone based on CO2 concentration and CO2 sensors are used to measure the CO2 concentration which indicates the number of occupants present in the zone. In response to the CO2 sensor, the outdoor ventilation air damper is adjusted accordingly to maintain the concentration within the setpoint.

At individual zone: During occupy mode, the CO2 concentration is maintained at 1000ppm based on the loop output (0 to 100%). Loop output refers to damper's position. From 0 to 50%, the minimum airflow setpoint is reset whereas from 50% to 100%, the minimum outdoor air is reset.

At the AHU: The minimum outdoor air setpoint is reset based on the highest zone CO2 loop signal between 50% and 100%.

Occupancy Controls

Occupancy sensors are used to detect a zone whether it's occupied or otherwise where the ventilation airflow is reduced to zero when there is no occupant. Typically, occupancy sensors are used in lighting system for the convenience of operation. Lights will be automatically switched off when people are not around. Technically, these sensors are motion sensors where they respond based on the motion surrounding. Using occupancy sensor alone is not enough as it only triggers the system to either switch on or switch off regardless of the occupancy load, whether it's high or low. The system is more efficient if motion sensors are used together with temperature sensors and CO2 sensors where the former will shut off the system when zero occupancy load and the latter will reduce the airflow when low occupancy load. Occupancy control can be either done separately for the aircon system itself or interlocked with lighting system.

2.3 Technical comparison

Several studies have been carried out by others comparing between VAV and ACB. According to the article written by Jeff Stein and Steven T. Taylor [12], VAV is proved to be more energy-saving and cost-saving compared to ACB. The comparison was done between three systems: ACB + DOAS, VAV Reheat and Hybrid based on a building located in US, The UC Davis Medical Center Graduate Studies Building (GSB), which consists of private offices, open offices and classroom/conference rooms.

Following are the design requirement used in the comparison analysis [13] [14] [15]:

1. For **Active Chilled Beam Design**, Dedicated Outdoor Air System (DOAS) is used to supply 100% outside air with average primary airflow rate of 0.6 cfm/ft2. The designed airflow is justified to be close to the minimum ventilation in high density spaces. The chilled water supply to the air handler and heat exchanger is 45 ^oF (7 ^oC) whereas to the chilled beam is 57 ^oF (14 ^oC). The primary air is maintained at 63 ^oF (17 ^oC).
2. For **VAV Reheat Design**, a single air handler is sized for 0.9 cfm/ft2 at load conditions. The VAV boxes for cooling-only have zero minimum flow rate and with reheat have minimum flow rates in the dead band between heating and cooling of 0.15 cfm/ft2. The supply air temperature varies from 55 ^oF (13 ^oC) to 65 ^oF (18 ^oC) depending on the zone room temperature.
3. For **Hybrid Design**, only 30% of the air-conditioned area uses hybrid VAV + ACB and 70% uses conventional VAV reheat. Reason being, the interior zones are low load zones where adding chilled beams doesn't bring significant impact to the reduction of primary airflow rates and conference rooms which have high peak ventilation rates require the CO2 controls. The air handler has designed airflow rate of 0.7 cfm/ft2 and supply air temperature of 55 ^oF (13 ^oC) to 65 ^oF (18 ^oC). Meanwhile, the chilled water supply to the air handler is 45 ^oF (7 ^oC) whereas to the chilled beam is 57 ^oF (14 ^oC).

From the simulation results, it shows that VAV reheat is the most efficient design followed by hybrid and ACB. Comparing to ACB, VAV reheat could save up to about 40% of energy used for HVAC application and hybrid is about 33%. as it uses 40% less energy than the ACB design whereas hybrid design uses 33% less. The savings for VAV reheat design is mainly contributed by the reduction of airflow rate during part load as the fan speed is equal to the cubic of fan power according to fan's law. When the fan speed is reduced, the fan power is reduced by the power of three. On top of that, the outdoor air intake is less for VAV reheat during part load and the minimum airflow rate is 0.15 cfm/ft2 (0.75 $l/s/m^2$) as compared to 0.6 cfm/ft2 (3 $l/s/m^2$) for ACB.

In terms of cost, again VAV reheat is the lowest ($ 25/ft2), followed by hybrid ($ 37/ft2) and ACB ($ 62/ft2). ACB has the highest cost largely due to high labor cost, high equipment cost and high material cost as it involves complicated control system and additional secondary chilled water system.

Meanwhile, benefits like higher floor-to-floor height and better indoor air quality for ACB system are proved to be overstated as the low airflow rate reduces the air velocity which results in the same or larger duct size used compared to VAV even though the airflow rate for VAV is higher since the air velocity used to size the duct is higher. In other words, the low velocity used to size the duct for ACB offset the space savings. In terms of indoor air quality, even though the outdoor air intake is higher for ACB, the possibility of condensation occurs at the secondary coil due to design fault or device failure could cause the growth of mold which consequently affects the indoor air quality.

Besides, number of shortcomings have been highlighted against ACB that include water leakage, tedious maintenance, restricted lighting fixture location, inflexibility of future tenant improvement and poor thermal comfort due to oversupply cooling.

On top of that, the cost of the system for ACB is comparatively higher than VAVR due to the system complexity and additional chilled water pipe.

However, TROX and Dadanco claimed that ACB provides better savings compared to VAV, disputing on the load conditions used by Jeff and Steven is not appropriate. To prove ACB is the better system in terms of energy saving and cost saving, TROX has done a detailed comparison between ACB and VAVR.

Comparison was done at three different operating conditions: space sensible and latent at 100%, space sensible at 75% & space latent at 90% and space sensible at 50% & space latent at 80%. Based on the load conditions used in ASHRAE's article, the total energy consumed by ACB is higher than VAVR especially during part load. This is because the design requirement used is different from each other, for example the supply air temperature and the amount of outdoor air intake.

However, applying the same load conditions shows that ACB system is comparatively more energy-saving than VAVR system especially during peak load (as shown in **Table 2.1 to Table 2.3**). Meanwhile, the cost for modified ACB system is significantly reduced to slightly closer to designed VAV system with only 22% higher as compared to designed ACB system with 150% higher than VAV (as shown in **Table 2.4**) .

Table 2.1 Comparison between Designed VAVR System, Designed ACB System and Modified ACB System at Full Load Condition

Load Conditions	**SAT**	**OA**	**RA**	**OA**	**AHU Cooling**	**Beam cooling**	**Fan**	**Pumps**	**Total Energy**	
(100% sensible & latent space loads)	**F**	**CFM**	**CFM**	**%**	**kW**	**kW**	**BHP**	**BHP**	**kW**	
VAVR system as described	55	8,475	41,525	17	49.9	0	45.6	5.5	88	
ACB system as described	63	30,000	0	100	40.5	23.5	26	8.7	89.9	Slightly higher
Modified ACB system										
Primary air @ 55 F DB, 53 F DP	55	16,667	0	100	28.7	24.4	4.5	7.6	62.1	30% less than VAVR
Mixing at air handling unit	55	8,475	8,192	51	21.6	24.4	4.5	6.8	54.5	38% less than VAVR

Table 2.2 Comparison between Designed VAVR System, Designed ACB System and Modified ACB System at Part Load Condition

Load Conditions	**SAT**	**OA**	**RA**	**OA**	**AHU Cooling**	**Beam cooling**	**Fan**	**Pumps**	**Total Energy**	
(75% sensible & 90% latent space loads)	**F**	**CFM**	**CFM**	**%**	**kW**	**kW**	**BHP**	**BHP**	**kW**	
VAVR system as described	55	8,475	29,025	23	26.6	0	26	2.9	48.2	
ACB system as described	63	30,000	0	100	40.2	14.3	26	7	79.2	64% more than VAVR
Modified ACB system										
Primary air @ 55 F DB, 53 F DP	55	16,667	0	100	28.5	15.3	4.5	5.9	51.5	6% more than VAVR
Mixing at air handling unit	55	8,475	8,192	51	10.3	15.3	4.5	3.9	31.8	34% less than VAVR

Table 2.3 Comparison between Designed VAVR System, Designed ACB System and Modified ACB System at Lowest Part Load Condition

Load Conditions	SAT	OA	RA	OA	AHU Cooling	Beam cooling	Fan	Pumps	Total Energy	
(50% sensible & 80% latent space loads)	**F**	**CFM**	**CFM**	**%**	**kW**	**kW**	**BHP**	**BHP**	**kW**	
VAVR system as described	55	8,475	16,125	34	13	0	6.6	2	19.4	
ACB system as described	63	30,000	0	100	15.6	5.1	26	1.4	41.2	112% higher than VAVR
Modified ACB system										
Primary air @ 55 F DB, 53 F DP	55	16,667	0	100	8.4	6.1	4.5	5.9	19.3	Similar
Mixing at air handling unit	55	16,667	0	100	8.4	6.1	4.5	3.9	19.3	

Table 2.4 Cost Comparison between Designed VAVR System, Designed ACB System and Modified ACB System

	VAVR system as designed		ACB system as designed		Modified ACB system
	Cost of Qty	**Cost/cfm**	**Cost or Qty**	**Cost/cfm**	**Cost or Qty**
Material cost ($)	215,179	4.3	576,496	19.22	320,282
Labor cost ($)	584,058	11.68	1,509,349	50.31	838,544
Equipment cost ($)	319,695	6.39	608,349	20.28	337,978
Subcontractors ($)	252,067	5.04	647,037	21.57	359,472
Lbs. of ductwork (lbs)	38,000		28,612		15,896
Chilled water piping (Lf)	310		10,244		5,691
Hot water piping (Lf)	2,085		9,630		5,350
Total HVAC cost ($)	1,370,999		3,341,231		1,856,277
HVAC cost ($/ft2)	**25**	**27**	**62**	**111**	**33**

On top of that, Dadanco highlighted the unusual design requirements used in the article where the primary airflow rate of 0.6 cfm/ft2 (3 l/s/m^2) used in the analysis is deemed to be unreasonably high, as compared to typical design with only 0.2 cfm/ft2 (0.97 l/s/ft^2) [16]. Based on the open plan office, only four 8ft long ACB's with 85 cfm are required to meet the load instead of twelve 8ft long ACB's. This requires total airflow rate of 340 cfm (0.2 cfm/ft2) for ACB as compared to 1,330 cfm (0.8 cfm/ft2) for VAVR at peak load. In other words, the system has been unnecessarily over-designed for ACB.

If 0.2 cfm/ft2 were used, even at part load condition (40%), the total airflow rate of ACB (340 cfm) is still lower than VAVR (532 cfm). In fact, it can be further reduced to as low as 120 cfm, the minimum ventilation rate required by using variable primary air volume.

Besides, Dadanco also mentioned that ACB has a proven record of safe operation without condensation occurring at the secondary coil and it can be achieved with minimal controls. Moreover, the velocity used to size the duct shall be made the same for both systems to ensure a fair comparison.

Summary

The fundamental principle, design considerations and control design in available literatures of VAV and ACB were covered in this chapter. Different design approach used by various authors and comparison between the two systems in terms of energy and cost were discussed. Appropriate load conditions will be used to ensure a fair comparison is made between the two systems.

CHAPTER 3. METHODOLOGY

3.1 Introduction

A detailed explanation on the cooling load calculation, the air distribution system design, chiller plant design and control system design for both variable air volume (VAV) and active chilled beam (ACB) are given in this chapter. Cooling load calculation is performed using Hourly Analysis Program (HAP) 4.90 by Carrier and air distribution system design is by using Excel Spreadsheet and TROX selection software. Since cooling load is the same for both systems, the calculation is done and presented for only once. For the air distribution system design, however, the approach is different from each other and thus a separate explanation on the design steps is made for respective system. Likewise, the control system is different for both systems and explanation is made separately. Duct sizing and pipe sizing are presented as well for both systems.

3.2 Cooling Load Calculation

3.2.1 Cooling Load Definition

Cooling load is defined by the rate at which energy is removed from a space by mechanical means in order to maintain the desired room temperature and humidity. It's often associated with heat gain where energy is transferred or generated within the space.

Heat gains generally can be divided into two components, sensible heat and latent heat. Following is the different forms of heat gains:

1. Solar radiations from external
2. Heat conduction and convection through roof
3. Heat conduction and convection through wall
   Heat conduction, convection and radiation through window
4. Heat generated from lighting fixtures

5. Heat generated from electrical devices or machineries
6. Heat generated from human bodies
7. Heat generated from infiltration

3.2.2 Cooling Load Calculation Method

Three methods can be used to calculate cooling load. These include:

1. Transfer Function Method (TFM)
2. CLTD/SCL/CLF Method
3. Radiant Time Series Method (RTSM)

Transfer Function Method (TFM) is a computer based method where it solves complicated heat transfer functions in predicting hourly cooling load. This method is widely used in the HVAC engineering community and in fact it's adopted by ASHRAE.

CLTD/SCL/CLF Method is a hand calculation method where it's based on tabulated results from transfer function method (TFM) in predicting hourly cooling load. CLTD refers to cooling load temperature difference where it is used to determine the heat gain of the wall and roof, SCL refers to solar cooling load where it is used to determine the solar gain through window and CLF refers to cooling load factors where it is used to determine the internal heat source. Compared to TFM, CLTD/SCL/CLF method has certain limitations and normally it's used for academic purpose. On top of that, the calculations process takes time.

Radiant Time Series Method (RTSM) is the latest method where it's well suited for both hand and computer use. In other words, it replaces both TFM and CLTD/SCL/CLF method. In this project, RTSM is used to determine the cooling load with the help of Hourly Analysis Program (HAP 4.90) by Carrier.

3.2.3 Hourly Analysis Program (HAP 4.90)

HAP is a computer tool for engineers to design HVAC system for buildings. It can be used to estimate cooling load, design system, simulate energy use and calculate energy costs. However, in this project, HAP is only used to estimate the cooling load. The design steps are as follows:

1. Key in the necessary data input:
2. Weather Data of the particular building site.
3. Space Data of the particular room space defined in the building:
    - General (Name, Floor Area, Ceiling Height, Building Weight and OA Ventilation Requirement)
    - Internals (Overhead Lighting, Task Lighting, Electrical Equipment, People and Misc. Load)
    - Walls, Windows, Doors (Exposure, Wall Gross Area, Window Quantity)
    - Roofs, Skylights (Roof Gross Area, Roof Slope and Skylight Quantity)
    - Infiltration (CFM/ACH)
    - Floors (Floor Type)
    - Partitions (Wall Partition/Ceiling Partition)
4. System Data
    - General (Name, Equipment Type and Air System Type)
    - System Components (Ventilation Air, Central Cooling, Supply Fan and etc.)
    - Zone Components (Space Assignment, Thermostats and Supply Terminals)
    - Sizing Data (System Sizing and Zone Sizing)
    - Equipment
5. Generate Design Results Report for each system defined. The report consists of the following details:
    - Air System Information

- Sizing Calculation Information
- Central Cooling Coil Sizing Data (Total coil load, Sensible coil load, Coil CFM and etc.)
- Supply Fan Sizing Data (Actual max CFM/ft2, Fan motor BHP, Fan motor kW and Fan static)
- Outdoor Ventilation Air Data (Design airflow CFM, CFM/ft2 and CFM/person)
- Total Zone Loads (Transmission, Lighting, People, Infiltration and etc.)
- Total System Loads (Plenum load, Fan load, Ventilation Load and etc.)

Tabulate the necessary information generated using excel spreadsheet. For VAV, both the zone load and system load are recorded but for ACB, only zone load is required.

3.2.4 Building Layout

In this project, a virtual building layout is used where it consists of total 13 floors including 2 sub-basements. Air-conditioning is provided from ground floor up to level 10 penthouse office. Since level 1 to 9 are typical floors, system layout for both VAV and ACB are designed based on three distinct floors: GF, L1-L9 and L10 as shown in **Figure 3.1, Figure 3.2** and **Figure 3.3** respectively.

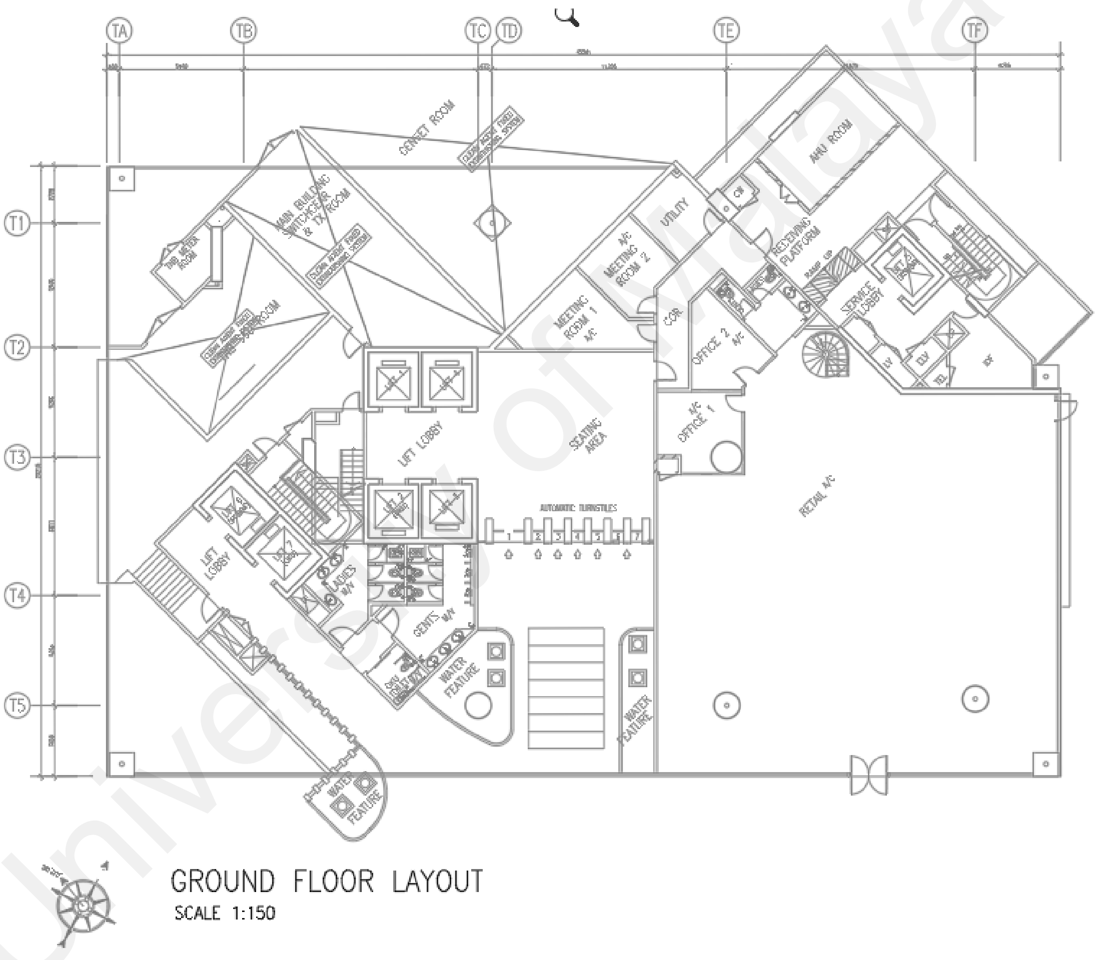


Figure 3.1 Ground Floor Layout

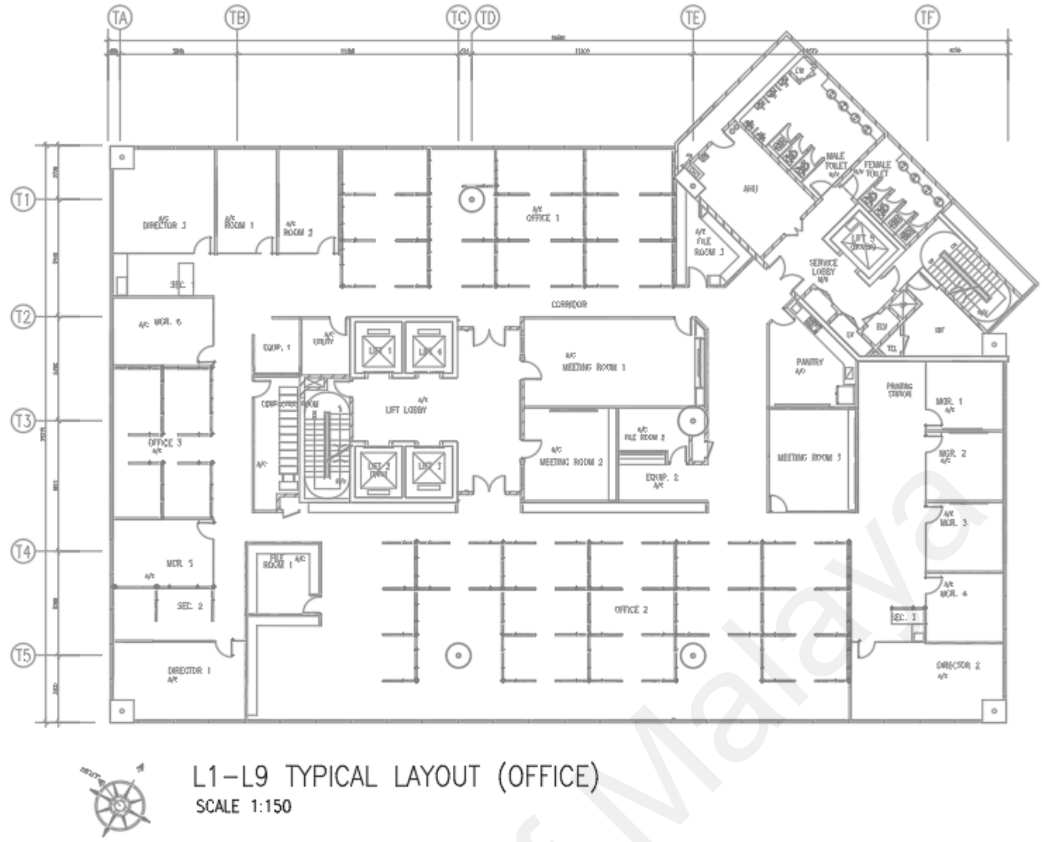


Figure 3.2 Level 1 to Level 9 Floor Layout

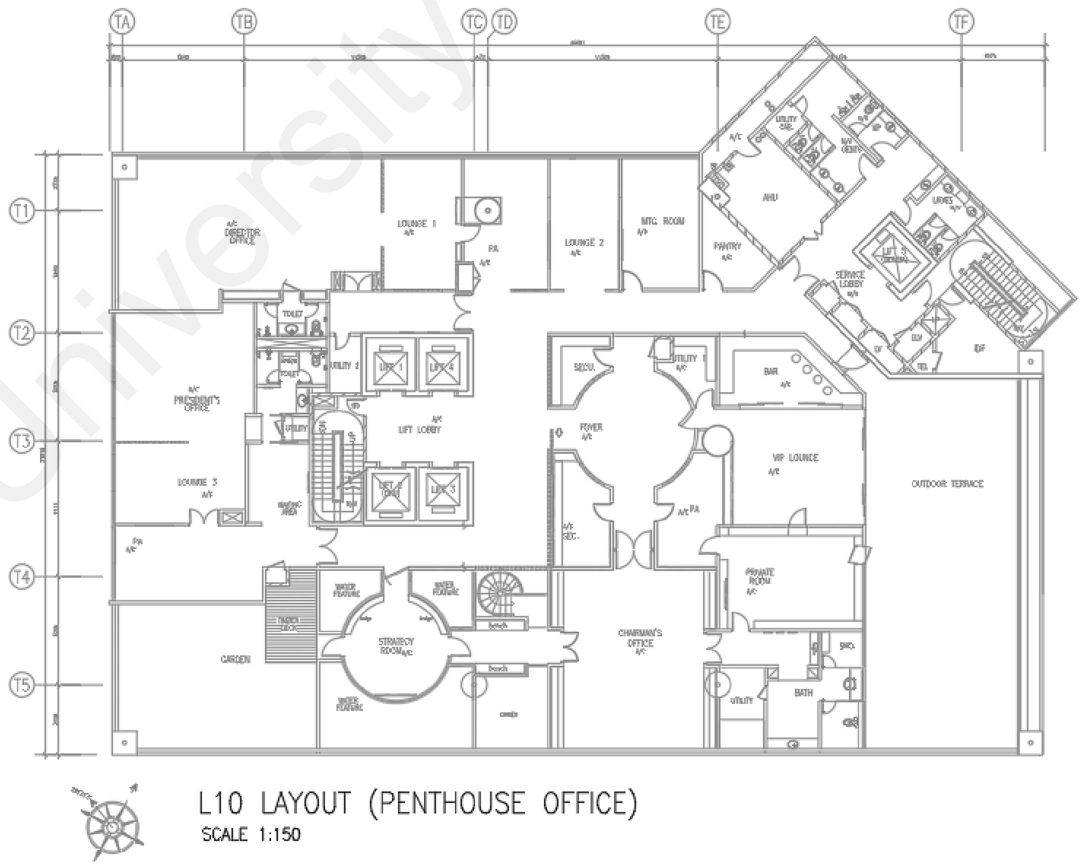


Figure 3.3 Level 10 Floor Layout

Assuming the building is located in the city of Kuala Lumpur, the indoor conditions and outdoor conditions are as shown in **Table 3.1.**

Table 3.1 Indoor & Outdoor Conditions

Indoor Conditions	Outdoor Conditions
Design Dry Bulb: 75 ºF (24 ºC)	Region: Asia/Pacific
Design Wet Bulb: 64 ºF (17.8 ºC)	Location: Malaysia
	City: Kuala Lumpur
	Latitude: 3.1º
	Longitude: -101.6º
	Elevation: 72 ft
	Design Dry Bulb: 95 ºF (35 º)
	Design Wet Bulb: 82 ºF (27.8 ºC)

3.2.5 Cooling Load Calculation Theory

The cooling load calculated in HAP 4.9 is based on transfer function method as follows:

$$Q_o = v_o q_o + v_1 q_1 + v_2 q_2 - w_1 Q_1 - w_2 Q_2$$

where **Q** is the load. The subscripts refer to specific points in time. **0** is the current hour, **1** is the previous hour and **2** is two hours before.

q is the heat gain. The subscripts **0, 1 and 2** refer to the same as of load.

v_0, v_1, v_2, w_1 **and** w_2 are transfer function coefficients. Values of these coefficients vary for each type of heat gain and room due to the different heat transfer processes involved in converting each type of heat gain into load. These coefficients can be obtained from ASHRAE's published journal.

This function is called room transfer function and it's used to determine different types of cooling load given that the heat gain and coefficients are known.

3.2.5.1 Wall and Roof Load

Wall and roof loads account for heat transferred through wall or roof due to solar radiation through the exterior surface and the temperature difference between indoor and outdoor air. The following equation is used to calculate the sol-air temperature:

$$T_{sa} = \mathbf{T_{oa}} \times \propto \mathbf{l/h_0} - \boldsymbol{\varepsilon}\Delta\mathbf{R/h_0}$$

where $\mathbf{T_{sa}}$ is sol-air temperature, F or C

$\mathbf{T_{oa}}$ is outdoor air dry-bulb temperature, F or C

$\boldsymbol{\alpha}$ is wall or roof exterior surface absorptivity for solar radiation

l is total solar flux on wall or roof surface, Btu/hr/hr/ft2 or W/m2

$\mathbf{h_0}$ is convective heat transfer coefficient on exterior wall or roof surface, 3 BTU/h-ft2-F or 17 W/m2-K

ε is emittance of exterior surface, 1

Δ**R** is difference between longwave radiation incident on exterior surface and blackbody radiation at T_{oa}, BTU/h-ft2 or W/m2. For vertical surfaces, ΔR = 0. For horizontal surfaces, ΔR = 20.

Wall and roof transmission loads involve special considerations on the heat gain calculation because of the delay between the heat gain occurs at the outer surface and the heat gain reaches to the interior surface of the wall or roof. Unlike others, for wall and roof transmission load, the heat gain is determined by other function called conduction transfer function and the following shows the conduction transfer function for the interior surface of wall.

$$\frac{q_o}{A} = \mathrm{b_o}t_{eo} + \mathrm{b_1}t_{e1} + \mathrm{b_2}t_{e2} + \mathrm{b_3}t_{e3} + \mathrm{b_4}t_{e4} + \mathrm{b_5}t_{e5} + \mathrm{b_6}t_{e6} - d_1q_1 - d_2q_2 - d_3q_3 - d_4q_4 - d_5q_5 - d_6q_6 - t_{rc}\sum C_n$$

Where **q** is the heat gain. The subscripts refer to specific points in time. **0** is the current hour, **1** is the previous hour and **2** is two hours before.

$\mathbf{t_e}$ is the sol-air temperature for the exterior surface of the wall.

b, d, and $\mathbf{c_n}$ are conduction transfer function coefficients. Values of these coefficients vary depending on the construction of the wall or roof.

$\mathbf{t_{rc}}$ is the indoor air temperature.

A is the exterior wall surface area.

Once the heat gain is known, the load is then determined using the Room Transfer Function Equation.

3.2.5.2 Window Transmission Load

Window transmission loads are the result of heat flow through windows due to the difference between indoor and outdoor temperature. The heat gain is calculated from the following equation:

$$q = \mathbf{U} \times \mathbf{A} \times (\mathbf{T_{oa}} - \mathbf{T_r})$$

where **q** is window transmission heat gain, BTU/h or W

U is overall window U-value, BTU/hr-ft2-F or W/m2-K

A is window area, ft2 or m2

$\mathbf{T_r}$ is room air temperature, F or C

T_{oa} is outdoor air temperature, F or C

H is average floor to ceiling height for space, ft

K is unit conversion factor (60 min/hr for English units m3/1000L for S.I. Metric units

3.2.5.3 Lighting Load

The heat gain is calculated from the following equation:

$$q = \mathbf{K} \times \mathbf{P} \times \mathbf{BM} \times \mathbf{Fs}/\mathbf{100}$$

where **q** is lighting heat gain, BTU/h or W

K is unit conversion factor (3.412 Btu/h / W for English unit or 1.0 for S.I. Metric unit)

P is lighting fixture power, W

BM is ballast multiplier, decimal

Fs is schedule percentage value, percent of maximum lighting watts for the hour

3.2.5.4 Electrical Equipment Load

The heat gain is calculated from the following equation:

$$q = \mathbf{K} \times \mathbf{P} \times \mathbf{Fs}/\mathbf{100}$$

where **q** is heat gain, BTU/h or W

K is unit conversion factor (3.412 Btu/h / W for English unit or 1.0 for S.I. Metric unit)

P is electrical equipment maximum power, W

Fs is schedule percentage value, percent of maximum power use

3.2.5.5 People Load

People loads are the result of sensible and latent heat gain from the occupants in a space. The latent component involves the transfer of moisture to room air and is thus converted to load directly. The sensible component however involves separate convective and radiative components and is evaluated using transfer function proceudres.

The sensible heat gain is calculated from the following equation:

$$q = \mathbf{HG} \times \mathbf{O} \times \mathbf{Fs/100}$$

where **q** is people heat gain, BTU/h or W

HG is unit heat gain, BTU/h/person or W/person

3.2.5.6 Infiltration Load

Infiltration loads are the result of uncontrolled leakage of air into the building. Infiltration airflow needs to be determine before getting the infiltration load. Following is the equation for infiltration airflow:

$$V_i = \mathbf{CFM/ft2} \times \mathbf{Area\ of\ Exterior\ Walls\ in\ Space}$$

$$V_i = \mathbf{ACH} \times \mathbf{A_f} \times \mathbf{H/K}$$

where $\mathbf{A_f}$ is floor area for space, ft2

H is average floor to ceiling height for space, ft

K is unit conversion factor (60 min/hr for English units m3/1000L for S.I. Metric units)

The infiltration load is calculated from the following equation:

$$Q_s = \boldsymbol{\rho}_\mathbf{a} \times \mathbf{C_{pa}} \times \mathbf{V_i} \times \mathbf{K}\ (\mathbf{T_{oa}} - \mathbf{T_r})$$

$$Q_l = \boldsymbol{\rho}_\mathbf{a} \times \mathbf{h_{fg}} \times \mathbf{V_i} \times \mathbf{K}\ (\boldsymbol{\omega}_\mathbf{oa} - \boldsymbol{\omega}_\mathbf{r})$$

where C_{pa} is heat capacity of air, 0.24 BTU/lbm-F or 1004.8 J/kg-K

ρ_a is density of air

Q_l is latent infiltration load, BTU/h or W

Q_s is sensible infiltration load, BTU/h or W

T_{oa} is outdoor air temperature, F or C

T_r is room temperature, F or C

h_{fg} is heat of vaporization of water, 1054.8 BTU/lbm or 2.4535 E+06 J/kg

ω_{oa} is outdoor air specific humidity, lb/lb or kg/kg

ω_r is room specific humidity, lb/lb or kg/kg

3.2.6 Example of cooling load calculation using HAP

1. Weather data is keyed in based on location of the building as shown in **Figure 3.4**. The following are the data input:
   - Region: Asia/Pacific
   - Location: Malaysia:
   - City: Kuala Lumpur
   - Latitude: 3.1 ^{o}
   - Longtitude: -101.6 ^{o}
   - Elevation: 72 ft
   - Dry Bulb Temperature: 95 ^{o}F
   - Wet Bulb Temperature: 82 ^{o}F

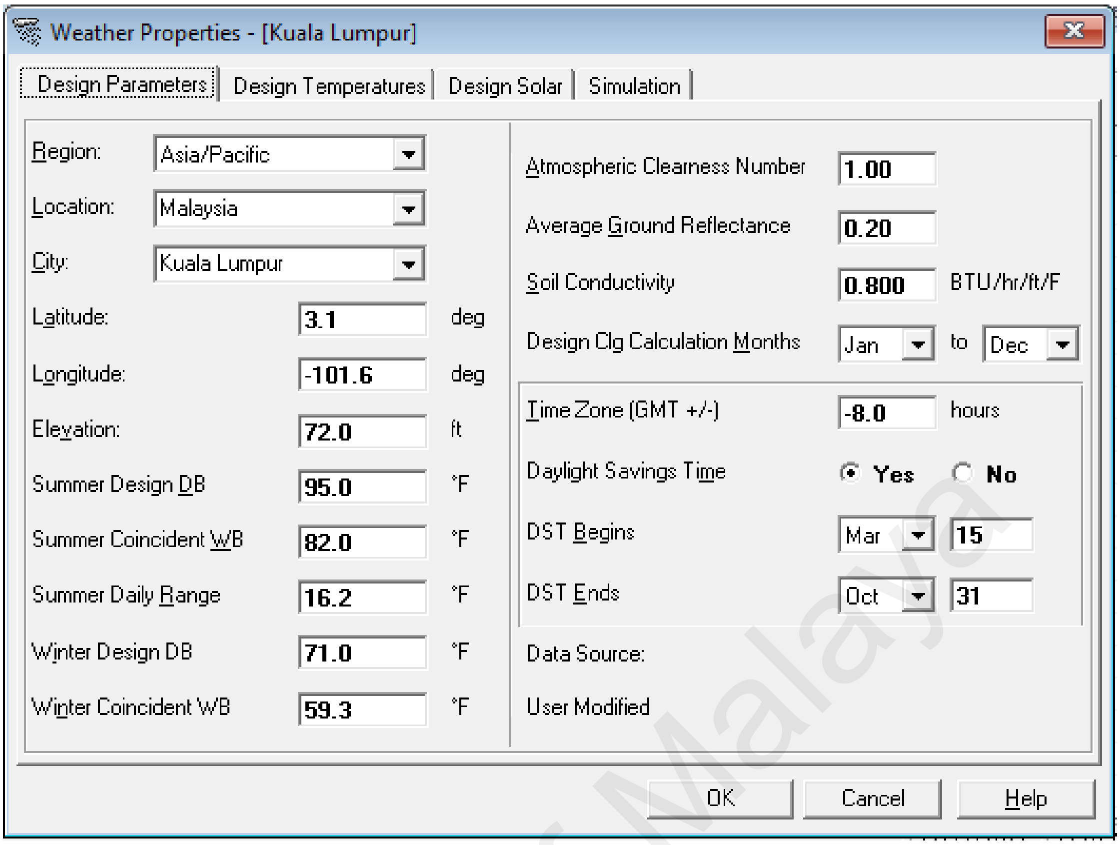


Figure 3.4 Weather Properties Tab in HAP

2. Space is defined by putting in appropriate inputs as shown in **Figure 3.5.**

<u>General</u>

- Name: Mgr 1
- Floor Area: 151 ft^2
- Avg Ceiling Height: 9 ft
- Building Weight: 70 lb/ft^2
- Outdoor Air Requirement:
  - Space Usage: Office
  - OA Requirement 1: 5 cfm/person
  - OA Requirement 2: 0.06 cfm/ft^2

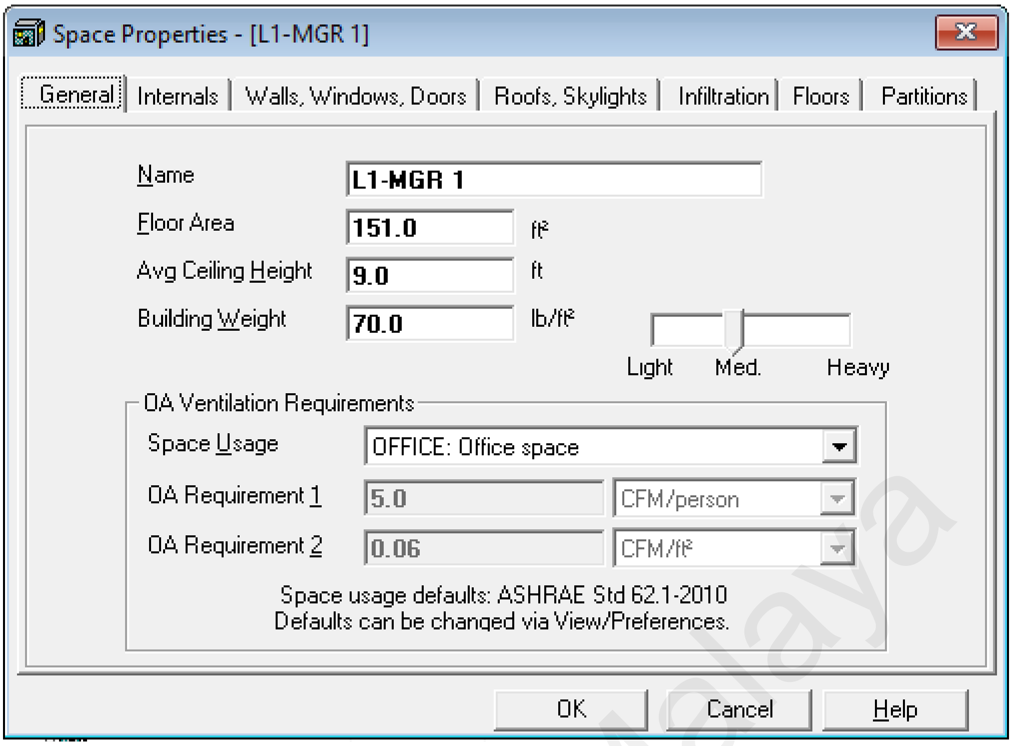


Figure 3.5 Space Properties [General]

<u>Internals</u>

- **Overhead Lighting**
  - Fixture Type: Recessed, unvented
  - Wattage: 2.00 W/ft^2
  - Ballast Multiplier: 1.00
  - Schedule: 90.1 Office Lights/Elec
- **Task Lighting**
  - Wattage: 1.00 W/ft^2
  - Schedule: 90.1 Office Lights/Elec
- **People**
  - Occupancy: 200 ft^2/person
  - Activity Level: Office Work
  - Sensible: 245 BTU/hr/person
  - Latent: 205 BTU/hr/person
  - Schedule: 90.1 Office Occupancy

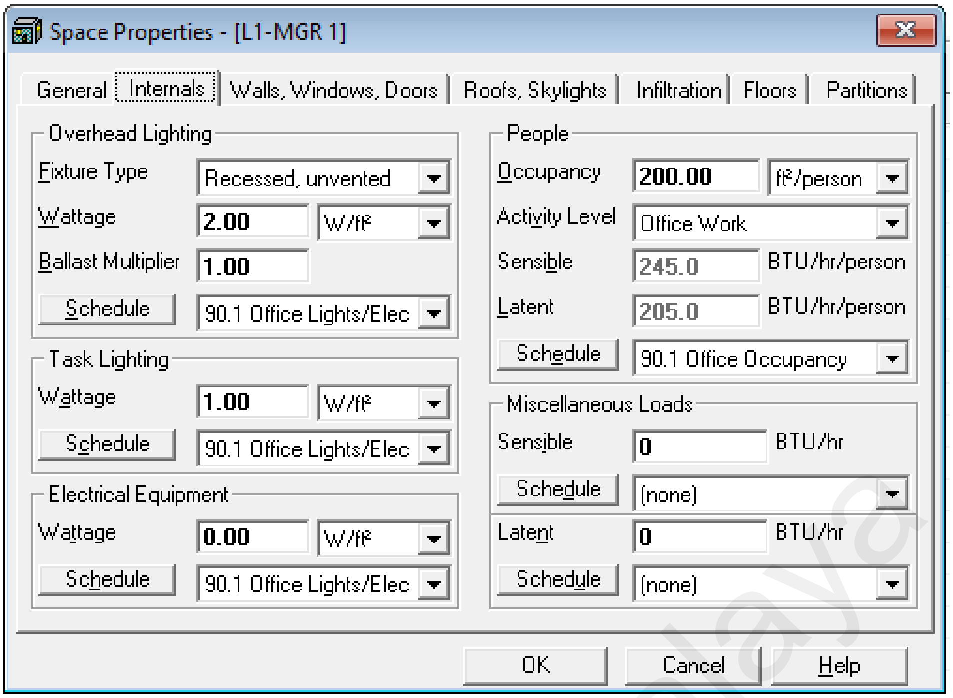


Figure 3.6 Space Properties [Internals]

Walls, Window, Doors

Based on the compass direction shown in the layout, the exposure to sunlight for Mgr 1 is determined as North East. The wall gross area is calculated from the ceiling height and and wall length. The window quantity is determined by using 0.9 window-to-wall ratio.

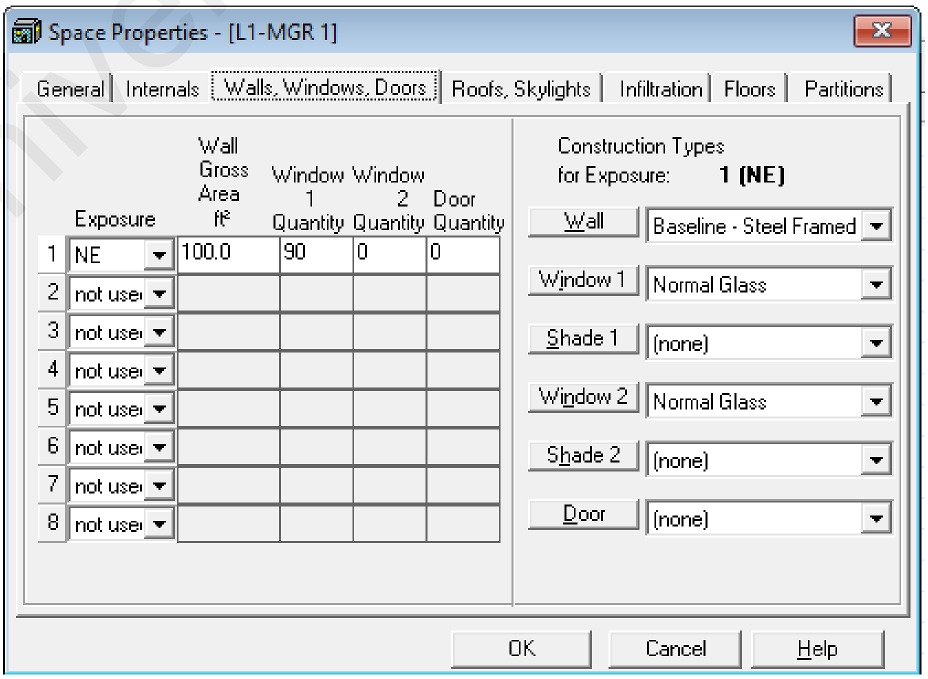


Figure 3.7 Space Properties [Walls, Windows, Doors]

Roof, Skylights

Mgr 1 is located at middle floors: Level 1 to Level 9, thus roof and skylight properties are not required. Only top most floor where roof and skylight are involved.

Infiltration

The minimum air filtration rate is set at 0.05 ACH at all hours.

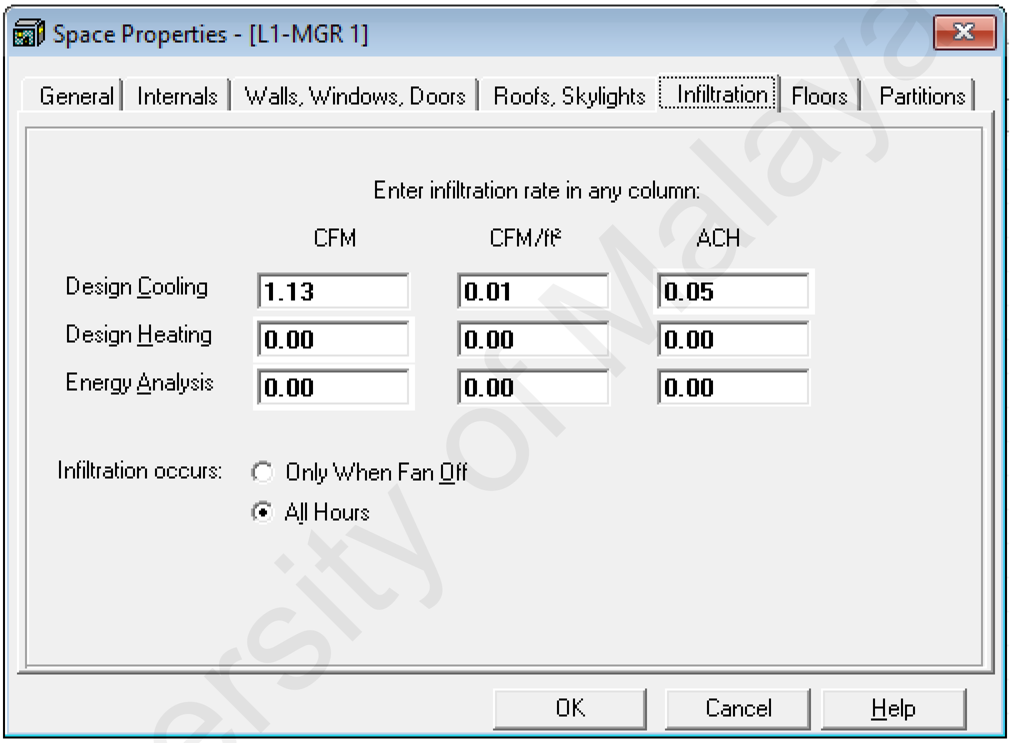


Figure 3.8 Space Properties [Infiltration]

Floors

The floor type is above conditioned space. Except ground floor, all the floors above are above conditioned space.

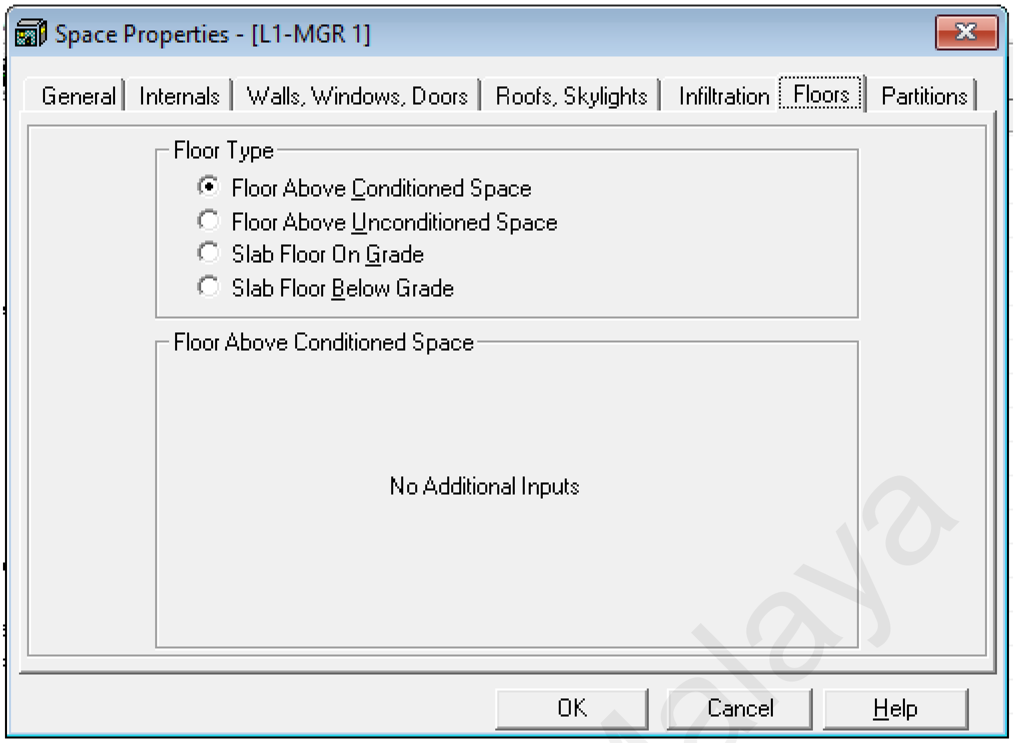


Figure 3.9 Space Properties [Floors]

Partitions

Partitions are not defined since the space surrounding the meeting room is air-conditioned.

Design report is generated once the air system properties are defined. Refer to the table highlighted in red.

	DESIGN COOLING			DESIGN HEATING		
	COOLING DATA AT Jun 1200 COOLING OA DB / WB 87.7 °F / 80.5 °F			HEATING DATA AT DES HTG HEATING OA DB / WB 71.0 °F / 59.3 °F		
ZONE LOADS	Details	Sensible (BTU/hr)	Latent (BTU/hr)	Details	Sensible (BTU/hr)	Latent (BTU/hr)
Window & Skylight Solar Loads	90 ft²	4445	-	90 ft²	-	-
Wall Transmission	10 ft²	18	-	10 ft²	0	-
Roof Transmission	0 ft²	0	-	0 ft²	0	-
Window Transmission	90 ft²	975	-	90 ft²	0	-
Skylight Transmission	0 ft²	0	-	0 ft²	0	-
Door Loads	0 ft²	0	-	0 ft²	0	-
Floor Transmission	0 ft²	0	-	0 ft²	0	-
Partitions	0 ft²	0	-	0 ft²	0	-
Ceiling	0 ft²	0	-	0 ft²	0	-
Overhead Lighting	272 W	825	-	0	0	-
Task Lighting	136 W	435	-	0	0	-
Electric Equipment	0 W	0	-	0	0	-
People	1	134	139	0	0	0
Infiltration	-	15	71	-	0	0
Miscellaneous	-	0	0	-	0	0
Safety Factor	10% / 10%	685	21	0%	0	0
>> Total Zone Loads	-	7532	231	-	0	0
Zone Conditioning	-	7597	231	-	-91	0
Plenum Wall Load	0%	0	-	0	0	-
Plenum Roof Load	0%	0	-	0	0	-
Plenum Lighting Load	0%	0	-	0	0	-
Return Fan Load	302 CFM	0	-	19 CFM	0	-
Ventilation Load	11 CFM	140	721	16 CFM	-35	-32
Supply Fan Load	302 CFM	251	-	19 CFM	-20	-
Space Fan Coil Fans	-	0	-	-	0	-
Duct Heat Gain / Loss	0%	0	-	0%	0	-
>> Total System Loads	-	7987	952	-	-146	-32
Central Cooling Coil	-	7987	952	-	-380	-32
Preheat Coil	-	0	-	-	0	-
Terminal Reheat Coils	-	0	-	-	234	-
>> Total Conditioning	-	7987	952	-	-146	-32
Key:	Positive values are clg loads Negative values are htg loads			Positive values are htg loads Negative values are clg loads		

Figure 3.10 Design Report [Cooling Load]

3.3 Air Distribution System Design

The design of air distribution system involves the sizing of cooling coil and AHU fan. The design approach is different for both systems where ACB is rather complicated compared to VAV as it involves more specific design considerations. These include:

1. Room latent load must not be too high

Due to limitation on the air flow rate of ACB (as high flow rate causes high pressure drop), part of the latent capacity of AHU is compromised. Technically, ACB only caters for the room sensible load and the room latent load is by AHU. Because the air flow is determined by the chilled beam, the latent capacity of AHU has been restricted and for this reason, room latent load is always the first consideration to be looked at when deciding whether to use ACB for that particular space. Spaces like restaurant where the latent load is high is not suitable for the use of ACB system.

2. CHWS temperature at the secondary coil must not less than room dew point temperature

Condensation is always the main problem faced by engineer when designing ACB system. It happens when the coil surface temperature is lower than the room dew point temperature. To avoid condensation, devices monitoring the room dew point and controlling the CHWS are put in place, integrated with a complete control system.

3. Adequate ceiling space for the placement of chilled beam

Not all the spaces have large ceiling space to fit in a 1.5m long and 0.593m wide chilled beam with a gap of 2m from the wall and 3m between two beams. Spaces with limited ceiling space have no choice but to use normal air diffusers instead of chilled beam. This in fact is one of the disadvantages of chilled beam system.

3.3.1 System Sizing

3.3.1.1 Variable Air Volume (VAV) system

The sizing of coiling coil and AHU fan for VAV system is somehow similar to Constant Air Volume (CAV) where it takes into account of the space cooling load, ventilation load and fan load. The difference is the varying fan speed in response to the varying load demand. In other words, VAV is more energy efficient compared to CAV as the air flow is based on the load demand.

The design sequence is as follows:

1. Cooling load is calculated for every conditioned space using HAP.
2. Air system is defined for every individual space in HAP.
3. Design report is then generated from HAP.
4. AHU capacity is calculated from the total system capacity of every individual space.
5. Zoning of space is done based on space function using VAV box. The capacity of VAV box is determined by the total airflow required for particular zone.

3.3.1.2 Example of system sizing for VAV

1. **Cooling load is calculated for every conditioned space using HAP.**

   Cooling load is calculated by defining the space with appropriate inputs as shown in the earlier part. The room sensible and latent load obtained for Mgr 1 are **7,532 Btu/hr and 231 Btu/hr** respectively.

2. **Air system is defined for every individual space in HAP.**

<u>General</u>

System is defined by the equipment type, air system type and number of zones as illustrated in **Figure 3.11**:

- Equipment Type: Chilled Water Air Handling Units
- Air System Type: VAV
- Number of Zones: 1

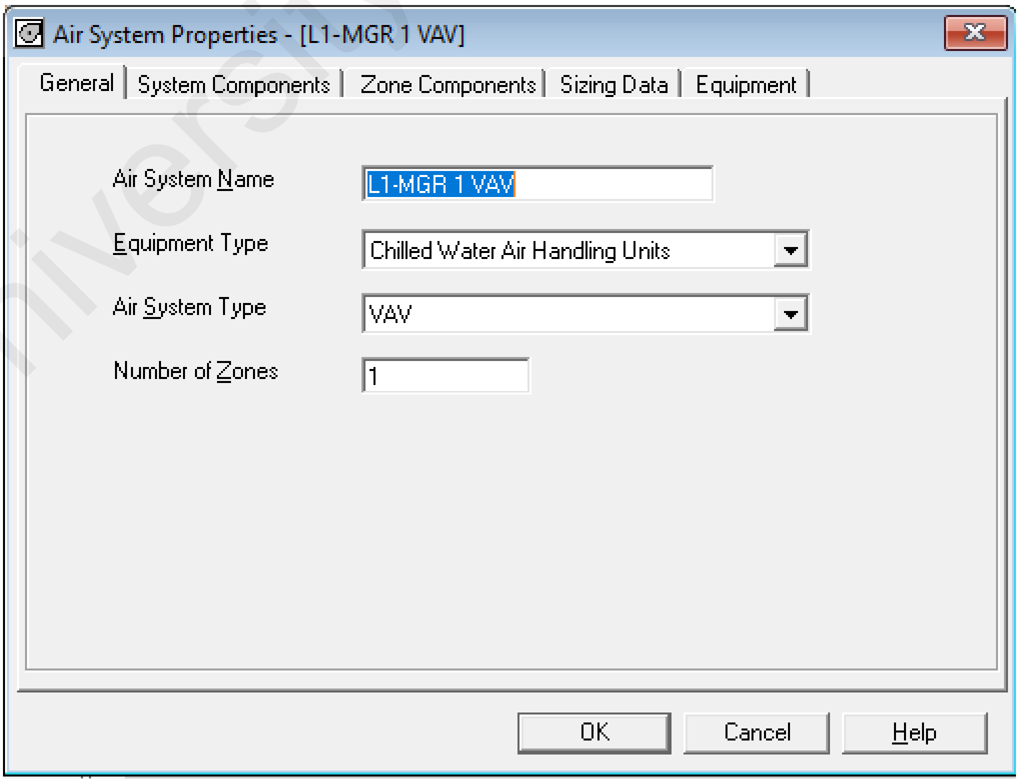


Figure 3.11 Air System Properties [General]

System Components

Ventilation air is defined by the following parameters as illustrated in **Figure 3.12**:

- Airflow Control: Demand Controlled Ventilation
- Ventilation Sizing Method: ASHRAE Std 62.1-2010
- Base Ventilation Rate:20%
- Unoccupied Damper Position: Closed
- Damper Leak Rate: 5%
- Minimum CO2 Differential: 100ppm
- Maximum CO2 Differential: 700ppm
- Outdoor Air CO2 Level: 400ppm

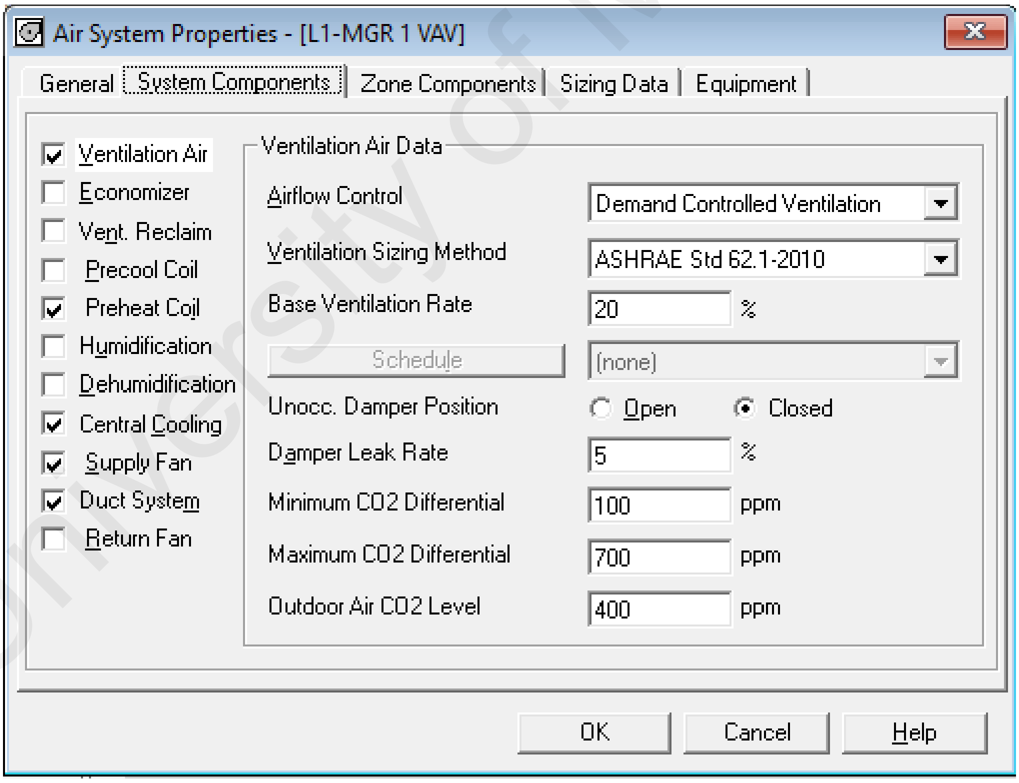


Figure 3.12 Air System Properties [System Components-Ventilation Air]

Central cooling is defined by the following parameters as illustrated in **Figure 3.13**:

- Supply Temperature: 53 ^{o}F (12 ^{o}C)
- Coil Bypass Factor: 0.1
- Cooling Source: Chilled Water
- Capacity Control: Constant Temp, Fan On

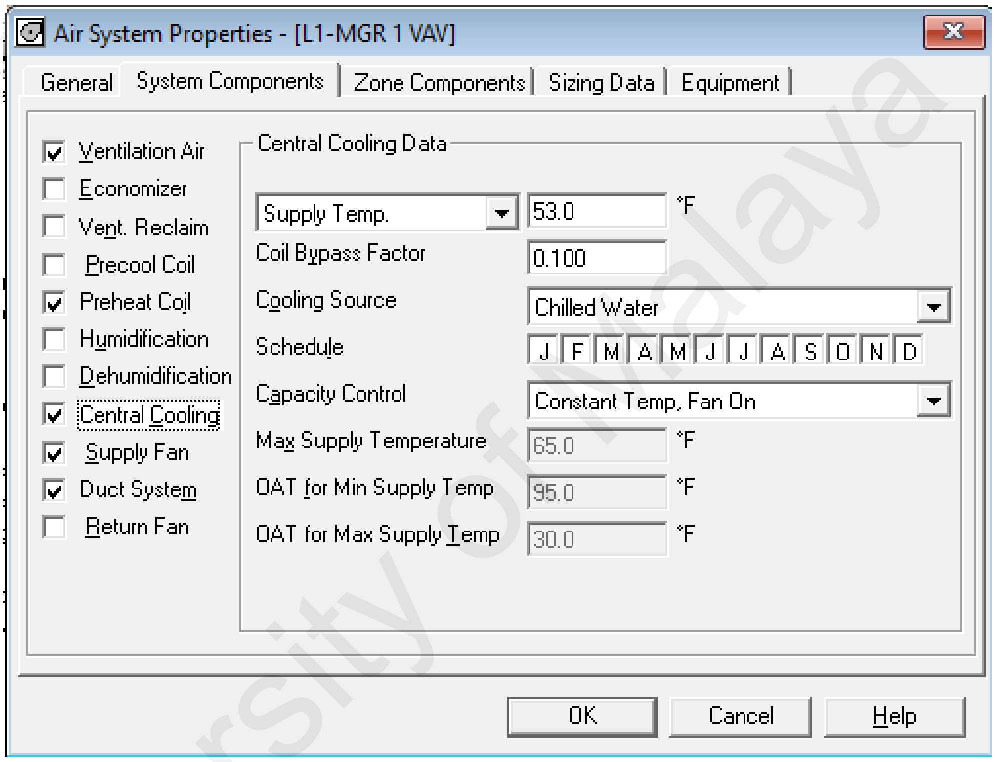


Figure 3.13 Air System Properties [System Components-Central Cooling]

Supply Fan is defined by the following parameters as illustrated in **Figure 3.14**:

- Fan Type: Forward Curve with Variable Frequency Drive
- Configuration: Draw-Thru
- Total Static: 1.50 in. wg.
- Overall Efficiency: 65%

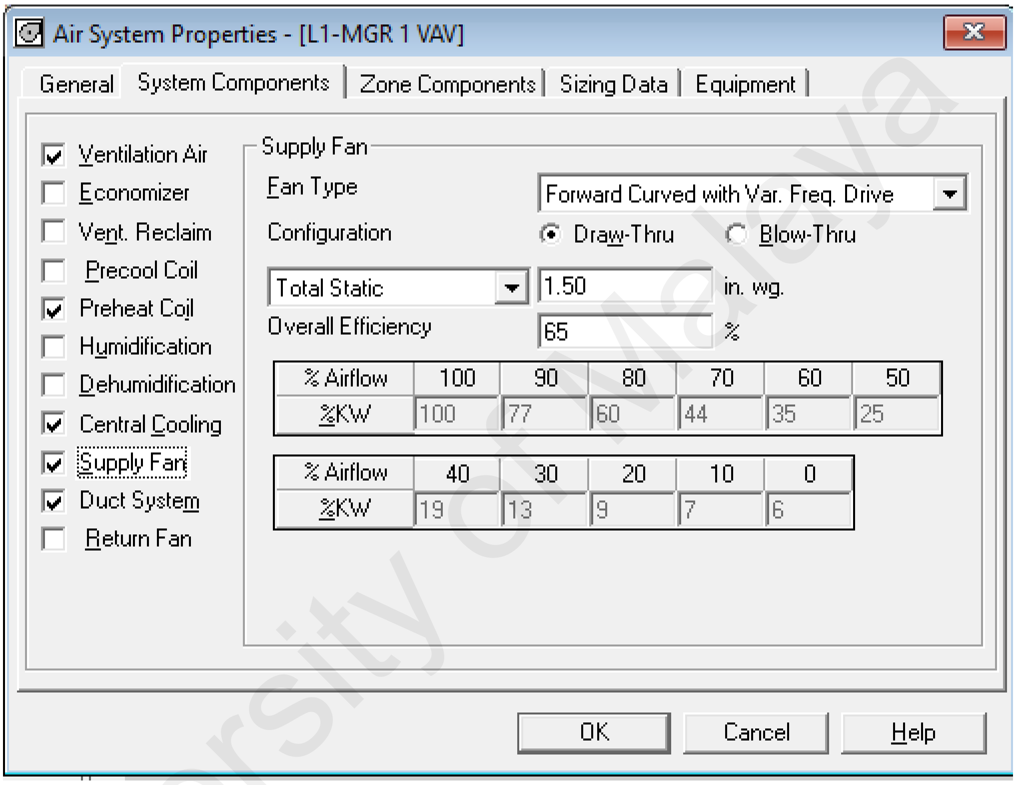


Figure 3.14 Air System Properties [System Components-Supply System]

Zone Components

Space is assigned to a particular system defined. Multiple spaces can be added to one system. However, to be more accurate so that more details are given, each system is assigned with one space as shown in **Figure 3.15.**

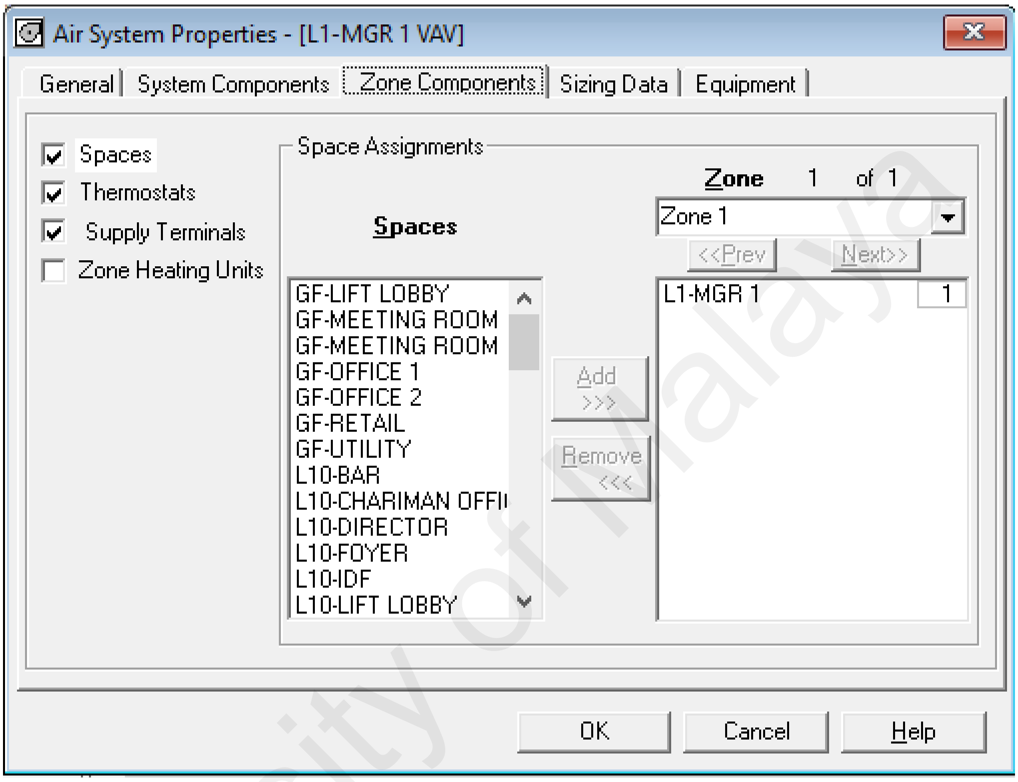


Figure 3.15 Air System Properties [Zone Components-Spaces]

Thermostats is defined by the following parameters as shown in **Figure 3.16**:

- Cooling T-sat setpoints: occupied – 75 °F unoccupied – 80 °F
- T-sat Throttling Range: 1.5 °F
- Diversity Factor: 90%
- Thermostat Schedule: Office
- Thermostat Schedule: 90.1 Office Template

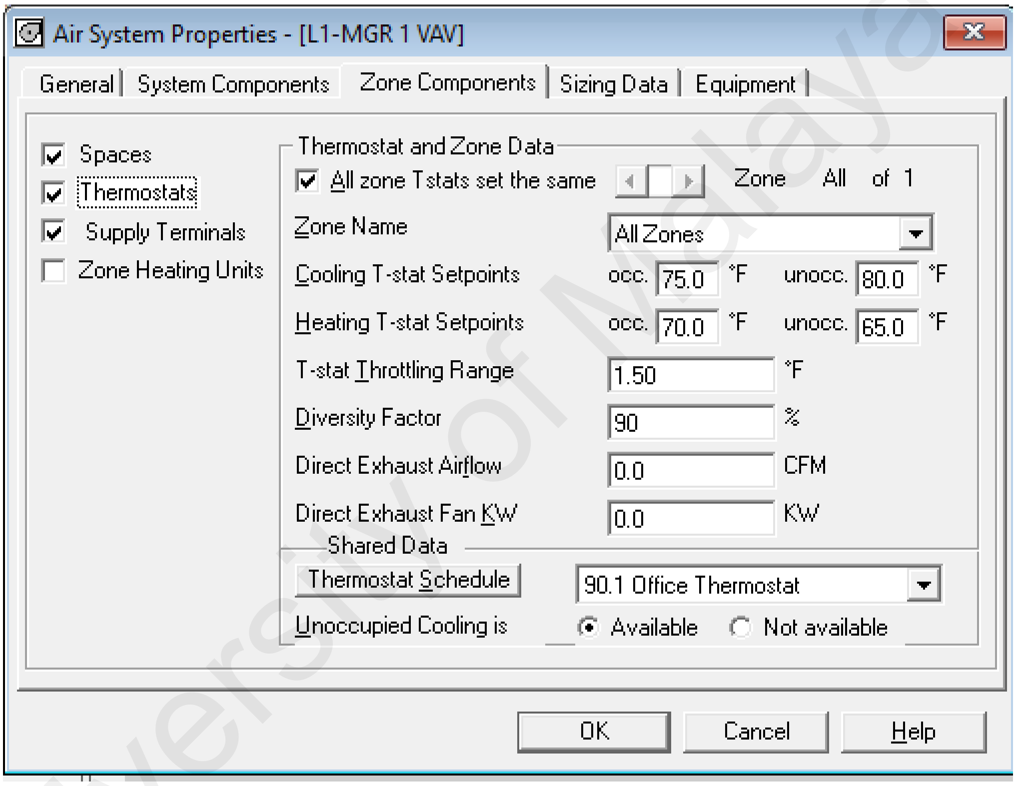


Figure 3.16 Air System Properties [Zone Components-Thermostats]

Supply Terminals are defined with the following inputs as shown in **Figure 3.17**:

- Zone: All Zones
- Terminal Type: VAV box with Reheat
- Minimum Airflow: 25 cfm/person

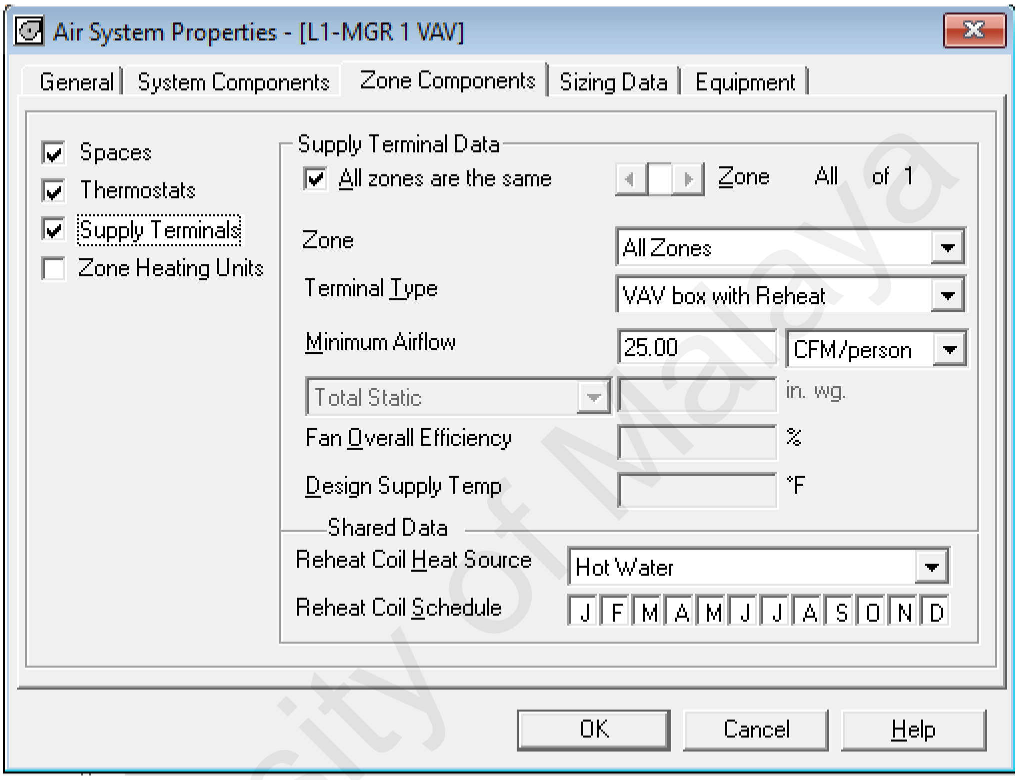


Figure 3.17 Air System Properties [Zone Components-Supply Terminals]

Sizing Data

System sizing data is based on computer-generated inputs and the chilled water delta T is determined by the difference between chilled water return temperature, 54 °F (12 °C) and chilled water supply temperature, 44 °F (6.7 °C), which is 10 °F (5.3 °C). Refer to **Figure 3.18.**

Equipment

Equipment properties is not required.

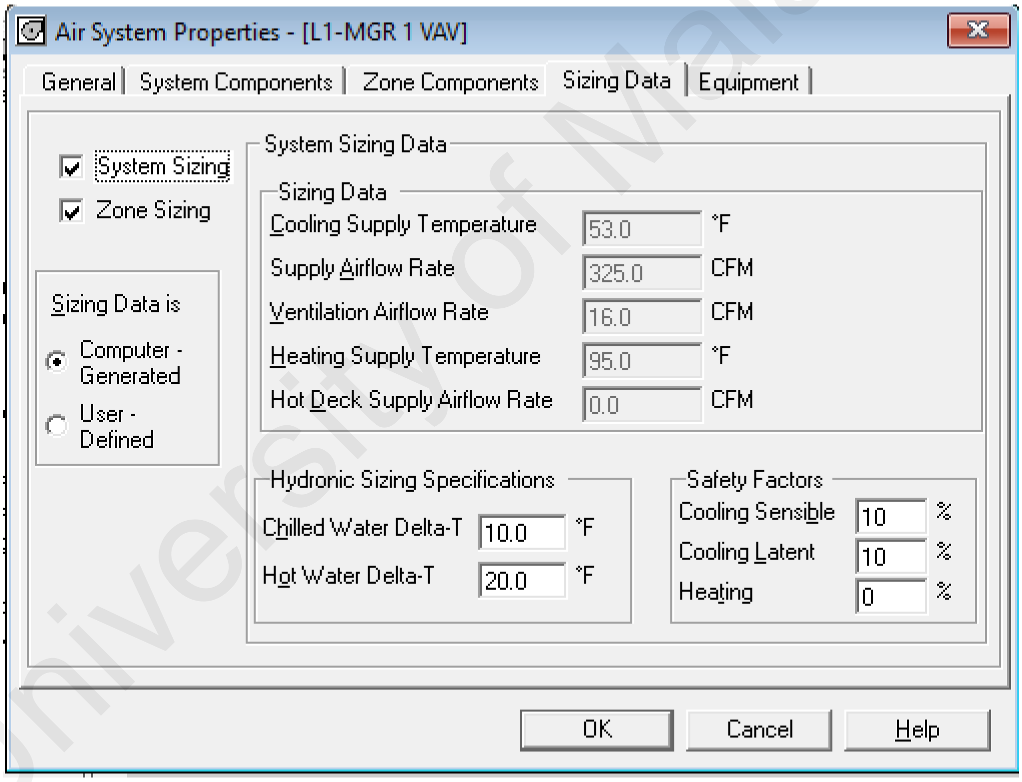


Figure 3.18 Air System Properties [System Sizing]

3. Design report is then generated from HAP.

The report of the design results is generated for each individual system defined for each individual space as shown in **Figure 3.19**. From the report, the system is sized based on the total system loads required under the column of design cooling as shown in **Figure 3.20.** The system capacity obtained for Mgr 1 is **7,987 Btu/hr sensible** and **952 Btu/hr latent**.

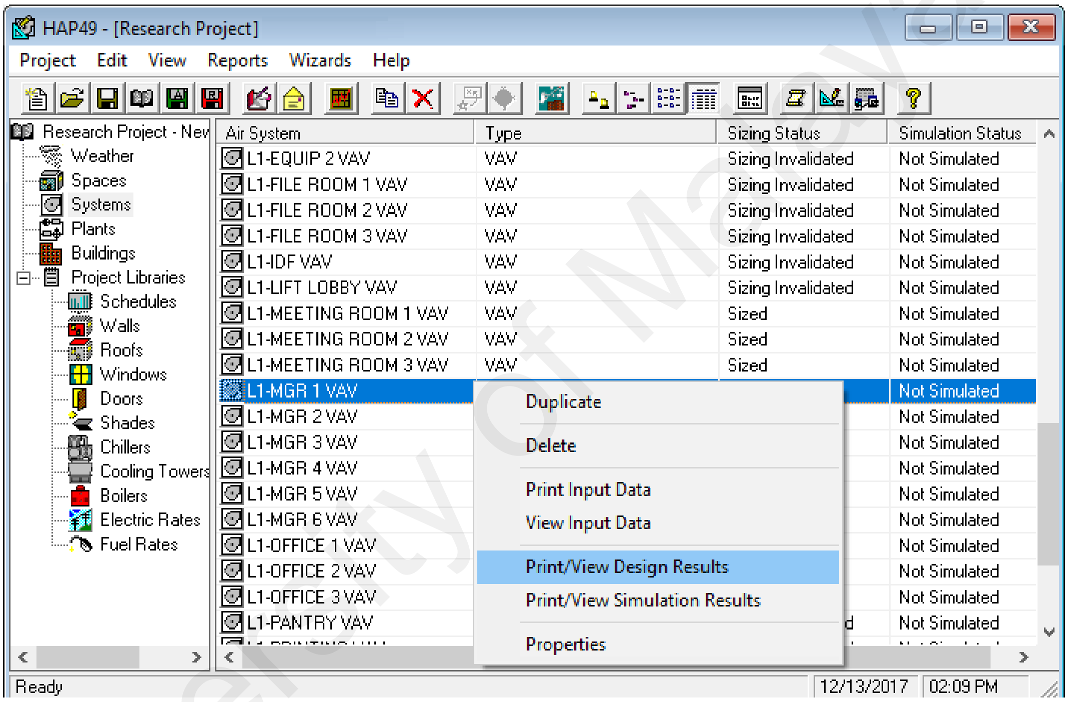


Figure 3.19 Generate Design Results

	DESIGN COOLING			DESIGN HEATING		
	COOLING DATA AT Jun 1200 COOLING OA DB / WB 87.7 °F / 80.5 °F			HEATING DATA AT DES HTG HEATING OA DB / WB 71.0 °F / 59.3 °F		
ZONE LOADS	Details	Sensible (BTU/hr)	Latent (BTU/hr)	Details	Sensible (BTU/hr)	Latent (BTU/hr)
Window & Skylight Solar Loads	90 ft²	4445	-	90 ft²	-	-
Wall Transmission	10 ft²	18	-	10 ft²	0	-
Roof Transmission	0 ft²	0	-	0 ft²	0	-
Window Transmission	90 ft²	975	-	90 ft²	0	-
Skylight Transmission	0 ft²	0	-	0 ft²	0	-
Door Loads	0 ft²	0	-	0 ft²	0	-
Floor Transmission	0 ft²	0	-	0 ft²	0	-
Partitions	0 ft²	0	-	0 ft²	0	-
Ceiling	0 ft²	0	-	0 ft²	0	-
Overhead Lighting	272 W	825	-	0	0	-
Task Lighting	136 W	435	-	0	0	-
Electric Equipment	0 W	0	-	0	0	-
People	1	134	139	0	0	0
Infiltration	-	15	71	-	0	0
Miscellaneous	-	0	0	-	0	0
Safety Factor	10% / 10%	685	21	0%	0	0
>> Total Zone Loads	-	7532	231	-	0	0
Zone Conditioning	-	7597	231	-	-91	0
Plenum Wall Load	0%	0	-	0	0	-
Plenum Roof Load	0%	0	-	0	0	-
Plenum Lighting Load	0%	0	-	0	0	-
Return Fan Load	302 CFM	0	-	19 CFM	0	-
Ventilation Load	11 CFM	140	721	16 CFM	-35	-32
Supply Fan Load	302 CFM	251	-	19 CFM	-20	-
Space Fan Coil Fans	-	0	-	-	0	-
Duct Heat Gain / Loss	0%	0	-	0%	0	-
>> Total System Loads	-	7987	952	-	-146	-32
Central Cooling Coil	-	7987	952	-	-380	-32
Preheat Coil	-	0	-	-	0	-
Terminal Reheat Coils	-	0	-	-	234	-
>> Total Conditioning	-	7987	952	-	-146	-32
Key:	Positive values are clg loads Negative values are htg loads			Positive values are htg loads Negative values are clg loads		

Figure 3.20 Design Report [System Capacity highlighted in red box]

4. **AHU capacity is calculated from the total system capacity of every individual space.**

   The results of every individual space are tabulated in terms of room load and system capacity as shown in **Table 3.2.** The total of all system capacity is the AHU capacity for that particular floor (highlighted in red).

Table 3.2 Tabulation of System Capacity for VAV [Level 1 to Level 9]

Space	Floor Area, ft2	Supply Air, CFM	Fresh Air, CFM	System Capacity		
				Sensible Load, BTU/hr	Latent Load, BTU/hr	Total Load, BTU/hr
Compactius Room	146	46	16	1,503	1,031	2,534
Corridor	1,808	680	249	22,349	17,926	40,275
Director 1	280	955	30	22,915	1,307	24,222
Director 2	323	919	34	22,060	1,782	23,842
Director 3	312	914	33	1,687	2,168	3,855
Equip 1	71	23	8	731	501	1,232
Equip 2	89	28	9	916	628	1,544
File Room 1	140	44	15	1,442	989	2,431
File Room 2	86	27	9	886	607	1,493
File Room 3	135	43	14	1,402	954	2,356
IDF	122	39	13	1,256	862	2,118
Lift Lobby	463	214	49	6,445	3,453	9,898
Meeting Room 1	420	330	58	8,769	4,396	13,165
Meeting Room 2	237	186	33	5,350	2,540	7,890
Meeting Room 3	248	195	34	5,178	2,596	7,774
Mgr 1	151	325	16	7,987	952	8,939
Mgr 2	151	325	16	7,987	952	8,939
Mgr 3	151	325	16	7,987	952	8,939
Mgr 4	151	325	16	7,987	952	8,939
Mgr 5	188	431	20	10,211	1,057	11,268
Mgr 6	188	431	20	10,211	1,057	11,268
Office 1	1,249	2,120	133	51,765	8,131	59,896
Office 2	2,799	4,456	297	108,426	16,453	124,879

Office 3	404	754	43	18,142	2,114	20,256
Pantry	200	93	21	2,789	1,492	4,281
Printing	334	152	35	4,597	2,408	7,005
Room 1	172	385	18	9,344	1,080	10,424
Room 2	173	386	18	9,358	1,089	10,447
Sec 1	118	54	13	1,624	851	2,475
Sec 2	140	64	15	1,927	1,009	2,936
Sec 3	205	93	22	2,821	1,478	4,299
Service Lobby	200	93	21	2,784	1,491	4,275
	11,854	**15,455**	**1,344**	**368,836**	**85,258**	**454,094**

Table 3.3 Tabulation of System Capacity for VAV [Level 1 to Level 9] (SI Unit)

Space	**Floor**	**Floor Area, m2**	**Supply Air, l/s**	**System Capacity**		
				Sensible Load, kW	**Latent Load, BTU/hr**	**Total Load, BTU/hr**
Compactius Room	L1	14	21.70	0.44	1,031	2,534
Corridor	L1	168	320.75	6.55	17,926	40,275
Director 1	L1	26	450.47	6.72	1,307	24,222
Director 2	L1	30	433.49	6.47	1,782	23,842
Director 3	L1	29	431.13	0.49	2,168	3,855
Equip 1	L1	7	10.85	0.21	501	1,232
Equip 2	L1	8	13.21	0.27	628	1,544
File Room 1	L1	13	20.75	0.42	989	2,431
File Room 2	L1	8	12.74	0.26	607	1,493
File Room 3	L1	13	20.28	0.41	954	2,356
IDF	L1	11	18.40	0.37	862	2,118

Lift Lobby	L1	43	100.94	1.89	3,453	9,898
Meeting Room 1	L1	39	155.66	2.57	4,396	13,165
Meeting Room 2	L1	22	87.74	1.57	2,540	7,890
Meeting Room 3	L1	23	91.98	1.52	2,596	7,774
Mgr 1	L1	14	153.30	2.34	952	8,939
Mgr 2	L1	14	153.30	2.34	952	8,939
Mgr 3	L1	14	153.30	2.34	952	8,939
Mgr 4	L1	14	153.30	2.34	952	8,939
Mgr 5	L1	17	203.30	2.99	1,057	11,268
Mgr 6	L1	17	203.30	2.99	1,057	11,268
Office 1	L1	116	1,000.00	15.17	8,131	59,896
Office 2	L1	260	2,101.89	31.78	16,453	124,879
Office 3	L1	38	355.66	5.32	2,114	20,256
Pantry	L1	19	43.87	0.82	1,492	4,281
Printing	L1	31	71.70	1.35	2,408	7,005
Room 1	L1	16	181.60	2.74	1,080	10,424
Room 2	L1	16	182.08	2.74	1,089	10,447
Sec 1	L1	11	25.47	0.48	851	2,475
Sec 2	L1	13	30.19	0.56	1,009	2,936
Sec 3	L1	19	43.87	0.83	1,478	4,299
Service Lobby	L1	19	43.87	0.82	1,491	4,275
		1,101	**7,290**	**108**	**85,258**	**454,094**

The AHU capacity for that particular floor (level 1 to level 9) is as follows:

- Sensible Load = 368,836 Btu/hr
- Latent Load = 82,258 Btu/hr
- Total Load = 454,094 Btu/hr
- Airflow = 15,455 cfm

5. **Zoning of space is done based on space function using VAV box.**

VAV box have a range of size in terms of inlet diameter and flow capacity as shown in **Table 3.4.** Based on the flow capacity, the type of VAV box is selected. For Mgr 1, since it's an individual room that serves for specific function, it's made into one zone. The total flow rate for that zone is 325 cfm and thus Type A VAV box is used as shown in **Figure 3.21.**

Table 3.4 VAV Type and Capacity

Type	Inlet Size Diameter (mm)	Capacity (cfm)
A	150	1-382
B	200	383-594
C	250	595-848
D	300	849-1293
E	350	1294-1802
F	400	1803-2290

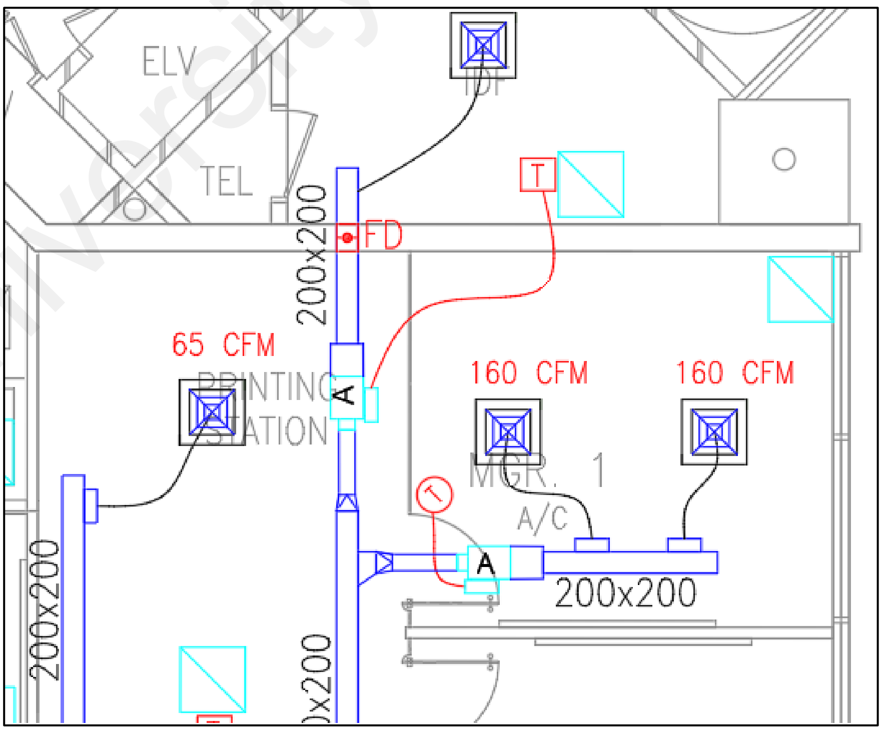


Figure 3.21 VAV System Layout

3.3.1.3 Active Chilled Beam (ACB)

Unlike VAV, the sizing of coil and fan for AHU considers only the room latent load, ventilation load and supply fan load where the room sensible load is catered by the beam itself.

The design sequence is as follows:

1. Cooling load for each and every room space is calculated.
2. Room sensible load is used to determine the number of beams required for individual space.
3. Total cooling load excluding room sensible is used to size air system for individual space.
4. The total of every individual system capacity is the capacity of AHU.

* Note that not all the spaces are provided with chilled beams such as corridor, files room, utility room where the ceiling space is limited.

TROX Software is used to size chilled beam with the following inputs (as shown in **Figure 3.22**):

- Primary air temperature = 12 ^{o}C
- Water flow temperature = 15 ^{o}C
- Water flow = 300 l/h
- Room air temperature = 24 ^{o}C
- Relative Humidity = 55%
- Air flow = 30 l/s

The maximum allowable water temperature difference is 3^{o}C and the supply air pressure drop is 250 pa. For this project, the water flow rate is set at 300 l/h (0.0833 l/s) maximum and the resulting water temperature difference is 2.9 K (2.9 ^{o}C). The water flow rate setpoint will be varied according to the room sensible load required in order to optimize the usage of water for individual zones. As such, the chilled beam capacity will be different in terms of total thermal capacity and water capacity in accordance with the water flow rate.

Tabulation of active chilled beam capacity based on water flow rate is as shown in **Table 3.5** where it is obtained from TROX selection tool.

Table 3.5 Active Chilled Beam Capacity

Water Flow Rate, l/h	Total Thermal Capacity, Btu/hr	Water Capacity, Btu/hr
300	5,002	3,504
225	4,794	3,296
200	4,692	3,197
150	4,405	2,911
100	3,903	2,406
75	3,511	2,013
50	3,023	1,525
38	2,774	1,280
30	2,603	1,106

Table 3.6 Active Chilled Beam Capacity (SI Unit)

Water Flow (l/s)	Water kW	Total kW
0.0833	1.03	1.47
0.0625	0.97	1.41
0.0556	0.94	1.38
0.0417	0.85	1.29
0.0278	0.71	1.14
0.0208	0.59	1.03
0.0139	0.45	0.89
0.0106	0.38	0.81
0.0083	0.32	0.76

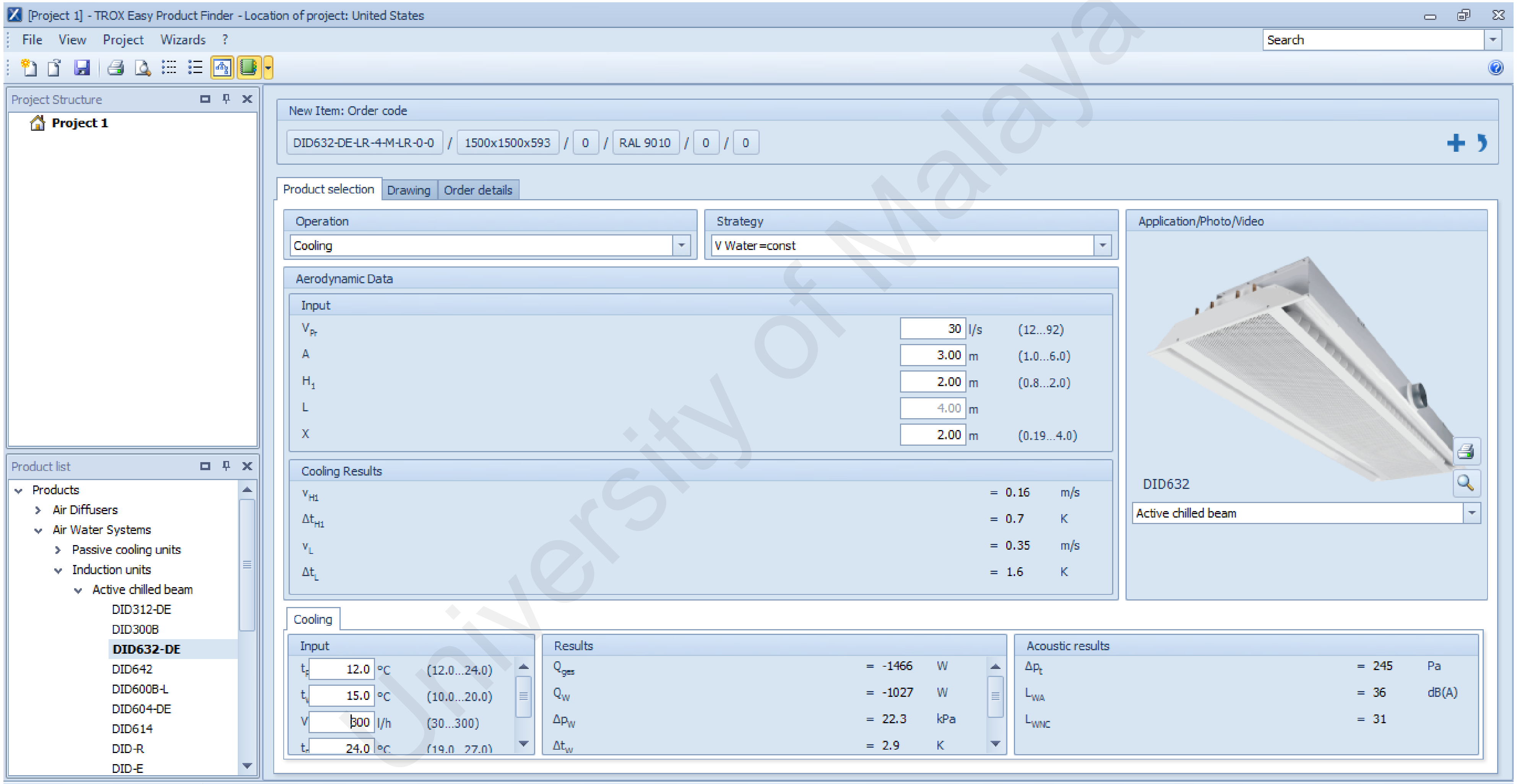


Figure 3.22 TROX Selection Software

3.3.1.4 Example of system sizing for ACB

1. **Cooling load for each and every room space is calculated.**

   Similar to VAV, cooling load for ACB is calculated using HAP which has been performed in earlier part. The room sensible and latent load obtained for Mgr 1 are **7,532 Btu/hr** and **231 Btu/hr** respectively.

2. **Room sensible load is used to determine the number of beams required for individual space.**

   Room sensible = 7,532 Btu/hr

   Based on the cooling capacity of chilled beam as shown in **Table 3.5**, two numbers of chilled beam are required with each having 100 l/hr water flowrate and 64 cfm air flowrate.

3. **Total cooling load excluding room sensible is used to size air system for individual space.**

   Individual air system (AHU) is sized to cater for all the load except room sensible as it has been catered by chilled beam itself. The system flow rate is based on the total air flow rate required by the chilled beams. However, the supply air flow rate and fresh air flow rate need to meet the minimum air requirement according to ASHRAE's standard. Calculations are shown as follows:

   Air-conditioned area = 151 ft^2

   Occupancy rate = 200 ft^2/ppl

   Total occupancy = 0.755 ppl

   Minimum supply air required = 20 cfm/ppl x 0.755 ppl = 15.1 cfm

   Minimum fresh air required = (5 cfm/ppl x 0.755 ppl) + (0.06 cfm/ft^2 x 151 ft^2) = 12.8 cfm

   Total supply air = 64 cfm/beam x 2 = 128 cfm

Total fresh air = 10% of 128 cfm = 12.8 cfm

Since

Total supply air -128 cfm is more than minimum supply air required - 15.1 cfm, it's fine.

Total fresh air - 12.8cfm is equal to minimum fresh air required - 12.8 cfm, it's fine.

Outdoor Air Dry Bulb Temperature = 95 ^{o}F

Outdoor Air Wet Bulb Temperature = 82 ^{o}F

Outdoor Air Moisture = 145 grain/lbs

Room Dry Bulb Temperature = 75 ^{o}F

Room Wet Bulb Temperature = 64 ^{o}F

Room Air Moisture = 71.5 grain/lbs

Supply Air Flow = 127 cfm

Fresh Air Flow = 13 cfm

Return Air Flow = 115 cfm

Mixed air temperature and moisture are determined based on the outdoor air and room air conditions:

Mixed Air Dry Bulb Temperature = 76.91 ^{o}F

Mixed Air Moisture = 78.5 grain/lbs

Off-coil is set at the conditions:

Dry bulb temperature = 53 ^{o}F

Moisture = 59.8 grain/lbs

The system capacity for Mgr 1 is determined from the equation below:

Sensible load

$Q_s = 1.08 \times airflow \times \Delta T$

Q_s = 1.08 x 128 cfm x (76.91-53) ^{o}F = 3,306 Btu/hr

Latent load

$Q_s = 0.68 \times airflow \times \Delta W$

Q_s = 0.68 x 128 cfm x (78.5-59.8) ^{o}F = 1,631 Btu/hr

4. **The total of every individual system capacity is the capacity of AHU.**

The capacity of AHU is determined from the total system capacity of every individual space as shown in **Table 3.7.**

The capacity of AHU is 150,213 Btu/hr sensible and 79,183 Btu/hr latent...

Table 3.7 Tabulation of System Capacity for ACB [Level 1 to Level 9]

Space	Floor Area, ft2	ACB				AHU			
		Total Air Flow Rate, cfm	Total Water Flow Rate, Gpm	Total Sensible, Btu/hr	Total Sensible, Btu/hr (water)	Air Flow,CFM	Sensible, BTU/hr	Latent, BTU/hr	Total
Compactius Room	146	-	-	-	-	46	1,503	1,031	2,534
Corridor	1,808	-	-	-	-	680	22,349	17,926	40,275
Director 1	280	256	2.1	20,008	10,512	256	6,437	2,905	9,342
Director 2	323	256	2.1	20,008	10,512	256	6,437	2,905	9,342
Director 3	312	256	2.1	20,008	10,512	256	6,437	2,905	9,342
Equip 1	71	-	-	-	-	23	731	501	1,232
Equip 2	89	-	-	-	-	28	916	628	1,544
File Room 1	140	-	-	-	-	44	1,442	989	2,431
File Room 2	86	-	-	-	-	27	886	607	1,493
File Room 3	135	-	-	-	-	43	1,402	954	2,356
IDF	122	-	-	-	-	39	1,256	862	2,118
Lift Lobby	463	64	2.1	5,002	10,512	64	1,833	1,231	3,064
Meeting Room 1	420	128	1.4	7,806	7,218	128	3,395	1,838	5,233
Meeting Room 2	237	64	1.4	3,903	7,218	64	1,833	1,231	3,064
Meeting Room 3	248	64	1.4	3,903	7,218	64	1,833	1,231	3,064
Mgr 1	151	128	1.4	7,806	7,218	128	3,306	1,631	4,937
Mgr 2	151	128	1.4	7,806	7,218	128	3,306	1,631	4,937
Mgr 3	151	128	1.4	7,806	7,218	128	3,306	1,631	4,937
Mgr 4	151	128	1.4	7,806	7,218	128	3,306	1,631	4,937
Mgr 5	188	128	2.1	10,004	10,512	128	3,306	1,631	4,937
Mgr 6	188	128	2.1	10,004	10,512	128	3,306	1,631	4,937
Office 1	1,249	640	2.1	50,020	10,512	640	14,008	5,469	19,477
Office 2	2,799	1280	2.1	100,040	10,512	1,280	30,811	11,481	42,292

Office 3	404	256	1.9	18,768	9,591	256	6,437	2,905	9,342
Pantry	200	64	0.9	3,023	4,575	64	1,937	1,473	3,410
Printing	334	64	1.4	3,903	7,218	64	1,937	1,473	3,410
Room 1	172	128	1.9	9,384	9,591	128	3,395	1,838	5,233
Room 2	173	128	1.9	9,384	9,591	128	3,395	1,838	5,233
Sec 1	118	-	-	-	-	54	1,624	851	2,475
Sec 2	140	-	-	-	-	64	1,927	1,009	2,936
Sec 3	205	-	-	-	-	93	2,821	1,478	4,299
Service Lobby	200	64	0.9	3,023	4,575	64	3,395	1,838	5,233
	11,854	**4,480**	**36**	**329,415**	**179,763**	**5,621**	**150,213**	**79,183**	**229,396**

Table 3.8 Tabulation of System Capacity for ACB [Level 1 to Level 9] (SI Unit)

Space	Floor Area, m2	ACB				AHU			
		Total Air Flow Rate, l/s	Total Water Flow Rate, l/s	Total Sensible, kW	Total Sensible, kW (water)	Air Flow,l/s	Sensible, kW	Latent, kW	Total, kW
Compactius Room	14	-	-	-	-	21.70	0.44	0.30	0.74
Corridor	168	-	-	-	-	320.75	6.55	5.25	11.80
Director 1	26	120.75	0.13	5.86	3.08	120.75	1.89	0.85	2.74
Director 2	30	120.75	0.13	5.86	3.08	120.75	1.89	0.85	2.74
Director 3	29	120.75	0.13	5.86	3.08	120.75	1.89	0.85	2.74
Equip 1	7	-	-	-	-	10.85	0.21	0.15	0.36
Equip 2	8	-	-	-	-	13.21	0.27	0.18	0.45
File Room 1	13	-	-	-	-	20.75	0.42	0.29	0.71
File Room 2	8	-	-	-	-	12.74	0.26	0.18	0.44
File Room 3	13	-	-	-	-	20.28	0.41	0.28	0.69
IDF	11	-	-	-	-	18.40	0.37	0.25	0.62

Lift Lobby	43	30.19	0.13	1.47	3.08	30.19	0.54	0.36	0.90
Meeting Room 1	39	60.38	0.09	2.29	2.12	60.38	0.99	0.54	1.53
Meeting Room 2	22	30.19	0.09	1.14	2.12	30.19	0.54	0.36	0.90
Meeting Room 3	23	30.19	0.09	1.14	2.12	30.19	0.54	0.36	0.90
Mgr 1	14	60.38	0.09	2.29	2.12	60.38	0.97	0.48	1.45
Mgr 2	14	60.38	0.09	2.29	2.12	60.38	0.97	0.48	1.45
Mgr 3	14	60.38	0.09	2.29	2.12	60.38	0.97	0.48	1.45
Mgr 4	14	60.38	0.09	2.29	2.12	60.38	0.97	0.48	1.45
Mgr 5	17	60.38	0.13	2.93	3.08	60.38	0.97	0.48	1.45
Mgr 6	17	60.38	0.13	2.93	3.08	60.38	0.97	0.48	1.45
Office 1	116	301.89	0.13	14.66	3.08	301.89	4.11	1.60	5.71
Office 2	260	603.77	0.13	29.32	3.08	603.77	9.03	3.36	12.39
Office 3	38	120.75	0.12	5.50	2.81	120.75	1.89	0.85	2.74
Pantry	19	30.19	0.06	0.89	1.34	30.19	0.57	0.43	1.00
Printing	31	30.19	0.09	1.14	2.12	30.19	0.57	0.43	1.00
Room 1	16	60.38	0.12	2.75	2.81	60.38	0.99	0.54	1.53
Room 2	16	60.38	0.12	2.75	2.81	60.38	0.99	0.54	1.53
Sec 1	11	-	-	-	-	25.47	0.48	0.25	0.73
Sec 2	13	-	-	-	-	30.19	0.56	0.30	0.86
Sec 3	19	-	-	-	-	43.87	0.83	0.43	1.26
Service Lobby	19	30.19	0.06	0.89	1.34	30.19	0.99	0.54	1.53
	1,101	**2,113**	**2**	**97**	**53**	**2,651**	**44**	**23**	**67**

3.3.2 Duct Sizing

Sizing of duct-works in ventilation systems can be done by the following method

i) Velocity Method
ii) Equal Friction Method

Equal Friction Method

Equal friction method is also known constant pressure method where the pressure is remained constant when performing duct sizing calculations. This method is most preferable as the calculation is much simpler compared to velocity method. Typical values for supply and return ducts would be 0.09, 0.095 or 0.100 in. w.g. per 100ft (22.41, 23.66, or 24.9 Pa per 30 m) [17].

To maintain the pressure at a constant value, the size of the duct and velocity will gradually reduce. The method may add more duct cross-sectional changes and increase the number of components in the system compared to other methods. For simplicity purpose, duct sizer – ***McQuay*** is used to calculate the minimum duct size as shown in **Figure 3.23.**

The sequence is as follows:

1. Set the value of head loss or in other words pressure loss (0.1 in w.g./100ft in normal practice).
2. Key in the air flow rate that passes through the duct.
3. Determine the dimension of the duct by ensuring the width-to-height ratio is within 4 as it may create massive head loss that consequently affects the airflow.
4. Determine the head loss for every section by multiplying with the section's length.
5. Determine the total head loss by summing up all the section losses which have been used to calculate the duct size earlier. This total head loss is the external static pressure (ESP) of the fan.

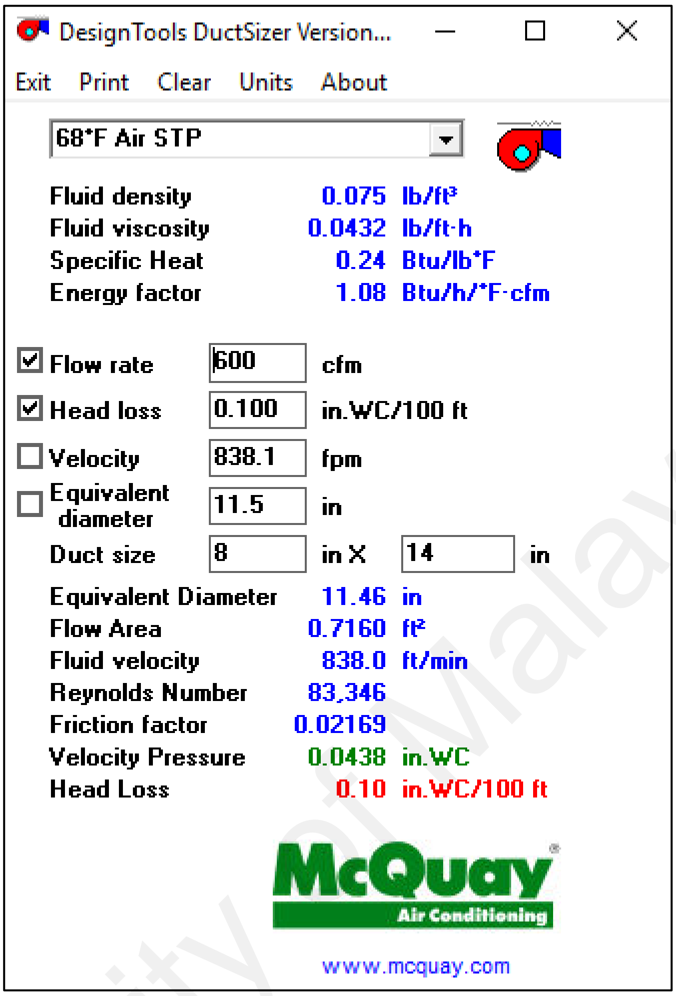


Figure 3.23 McQuay Duct Sizer

3.4 Chiller Plant Design

There are many ways to design a chilled water air-conditioning system and the first thing to do after getting the cooling load is to decide on what type of pumping scheme to be used for the system. Pumping scheme determines the system flow. Generally, there are three common types of pumping schemes used where they include:

- Constant Primary Flow (CPF)
- Constant Primary - Variable Secondary Flow (P/S)
- Variable Primary Flow (VPF)

Constant Primary Flow (CPF) is a simple pumping scheme where it doesn't require sophisticated equipment and complicated control to form a chilled water system. However, the system is claimed to be inefficient in terms of energy consumption as the system operation is fixed where it doesn't react to the actual load demand. In other words, be it in high load or low load conditions, the system will run at full load all the time.

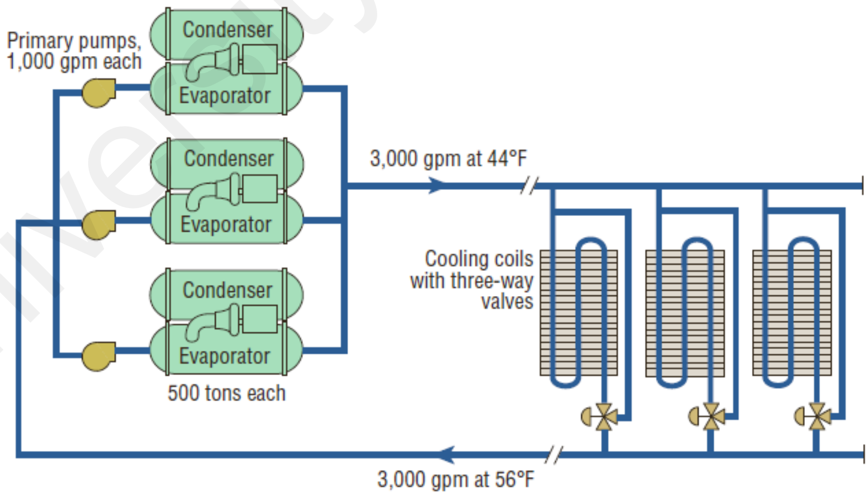


Figure 3.24 Constant Primary Flow (CPF) Schematic [18]

Constant Primary – Variable Secondary Flow (P/S), commonly known as primary-secondary flow is a rather complicated pumping scheme compared to constant primary flow as it involves two loops: primary and secondary with dedicated pump sets that requires advanced control system to communicate between the equipment involved. Generally, it's composed of constant primary pump that serves the chiller itself and variable secondary pump (with VSD) that serves the load demand. A decoupler is used to separate the primary and secondary loops with a flowmeter that monitors the flow across the channel which determines the staging of the pump and the chiller. How the system works is basically start from the load demand, where the room temperature sensor triggers the motorized valve to on or off, which turns affects the differential pressure readings as displayed in the differential pressure sensor (DPS) and consequently triggers the secondary pump to stage up or down. When staging of the secondary pumps happens, the flow in the decouple line will experience a sudden change in flow which call the chillers to start or stop. One of the main problems faced in such system is low delta T syndrome during low load. However, it's relatively more energy efficient than the conventional primary constant pumping scheme.

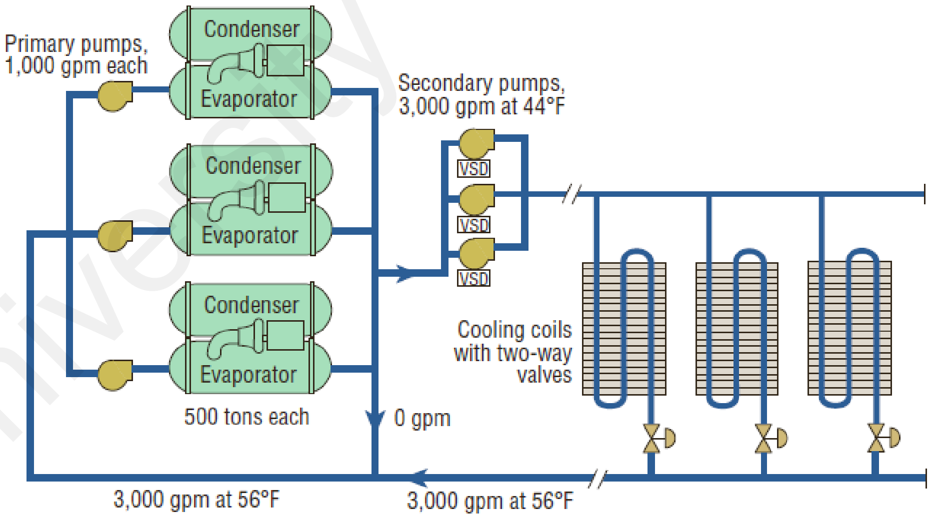


Figure 3.25 Constant Primary-Variable Secondary Flow Schematic. [18]

Variable Primary Flow (VPF) is the latest pumping scheme compared to the other two where it doesn't require another set of pumps for another loop. But the control will be much more complicated than primary-secondary flow as it involves the control of water flow directly at the chiller side in response to the load demand. This technically means a variable speed chiller is needed to cater for the varying water flow as normal chillers are designed for constant water flow. The working principle is somehow different from primary-secondary flow where the pump serving the chillers is of variable speed. Because of the direct control of flow at the chiller side, a bypass is needed to ensure minimum flow of water back to the chiller to avoid freezing of the evaporator tubes. Similarly, the same thing happens where load variations triggers the motorized valve to on or off, which in turns affects the DP readings and consequently ramps up or down the primary variable pumps, resulting the chillers to start or stop. In terms of energy efficiency, it's comparable to primary-secondary flow and one of its biggest drawbacks is the cost of the chiller where it usually costs double the price of a normal constant speed chiller. For that reason, most of the building owners would prefer primary-secondary flow than primary variable flow.

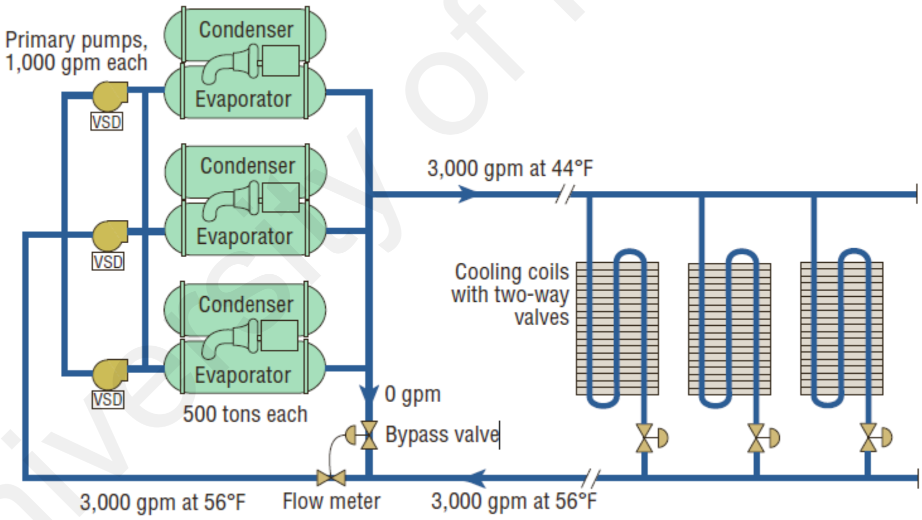


Figure 3.26 Variable Primary Flow (VPF) Schematic [18]

Between the three pumping schemes, VPF has the greatest potential in terms of energy saving because of its efficient variable-speed pumping characteristics. Besides, VPF makes the most efficient use of over-pumping to mitigate low delta T syndrome. Though, the control is rather complicated compared to P/S and CPF. On top of that, the equipment cost is higher as the chiller used is not a normal chiller where it needs to be variable speed type and it usually costs two times higher than a normal chiller in terms of RM/RT. Following table summarizes the comparison between the three pumping schemes:

	CPF	P/S	VPF
Chiller Type	Constant flow	Constant flow	Variable flow
Pump Energy	Base case	50 – 60 % less	60 – 75 % less
Valve Type	Three-way	Two-way	Two-way
Control	simple	simple	Complex
Overall Investment Cost	Base case	5 % higher	10 % higher
Plant Space	Base case	larger	Same as base case

Figure 3.27 Comparison Between CPF, P/S and VPF

As far as energy is concerned, VPF is proposed in this project since it provides significant savings on the operation cost even though the overall investment cost is high. However, the selection of pumping scheme type doesn't affect the results comparison between the two different air distribution systems, VAV and ACB as both use the same pumping scheme.

3.5 System Control

System control forms the central part of a chiller plant that integrates all devices and equipment, enabling them to communicate among each other and work in a sequential manner. ACB involves a more sophisticated control compared to VAV as it needs to take into account of the condensation issue at the secondary coil. The control should be designed in such a way that the chilled water supply temperature is not less than the room dew point temperature.

3.5.1 Variable Air Volume (VAV) system

VAV consists of VAV box and VSD fan that varies the flow of conditioned air into individual zones depending on room temperature. Temperature sensor and thermostat are used to monitor the room temperature.

The control sequence is as follows (refer to **Figure 3.28**):

Room temperature for individual zone is set at specific setpoint. Any deviation on the room temperature changes the damper's position of VAV box. Assuming the occupancy load is high and the room temperature exceeds its setpoint, the damper will be adjusted in a position where it allows more air into the room. This consequently causes the air static pressure to reduce. In order to maintain the static pressure at its setpoint, the VSD fan will need to increase its speed. As the fan's speed increases, the return air flow increases and to a point when it exceeds its setpoint, the PIBCV valve will modulate to allow more chilled water to pass through the AHU's coil. CO2 sensor is to modulate the outdoor air damper when the amount of CO2 deviates from its setpoint.

3.5.2 Active Chilled Beam (ACB)

ACB consists of primary and secondary coils. Primary refers to the AHU coil and secondary refers to the chilled beam coil where it's separated by a heat exchanger. Temperature sensor is placed at the return air grill for common area and temperature thermostat is used at individual room where the temperature setpoint is remotely controlled by the occupant.

The control sequence is as follows (refer to **Figure 3.29**):

The room temperature and dew point temperature are set at specific setpoint. Any deviation on the temperature modulates the PICBV valve. As far as condensation is concerned, the room dew point temperature is given priority over the room temperature. Assuming the occupancy load is high and the room temperature exceeds its setpoint, the PIBCV will open to allow more chilled water to pass through the beam and the differential pressure sensor will then trigger the VSD pump to run in a higher speed. This consequently causes the supply temperature to reduce and triggers the PIBCV on the primary side to open. Likewise, the PIBCV at the AHU will be triggered by the return air temperature sensor when it exceeds its setpoint. Eventually, the differential pressure sensor will send the signal to the main VSD pump to increase its speed. CO2 sensor is to modulate the outdoor air damper when the amount of CO2 deviates from its setpoint.

In short, the difference in control between the two systems is the varying flow of the air and water in response to room temperature for VAV and ACB respectively.

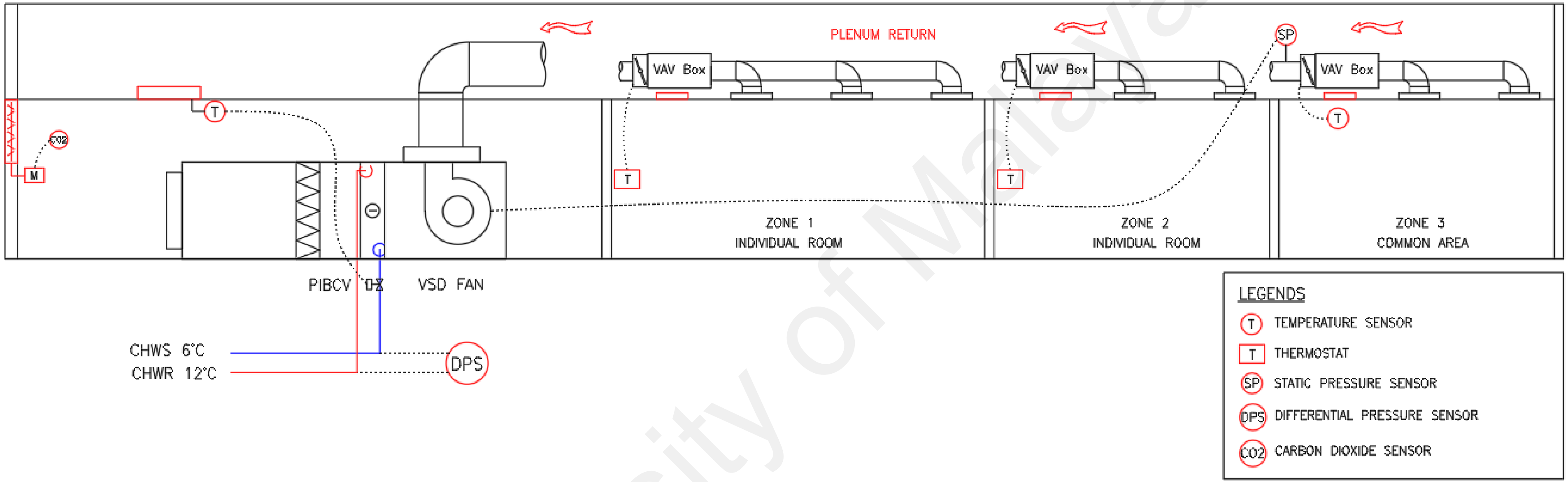


Figure 3.28 VAV system control schematic

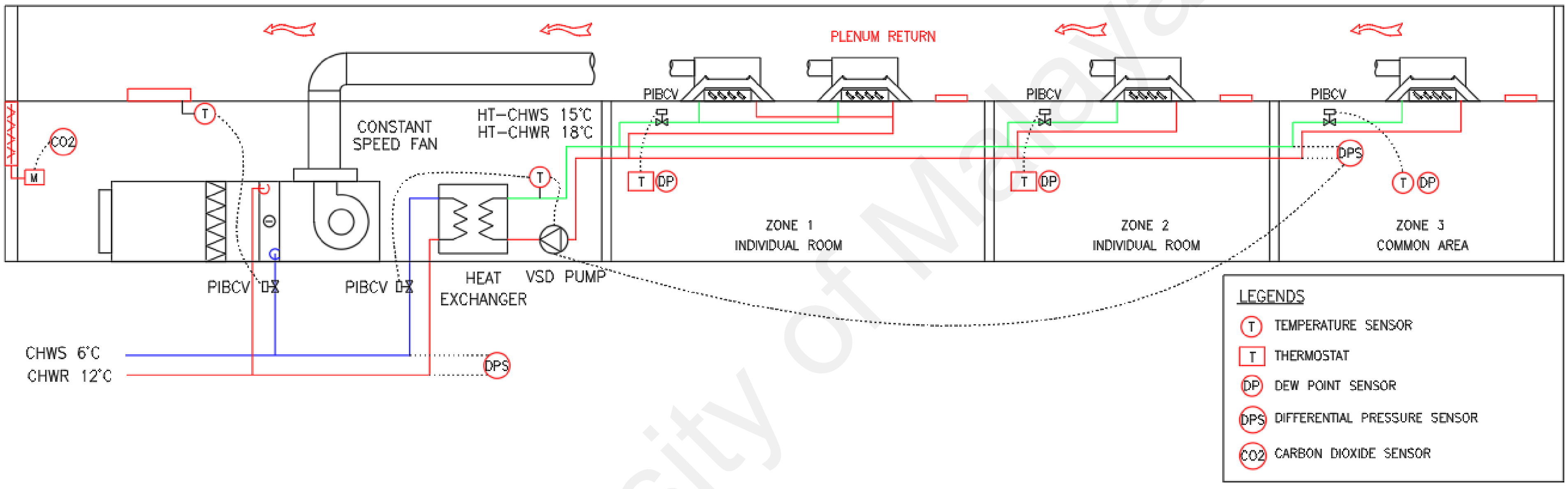


Figure 3.29 ACB System Control Schematic

CHAPTER 4. RESULTS

4.1 Introduction

The results obtained from relevant design calculations for both VAV and ACB system were discussed in this chapter. Cooling load was presented in the form of table for all the floors as well as the system capacity. System layout was also presented to show the difference between the two systems in terms of design layout and space required.

4.2 Cooling Load

Cooling load results is obtained from Hourly Analysis Program (HAP) 4.90. Based on the functions discussed in Chapter 3 Methodology, the total cooling load is determined for all individual spaces in every floor. The cooling load is the same for both VAV and ACB.

From **Table 4.1**, it shows that the room sensible and latent load required for ground floor are 96,192 Btu/hr and 8,924 Btu/hr respectively. Whereas for Level 1 to Level 9, the room sensible is 353,128 Btu/hr and room latent is 19,932 Btu/hr as shown in **Table 4.3.** For level 10, the room sensible is 237,313 Btu/hr and room latent is 24,460 Btu/hr as shown in **Table 4.5.**

Table 4.1 Space Cooling Load for Level Ground Floor

Space	Floor	Floor Area, ft2	Supply Air, CFM	Fresh Air, CFM	Room		
					Sensible Load, BTU/hr	Latent Load, BTU/hr	Total Load, BTU/hr
Lift Lobby	GF	1,012	520	108	10,822	1,834	12,656
Meeting Room 1	GF	162	127	22	2,659	407	3,066
Meeting Room 2	GF	135	106	19	2,216	338	2,819
Office 1	GF	172	87	18	1,814	257	2,071
Office 2	GF	129	65	14	1,361	193	1,554
Retail	GF	3,724	3,361	396	75,291	5,659	80,950
IDF	GF	122	39	13	890	125	1,015
Utility	GF	108	49	11	1,139	111	1,250
		5,564	**4,354**	**601**	**96,192**	**8,924**	**105,381**

Table 4.2 Space Cooling Load for Level Ground Floor (SI Unit)

Space	Floor	Floor Area, m2	Supply Air, l/s	Fresh Air, l/s	Room		
					Sensible Load, kW	Latent Load, kW	Total Load, kW
Lift Lobby	GF	94	245.28	50.94	3.17	0.54	3.71
Meeting Room 1	GF	15	59.91	10.38	0.78	0.12	0.90
Meeting Room 2	GF	13	50.00	8.96	0.65	0.10	0.83
Office 1	GF	16	41.04	8.49	0.53	0.08	0.61
Office 2	GF	12	30.66	6.60	0.40	0.06	0.46
Retail	GF	346	1,585.38	186.79	22.07	1.66	23.72
IDF	GF	11	18.40	6.13	0.26	0.04	0.30
Utility	GF	10	23.11	5.19	0.33	0.03	0.37
		517	**2,054**	**283**	**28**	**3**	**31**

Table 4.3 Space Cooling Load for Level 1 to Level 9

Space	Floor	Floor Area, ft2	Supply Air, CFM	Fresh Air, CFM	Room		
					Sensible Load, BTU/hr	Latent Load, BTU/hr	Total Load, BTU/hr
Compactius Room	L1	146	46	16	1,065	150	1,215
Corridor	L1	1,808	680	249	15,608	4,882	20,490
Director 1	L1	280	955	30	22,307	397	22,704
Director 2	L1	323	919	34	21,401	479	21,880
Director 3	L1	312	914	33	21,284	463	21,917
Equip 1	L1	71	23	8	518	73	591
Equip 2	L1	89	28	9	649	91	740
File Room 1	L1	140	44	15	1,021	144	1,165
File Room 2	L1	86	27	9	627	88	715
File Room 3	L1	135	43	14	984	138	1,122
IDF	L1	122	39	13	890	125	1,015
Lift Lobby	L1	463	214	49	4,951	625	5,576
Meeting Room 1	L1	420	330	58	6,894	1,053	7,947
Meeting Room 2	L1	237	186	33	4,318	648	4,966
Meeting Room 3	L1	248	195	34	4,071	622	4,693
Mgr 1	L1	151	325	16	7,532	231	7,763
Mgr 2	L1	151	325	16	7,532	231	7,763
Mgr 3	L1	151	325	16	7,532	231	7,763
Mgr 4	L1	151	325	16	7,532	231	7,763
Mgr 5	L1	188	431	20	9,806	277	10,083
Mgr 6	L1	188	431	20	9,806	277	10,083
Office 1	L1	1,249	2,120	133	48,787	1,910	50,697
Office 2	L1	2,799	4,456	297	100,074	4,108	104,182
Office 3	L1	404	754	43	17,392	572	17,964
Pantry	L1	200	93	21	2,145	270	2,415

Printing	L1	334	152	35	3,522	342	3,864
Room 1	L1	172	385	18	8,924	264	9,188
Room 2	L1	173	386	18	8,935	265	9,200
Sec 1	L1	118	54	13	1,244	121	1,365
Sec 2	L1	140	64	15	1,476	144	1,620
Sec 3	L1	205	93	22	2,162	210	2,372
Service Lobby	L1	200	93	21	2,139	270	2,409
		11,854	**15,455**	**1,344**	**353,128**	**19,932**	**373,230**

Table 4.4 Space Cooling Load for Level 1 to Level 9 (SI Unit)

Space	**Floor**	**Floor Area, m2**	**Supply Air, l/s**	**Fresh Air, l/s**	**Room**		
					Sensible Load, kW	**Latent Load, kW**	**Total Load, BTU/hr**
Compactius Room	L1	14	21.70	7.55	0.31	0.04	1,215
Corridor	L1	168	320.75	117.45	4.57	1.43	20,490
Director 1	L1	26	450.47	14.15	6.54	0.12	22,704
Director 2	L1	30	433.49	16.04	6.27	0.14	21,880
Director 3	L1	29	431.13	15.57	6.24	0.14	21,917
Equip 1	L1	7	10.85	3.77	0.15	0.02	591
Equip 2	L1	8	13.21	4.25	0.19	0.03	740
File Room 1	L1	13	20.75	7.08	0.30	0.04	1,165
File Room 2	L1	8	12.74	4.25	0.18	0.03	715
File Room 3	L1	13	20.28	6.60	0.29	0.04	1,122
IDF	L1	11	18.40	6.13	0.26	0.04	1,015
Lift Lobby	L1	43	100.94	23.11	1.45	0.18	5,576
Meeting Room 1	L1	39	155.66	27.36	2.02	0.31	7,947
Meeting Room 2	L1	22	87.74	15.57	1.27	0.19	4,966

Meeting Room 3	L1	23	91.98	16.04	1.19	0.18	4,693
Mgr 1	L1	14	153.30	7.55	2.21	0.07	7,763
Mgr 2	L1	14	153.30	7.55	2.21	0.07	7,763
Mgr 3	L1	14	153.30	7.55	2.21	0.07	7,763
Mgr 4	L1	14	153.30	7.55	2.21	0.07	7,763
Mgr 5	L1	17	203.30	9.43	2.87	0.08	10,083
Mgr 6	L1	17	203.30	9.43	2.87	0.08	10,083
Office 1	L1	116	1,000.00	62.74	14.30	0.56	50,697
Office 2	L1	260	2,101.89	140.09	29.33	1.20	104,182
Office 3	L1	38	355.66	20.28	5.10	0.17	17,964
Pantry	L1	19	43.87	9.91	0.63	0.08	2,415
Printing	L1	31	71.70	16.51	1.03	0.10	3,864
Room 1	L1	16	181.60	8.49	2.62	0.08	9,188
Room 2	L1	16	182.08	8.49	2.62	0.08	9,200
Sec 1	L1	11	25.47	6.13	0.36	0.04	1,365
Sec 2	L1	13	30.19	7.08	0.43	0.04	1,620
Sec 3	L1	19	43.87	10.38	0.63	0.06	2,372
Service Lobby	L1	19	43.87	9.91	0.63	0.08	2,409
		1,101	**7,290**	**634**	**103**	**6**	**109**

Table 4.5 Space Cooling Load for Level 10

Space	Floor	Floor Area, ft2	Supply Air, CFM	Fresh Air, CFM	Room		
					Sensible Load, BTU/hr	Latent Load, BTU/hr	Total Load, BTU/hr
Bar	L10	215	110	58	2,299	389	2,688
Chairman Office	L10	700	939	74	21,370	1,026	22,396
Director	L10	872	955	30	22,307	397	22,704
Foyer	L10	431	180	59	3,760	1,340	5,100
IDF	L10	118	55	13	1,262	159	1,421
Lift Lobby	L10	1,195	614	127	12,779	2,165	14,944
Lounge 1	L10	248	416	26	9,572	379	9,951
Lounge 2	L10	237	386	25	8,862	362	9,224
Lounge 3	L10	248	411	26	9,334	364	9,698
Meeting Room	L10	258	421	27	9,679	395	10,074
Outdoor Terrace	L10	3,957	2,848	544	63,404	12,462	75,866
PA	L10	280	512	30	11,811	428	12,239
PA 1	L10	178	90	19	1,878	266	2,144
PA 2	L10	355	520	38	11,767	521	12,288
Pantry	L10	108	55	11	1,139	162	1,301
Private Room	L10	371	188	39	3,913	555	4,468
Residence Office	L10	452	720	48	16,845	650	17,495
Sec	L10	140	71	15	1,477	209	1,942
Secu	L10	83	42	9	876	124	1,000
Service Lobby	L10	304	156	32	3,251	551	3,802
Strategy	L10	312	144	33	3,338	459	3,797
Utility 1	L10	72	33	8	759	74	833
Utility 2	L10	46	21	5	488	47	535
VIP Lounge	L10	398	615	42	14,122	609	14,731
Waiting	L10	118	49	16	1,021	367	1,388
		11,696	**10,551**	**1,354**	**237,313**	**24,460**	**262,029**

Table 4.6 Space Cooling Load for Level 10 (SI Unit)

Space	Floor	Floor Area, m2	Supply Air, l/s	Fresh Air, l/s	Room		
					Sensible Load, kW	Latent Load, kW	Total Load, kW
Bar	L10	20	51.89	27.36	0.67	0.11	0.79
Chairman Office	L10	65	442.92	34.91	6.26	0.30	6.56
Director	L10	81	450.47	14.15	6.54	0.12	6.65
Foyer	L10	40	84.91	27.83	1.10	0.39	1.49
IDF	L10	11	25.94	6.13	0.37	0.05	0.42
Lift Lobby	L10	111	289.62	59.91	3.75	0.63	4.38
Lounge 1	L10	23	196.23	12.26	2.81	0.11	2.92
Lounge 2	L10	22	182.08	11.79	2.60	0.11	2.70
Lounge 3	L10	23	193.87	12.26	2.74	0.11	2.84
Meeting Room	L10	24	198.58	12.74	2.84	0.12	2.95
Outdoor Terrace	L10	368	1,343.40	256.60	18.58	3.65	22.23
PA	L10	26	241.51	14.15	3.46	0.13	3.59
PA 1	L10	17	42.45	8.96	0.55	0.08	0.63
PA 2	L10	33	245.28	17.92	3.45	0.15	3.60
Pantry	L10	10	25.94	5.19	0.33	0.05	0.38
Private Room	L10	34	88.68	18.40	1.15	0.16	1.31
Residence Office	L10	42	339.62	22.64	4.94	0.19	5.13
Sec	L10	13	33.49	7.08	0.43	0.06	0.57
Secu	L10	8	19.81	4.25	0.26	0.04	0.29
Service Lobby	L10	28	73.58	15.09	0.95	0.16	1.11
Strategy	L10	29	67.92	15.57	0.98	0.13	1.11
Utility 1	L10	7	15.57	3.77	0.22	0.02	0.24
Utility 2	L10	4	9.91	2.36	0.14	0.01	0.16
VIP Lounge	L10	37	290.09	19.81	4.14	0.18	4.32
Waiting	L10	11	23.11	7.55	0.30	0.11	0.41
		1,087	**4,977**	**639**	**70**	**7**	**77**

4.3 System Capacity

System capacity is determined based on the total space cooling load and the total ventilation air required. For both VAV and ACB, the cooling coil is sized based on 53 ^{o}F off-coil and 75DB/64WB ^{o}F room temperature.

4.3.1 VAV

From **Table 4.7,** it shows that the total AHU capacity required for Ground Floor is 150,376 BTU/hr, where 110,814 BTU/hr is sensible and 39,562 BTU/hr is latent. Whereas, for Level 1 to Level 9, the total AHU capacity is 454,094 Btu/hr with 368,836 Btu/hr sensible and 85,258 Btu/hr latent as shown in **Table 4.9.** For level 10, the total AHU capacity is 398,674 Btu/hr, with 305,532 Btu/hr sensible and 93,142 Btu/hr latent as shown in **Table 4.11. Table 4.13** shows the summary of AHU capacity for all levels.

Table 4.7 AHU Capacity for Ground Floor

Space	Floor	Floor Area, ft2	Supply Air, CFM	Fresh Air, CFM	Cooling Coil, AHU		
					Sensible Load, BTU/hr	Latent Load, BTU/hr	Total Load, BTU/hr
Lift Lobby	GF	1,012	520	108	14,382	7,590	21,972
Meeting Room 1	GF	162	127	22	3,696	1,746	5,442
Meeting Room 2	GF	135	106	19	1,413	1,344	2,757
Office 1	GF	172	87	18	2,386	1,153	3,539
Office 2	GF	129	65	14	1,790	864	2,654
Retail	GF	3,724	3,361	396	84,391	25,224	109,615
IDF	GF	122	39	13	1,256	862	2,118
Utility	GF	108	49	11	1,500	779	2,279
		5,564	**4,354**	**601**	**110,814**	**39,562**	**150,376**

Table 4.8 AHU Capacity for Ground Floor (SI Unit)

Space	Floor	Floor Area, m2	Supply Air, l/s	Fresh Air, l/s	Cooling Coil, AHU		
					Sensible Load, kW	Latent Load, kW	Total Load, kW
Lift Lobby	GF	94	245.28	50.94	4.21	2.22	6.44
Meeting Room 1	GF	15	59.91	10.38	1.08	0.51	1.59
Meeting Room 2	GF	13	50.00	8.96	0.41	0.39	0.81
Office 1	GF	16	41.04	8.49	0.70	0.34	1.04
Office 2	GF	12	30.66	6.60	0.52	0.25	0.78
Retail	GF	346	1,585.38	186.79	24.73	7.39	32.13
IDF	GF	11	18.40	6.13	0.37	0.25	0.62
Utility	GF	10	23.11	5.19	0.44	0.23	0.67
		517	**2,054**	**283**	**32**	**12**	**44**

Table 4.9 AHU Capacity for Level 1 to Level 9

Space	Floor	Floor Area, ft2	Supply Air, CFM	Fresh Air, CFM	Cooling Coil, AHU		
					Sensible Load, BTU/hr	Latent Load, BTU/hr	Total Load, BTU/hr
Compactius Room	L1	146	46	16	1,503	1,031	2,534
Corridor	L1	1,808	680	249	22,349	17,926	40,275
Director 1	L1	280	955	30	22,915	1,307	24,222
Director 2	L1	323	919	34	22,060	1,782	23,842
Director 3	L1	312	914	33	1,687	2,168	3,855
Equip 1	L1	71	23	8	731	501	1,232
Equip 2	L1	89	28	9	916	628	1,544
File Room 1	L1	140	44	15	1,442	989	2,431
File Room 2	L1	86	27	9	886	607	1,493
File Room 3	L1	135	43	14	1,402	954	2,356
IDF	L1	122	39	13	1,256	862	2,118
Lift Lobby	L1	463	214	49	6,445	3,453	9,898
Meeting Room 1	L1	420	330	58	8,769	4,396	13,165
Meeting Room 2	L1	237	186	33	5,350	2,540	7,890
Meeting Room 3	L1	248	195	34	5,178	2,596	7,774
Mgr 1	L1	151	325	16	7,987	952	8,939
Mgr 2	L1	151	325	16	7,987	952	8,939
Mgr 3	L1	151	325	16	7,987	952	8,939
Mgr 4	L1	151	325	16	7,987	952	8,939
Mgr 5	L1	188	431	20	10,211	1,057	11,268
Mgr 6	L1	188	431	20	10,211	1,057	11,268
Office 1	L1	1,249	2,120	133	51,765	8,131	59,896
Office 2	L1	2,799	4,456	297	108,426	16,453	124,879

Office 3	L1	404	754	43	18,142	2,114	20,256
Pantry	L1	200	93	21	2,789	1,492	4,281
Printing	L1	334	152	35	4,597	2,408	7,005
Room 1	L1	172	385	18	9,344	1,080	10,424
Room 2	L1	173	386	18	9,358	1,089	10,447
Sec 1	L1	118	54	13	1,624	851	2,475
Sec 2	L1	140	64	15	1,927	1,009	2,936
Sec 3	L1	205	93	22	2,821	1,478	4,299
Service Lobby	L1	200	93	21	2,784	1,491	4,275
		11,854	**15,455**	**1,344**	**368,836**	**85,258**	**454,094**

Table 4.10 AHU Capacity for Level 1 to Level 9 (SI Unit)

Space	Floor	Floor Area, m2	Supply Air, l/s	Fresh Air, l/s	Cooling Coil, AHU		
					Sensible Load, kW	**Latent Load, kW**	**Total Load, kW**
Compactius Room	L1	14	21.70	7.55	0.44	0.30	0.74
Corridor	L1	168	320.75	117.45	6.55	5.25	11.80
Director 1	L1	26	450.47	14.15	6.72	0.38	7.10
Director 2	L1	30	433.49	16.04	6.47	0.52	6.99
Director 3	L1	29	431.13	15.57	0.49	0.64	1.13
Equip 1	L1	7	10.85	3.77	0.21	0.15	0.36
Equip 2	L1	8	13.21	4.25	0.27	0.18	0.45
File Room 1	L1	13	20.75	7.08	0.42	0.29	0.71
File Room 2	L1	8	12.74	4.25	0.26	0.18	0.44
File Room 3	L1	13	20.28	6.60	0.41	0.28	0.69
IDF	L1	11	18.40	6.13	0.37	0.25	0.62

Lift Lobby	L1	43	100.94	23.11	1.89	1.01	2.90
Meeting Room 1	L1	39	155.66	27.36	2.57	1.29	3.86
Meeting Room 2	L1	22	87.74	15.57	1.57	0.74	2.31
Meeting Room 3	L1	23	91.98	16.04	1.52	0.76	2.28
Mgr 1	L1	14	153.30	7.55	2.34	0.28	2.62
Mgr 2	L1	14	153.30	7.55	2.34	0.28	2.62
Mgr 3	L1	14	153.30	7.55	2.34	0.28	2.62
Mgr 4	L1	14	153.30	7.55	2.34	0.28	2.62
Mgr 5	L1	17	203.30	9.43	2.99	0.31	3.30
Mgr 6	L1	17	203.30	9.43	2.99	0.31	3.30
Office 1	L1	116	1,000.00	62.74	15.17	2.38	17.55
Office 2	L1	260	2,101.89	140.09	31.78	4.82	36.60
Office 3	L1	38	355.66	20.28	5.32	0.62	5.94
Pantry	L1	19	43.87	9.91	0.82	0.44	1.25
Printing	L1	31	71.70	16.51	1.35	0.71	2.05
Room 1	L1	16	181.60	8.49	2.74	0.32	3.05
Room 2	L1	16	182.08	8.49	2.74	0.32	3.06
Sec 1	L1	11	25.47	6.13	0.48	0.25	0.73
Sec 2	L1	13	30.19	7.08	0.56	0.30	0.86
Sec 3	L1	19	43.87	10.38	0.83	0.43	1.26
Service Lobby	L1	19	43.87	9.91	0.82	0.44	1.25
		1,101	**7,290**	**634**	**108**	**25**	**133**

Table 4.11 AHU Capacity for Level 10

Space	Floor	Floor Area, ft2	Supply Air, CFM	Fresh Air, CFM	Cooling Coil, AHU		
					Sensible Load, BTU/hr	Latent Load, BTU/hr	Total Load, BTU/hr
Bar	L10	215	110	58	34,567	2,525	37,092
Chairman Office	L10	700	939	74	23,613	4,180	27,793
Director	L10	872	955	30	22,915	1,307	24,222
Foyer	L10	431	180	59	5,560	4,465	10,025
IDF	L10	118	55	13	1,642	880	2,522
Lift Lobby	L10	1,195	614	127	16,982	8,962	25,944
Lounge 1	L10	248	416	26	10,161	1,616	11,777
Lounge 2	L10	237	386	25	9,425	1,548	10,973
Lounge 3	L10	248	411	26	9,811	1,456	11,267
Meeting Room	L10	258	421	27	10,341	1,689	12,030
Outdoor Terrace	L10	3,957	2,848	544	78,347	43,878	122,225
PA	L10	280	512	30	12,483	1,812	14,295
PA 1	L10	178	90	19	2,469	1,193	3,662
PA 2	L10	355	520	38	12,448	2,112	14,560
Pantry	L10	108	55	11	1,498	724	2,222
Private Room	L10	371	188	39	5,147	2,486	7,633
Residence Office	L10	452	720	48	17,652	1,645	19,297
Sec	L10	140	71	15	1,942	938	2,880
Secu	L10	83	42	9	1,179	638	1,817
Service Lobby	L10	304	156	32	4,320	2,280	6,600
Strategy	L10	312	144	33	4,325	2,121	6,446
Utility 1	L10	72	33	8	1,000	519	1,519
Utility 2	L10	46	21	5	643	334	977

VIP Lounge	L10	398	615	42	15,493	2,604	18,097
Waiting	L10	118	49	16	1,569	1,230	2,799
		11,696	**10,551**	**1,354**	**305,532**	**93,142**	**398,674**

Table 4.12 AHU Capacity for Level 10 (SI Unit)

Space	Floor	Floor Area, m2	Supply Air, l/s	Fresh Air, l/s	Cooling Coil, AHU		
					Sensible Load, kW	Latent Load, kW	Total Load, kW
Bar	L10	20	51.89	27.36	10.13	0.74	10.87
Chairman Office	L10	65	442.92	34.91	6.92	1.23	8.15
Director	L10	81	450.47	14.15	6.72	0.38	7.10
Foyer	L10	40	84.91	27.83	1.63	1.31	2.94
IDF	L10	11	25.94	6.13	0.48	0.26	0.74
Lift Lobby	L10	111	289.62	59.91	4.98	2.63	7.60
Lounge 1	L10	23	196.23	12.26	2.98	0.47	3.45
Lounge 2	L10	22	182.08	11.79	2.76	0.45	3.22
Lounge 3	L10	23	193.87	12.26	2.88	0.43	3.30
Meeting Room	L10	24	198.58	12.74	3.03	0.49	3.53
Outdoor Terrace	L10	368	1,343.40	256.60	22.96	12.86	35.82
PA	L10	26	241.51	14.15	3.66	0.53	4.19
PA 1	L10	17	42.45	8.96	0.72	0.35	1.07
PA 2	L10	33	245.28	17.92	3.65	0.62	4.27
Pantry	L10	10	25.94	5.19	0.44	0.21	0.65
Private Room	L10	34	88.68	18.40	1.51	0.73	2.24
Residence Office	L10	42	339.62	22.64	5.17	0.48	5.66
Sec	L10	13	33.49	7.08	0.57	0.27	0.84

Secu	L10	8	19.81	4.25	0.35	0.19	0.53
Service Lobby	L10	28	73.58	15.09	1.27	0.67	1.93
Strategy	L10	29	67.92	15.57	1.27	0.62	1.89
Utility 1	L10	7	15.57	3.77	0.29	0.15	0.45
Utility 2	L10	4	9.91	2.36	0.19	0.10	0.29
VIP Lounge	L10	37	290.09	19.81	4.54	0.76	5.30
Waiting	L10	11	23.11	7.55	0.46	0.36	0.82
		1,087	**4,977**	**639**	**90**	**27**	**117**

Table 4.13 Summary of AHU Capacity for All Levels

Floor Level	Reference no.	Area Served	Floor Area, ft2	Sensible, Btu/hr	Cooling Capacity, Btu/hr	On Coil	Off coil	Air Flow, cfm	Static, pa	Water Flow, gpm
GF	AHU-OFF-GF	GF	5,564	110,814	150,376	77	53	4,354	500	30.08
L1-L9	AHU-OFF-L1 TO L9	L1	11,854	368,836	454,094	75	53	15,455	500	90.82
L10	AHU-OFF-L10	L10	11,696	305,532	398,674	77	53	10,551	500	79.73

Table 4.14 Summary of AHU Capacity for All Levels (SI Unit)

Floor Level	Reference no.	Area Served	Floor Area, m2	Sensible, kW	Cooling Capacity, kW	On Coil	Off coil	Air Flow, l/s	Static, pa	Water Flow, l/s
GF	AHU-OFF-GF	GF	517	32	44	25	12	2,054	500	1.90
L1-L9	AHU-OFF-L1 TO L9	L1	1,101	108	133	24	12	7,290	501	5.73
L10	AHU-OFF-L10	L10	1,087	90	117	25	12	4,977	502	5.03

4.3.2 ACB

For ACB system, the total AHU capacity is significantly lesser than VAV as the room sensible is catered by chilled beams. As shown in **Table 4.15**, for Ground Floor, the total AHU capacity is 64,302 Btu/hr and the total sensible capacity of chilled beam is 100,591 Btu/hr. Whereas, for Level 1 to Level 9, the total AHU capacity and total sensible capacity of chilled beam are 229,396 Btu/hr and 329,415 Btu/hr respectively as shown in **Table 4.17**. For level 10, the total AHU capacity is 216,442 Btu/hr and the total sensible capacity of chilled beam is 254,879 Btu/hr as shown in **Table 4.19**. **Table 4.21** shows the summary of AHU capacity and chilled beam capacity for all levels.

Table 4.15 AHU Capacity and Chilled Beam Capacity for Ground Floor

Space	Floor Area, ft2	ACB				AHU			
		Total Air Flow Rate, cfm	Total Water Flow Rate, Gpm	Total Sensible, Btu/hr	Total Sensible, Btu/hr (water)	Air Flow,CFM	Sensible, BTU/hr	Latent, BTU/hr	Total, Btu/hr
Lift Lobby	1012	192	1.4	11,709	7,218	342	9,648	6,290	15,938
Meeting Room 1	162	64	1.4	3,903	7,218	64	1,833	1,231	3,064
Meeting Room 2	135	64	1.4	3,903	7,218	64	1,833	1,231	3,064
Office 1	172	64	0.9	3,023	4,575	64	1,787	1,126	2,913
Office 2	129	64	0.9	3,023	4,575	64	1,731	995	2,726
Retail	3724	960	2.1	75,030	10,512	960	23,065	8,511	31,576
IDF	112	-	-	-	-	39	1,015	1,256	2,271
Utility	108	-	-	-	-	49	1,250	1,500	2,750
	5,442	**1,408**	**8.26**	**100,591**	**41,316**	**1,646**	**42,162**	**22,140**	**64,302**

Table 4.16 AHU Capacity and Chilled Beam Capacity for Ground Floor (SI Unit)

Space	Floor Area, m2	ACB				AHU			
		Total Air Flow Rate, l/s	Total Water Flow Rate, l/s	Total Sensible, kW	Total Sensible, kW (water)	Air Flow,l/s	Sensible, kW	Latent, kW	Total, kW
Lift Lobby	94	90.57	0.09	3.43	2.12	161.32	2.83	1.84	4.67
Meeting Room 1	15	30.19	0.09	1.14	2.12	30.19	0.54	0.36	0.90
Meeting Room 2	13	30.19	0.09	1.14	2.12	30.19	0.54	0.36	0.90
Office 1	16	30.19	0.06	0.89	1.34	30.19	0.52	0.33	0.85
Office 2	12	30.19	0.06	0.89	1.34	30.19	0.51	0.29	0.80
Retail	346	452.83	0.13	21.99	3.08	452.83	6.76	2.49	9.25
IDF	10	-	-	-	-	18.40	0.30	0.37	0.67
Utility	10	-	-	-	-	23.11	0.37	0.44	0.81
	516	**664.15**	**0.52**	**29.48**	**12.11**	**776.42**	**12.36**	**6.49**	**18.85**

Table 4.17 AHU Capacity and Chilled Beam Capacity for Level 1 to Level 9

Space	Floor Area, ft2	ACB				AHU			
		Total Air Flow Rate, cfm	Total Water Flow Rate, Gpm	Total Sensible, Btu/hr	Total Sensible, Btu/hr (water)	Air Flow,CFM	Sensible, BTU/hr	Latent, BTU/hr	Total, Btu/hr
Compactius Room	146	-	-	-	-	46	1,503	1,031	2,534
Corridor	1,808	-	-	-	-	680	22,349	17,926	40,275
Director 1	280	256	2.1	20,008	10,512	256	6,437	2,905	9,342
Director 2	323	256	2.1	20,008	10,512	256	6,437	2,905	9,342
Director 3	312	256	2.1	20,008	10,512	256	6,437	2,905	9,342
Equip 1	71	-	-	-	-	23	731	501	1,232
Equip 2	89	-	-	-	-	28	916	628	1,544
File Room 1	140	-	-	-	-	44	1,442	989	2,431
File Room 2	86	-	-	-	-	27	886	607	1,493
File Room 3	135	-	-	-	-	43	1,402	954	2,356
IDF	122	-	-	-	-	39	1,256	862	2,118
Lift Lobby	463	64	2.1	5,002	10,512	64	1,833	1,231	3,064
Meeting Room 1	420	128	1.4	7,806	7,218	128	3,395	1,838	5,233
Meeting Room 2	237	64	1.4	3,903	7,218	64	1,833	1,231	3,064
Meeting Room 3	248	64	1.4	3,903	7,218	64	1,833	1,231	3,064
Mgr 1	151	128	1.4	7,806	7,218	128	3,306	1,631	4,937
Mgr 2	151	128	1.4	7,806	7,218	128	3,306	1,631	4,937
Mgr 3	151	128	1.4	7,806	7,218	128	3,306	1,631	4,937
Mgr 4	151	128	1.4	7,806	7,218	128	3,306	1,631	4,937
Mgr 5	188	128	2.1	10,004	10,512	128	3,306	1,631	4,937
Mgr 6	188	128	2.1	10,004	10,512	128	3,306	1,631	4,937
Office 1	1,249	640	2.1	50,020	10,512	640	14,008	5,469	19,477
Office 2	2,799	1280	2.1	100,040	10,512	1,280	30,811	11,481	42,292
Office 3	404	256	1.9	18,768	9,591	256	6,437	2,905	9,342

Pantry	200	64	0.9	3,023	4,575	64	1,937	1,473	3,410
Printing	334	64	1.4	3,903	7,218	64	1,937	1,473	3,410
Room 1	172	128	1.9	9,384	9,591	128	3,395	1,838	5,233
Room 2	173	128	1.9	9,384	9,591	128	3,395	1,838	5,233
Sec 1	118	-	-	-	-	54	1,624	851	2,475
Sec 2	140	-	-	-	-	64	1,927	1,009	2,936
Sec 3	205	-	-	-	-	93	2,821	1,478	4,299
Service Lobby	200	64	0.9	3,023	4,575	64	3,395	1,838	5,233
	11,854	**4,480**	**36**	**329,415**	**179,763**	**5,621**	**150,213**	**79,183**	**229,396**

Table 4.18 AHU Capacity and Chilled Beam Capacity for Level 1 to Level 9 (SI Unit)

Space	Floor Area, m2	ACB				AHU			
		Total Air Flow Rate, l/s	Total Water Flow Rate, l/s	Total Sensible, kW	Total Sensible, kW (water)	Air Flow,l/s	Sensible, kW	Latent, kW	Total, kW
Compactius Room	14	-	-	-	-	21.70	0.44	0.30	0.74
Corridor	168	-	-	-	-	320.75	6.55	5.25	11.80
Director 1	26	120.75	0.13	5.86	3.08	120.75	1.89	0.85	2.74
Director 2	30	120.75	0.13	5.86	3.08	120.75	1.89	0.85	2.74
Director 3	29	120.75	0.13	5.86	3.08	120.75	1.89	0.85	2.74
Equip 1	7	-	-	-	-	10.85	0.21	0.15	0.36
Equip 2	8	-	-	-	-	13.21	0.27	0.18	0.45
File Room 1	13	-	-	-	-	20.75	0.42	0.29	0.71
File Room 2	8	-	-	-	-	12.74	0.26	0.18	0.44
File Room 3	13	-	-	-	-	20.28	0.41	0.28	0.69
IDF	11	-	-	-	-	18.40	0.37	0.25	0.62
Lift Lobby	43	30.19	0.13	1.47	3.08	30.19	0.54	0.36	0.90
Meeting Room 1	39	60.38	0.09	2.29	2.12	60.38	0.99	0.54	1.53

Meeting Room 2	22	30.19	0.09	1.14	2.12	30.19	0.54	0.36	0.90
Meeting Room 3	23	30.19	0.09	1.14	2.12	30.19	0.54	0.36	0.90
Mgr 1	14	60.38	0.09	2.29	2.12	60.38	0.97	0.48	1.45
Mgr 2	14	60.38	0.09	2.29	2.12	60.38	0.97	0.48	1.45
Mgr 3	14	60.38	0.09	2.29	2.12	60.38	0.97	0.48	1.45
Mgr 4	14	60.38	0.09	2.29	2.12	60.38	0.97	0.48	1.45
Mgr 5	17	60.38	0.13	2.93	3.08	60.38	0.97	0.48	1.45
Mgr 6	17	60.38	0.13	2.93	3.08	60.38	0.97	0.48	1.45
Office 1	116	301.89	0.13	14.66	3.08	301.89	4.11	1.60	5.71
Office 2	260	603.77	0.13	29.32	3.08	603.77	9.03	3.36	12.39
Office 3	38	120.75	0.12	5.50	2.81	120.75	1.89	0.85	2.74
Pantry	19	30.19	0.06	0.89	1.34	30.19	0.57	0.43	1.00
Printing	31	30.19	0.09	1.14	2.12	30.19	0.57	0.43	1.00
Room 1	16	60.38	0.12	2.75	2.81	60.38	0.99	0.54	1.53
Room 2	16	60.38	0.12	2.75	2.81	60.38	0.99	0.54	1.53
Sec 1	11	-	-	-	-	25.47	0.48	0.25	0.73
Sec 2	13	-	-	-	-	30.19	0.56	0.30	0.86
Sec 3	19	-	-	-	-	43.87	0.83	0.43	1.26
Service Lobby	19	30.19	0.06	0.89	1.34	30.19	0.99	0.54	1.53
	1,101	**2,113**	**2**	**97**	**53**	**2,651**	**44**	**23**	**67**

Table 4.19 AHU Capacity and Chilled Beam Capacity for Level 10

Space	Floor Area, ft2	ACB				AHU			
		Total Air Flow Rate, cfm	Total Water Flow Rate, Gpm	Total Sensible, Btu/hr	Total Sensible, Btu/hr (water)	Air Flow Rate, CFM	Sensible, BTU/hr	Latent, BTU/hr	Total
Bar	215	64	2.1	5,002	10,512	64	1,839	1,245	3,084
Chairman Office	700	320	1.9	23,460	9,591	320	8,684	5,141	13,825
Director	872	320	1.9	23,460	9,591	320	8,907	5,656	14,563
Foyer	431	64	1.4	3,903	7,218	64	1,937	1,473	3,410
IDF	118	-	-	-	-	55	1,642	880	2,522
Lift Lobby	1,195	192	1.9	14,076	9,591	392	11,105	7,309	18,414
Lounge 1	248	128	2.1	10,004	10,512	128	3,451	1,966	5,417
Lounge 2	237	128	1.9	9,384	9,591	128	3,435	1,930	5,365
Lounge 2	237	128	2.1	10,004	10,512	128	3,451	1,966	5,417
Meeting Room	258	128	2.1	10,004	10,512	128	3,465	1,998	5,463
Outdoor Terrace	259	832	2.1	65,026	10,512	1,832	49,821	29,371	79,192
PA	280	192	1.4	11,709	7,218	192	5,017	2,627	7,644
PA 1	178	64	0.9	3,023	4,575	64	1,795	1,143	2,938
PA 2	355	192	1.9	14,076	9,591	192	5,127	2,881	8,008
Pantry	108	-	-	-	-	55	1,498	724	2,222
Private Room	371	64	2.1	5,002	10,512	64	1,991	1,597	3,588
Residence Office	452	256	1.9	18,768	9,591	256	6,815	3,778	10,593
Sec	140	64	0.9	3,023	4,575	64	1,746	1,030	2,776
Secu	83	-	-	-	-	42	1,179	638	1,817
Service Lobby	304	64	0.9	3,023	4,575	64	1,931	1,459	3,390
Strategy	312	64	1.4	3,903	7,218	64	1,939	1,477	3,416
Utility 1	72	-	-	-	-	33	1,000	519	1,519

Utility 2	46	-	-	-	-	21	643	334	977
VIP Lounge	398	192	2.1	15,006	10,512	192	5,187	3,020	8,207
Waiting	118	64	0.9	3,023	4,575	64	1,715	960	2,675
	7,987	**3,520**	**34**	**254,879**	**171,084**	**4,926**	**135,320**	**81,122**	**216,442**

Table 4.20 AHU Capacity and Chilled Beam Capacity for Level 10 (SI Unit)

Space	Floor Area, m2	ACB				AHU			
		Total Air Flow Rate, l/s	Total Water Flow Rate, l/s	Total Sensible, kW	Total Sensible, kW (water)	Air Flow Rate, l/s	Sensible, kW	Latent, kW	Total, kW
Bar	20	64.00	2.10	5002.00	10512.00	30.19	0.54	0.36	0.90
Chairman Office	65	320.00	1.92	23460.00	9591.00	150.94	2.55	1.51	4.05
Director	81	150.94	0.12	6.88	2.81	150.94	2.61	1.66	4.27
Foyer	40	30.19	0.09	1.14	2.12	30.19	0.57	0.43	1.00
IDF	11	-	-	-	-	25.94	0.48	0.26	0.74
Lift Lobby	111	192.00	1.92	14076.00	9591.00	184.91	3.25	2.14	5.40
Lounge 1	23	128.00	2.10	10004.00	10512.00	60.38	1.01	0.58	1.59
Lounge 2	22	128.00	1.92	9384.00	9591.00	60.38	1.01	0.57	1.57
Lounge 2	22	128.00	2.10	10004.00	10512.00	60.38	1.01	0.58	1.59
Meeting Room	24	128.00	2.10	10004.00	10512.00	60.38	1.02	0.59	1.60
Outdoor Terrace	24	832.00	2.10	65026.00	10512.00	864.15	14.60	8.61	23.21
PA	26	192.00	1.44	11709.00	7218.00	90.57	1.47	0.77	2.24
PA 1	17	64.00	0.92	3023.00	4575.00	30.19	0.53	0.33	0.86
PA 2	33	192.00	1.92	14076.00	9591.00	90.57	1.50	0.84	2.35
Pantry	10	-	-	-	-	25.94	0.44	0.21	0.65
Private Room	34	64.00	2.10	5002.00	10512.00	30.19	0.58	0.47	1.05

Residence Office	42	256.00	1.92	18768.00	9591.00	120.75	2.00	1.11	3.10
Sec	13	64.00	0.92	3023.00	4575.00	30.19	0.51	0.30	0.81
Secu	8	-	-	-	-	19.81	0.35	0.19	0.53
Service Lobby	28	64.00	0.92	3023.00	4575.00	30.19	0.57	0.43	0.99
Strategy	29	64.00	1.44	3903.00	7218.00	30.19	0.57	0.43	1.00
Utility 1	7	-	-	-	-	15.57	0.29	0.15	0.45
Utility 2	4	-	-	-	-	9.91	0.19	0.10	0.29
VIP Lounge	37	192.00	2.10	15006.00	10512.00	90.57	1.52	0.89	2.41
Waiting	11	64.00	0.92	3023.00	4575.00	30.19	0.50	0.28	0.78
	742	**3,317**	**31**	**227,524**	**154,280**	**2,324**	**40**	**24**	**63**

Table 4.21 Summary of AHU Capacity and Chilled Beam Capacity for All Levels

Space	Floor area, ft2	ACB				AHU				
		Total Air Flow Rate, cfm	Total Sensible, Btu/hr	Total Sensible, Btu/hr (water)	Total Water Flow Rate, USgpm	Air Flow Rate, CFM	Sensible, BTU/hr	Latent, BTU/hr	Total, Btu/hr	Water Flow Rate, USgpm
GF	5564	1,408	100,591	41,316	8	1,646	42,162	22,140	64,302	13
L1-L9	11854	4,480	329,415	179,763	36	5,621	150,213	79,183	229,396	46
L10	11696.3	3,520	254,879	171,084	34	4,926	135,320	81,122	216,442	43

Table 4.22 Summary of AHU Capacity and Chilled Beam Capacity for All Levels (SI Unit)

Space	Floor Area, m2	ACB				AHU				
		Total Air Flow Rate, l/s	Total Sensible, kW	Total Sensible, kW (water)	Total Water Flow Rate, l/s	Air Flow Rate, l/s	Sensible, kW	Latent, kW	Total, kW	Water Flow Rate, l/s
GF	517	664.15	47,448.58	12.11	0.52	776	12.36	6.49	18.85	0.81
L1-L9	1101	2,113.21	155,384.43	52.68	2.27	2,651	44.02	23.21	67.23	2.89
L10	1087	1,660.38	120,225.94	50.14	2.16	2,324	39.66	23.77	63.43	2.73

4.4 System Layout

Air duct is sized based on procedures explained in Chapter 3 Methodology for both systems. It involves only ducting for VAV at every individual zone where VAV box is used to control the air flow into the conditioned space. Whereas for ACB, it involves both ducting and piping where the air flow is constant all the time but the water flow varies in response to room temperature. Zoning is done by using PIBCV valve to control the secondary chilled water flow into the chilled beams based on room temperature for each particular zone. For each zone, temperature sensor or thermostat is used to measure the room temperature and send the signal to VAV box or PIBCV valve to modulate the air flow and water flow respectively. Temperature sensor is used for open areas where the conditioned space is not confined within a compartment or a room. For close areas like manager office, thermostat is used to allow user to control the desired temperature. From the following figures, it can be observed that the duct required is lesser for ACB compared to VAV. However, additional piping is required for ACB. **Figure 4.1** shows the layout of VAV system where it involves only ducting and **Figure 4.2** shows the layout of ACB system where it involves both ducting and piping. Refer to **Appendix 3 and 4** for complete layout.

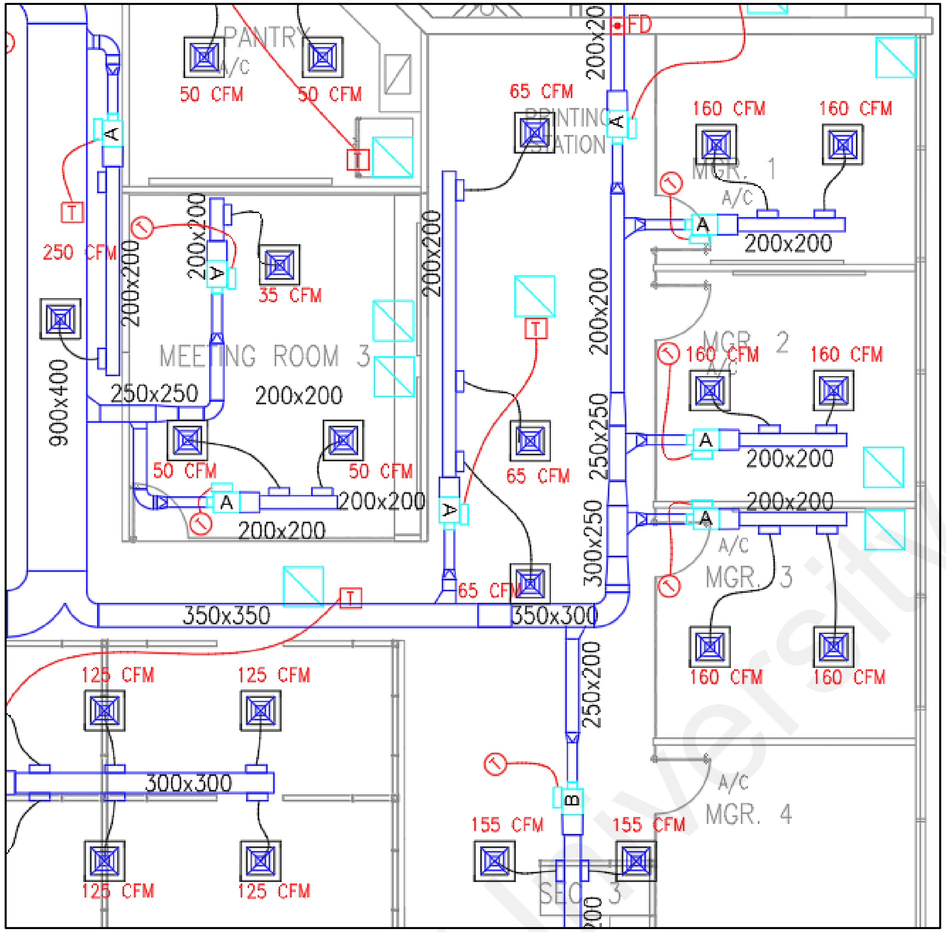


Figure 4.1 VAV System Layout

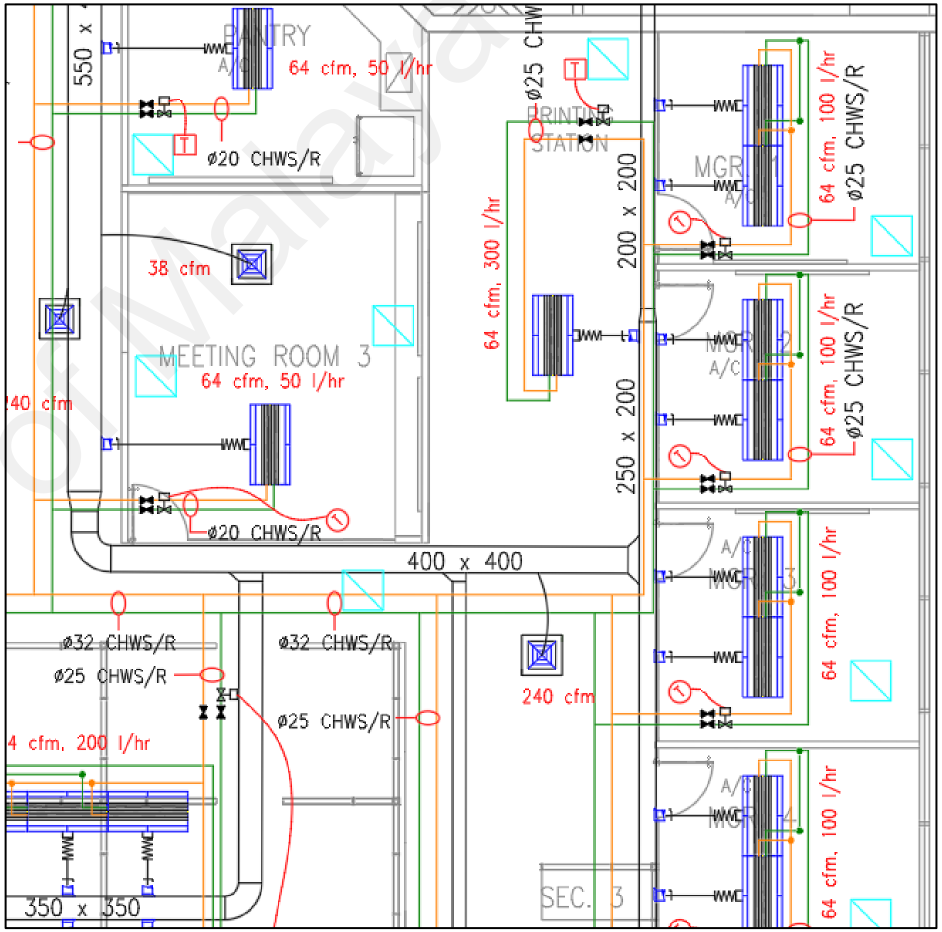


Figure 4.2 ACB System Layout

CHAPTER 5. ENERGY & COST ANALYSIS AND DISCUSSION

5.1 Introduction

A detailed analysis on the energy and cost comparing between VAV and ACB is presented in this chapter. Both short-term and long-term savings are determined and justified.

5.2 Energy Comparison

Energy comparison is performed based on individual floors and overall building at three different load conditions: 100%, 75% sensible & 90% latent, and 50% sensible & 80% latent. At these three conditions, the system capacity and power consumption are determined. System capacity includes the capacity of AHU, pump, chilled beam, chiller and cooling tower. Likewise, the power consumption includes the equipment involved in the system and analysis is performed to determine which system gives better saving.

5.2.1 Individual Floors

5.2.1.1 Ground Floor

In terms of AHU capacity, VAV is much higher than ACB with 57% more at full load and part load conditions, and 55% more at lowest load condition. Likewise, VAV has higher power consumption than ACB where at full load condition, the power consumption is 50% higher than the latter with 10.9 kW compared to 7.3 kW as shown in **Table 5.1**. At part load conditions, VAV has higher power consumption than ACB with 8.4 kW and 6.1 kW compared to 6.2 kW and 5.1 kW respectively. In other words, ACB is more energy-saving compared to VAV at all three conditions for ground floor.

5.2.1.2 Level 1 to Level 9

The AHU capacity for VAV is higher than ACB at all three conditions, between the range 45 – 50%. In terms of power consumption, VAV is 21% higher than ACB at full load condition with 34 kW compared to 28.0 kW as shown in **Table 5.3.** Likewise, at normal part load condition, VAV has higher power consumption than ACB, with 25.7 kW compared to 21.9 kW. However, at lowest part load condition, the power consumption for VAV is lower than ACB, with 18.1 kW compared to 20.1 kW.

5.2.1.3 Level 10

Comparing between the two systems, VAV has higher AHU capacity than ACB at all three conditions, at the range of 42 – 46%. In terms of power consumption, VAV is 8% higher than ACB at full load condition, with 28.3 kW compared to 26.2 kW. However, at part load conditions, the savings is on the VAV's side where the power consumption is 22.5 kW and 16.0 kW compared to 22.5 kW and 19.2 kW respectively for ACB.

Table 5.1 Total Power Consumption at 3 Different Load Conditions for Ground Level

		100%		75% sensible	90% latent	50% sensible	80% latent
LOAD & CAPACITY		**VAV**	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Required Building & System Load	Zone Sensible Heat(Btu/hr)	96,192	96,192	72,144	72,144	48,096	48,096
	Zone Latent Heat(Btu/hr)	8,924	8,924	8,032	8,032	7,139	7,139
	Total Zone Load(Btu/hr)	105,116	105,116	80,176	80,176	55,235	55,235
System Capacity	ACB Water Capacity (Btu/hr)	-	41,316	-	35,685	-	29,094
	ACB Capacity (Btu/hr)	-	100,591	-	95,013	-	86,396
	AHU Capacity Sensible (Btu/hr)	110,814	42,162	83,111	31,622	55,407	21,081
	AHU Capacity Latent (Btu/hr)	39,562	22,140	35,606	19,926	31,650	17,712
	Total AHU Capacity (Btu/hr)	150,376	64,302	118,716	51,548	87,057	38,793
	AHU Air flow (cfm)	4,354	1,646	3,206	1,496	2,138	1,646
	AHU Chilled Water flow (gpm)	30.1	12.9	23.7	10.3	17.4	7.8
	ACB Chilled Water flow - Primary (gpm)	-	13.2	-	11.4	-	9.3
	ACB Chilled Water flow - Secondary (gpm)	-	8.3	-	7.1	-	5.8
	Condenser Water flow (gpm)	39.1	27.5	30.9	22.7	22.6	17.7
	Chiller Capacity (RT)	12.5	8.8	9.9	7.3	7.3	5.7
	Cooling Tower Capacity (HRT)	16.3	11.4	12.9	9.5	9.4	7.4
Power Consumption							
Water side (Pump)	AHU Power Input (kW)	0.5	0.2	0	0.2	0.3	0
	ACB Power Input - Primary (kW)	-	0.2	-	0.2	-	0.1
	ACB Power Input - Secondary (kW)	-	0.1	-	0.1	-	0.1

Air side (Fan)	AHU Power Input (kW)	2.3	1.2	1.7	1.1	1.1	1.2
	Chiller Power Input (kW)	7.5	5.3	5.9	4.4	4.4	3.4
	Cooling Tower Power Input (kW)	0.5	0.3	0.4	0.3	0.3	0.2
	Total Power Input (kW)	**10.9**	**7.3**	**8.4**	**6.2**	**6.1**	**5.1**

Table 5.2 Total Power Consumption at 3 Different Load Conditions for Ground Level (SI Unit)

		100%		**75% sensible**	**90% latent**	**50% sensible**	**80% latent**
LOAD & CAPACITY		**VAV**	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Required Building & System Load	Zone Sensible Heat(kW)	28	28	21	21	14	14
	Zone Latent Heat(kW)	3	3	2	2	2	2
	Total Zone Load(kW)	31	31	23	23	16	16
System Capacity	ACB Water Capacity (kW)	-	12	-	10	-	9
	ACB Capacity (kW)	-	29	-	28	-	25
	AHU Capacity Sensible (kW)	32	12	24	9	16	6
	AHU Capacity Latent (kW)	12	6	10	6	9	5
	Total AHU Capacity (kW)	44	19	35	15	26	11
	AHU Air flow (l/s)	2,054	776	1,512	706	1,008	776
	AHU Chilled Water flow (l/s)	1.9	0.8	1.5	0.7	1.1	0.5
	ACB Chilled Water flow - Primary (l/s)	-	0.8	-	0.7	-	0.6
	ACB Chilled Water flow - Secondary (l/s)	-	0.5	-	0.5	-	0.4
	Condesner Water flow (l/s)	2.5	1.7	1.9	1.4	1.4	1.1

	Chiller Capacity (kW)	44	31	35	26	26	20
	Cooling Tower Capacity (kW)	57	40	45	33	33	26
Power Consumption							
Water side (Pump)	AHU Power Input (kW)	0.5	0.2	0.4	0.2	0.3	0.1
	ACB Power Input - Primary (kW)	-	0.2	-	0.2	-	0.1
	ACB Power Input - Secondary (kW)	-	0.1	-	0.1	-	0.1
Air side (Fan)	AHU Power Input (kW)	2.3	1.2	1.7	1.1	1.1	1.2
	Chiller Power Input (kW)	7.5	5.3	5.9	4.4	4.4	3.4
	Cooling Tower Power Input (kW)	0.5	0.3	0.4	0.3	0.3	0.2
	Total Power Input (kW)	**10.9**	**7.3**	**8.4**	**6.2**	**6.1**	**5.1**

Table 5.3 Total Power Consumption at 3 Different Load Conditions for Level 1 to Level 9

		100%		75% sensible	90% latent	50% sensible	80% latent
LOAD & CAPACITY		**VAV**	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Required Building & System Load	Zone Sensible Heat(Btu/hr)	353,128	353,128	264,846	264,846	176,564	176,564
	Zone Latent Heat(Btu/hr)	19,932	19,932	17,939	17,939	15,946	15,946
	Total Zone Load(Btu/hr)	373,060	373,060	282,785	282,785	192,510	192,510
System Capacity	ACB Water Capacity (Btu/hr)	-	179,763	-	122,343	-	134,754
	ACB Capacity (Btu/hr)	-	329,415	-	221,905	-	274,732
	AHU Capacity Sensible (Btu/hr)	368,836	150,213	276,627	112,660	184,418	75,107
	AHU Capacity Latent (Btu/hr)	85,258	79,183	76,732	71,265	68,206	63,346
	Total AHU Capacity (Btu/hr)	454,094	229,396	353,359	183,924	252,624	138,453
	AHU Air flow (cfm)	15,455	5,621	10,672	5,621	7,115	5,621
	AHU Chilled Water flow (gpm)	90.8	45.9	70.7	36.8	50.5	27.7
	ACB Chilled Water flow - Primary (gpm)	-	57.5	-	39.1	-	43.1
	ACB Chilled Water flow - Secondary (gpm)	-	36.0	-	24.5	-	27.0
	Condesner Water flow (gpm)	118.1	106.4	91.9	79.6	65.7	71.0
	Chiller Capacity (RT)	37.8	34.1	29.4	25.5	21.1	22.8
	Cooling Tower Capacity (HRT)	49.2	44.3	38.3	33.2	27.4	29.6
Power Consumption							
Water side (Pump)	AHU Power Input (kW)	1.6	0.7	1.3	0.6	0.9	0.4
	ACB Power Input - Primary (kW)	-	0.9	-	0.6	-	0.7
	ACB Power Input - Secondary (kW)	-	0.6	-	0.4	-	0.4

Air side (Fan)	AHU Power Input (kW)	8.2	4.0	5.7	4.0	3.8	4.0
	Chiller Power Input (kW)	22.7	20.5	17.7	15.3	12.6	13.7
	Cooling Tower Power Input (kW)	1.5	1.3	1.1	1.0	0.8	0.9
	Total Power Input (kW)	**34.0**	**28.0**	**25.7**	**21.9**	**18.1**	**20.1**

Table 5.4 Total Power Consumption at 3 Different Load Conditions for Level 1 to Level 9 (SI Unit)

		100%		**75% sensible**	**90% latent**	**50% sensible**	**80% latent**
LOAD & CAPACITY		**VAV**	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Required Building & System Load	Zone Sensible Heat(kW)	103	103	78	78	52	52
	Zone Latent Heat(kW)	6	6	5	5	5	5
	Total Zone Load(kW)	109	109	83	83	56	56
System Capacity	ACB Water Capacity (kW)	-	53	-	36	-	39
	ACB Capacity (kW)	-	97	-	65	-	81
	AHU Capacity Sensible (kW)	108	44	81	33	54	22
	AHU Capacity Latent (kW)	25	23	22	21	20	19
	Total AHU Capacity (kW)	133	67	104	54	74	41
	AHU Air flow (l/s)	7,290	2,651	5,034	2,651	3,356	2,651
	AHU Chilled Water flow (l/s)	5.7	2.9	4.5	2.3	3.2	1.7
	ACB Chilled Water flow - Primary (l/s)	-	3.6	-	2.5	-	2.7
	ACB Chilled Water flow - Secondary (l/s)	-	2.3	-	1.5	-	1.7
	Condesner Water flow (l/s)	7.4	6.7	5.8	5.0	4.1	4.5

	Chiller Capacity (kW)	133	120	104	90	74	80
	Cooling Tower Capacity (kW)	173	156	135	117	96	104
Power Consumption							
Water side (Pump)	AHU Power Input (kW)	1.6	0.7	1.3	0.6	0.9	0.4
	ACB Power Input - Primary (kW)	-	0.9	-	0.6	-	0.7
	ACB Power Input - Secondary (kW)	-	0.6	-	0.4	-	0.4
Air side (Fan)	AHU Power Input (kW)	8.2	4.0	5.7	4.0	3.8	4.0
	Chiller Power Input (kW)	22.7	20.5	17.7	15.3	12.6	13.7
	Cooling Tower Power Input (kW)	1.5	1.3	1.1	1.0	0.8	0.9
	Total Power Input (kW)	**34.0**	**28.0**	**25.7**	**21.9**	**18.1**	**20.1**

Table 5.5 Total Power Consumption at 3 Different Load Conditions for Level 10

		100%		75% sensible	90% latent	50% sensible	80% latent
LOAD & CAPACITY		**VAV**	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Required Building & System Load	Zone Sensible Heat(Btu/hr)	237,313	237,313	177,985	177,985	118,657	118,657
	Zone Latent Heat(Btu/hr)	24,460	24,460	22,014	22,014	19,568	19,568
	Total Zone Load(Btu/hr)	261,773	261,773	199,999	199,999	138,225	138,225
System Capacity	ACB Water Capacity (Btu/hr)	-	171,084	-	158,628	-	133,950
	ACB Capacity (Btu/hr)	-	254,879	-	242,577	-	217,953
	AHU Capacity Sensible (Btu/hr)	305,532	135,320	229,149	101,490	152,766	67,660
	AHU Capacity Latent (Btu/hr)	93,142	81,122	83,828	73,010	74,514	64,898
	Total AHU Capacity (Btu/hr)	398,674	216,442	312,977	174,500	227,280	132,558
	AHU Air flow (cfm)	10,551	4,926	8,841	4,926	5,894	4,926
	AHU Chilled Water flow (gpm)	79.7	43.3	62.6	34.9	45.5	26.5
	ACB Chilled Water flow - Primary (gpm)	-	54.7	-	50.8	-	42.9
	ACB Chilled Water flow - Secondary (gpm)	-	34.2	-	31.7	-	26.8
	Condesner Water flow (gpm)	103.7	100.8	81.4	86.6	59.1	69.3
	Chiller Capacity (RT)	33.2	32.3	26.1	27.8	18.9	22.2
	Cooling Tower Capacity (HRT)	43.2	42.0	33.9	36.1	24.6	28.9
Power Consumption							
Water side (Pump)	AHU Power Input (kW)	1.4	0.7	1	0.6	0.8	0
	ACB Power Input - Primary (kW)	-	0.9	-	0.8	-	0.7
	ACB Power Input - Secondary (kW)	-	0.5	-	0.5	-	0.4

Air side (Fan)	AHU Power Input (kW)	5.6	3.5	4.7	3.5	3.1	3.5
	Chiller Power Input (kW)	19.9	19.4	15.6	16.7	11.4	13.3
	Cooling Tower Power Input (kW)	1.3	1.3	1.0	1.1	0.7	0.9
	Total Power Input (kW)	**28.3**	**26.2**	**22.5**	**23.1**	**16.0**	**19.2**

Table 5.6 Total Power Consumption at 3 Different Load Conditions for Level 10 (SI Units)

		100%		**75% sensible**	**90% latent**	**50% sensible**	**80% latent**
LOAD & CAPACITY		**VAV**	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Required Building & System Load	Zone Sensible Heat(kW)	70	70	52	52	35	35
	Zone Latent Heat(kW)	7	7	6	6	6	6
	Total Zone Load(kW)	77	77	59	59	41	41
System Capacity	ACB Water Capacity (kW)	-	50	-	46	-	39
	ACB Capacity (kW)	-	75	-	71	-	64
	AHU Capacity Sensible (kW)	90	40	67	30	45	20
	AHU Capacity Latent (kW)	27	24	25	21	22	19
	Total AHU Capacity (kW)	117	63	92	51	67	39
	AHU Air flow (l/s)	4,977	2,324	4,170	2,324	2,780	2,324
	AHU Chilled Water flow (l/s)	5.0	2.7	3.9	2.2	2.9	1.7
	ACB Chilled Water flow - Primary (l/s)	-	3.5	-	3.2	-	2.7
	ACB Chilled Water flow - Secondary (l/s)	-	2.2	-	2.0	-	1.7
	Condesner Water flow (l/s)	6.5	6.4	5.1	5.5	3.7	4.4

	Chiller Capacity (kW)	117	114	92	98	67	78
	Cooling Tower Capacity (kW)	152	148	119	127	87	102
Power Consumption							
Water side (Pump)	AHU Power Input (kW)	1.4	0.7	1.1	0.6	0.8	0.4
	ACB Power Input - Primary (kW)	-	0.9	-	0.8	-	0.7
	ACB Power Input - Secondary (kW)	-	0.5	-	0.5	-	0.4
Air side (Fan)	AHU Power Input (kW)	5.6	3.5	4.7	3.5	3.1	3.5
	Chiller Power Input (kW)	19.9	19.4	15.6	16.7	11.4	13.3
	Cooling Tower Power Input (kW)	1.3	1.3	1.0	1.1	0.7	0.9
	Total Power Input (kW)	**28.3**	**26.2**	**22.5**	**23.1**	**16.0**	**19.2**

5.2.2 Overall Building

For overall building AHU capacity, VAV is higher than ACB at all three load conditions, by 50% at full load, 48% at part load and 45% at lowest part load. ACB has lower AHU capacity mainly because part of the cooling load (room sensible) is catered by chilled beams. Meanwhile, for overall building power consumption, VAV is higher than ACB at full load and normal part load conditions, with 345 kW and 262.1 kW compared to 284.5 kW and 226.1 kW respectively as shown in **Table 5.7.** However, at lowest part load condition, VAV has lower power consumption with 185 kW compared to 204.1 kW for ACB. The higher power consumption for ACB at lowest part load condition can be explained by the use of constant air volume diffuser at particular zones where the space available is too small for the placement of chilled beams. To improve the overall system, VAV can be used for spaces where chilled beams are not allowed. However, the penalty is the increase in initial cost as the cost of VAV box is comparably high against normal CAV system.

Table 5.7 Total Power Input at 3 Different Load Conditions for Overall Building

		100%		75% sensible	90% latent	50% sensible	80% latent
LOAD & CAPACITY		**VAV**	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Required Building & System Load	Zone Sensible Heat(Btu/hr)	3,511,657	3,511,657	2,633,743	2,633,743	1,755,829	1,755,829
	Zone Latent Heat(Btu/hr)	212,772	212,772	191,495	191,495	170,218	170,218
	Total Zone Load(Btu/hr)	3,724,429	3,724,429	2,825,238	2,825,238	1,926,046	1,926,046
System Capacity	ACB Water Capacity (Btu/hr)	-	1,830,267	-	1,295,400	-	1,375,830
	ACB Capacity (Btu/hr)	-	3,320,205	-	2,334,735	-	2,776,937
	AHU Capacity Sensible (Btu/hr)	3,735,870	1,529,399	2,801,903	1,147,049	1,867,935	764,700
	AHU Capacity Latent (Btu/hr)	900,026	815,909	810,023	734,318	720,021	652,727
	Total AHU Capacity (Btu/hr)	4,635,896	2,345,308	3,611,926	1,881,367	2,587,956	1,417,427
	AHU Air flow (cfm)	154,000	57,161	108,098	57,011	72,065	57,161
	AHU Chilled Water flow (gpm)	927.2	469.1	722.4	376.3	517.6	283.5
	ACB Chilled Water flow - Primary (gpm)	-	585.7	-	414.5	-	440.3
	ACB Chilled Water flow - Secondary (gpm)	-	366.1	-	259.1	-	275.2
	Condesner Water flow (gpm)	1205.3	1085.6	939.1	826.0	672.9	726.2
	Chiller Capacity (RT)	386.3	348.0	301.0	264.7	215.7	232.8
	Cooling Tower Capacity (HRT)	502.2	452.4	391.3	344.1	280.4	302.6
Power Consumption							
Water side (Pump)	AHU Power Input (kW)	16.4	7.5	13	6.0	9.2	5
	ACB Power Input - Primary (kW)	-	9.3	-	6.6	-	7.0

	ACB Power Input - Secondary (kW)	-	5.8	-	4.1	-	4.4
Air side (Fan)	AHU Power Input (kW)	81.9	40.5	57.5	40.4	38.3	40.5
	Chiller Power Input (kW)	231.8	208.8	180.6	158.8	129.4	139.7
	Cooling Tower Power Input (kW)	15.1	13.6	11.7	10.3	8.4	9.1
	Total Power Input (kW)	**345.2**	**285.5**	**262.6**	**226.3**	**185.3**	**205.2**

Table 5.8 Total Power Input at 3 Different Load Conditions for Overall Building (SI unit)

		100%		75% sensible	90% latent	50% sensible	80% latent
LOAD & CAPACITY		**VAV**	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Required Building & System Load	Zone Sensible Heat(kW)	1,029	1,029	772	772	515	515
	Zone Latent Heat(kW)	62	62	56	56	50	50
	Total Zone Load(kW)	1,092	1,092	828	828	564	564
System Capacity	ACB Water Capacity (kW)	-	536	-	380	-	403
	ACB Capacity (kW)	-	973	-	684	-	814
	AHU Capacity Sensible (kW)	1,095	448	821	336	547	224
	AHU Capacity Latent (kW)	264	239	237	215	211	191
	Total AHU Capacity (kW)	1,359	687	1,059	551	758	415
	AHU Air flow (l/s)	72,642	26,963	50,990	26,892	33,993	26,963
	AHU Chilled Water flow (l/s)	58.5	29.6	45.6	23.7	32.7	17.9
	ACB Chilled Water flow - Primary (l/s)	-	37.0	-	26.2	-	27.8
	ACB Chilled Water flow - Secondary (l/s)	-	23.1	-	16.3	-	17.4
	Condesner Water flow (l/s)	76.0	68.5	59.2	52.1	42.5	45.8
	Chiller Capacity (kW)	1,359	1,224	1,059	931	758	819
	Cooling Tower Capacity (kW)	1,766	1,591	1,376	1,210	986	1,064
Power Consumption							
Water side (Pump)	AHU Power Input (kW)	16.4	7.5	12.8	6.0	9.2	4.5
	ACB Power Input - Primary (kW)	-	9.3	-	6.6	-	7.0

	ACB Power Input - Secondary (kW)	-	5.8	-	4.1	-	4.4
Air side (Fan)	AHU Power Input (kW)	81.9	40.5	57.5	40.4	38.3	40.5
	Chiller Power Input (kW)	231.8	208.8	180.6	158.8	129.4	139.7
	Cooling Tower Power Input (kW)	15.1	13.6	11.7	10.3	8.4	9.1
	Total Power Input (kW)	**345.2**	**285.5**	**262.6**	**226.3**	**185.3**	**205.2**

5.3 Cost Comparison

Cost comparison is divided into two parts: initial cost and operation cost. Initial cost will determine the short-term savings and operation cost on the other hand will determine the long-term savings.

5.3.1 Initial Cost

The total initial cost can be divided into four parts: preliminaries and preambles, water side, air side and BMS. Preliminaries and preambles covers the cost for training, testing & commissioning, drawings, insurance and etc. as per specifications and conditions of contract. For water side, it covers the cost of equipment and material for both chilled water and condenser water that include chiller, cooling tower, pump, expansion tank, piping and etc. On the other hand, for air side, the cost of equipment and material include AHU, FCU, diffuser, damper, ducting and etc. For BMS, it covers the cost for input/output devices and control system equipment where it's quoted separately by specialists.

Comparing between the two systems in terms of total initial cost, ACB is approximately 5% higher than VAV with RM 8,259,777.73 compared to RM 7,882,188.34 where it's largely contributed by the water side for the additional chilled water piping and equipment at the secondary side such as secondary pump, heat exchanger and chilled beams as shown in **Table 5.9.**

The cost difference for air side is significant, approximately 72% lesser for ACB over VAV, with merely RM 783,677.73 compared to RM 2,810,948.34. In other words, it can be deduced that the reduction of air flow rate required significantly reduces the cost for the air side.

Table 5.9 Total Cost of The Entire Chiller Plant

VAV	Cost, RM		ACB	Cost, RM
Preliminaries and Preambles	**161,500.00**		**Preliminaries and Preambles**	**161,500.00**
Water Side			**Water Side**	
Chiller	600,000.00		Chiller	525,000.00
Chilled Water Pump			Chilled Water Pump	
Primary	30,000.00		Primary	30,000.00
Secondary			Secondary	30,000.00
Condenser Water Pump	45,000.00		Condenser Water Pump	45,000.00
Cooling Tower	600,000.00		Cooling Tower	528,000.00
Chilled Water Piping	568,270.00		Chilled Water Piping	2,096,130.00
Condenser Water Piping	350,720.00		Condenser Water Piping	350,720.00
Valves	80,000.00		Valves	200,000.00
Decoupler (bypass line)	15,000.00		Decoupler (bypass line)	15,000.00
Make-up water piping	12,750.00		Make-up water piping	12,750.00
Expansion Tank	5,000.00		Expansion Tank	5,000.00
Motor Control Center (MCC)	840,000.00		Heat Exchanger	16,000.00
Power cables and Control Cable	300,000.00		Motor Control Center (MCC)	840,000.00
Master Controller	50,000.00		Power cables and Control Cable	300,000.00
Chemical Treatment	45,000.00		Master Controller	50,000.00
Flushing and Water Treatment	6,000.00		Chemical Treatment	45,000.00
Testing & Commissioning	12,000.00		Flushing and Water Treatment	6,000.00
			Testing & Commissioning	12,000.00
			Active Chilled Beam	813,000.00
	3,559,740.00			**5,919,600.00**
Air Side			**Air Side**	
AHUs & FCUs	290,820.00		AHUs & FCUs	122,538.00
Condensate Water Piping	52,000.00		Condensate Water Piping	33,800.00
Ductworks	966,878.34		Ductworks	303,839.73
Silencers	26,000.00		Silencers	26,000.00
Diffusers	465,250.00		Diffusers	237,500.00
Control Panel	50,000.00		Control Panel	50,000.00
Power cable and control cable	10,000.00		Power cable and control cable	10,000.00
VAV box	950,000.00			
	2,810,948.34			**783,677.73**
BMS	**1,350,000.00**		**BMS**	**1,395,000.00**
Total	**7,882,188.34**		**Total**	**8,259,777.73**

Table 5.10 Total Cost of The Entire Chiller Plant (USD)

VAV	Cost, $
Preliminaries and Preambles	**40,375.00**
Water Side	
Chiller	150,000.00
Chilled Water Pump	
Primary	7,500.00
Secondary	-
Condenser Water Pump	11,250.00
Cooling Tower	150,000.00
Chilled Water Piping	142,067.50
Condenser Water Piping	87,680.00
Vavles	20,000.00
Decoupler (bypass line)	3,750.00
Make-up water piping	3,187.50
Expansion Tank	1,250.00
Motor Control Center (MCC)	210,000.00
Power cables and Control Cable	75,000.00
Master Controller	12,500.00
Chemical Treatment	11,250.00
Flushing and Water Treatment	1,500.00
Testing & Commisioning	3,000.00
	889,935.00
Air Side	
AHUs & FCUs	72,705.00
Condenstate Water Piping	13,000.00
Ductworks	241,719.59
Silencers	6,500.00
Diffusers	116,312.50
Control Panel	12,500.00
Power cable and control cable	2,500.00
VAV box	237,500.00
	702,737.09
BMS	**337,500.00**
Total	**1,970,547.09**

ACB	Cost, $
Preliminaries and Preambles	**40,375.00**
Water Side	
Chiller	131,250.00
Chilled Water Pump	
Primary	7,500.00
Secondary	7,500.00
Condenser Water Pump	11,250.00
Cooling Tower	132,000.00
Chilled Water Piping	274,032.50
Condenser Water Piping	87,680.00
Vavles	50,000.00
Decoupler (bypass line)	3,750.00
Make-up water piping	3,187.50
Expansion Tank	1,250.00
Heat Exchanger	4,000.00
Motor Control Center (MCC)	210,000.00
Power cables and Control Cable	75,000.00
Master Controller	12,500.00
Chemical Treatment	11,250.00
Flushing and Water Treatment	1,500.00
Testing & Commisioning	3,000.00
ACB	453,250.00
	1,479,900.00
Air Side	
AHUs & FCUs	30,634.50
Condenstate Water Piping	8,450.00
Ductworks	75,959.93
Silencers	6,500.00
Diffusers	59,375.00
Control Panel	12,500.00
Power cable and control cable	2,500.00
	195,919.43
BMS	**348,750.00**
Total	**2,064,944.43**

5.3.2 Operation Cost

The system operation cost reflects on the total energy demand and consumption. **Table 5.11** shows the TNB tariff rate used to calculate the operation cost. **Table 5.13** shows the energy consumption in monthly and yearly basis and **Table 5.14** shows the total cost savings in monthly and yearly basis. From the results, at full load and normal part load conditions, the yearly cost savings is on ACB's side with RM 62,708 and RM 38,153 respectively. However, at lowest part load condition, the savings is on VAV's side with RM 20,910. As mentioned earlier, some of the conditioned space are equipped with constant air volume (CAV) diffusers for ACB system and because of this, ACB is less efficient at lowest part load condition compared to VAV. Nevertheless, the amount of savings at full load and normal part load conditions is more than the losses at lowest part load condition.

Table 5.11 TNB Tariff

Operation Cost	**Rate**	**Unit**
Demand	30.3	RM/kW
Consumption	0.365	RM/kWh

* *Tariff C1-Medium voltage general commercial tariff*

Table 5.12 TNB Tariff (USD)

Operation Cost	**Rate**	**Unit**
Demand	7.757	$/kW
Consumption	0.09125	$/kWh

* *Tariff C1-Medium voltage general commercial tariff*

Table 5.13 Energy Consumption in Monthly and Yearly Basis

	100%		**75% sensible**	**90% latent**	**50% sensible**	**80% latent**
	VAV	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Demand (kW)	345	286	263	226	185	205
Consumption kWh (monthly)	82,841	68,524	63,026	54,316	44,471	49,245
Consumption kWh (yearly)	994,097	822,294	756,317	651,789	533,653	590,941
Savings (yearly)		**171,804**		**104,529**		**(57,288)**

Table 5.14 Total Cost Savings in Monthly and Yearly Basis

	100%		75% sensible	90% latent	50% sensible	80% latent
	VAV	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Demand RM	10,459	8,651	7,957	6,857	5,614	6,217
Consumption RM (monthly)	30,237	25,011	23,005	19,825	16,232	17,974
Consumption RM (yearly)	362,846	300,137	276,056	237,903	194,783	215,694
Savings (yearly)		**62,708**		**38,153**		**(20,910)**

Table 5.15 Total Cost Savings in Monthly and Yearly Basis (USD)

	100%		75% sensible	90% latent	50% sensible	80% latent
	VAV	**ACB**	**VAV**	**ACB**	**VAV**	**ACB**
Demand $	2,615	2,163	1,989	1,714	1,404	1,554
Consumption $ (monthly)	7,559	6,253	5,751	4,956	4,058	4,494
Consumption $ (yearly)	90,711	75,034	69,014	59,476	48,696	53,923
Savings (yearly)		**15,677**		**9,538**		**(5,228)**

CHAPTER 6. CONCLUSION & RECOMMENDATION

6.1 Introduction

The primary objective of this research was to propose a sustainable air distribution system that provides long term savings based on the energy and cost analysis results comparing between ACB and VAV.

6.2 Conclusions

From the analysis results, it can be concluded that ACB is better than VAV in terms of total energy consumption and energy cost. In other words, for long term saving, ACB is recommended even though the initial cost is relatively high compared to VAV. However, in terms of system design, ACB is more complicated than VAV as it involves many specific design considerations at design stage and sophisticated system control during operation.

6.3 Recommendations

The results discussed in this thesis is obtained by numerical method where the validity may be questioned by others. One of the ways to verify the validity of the results is by performing energy audit on the existing system for an actual building. This will give actual load data of the building and system performance in timely basis where it can be used to compare with the computed results.

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APPENDICES

Appendix: Layout Drawings

- Appendix 1 Ground Floor – ACB Layout
- Appendix 2 Ground Floor – VAV Layout
- Appendix 3 Level 1 to Level 9 – ACB Layout
- Appendix 4 Level 1 to Level 9 – VAV Layout
- Appendix 5 Level 10 – ACB Layout
- Appendix 6 Level 10 – VAV Layout