Cairo University
Faculty of Engineering
Mech. Power Department

مشروع تطبيقات التحكم الأوتوماتيكي في نظم القوى الميكانيكية
MEP 4801 B.Sc. Project
2022/2023

Application of Virtual Lab in Analysis of Automatic Control Systems

Case Study: Analysis of HVAC Control System, International Branch of Cairo University, 6th of October City

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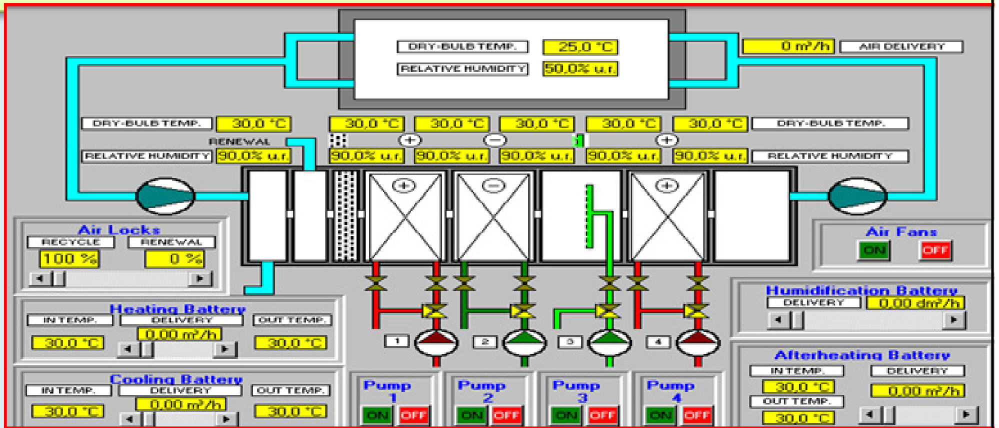
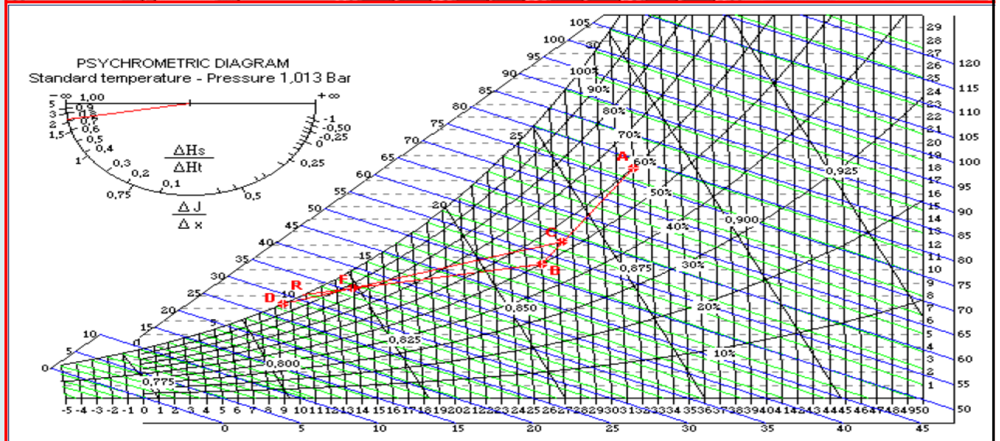
Abstract: This project consists of 2 parts. 1st part is an investigation and analysis of automatic control virtual lab for a typical HVAC system. 2nd part is detailed design for the AHU control part of 2 real HVAC systems at Cairo University, International Branch at the 6th of October City.

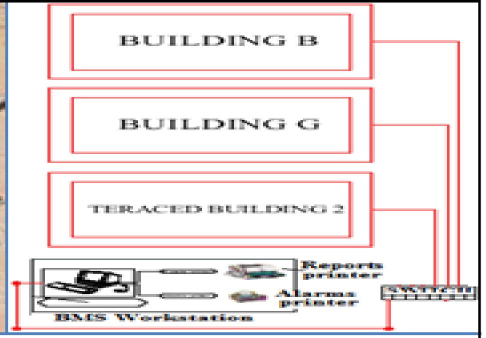
Part-1-Overview: The control Virtual Lab. is an interactive PC-based training software simulates various operation & control processes in a single zone HVAC system which has AHU of total-air VAV type. As shown on next fig., the AHU has 2 Air-fans, a mixing chamber with air locks, air filter and 4 main sections/batteries for doing: Air Heating, Cooling, Humidification and After-heating. Air-locks are used to allow different adjustable ratios of recycled air brought back to the building mixed with renewal air. Each pump has its on/off control board. Each battery cell has a control board that includes pump flow rate-meter & both inlet and outlet water and air temperatures (except the humidification cell). The AHU has also an on/off air fans control board and air locks control board. The Virtual Lab also includes an On-line, real psychometric diagram to show all performed HVAC processes. The diagram shows all physical points for Renewal air, Recycled air taken from inside the environment, mixture of Renewal and Recycled air, the air outlet from various AHU batteries, and the air going to the building. To perform the AHU control task, the simulation includes all needed flow control valves and temperature read-out gauges, critical control alarms, input/output signals, operation &instrumentation parameter-boards, diagnostic tool, error-report filling, help/trouble-shooting tool and “Thermal Balance Calculations” and graphical Plotting tools. Part-1 is also extended to include a review study for an experimental training AHU that is used to extend the understanding of the requirements of real sensors, meters and control devices used in executing many different real thermodynamic processes in typical HVAC systems to achieve an optimum control & performance.



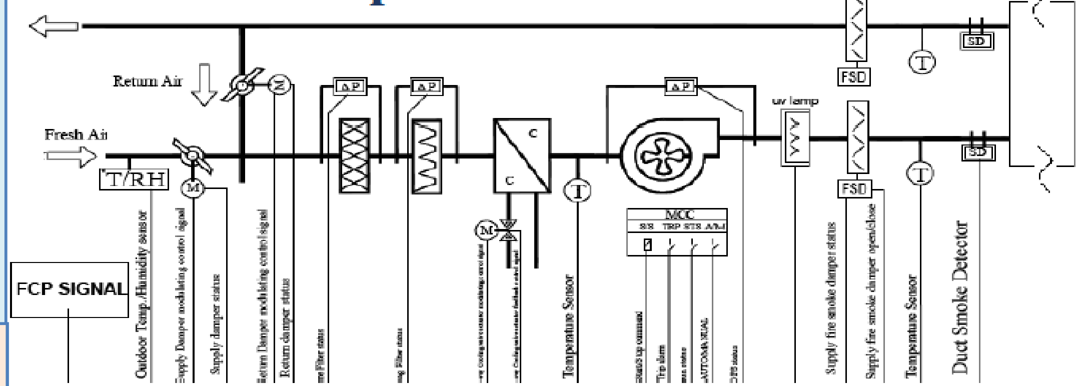


Part-2-Overview: The objective of part-2 is to enhance students' knowledge in the area of design of HVAC control & BMS and to practice some of many-different practical procedures and requirements associated with the design, implementation, installation and commissioning of real automatic control of HVAC & AHU Systems. 2nd part includes some detailed design for the control part of 2 real HVAC systems at Cairo University, International Branch, 6th of October City. One system is Buildings B & G, while the other system is one of the two Terraced Buildings. Due to short time limitation, the scope of part-2 was limited to a few steps of design of automatic control of a pre-specified HVAC system. Therefore, Part-2 has not any thermal load calculations but it has a few calculations and sizing for some of the AHU equipments. On the other hand, Part-2 includes the following: 1. Contents of Building's HVAC utilities. 2. Points list with some selected DDCs. 3. Valve sizing and selection for AHUs and FCUs. 4. Bill of quantities. 5. Schematic diagrams for various components. 6. Sequence of operation for the 3 buildings of Part-2.

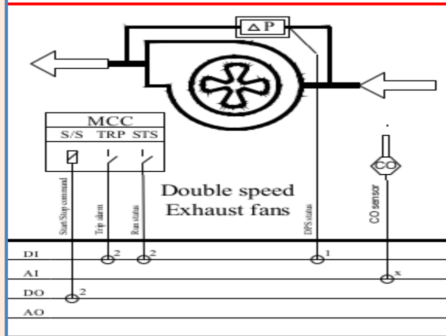
Why do we use Variable Air Volume (VAV) system? It is usually used to simultaneously meet variety of cooling & heating loads in a relatively efficient manner. The system achieves this by varying distribution of air depending on the cooling or heating loads of each zoon. Air flow variation allows for adjusting the temp. in single zone without changing the temp. of air in whole system, minimizing any instances of overcooling or overheating. This flexibility has made this one of the most popular HVAC systems for large buildings with varying conditioning needs such as office buildings or schools. In the schematic above, the VAV system brings outside air and return air to the Air Handling Unit where both are mixed. The mixed air is drawn through a cooling coil, which drops the temperature to a fixed supply air temperature. The temperature in the individual zoons (#1 & #2 as shown in next fig.) is measured by a Thermostat, which directly control the dampers in the VAV units. The supply air fan is Speed controlled by a variable speed drive, that controls the air volume flow rate by keeping the duct static pressure constant. The pressure is measured by the sensor located approximately 2/3rd of the way down the main duct starting air handling unit. As the zone dampers throttle back, the duct pressure rises, and the fan is controlled to reduce the duct pressure.

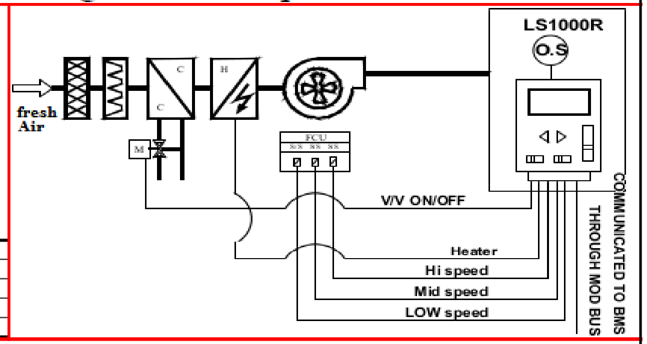


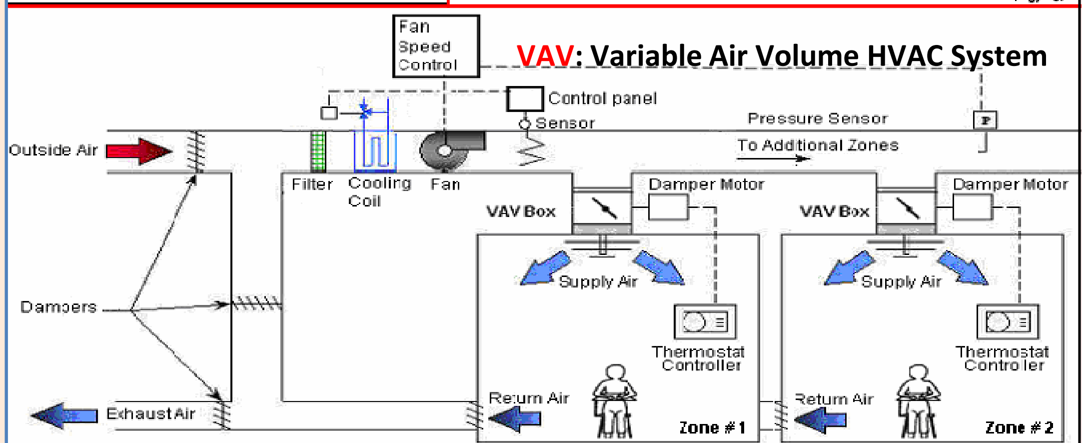
Basic components of AHUs



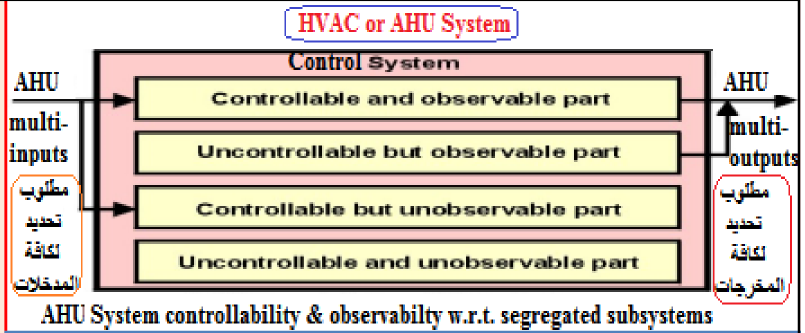
Recirculating AHU example







Part-1: **What is HVAC System?** From the control theory point of view, the HVAC system is multi-inputs/multi-outputs & transient control system which have many electric & mechanical components such as sensors, field devices, actuators and have also some type of a controller. The main objective of HVAC system is to supply clean air at some pre-specified temperature & RH inside the zoon of interest. Inlet air is to be mixed with air indoor in order to reach the needed comfortable conditions inside that zoon. Due to varying thermal loads and heat loss from or to the zoon, the indoor conditions keep drifting away from that required comfortable conditions. The HVAC system has to keep monitoring the set points of the indoor conditions and has to do required closed-loop corrective control actions whenever they are needed.



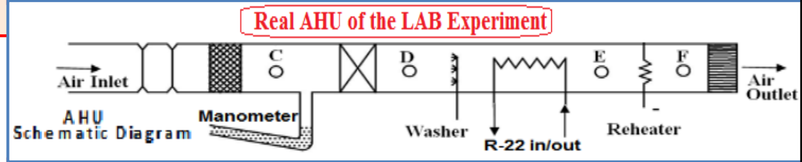
The AHU system has multi independent <u>input</u> control or process variables such as:

a- DBT of fresh and recycle inlet air flow. b- Relative Humidity, Ø, of fresh and recycle inlet air

c- Volumetric flow rate of fresh and recycle inlet air. d- Heating energy input from AHU battery.

e- Cooling energy input from AHU battery f- Water flow rate input from AHU for Humidification

g- Inlet water temperature from AHU battery for Humidification.



The AHU system has also multi independent <u>output</u> control or process variables such as:

a- DBT of the total AHU outlet air. b- Relative Humidity, Ø, of the total AHU outlet air

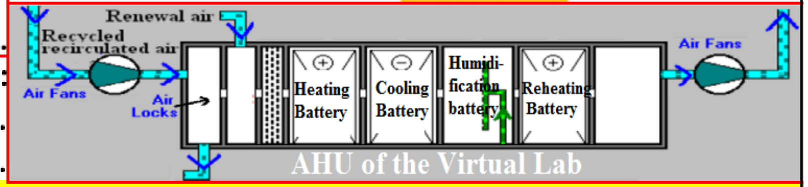
c- Volumetric flow rate of outlet air flow (not the same as inlet due to humidification).

d- Heat losses from the AHU to the outside atmosphere due to convection and radiation.

For AHU as closed-loop feedback system, we measure <u>output control or process variables</u>:

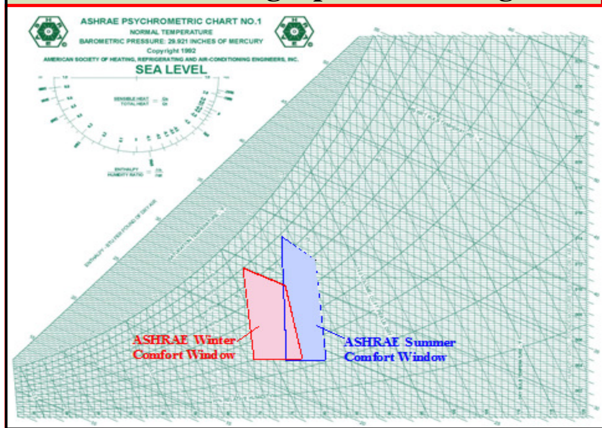
a- DBT of the total AHU outlet air. b- Relative Humidity, Ø, of the total AHU outlet air flow.

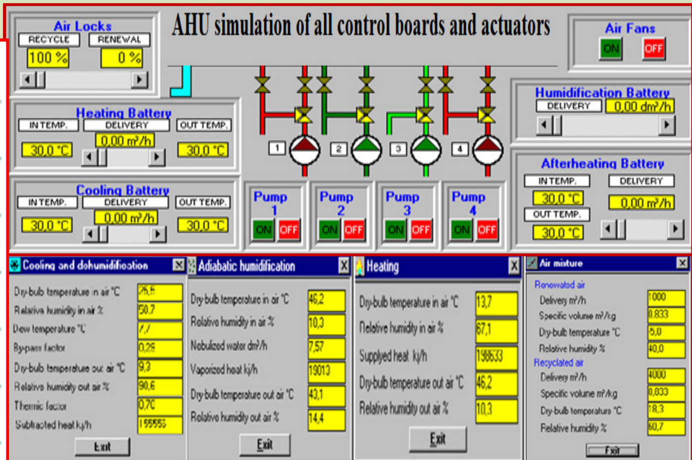
c- Volumetric flow rate of AHU outlet air flow (not same as air inlet due to humidification).



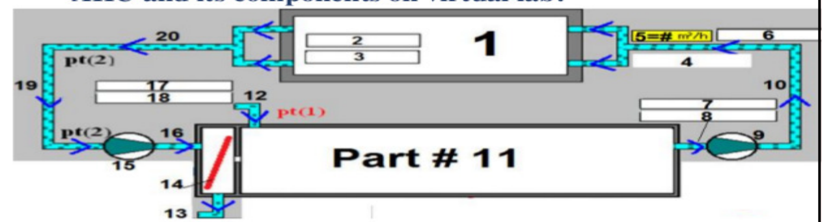
Why do we use Virtual Lab? HVAC system is a complex machine with multi I/O variables & unknowns with some uncertainty in finding maximum thermal loads which are 1st essential data to get for doing optimum sizing/selection of AHU parts (HAP Commercial Software is available to get the design Loads).

Advantages of using HVAC Virt-Lab: It provides a simple-accurate approach to study, analyze and visualize various real thermodynamic processes in AHU for many pre-given 2 thermal load types. No sizing-calculations nor selection of AHU equipments is involved. No real sensors nor actuators are used in the Lab. The Lab includes on-line, real psychometric diagram to show all performed HVAC processes & all physical points for each part of the AHU. To do the control task, the simulation includes all needed flow control valves and temperature read-out gauges, many critical control alarms, input/output signals, operation and instrumentation parameter-boards, diagnostic tools, error-report filling, help/trouble-shooting and Thermal Balance Calculations and graphical Plotting tools.





AHU and its components on virtual lab:



1- Room to be air conditioned. 2- Dry-bulb temperature of the room.
3- Relative humidity of the room. 4- Total air rate delivered.
5- 3000 m^3/hr (selected Total Air) 6- Air delivery.
7- Out dry-bulb temperature from AHU. 8- Out relative humidity from AHU.
9- Fan. 10- Air path ducts to the room. 11- AHU. 12- Fresh air inlet to AHU.
13- Fresh air outlet. 14- Air-Damper to control ratio of fresh air to Recycled air.
15- Fan. 16- Recycled air inlet to AHU. 17- inlet dry-bulb temperature to AHU.
18- inlet relative humidity to AHU. 19- Recycled air path to the AHU.
20- Recycled air from the room.

Part-1 Back Ground information: Types of Central HVAC systems:

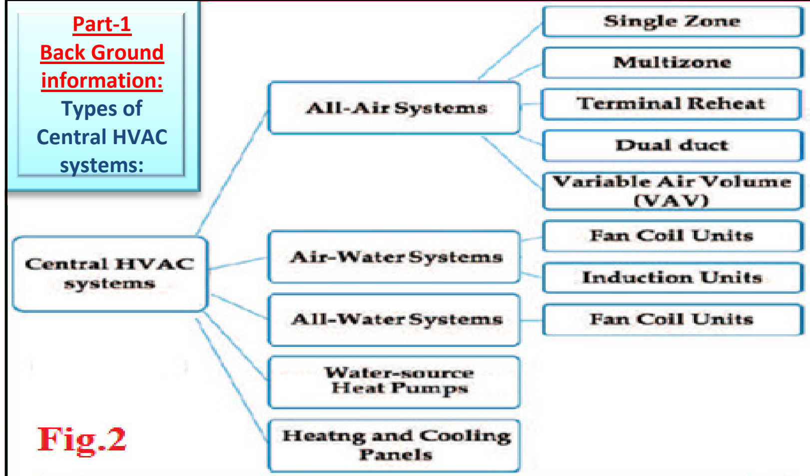


Fig.2

Hierarchy representation of main types of central HVAC systems.

Note: In both Part-1 (automatic control Virtual Lab) and Part-2 (the two design case studies), we use the All-air HVAC systems.

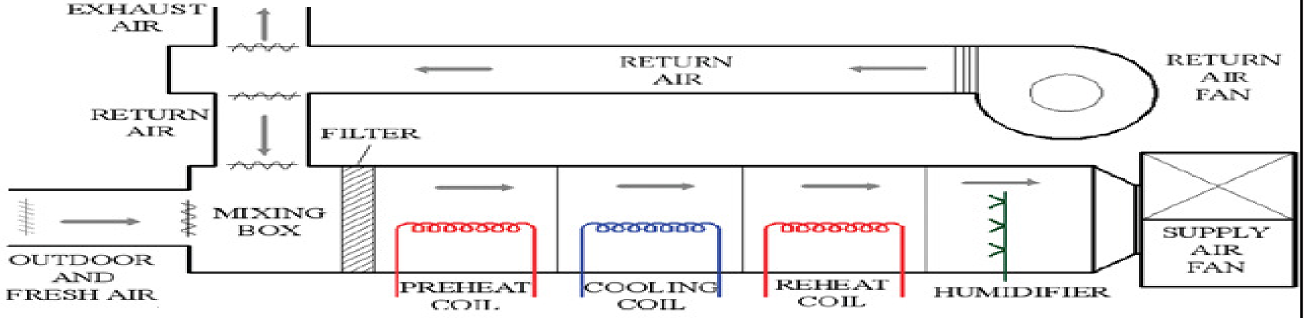


Figure 3. Equipment arrangement for central HVAC system.

A central HVAC system may serve one or more thermal zones, and its major equipment is located outside of the served zone(s) in a suitable central location whether inside, on top, or adjacent to the building [4, 5]. Central systems must condition zones with their equivalent thermal load. Central HVAC systems will have as several control points such as thermostats for each zone. The medium used in the control system to provide the thermal energy sub-classifies central HVAC system, as shown in **Figure 2**. The thermal energy transfer medium can be air or water or both, which represent as all-air systems, air-water systems, all-water systems. Also, central systems include water-source heat pumps & heating and cooling panels. All of these subsystems are discussed below. Central HVAC system has combined devices in an air handling unit, as shown in **Fig.3**, which contains supply and return air fans, humidifier, reheat coil, cooling coil, preheat coil, mixing box, filter, and outdoor air.

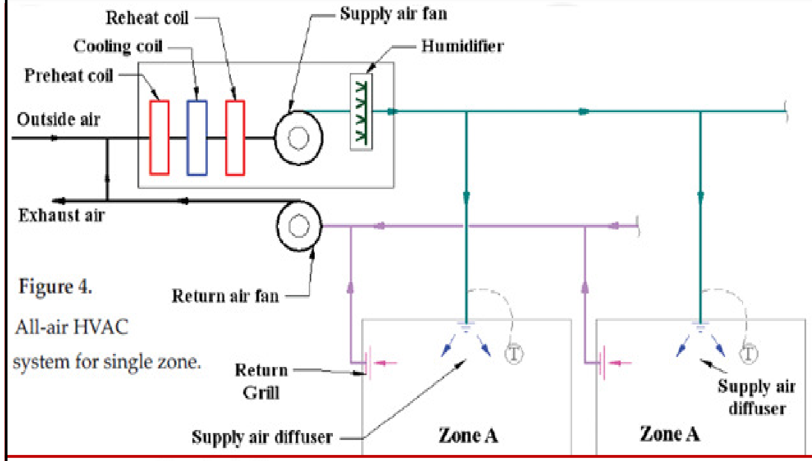


Figure 4. All-air HVAC system for single zone.

All-air systems

The thermal energy transfer medium through the building delivery systems is air. All-air systems can be sub-classified based on the zone as single zone and multizone, airflow rate for each zone as constant air volume and variable air volume, terminal reheat, and dual duct.

1. Single zone

A single zone system consists of an air handling unit, a heat source and cooling source, distribution ductwork, & appropriate delivery devices. The air handling units can be wholly integrated where heat & cooling sources are available or separate where heat & cooling source are detached. The integrated package is most-commonly a rooftop unit & connected to ductwork to deliver conditioned air into several spaces with the same thermal zone. The main advantage of single zone systems is simplicity in design and maintenance and low first cost compared to other systems. However, its main disadvantage is serving a single thermal zone when improperly applied.

In a single zone all-air HVAC system, one control device such as thermostat located in the zone controls the operation of the system, as shown in **Figure 4**. Control may be either modulating or on–off to meet the required thermal load of the single zone. This can be achieved by adjusting the output of heating and cooling source within the packaged unit. Although few buildings can be a single thermal zone, a single zone can be found in several applications. One family residential buildings can be treated as single zone systems, while other types of residential buildings can include different thermal energy based on the occupation and building structure. Movements of occupants affect the thermal load of the building, which results in dividing the building into several single zones to provide the required environmental condition. This can be observed in larger residences, where two (or more) single zone systems may be used to provide thermal zoning. In low-rise apartments, each apartment unit may be conditioned by a separate single zone system. Many sizeable single story buildings such as supermarkets, discount stores, can be effectively conditioned by a series of single zone systems. Large office buildings are sometimes conditioned by a series of separate single zone systems.

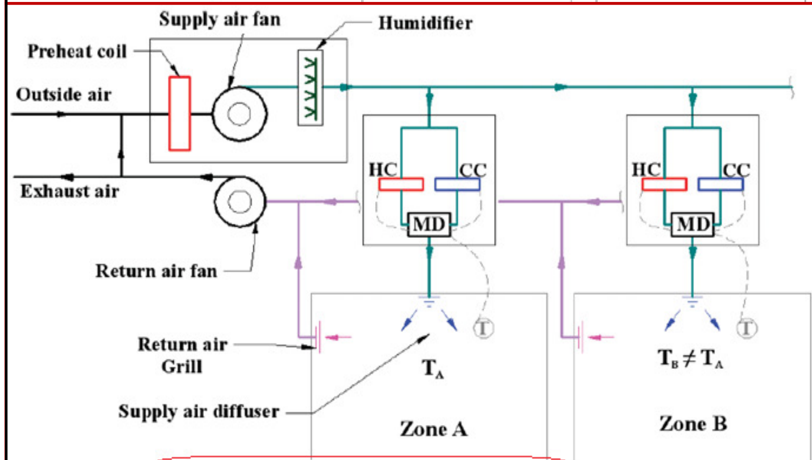


Figure 5. All-air HVAC system for multiple zones.

2. Multi-zone

In a multi-zone all-air system, individual supply air ducts are provided for each zone in a building. Cold air and hot (or return) air are mixed at air handling unit to achieve the thermal requirement of each zone. A particular zone has its conditioned air that cannot be mixed with that of other zones, and all multiple zones with different thermal requirement demand separate supply ducts, as shown in **Figure 5**. Multi-zone all-air system consists of air handling unit with parallel flow paths through cooling coils and heating coils and internal mixing dampers. It is recommended that one multi-zone serve a maximum of 12 zones because of physical restrictions on duct connections and damper size. If more zones are required, additional air handlers may be used. The advantage of multi-zone system is to adequately condition several zones without energy waste associated with a terminal reheat system. However, leakage between the decks of air handler may reduce energy efficiency. The main disadvantage is the need for multiple supply air ducts to serve multiple zones.

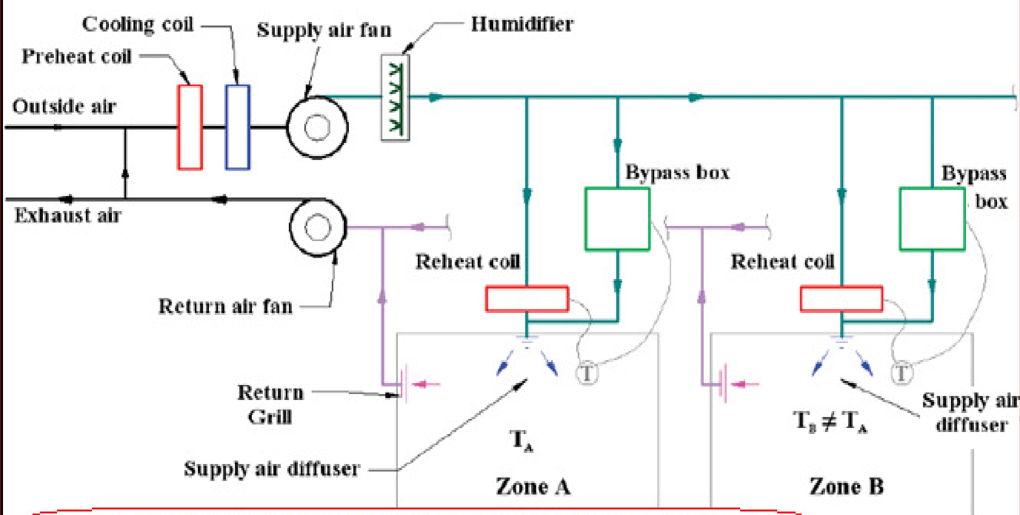


Figure 6. Single duct system with reheat terminal devices and bypass units.

3. Terminal reheat

A terminal reheat all-air system is a multiple zone, which considers an adaptation of single zone system, as shown in **Figure 6**. This can be performed by adding heating equipment, such as hot water coil or electric coil, to the downstream of the supply air from air handling units near each zone. Each zone is controlled by a thermostat to adjust the heat output of heating equipment to meet the thermal condition. The supply air from air handling units is cooled to the lowest cooling point, and the terminal reheat adds the required heating load. The advantage of terminal reheat is flexible and can be installed or removed to accommodate changes in zones, which provides better control of the thermal conditions in multiple zones. However, the design of terminal reheat is not energy-efficient system because a significant amount of extremely cooling air is not regularly needed in zones, which can be considered as waste energy. Therefore, energy codes and standards regulate the use of reheat systems.

4. Dual duct

The dual duct all-air system is a terminal-controlled modification of the multi-zone concept. A central air handling unit provides two conditioned air streams such as a cold deck and a hot deck, as shown in **Figure 7**. These air streams are distributed throughout the area served by the air handling unit in separate and parallel ducts. Each zone has a terminal mixing box controlled by zone thermostat to adjust the supply air temperature by mix the supply cold and hot air. This type of system will minimize the disadvantages of previous systems and become more flexible by using terminal control.

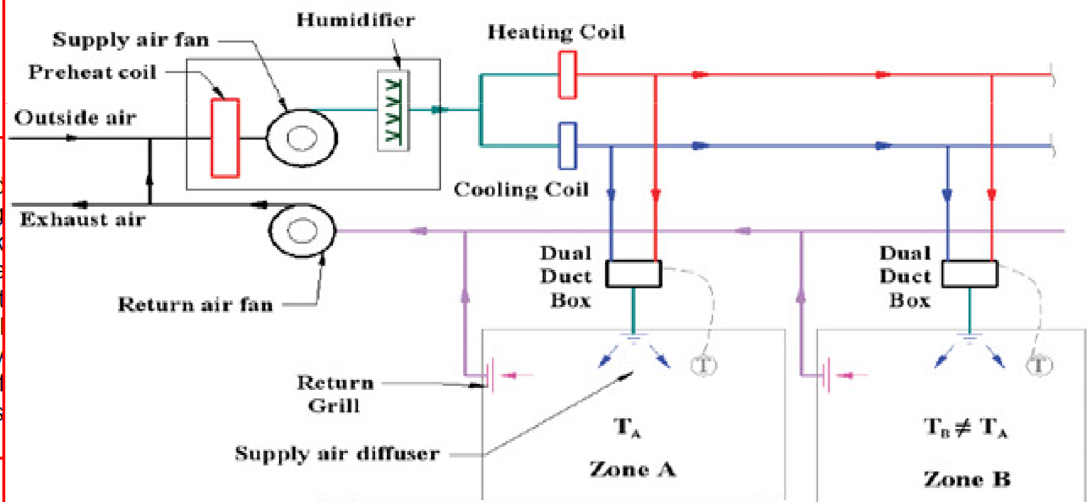


Figure 7. All-air HVAC dual-duct system.

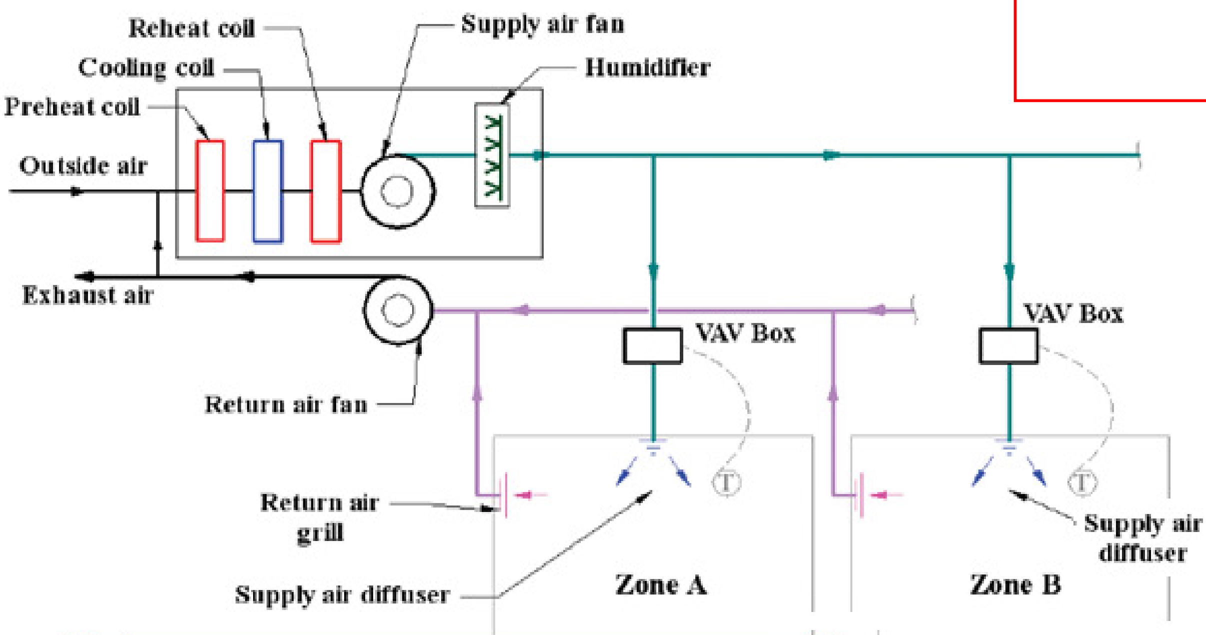


Figure 8. All-air HVAC systems with VAV terminal units.

5. Variable air volume

Some spaces require different airflow of supply air due to the changes in thermal loads. Therefore, a variable-air-volume (VAV) all-air system is the suitable solution for achieving thermal comfort. The previous four types of all-air systems are constant volume systems. The VAV system consists of a central air handling unit which provides supply air to the VAV terminal control box that located in each zone to adjust the supply air volume, as shown in **Figure 8**. The temperature of supply air of each zone is controlled by manipulating the supply air flow rate. The main disadvantage is that the controlled airflow rate can negatively impact other adjacent zones with different or similar airflow rate and temperature. Also, part-load conditions in buildings may require low air-flow rate which reduces the fan power resulting in energy savings. It may also reduce the ventilation flow rate, which can be problematic to the HVAC system and affecting the indoor air quality of the building.

How do we get Thermal Loads to design real HVAC System? ***In spite of the fact that we don't do any load or sizing calculations in this project, but it is very important to show how are those essential thermal loads obtained as 1st step in real design of HVAC system.*** **It's meant by conditioning a space to provide a comfort conditions to this space, so the heat that generated into the space must be removed. To remove that heat a suitable air conditioning machine will be used. By calculating the cooling load or the heat that must be removed the air conditioning machine power will be specified. Outside weather conditions and the sun combine to produce a cooling or heating load through the building envelop. The load depends on:1-The thermal characteristics of the walls, roof, fenestration, floor, interior building furnishings, and construction..2-The driving force resulting from the difference between the outside conditions (including solar) and inside conditions. Cooling loads result from many conduction, convection, and radiation heat transfer processes through the building envelope and from internal sources and system components. Building components or contents that may affect cooling loads include the following: External: Walls, roofs, windows, partitions, ceilings, and floors. Internal: Lights, people, appliances, and equipment Infiltration: Air leakage and moisture migration. System: Outside air, duct leakage, reheat, and fan and pump energy These all parameter are discussed with introducing some of design criteria and introducing how to insure complete comfort condition inside the building.**

Outdoor Design Conditions:

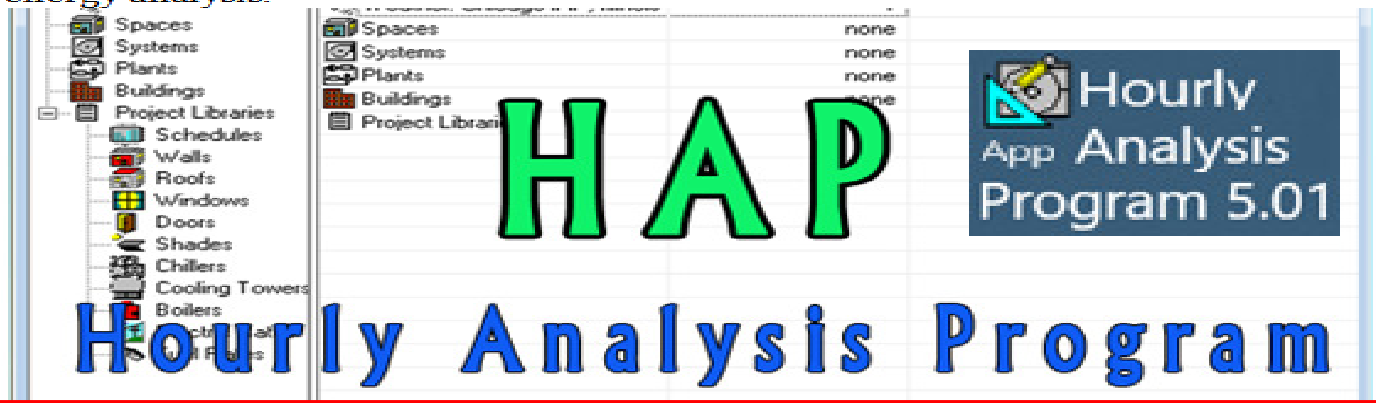
Outside Conditions	ASHRAE Handbook		Design Values	
	Summer	winter	Summer	winter
Dry bulb Temperature (°C)	36.3	-5.4	42.1	-2.8
Wet bulb Temperature (°C)	20.3	15.9	23.3	15.9
Daily Range (°C)	11.8	12.7	11.8	12.7
Elevation (ft)	4753			
Latitude (deg)	21.48N			
Longitude (deg)	40.55E			
Time zone (hr)	3			
Standard pressure at station elevation (kPa)	85.09			

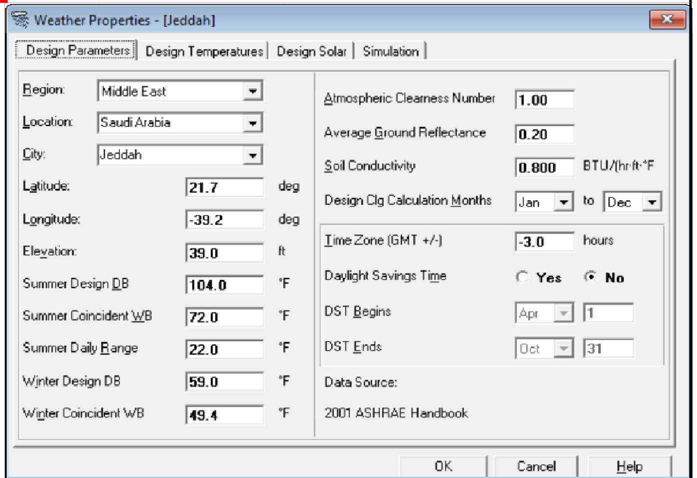
Inside Design Conditions (ASHRAE Standard55).

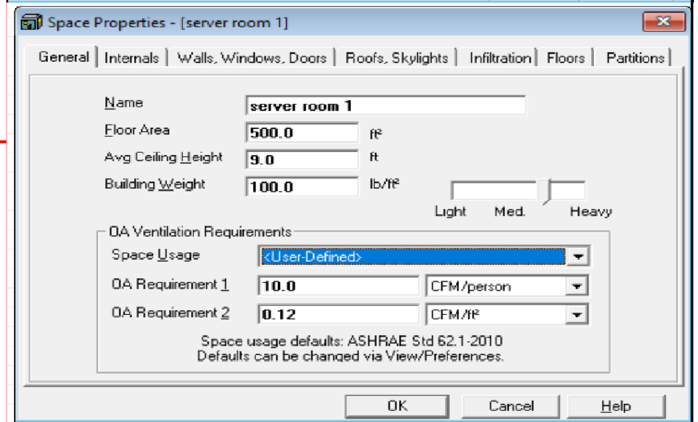
Space	ASHRAE Recommendation		Present Design	
	Temperature	Relative Humidity	Temperature	Relative Humidity
Office space	23 to 26 °C	50 to 60 %	24±1 °C	55 ±5%
Control room	23 to 26 °C	50 to 60 %	24±1 °C	55 ±5%
Lobbies and Corridors	23 to 26 °C	40 to 50 %	24±1 °C	45 ±5%
Telecom Room	°C(25-20)	%(55-40)	±1 °C24	50±5%
Power Room	°C(25-20)	(55-40)%	24±1 °C	50%5±

Load estimation by using HAP:

HAP is a computer tool which assists engineers in designing HVAC systems for commercial buildings. HAP is two tools in one. First it is a tool for estimating loads and designing systems. Second, it is a tool for simulating energy use and calculating energy costs. HAP uses the ASHRAE-endorsed transfer function method for load calculations and detailed 8,760 hour-by-hour energy simulation techniques for the energy analysis.

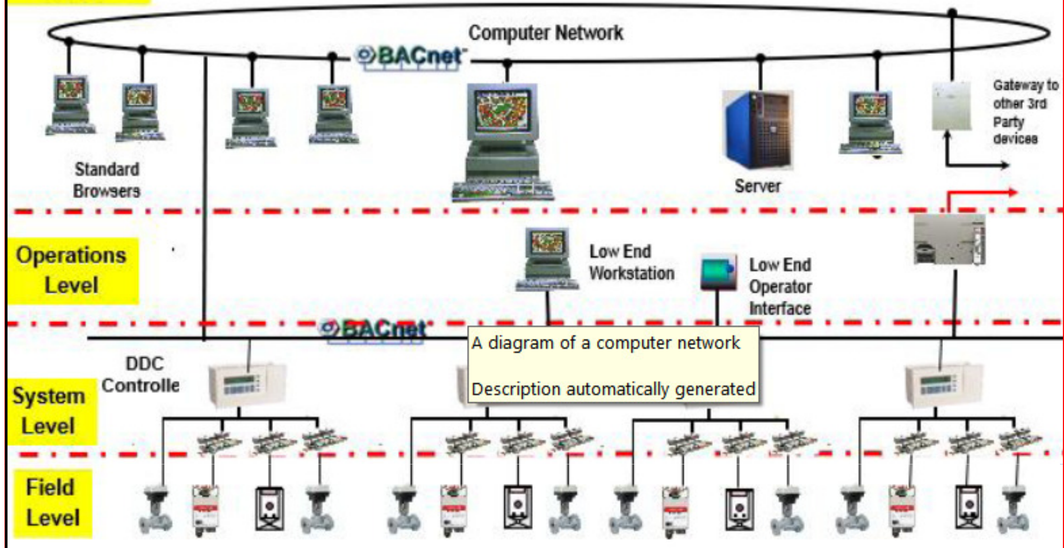


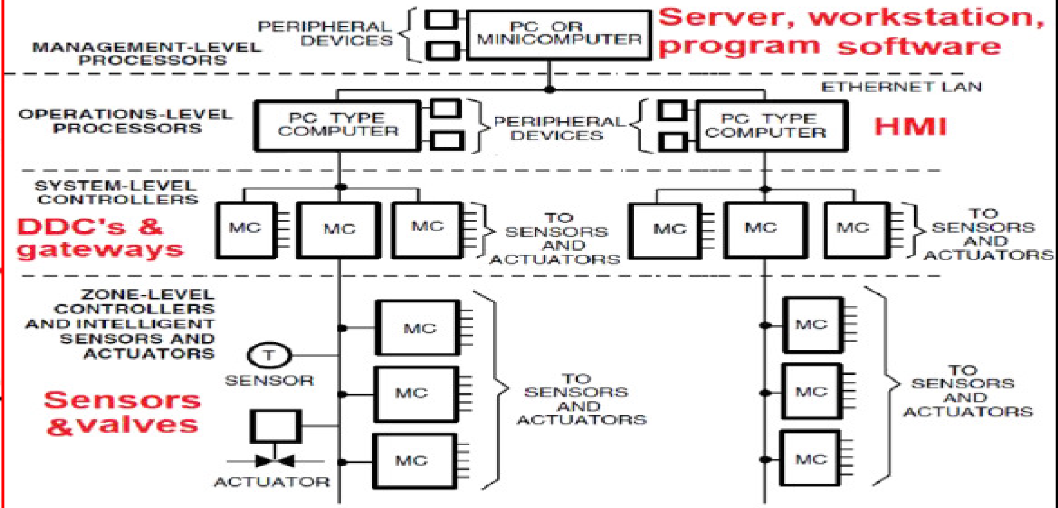




HAP is a computer tool which assists engineers in designing HVAC systems for commercial buildings. HAP is two tools in one. First it is a tool for estimating loads and designing systems. Second, it is a tool for simulating energy use and calculating energy costs. In this capacity it is useful for LEED®, schematic design and detailed design energy cost evaluations. HAP uses the ASHRAE-endorsed transfer function method for load calculations and detailed 8,760 hour-by-hour energy simulation techniques for the energy analysis.

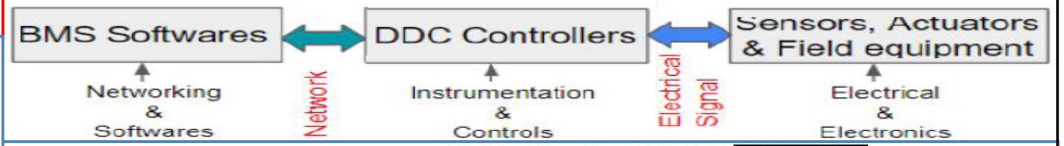
BMS Architecture Levels





Hierarchical BMS Configuration.

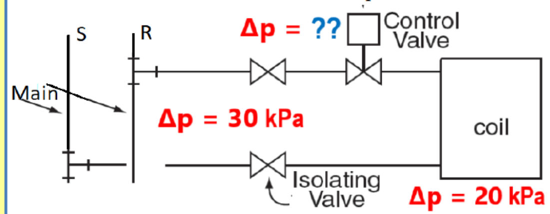
How BMS works



Control valve selection & sizing:

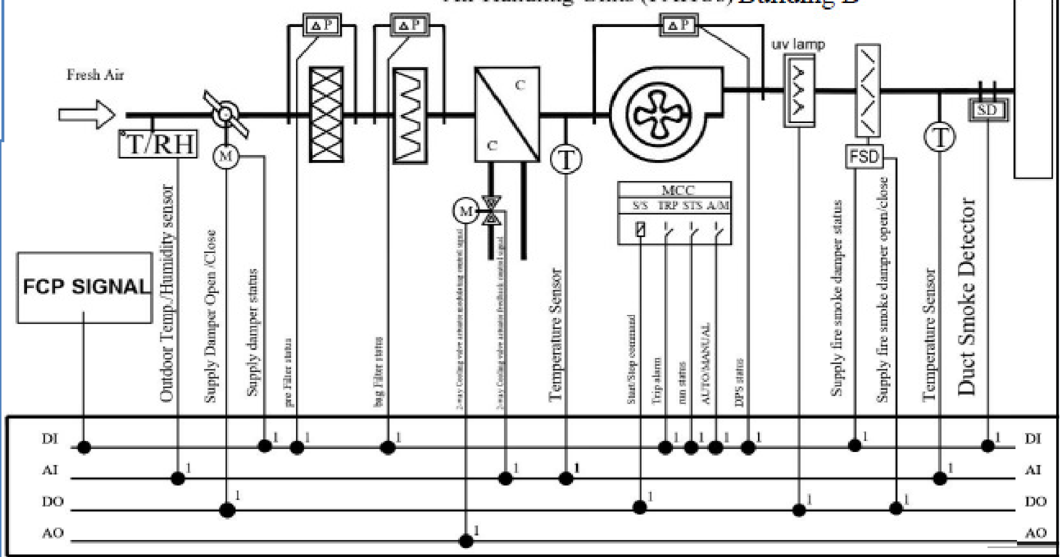
1.The fluid being controlled.
2. Valve style ;(2-way, 3-way).
3. Control mode; two-position, floating "tri-state", or modulating.
4. Max fluid temperature (packing & material).
5. Max inlet pressure(valve body selection).
6. Desired flow characteristics (for modulating applications).
Equal percentage, linear, or quick opening.
7. Max fluid flow rate Q (from cooling coil data)
8. Desired pressure drop - Δp when valve is full open (for modulation) to get Kvs.
9. Turn down ratio; (max usable rate/min rate).
10. Close-off pressure.
11. End Connection types.

Valve Sizing & Selection: How much Δp should valve have?



Coil Subsystem A typical subsystem for a cooling or heating coil in an AHU.

Air Handling Units (FAHUs) Building B



Building G:

Building's HVAC utilities: **Table 10 Building G utilities [8]**

AHU	Qty	CFM total	cfm(fresh)	Tr
# 01	1	9692	689	21
# 02	1	7098	546	15
# 03	1	5551	5551	20
sum	3			
Fan coil	Qty	cfm		Tr
# 08	10	800		2
# 10	30	1000		2.5
# 12	18	1200		3
# 14	19	1400		3.5
sum	77			
mini split DX	Qty	cfm	btu/hr	Tr
	6	400	12000	1
	4	800	18000	1.5
sum	10			
exhaust fans	Qty	cfm		
#01	1	742		
#02	1	878		
#03, #04, #08	4	636		
#05, #06	2	1335		
#07	1	16951		
#09	1	1377		
#10	3	148		
#11 (VSD)	1	21189/33902		
sum	14			
Supply Fan	Qty	cfm		
#01 Pressurized	2	25426		

Bill of quantities: **Table 16 BOQ Building G**

Equipment	Quantity
Part 1: Field devices	
LCP 01	
Air differential pressure switch	5
Temp & relative humidity sensor	1
Supply air damper actuator (on/off)	2
UV lamp (on/off)	1
supply fire smoke damper actuator (on/off)	1
Duct temperature sensor	1
Duct smoke detector	1
LCP 02	
Air differential pressure switch	5
Temp & relative humidity sensor	1
Supply air damper actuator (on/off)	2
UV lamp (on/off)	1
supply fire smoke damper actuator (on/off)	1
Duct temperature sensor	1
Duct smoke detector	1
LCP 03	
Air differential pressure switch	5
Temp & relative humidity sensor	1
Supply air damper actuator (on/off)	1
UV lamp (on/off)	1
supply fire smoke damper actuator (on/off)	1
Duct temperature sensor	1
Duct smoke detector	1
LCP 04	
Air differential pressure switch	5
Supply air damper actuator (on/off)	2
Pressure sensor	2
LCP 05	

Sequence Of Operation:

1. Circulation AHU:
a.- Run Conditions. - Mixing and Exhaust air dampers shall open.
b. Smoke Detection:
c. Prefilter & Bag filter Status:
d. Return Air Temperature Set point - Optimized:
e. Supply Fans
f. Cooling Coil Valve:

2-FRESH AIR HANDLING UNIT:

a. Run Conditions - Continuous
b. b- Smoke Detection:
-c. Prefilter & Bag filter Status:
d. Supply Air Temperature Set point - Optimized:
Supply Fan:
The supply fan shall run anytime the unit
e. Cooling Coil Valve: