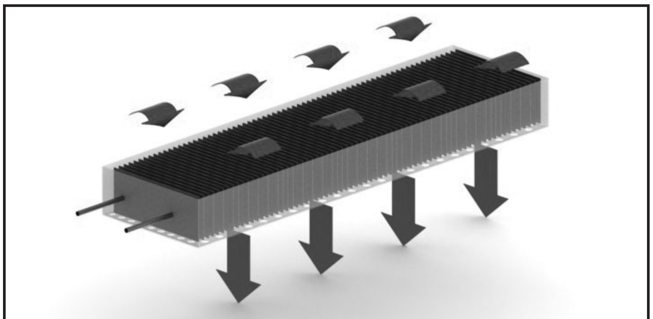
Introduction

Chilled ceiling systems consist of three main product types: active chilled beams, passive chilled beams, and radiant ceiling panels/sails. Even though these units are commonly referred to as "chilled" products they are also effectively used for both cooling and heating.

Both active and passive beams utilize water coils to provide sensible cooling, reducing the total load that must be addressed through the building's air handlers. Since chilled beams provide sensible only cooling they are best suited for spaces with low to moderate latent loads. This offers considerable potential for energy savings due to the volumetric heat transfer capacity of water and trade-off between fan energy and pumping power.

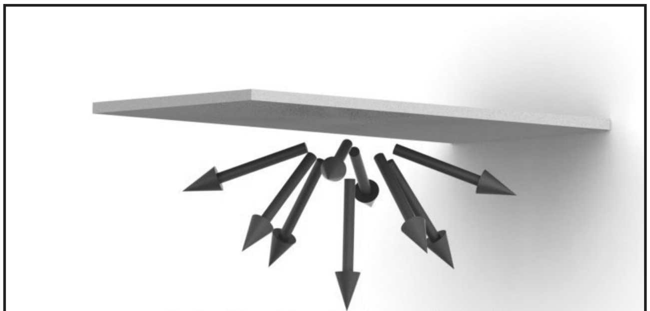
Passive beams consist of a water coil and an enclosure. The enclosure is primarily cosmetic, but helps to maintain even heat transfer across the coil. Passive beams provide cooling primarily through convective heat transfer. A convection current is created where higher density cool air sinks into the space, inducing warm low density air at the ceiling level through the coil. When using passive beams ventilation air must be introduced to the space either through natural or mechanical means.



Convective heat transfer with a passive beam

Incorporating supply air into a beam creates an active diffuser. Ventilation air pressurizes a plenum and the aerodynamically designed jets induce room air over water coils. Forced induction dramatically increases the heating and cooling capacity per square foot, compared to passive beams and radiant products. Active chilled beams harness the energy of the supply air to further reduce total energy consumption.

Radiant ceilings systems emit heating and cooling by both convection and radiation. During cooling, ambient air near the ceiling cools and falls to the occupied area, due to its higher density. The ceiling panels emit cooling and heating to the surrounding surfaces in the area by radiation. Radiant heat transfer typically results in high thermal comfort since the ambient temperature will feel 2.5°F to 5°F cooler/warmer than actual room temperature. This effect has the advantage that the room requires less conditioning than a traditional system, introducing an additional opportunity for energy savings.

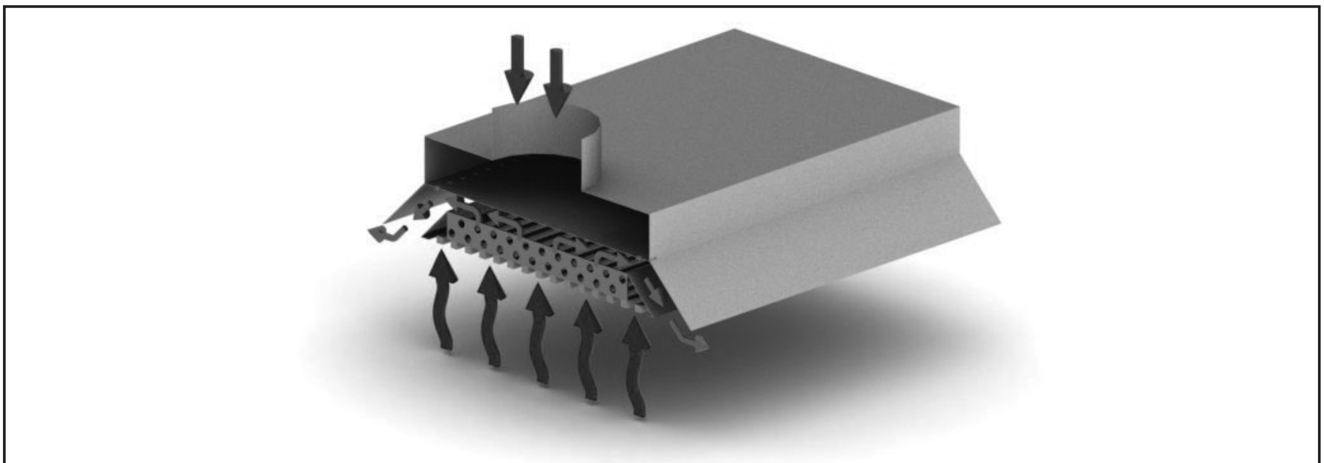


Radiant heat transfer from chilled ceiling panel

History

Modern chilled ceiling systems, more specifically active chilled beams, got their start in the 1920s when Willis Carrier began to develop the concepts for under-sill induction units. Patents were applied for and first installations of these units were completed in 1940. The use of an air-water terminal located in the space was an important advance in and of itself; however, these systems solidified the advantages of an air-water system over an all-air system.

- Water is much more efficient heat transfer medium than air.
- Reduced duct size required to only supply ventilation air increased usable space, and reduced the material cost and installation time.



Active Chilled Beam Operation

Scandinavian engineers, during the mid-1970's, adapted this technology along with radiant heating/cooling panels for overhead applications to work with new buildings designed to utilize natural ventilation. The result of their efforts was the passive chilled beam.

In regions where using natural ventilation was not effective, engineers integrated the mechanical ventilation into chilled beam. Utilizing the same principles used in the under-sill induction boxes, the active chilled beam was developed.

Theoretical Background

HEAT TRANSFER

ASHRAE defines heat transfer as "the flow of heat energy induced by a temperature difference."
Thermal energy can be transferred or be affected by:

- Conduction
- Convection
- Radiation
- Humidity

Thermal conduction is the mechanism of heat transfer by the transfer of kinetic energy between particles or groups of particles at the atomic level.

With solid bodies, such as with an air jet near a window, thermal conduction dominates only very close to the solid surface.

Thermal convection is the transfer by eddy mixing and diffusion in addition to conduction.

The transfer of fluid currents produced by external sources, such as by a blower, is called forced convection.

When the fluid air movement is caused by the difference in density and the action of gravity, it is called natural convection. Natural convection is very active near windows and near heat sources in the occupied spaces. The colder air falls and the warmer air rises.

Radiant heat transfer takes place through matter. It is a change in energy form, from internal energy at the source to electromagnetic energy for transmission, then back to internal energy at the receiver. Examples of radiation are sunshine through the air and window to the inside floor or ceiling light to occupants and to the floor.

All of these methods of heat transfer effect a person's comfort reaction. In addition, humidity has some effect caused by a change in evaporation rate from the body.

Heat transfer is also affected by the following factors:

- A greater temperature difference will result in a greater amount of heat transfer.
- The amount of surface area is directly proportional to the amount of heat transfer.
- The amount of time is also directly proportional to the amount of heat transfer.
- The thermal resistance of the material use affects the rate of heat transfer.

Heat loss is measured in "BTU" which is the amount of heat required to raise 1 lb. of water 1°F. Coefficients used to estimate the value of the heat loss include:

- 'K' Factor: amount of heat transferred in 1 hour through 1 sq. ft. of material, 1" thick at 1°F of temperature difference.
- 'C' Factor: amount of heat transferred in 1 hour through 1 sq. ft. of material through the specified thickness of the material used.
- 'R' Value: resistance to heat transfer, measured as the reciprocal of conductance (1/K or 1/C).
- 'U' Value: designates the overall transmission of heat in 1 hour per sq. ft. of area for the difference of 1°F across specified material.
- Conductance of individual materials is not directly applicable to the heat loss calculation. First, it must be converted to the 'R' value, which is (1/K or 1/C).

Equation 1: For a structure with multiple skin materials, the total heat transmission can be calculated as:

$$U = 1/(R1 + R2 + \ldots Rn)$$

For hydronic heating and cooling systems heat is removed from the occupied space (cooling) or added to the occupied space (heating) via a closed loop water system. Return air from the space passes across a fin tube coil.

PSYCHROMETRICS

One of the four major elements of thermal energy and comfort is humidity. Psychrometrics uses thermodynamics properties to analyze conditions and processes involving moist air. A detailed study of psychrometrics can be found in Chapter 1 of ASHRAE 2009 Fundamentals Handbook. This section is a summary of how knowledge of psychrometrics can be used to maximize space comfort and system performance.

Atmospheric Air (the air that you breathe), contains many gaseous components including water vapor and containments. Dry Air is atmospheric air with all moisture removed and is used only as a point of reference. Moist Air is a combination of dry air and water vapor and can be considered equal to atmospheric air for this discussion.

A psychrometric chart (FIGURE 4) is a graphical representation of the thermodynamic properties of moist air. There are several charts available to cover all common conditions. The one shown here is taken from ASHRAE Fundamentals Handbook, Chapter 1 and illustrates conditions of 32 to 100°F at sea level.

The Dry-bulb Temperature (DBT), is the temperature measured using a standard thermometer. Dry-bulb is also known as the sensible temperature.

The Wet-bulb Temperature (WBT), is the temperature measured using a 'wetted' thermometer. Wet-bulb is used to determine the moisture content of air.

The Absolute Humidity (AH), is the vapor content of air. It is described in terms of moisture per lb of dry air or grains of moisture per lb. of dry air. AH is also referred to as 'moisture content' or 'humidity ratio.' There are 7000 grains in a lb. of water.

The Relative Humidity (RH), is the vapor content of air. It is described as the percentage of saturation humidity at the same temperature (%). The goal for optimum space comfort is 30-35% for heating conditions, and 45-60% for cooling conditions. Saturation humidity is the maximum vapor content (lb./lb.) per lb. dry air that air can hold at a fixed temperature.

The Dew Point Temperature (DPT), is the temperature at which vapor begins to fall out of air to form condensation. DPT is the temperature at which a state of saturation humidity occurs, or 100% RH. It is also known as the saturation temperature.

The Specific Volume (Spv), is the reciprocal of air density which is described in terms of cubic feet per lb of dry air (cu ft/lb.). An increase in air temperature will result in a decrease in density and an increase in volume. A decrease in atmospheric pressure also decreased air density while increasing volume. At 5000 feet above sea level, density is decreased by 17%. Higher altitudes require larger motors and blowers to move the same effective mass, due to the increase in specific volume.

The Enthalpy (H) is the heat content of air. Enthalpy is also known as the total heat of air. Enthalpy is defendant on the wet-bulb temperature of air. It is described in terms of Btu's per lb. dry air (Btu/lb.).

A Status Point is a location on the psychrometric chart defined by any two psychrometric properties. A hydrometer or psychrometer is commonly used to define a status point.

At 100% RH the wet-bulb will equal the dry-bulb temperature. As the temperature difference between temperatures increases, the RH will decrease.

To locate a status-point, find the dry-bulb temperature on the bottom of the psychrometric chart. Follow this line upward until it intersects with the wet-bulb temperature from the left side of the chart.

From the 'status point' you can locate:

- Absolute Humidity (AH)
- Relative Humidity (RH)
- Dew Point Temperature (DPT)
- Specific Volume (Spv)

When will condensation occur? To determine if a supply air duct or air outlet device will form condensation on the surface:

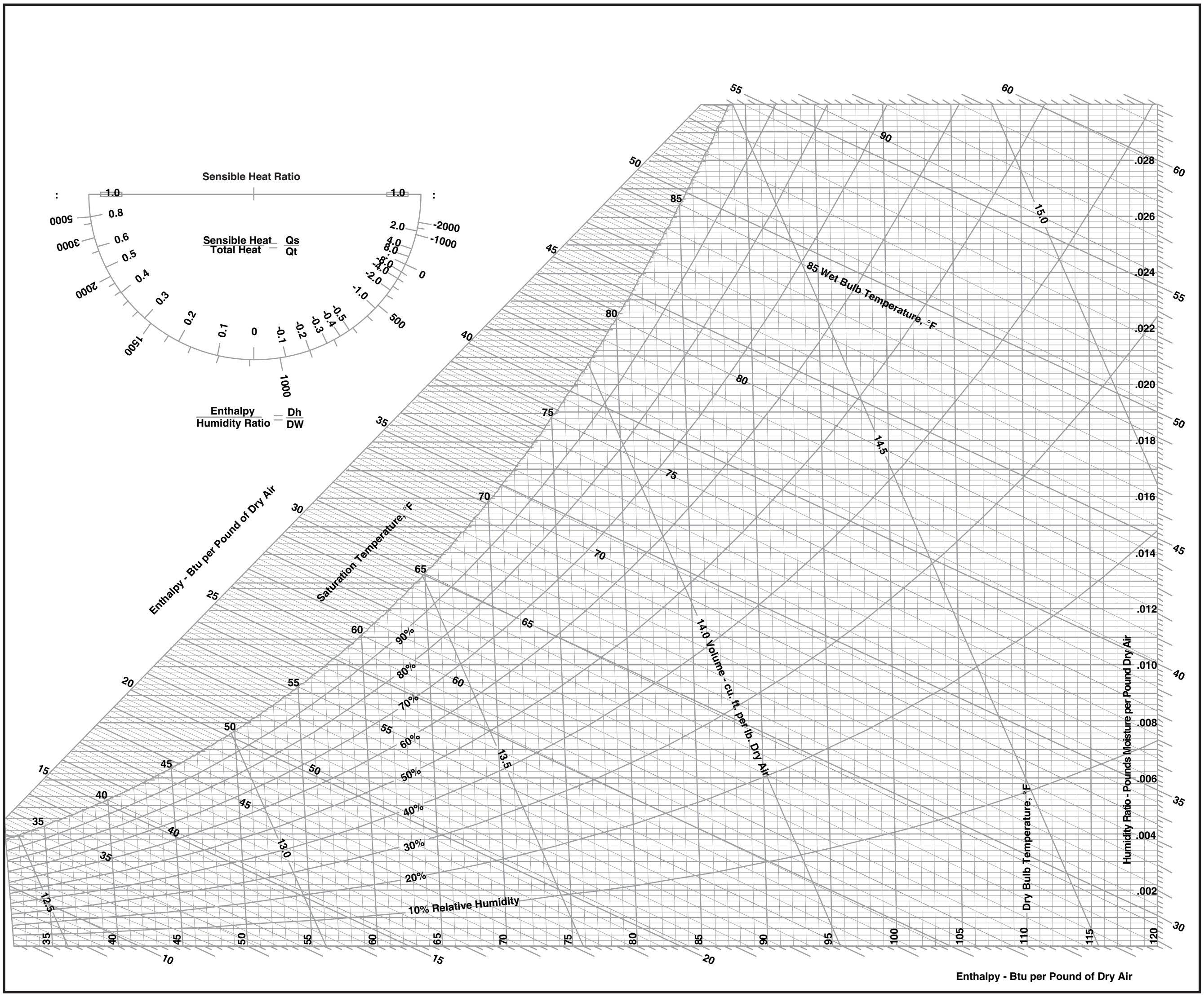


Figure 4. Psychrometric Chart

First, using the R-value of any thermal barrier, determine the minimum surface temperature.

Next, determine the DPT of the atmospheric air in contact with the surface.

If the surface temperature is equal or lower than the DPT, the surface will form condensation. If yes, an additional thermal barrier or other condensation prevention strategies may be required to solve the problem.

Sensible heating (Qsen), is the heat that raises the dry-bulb temperature of air without increasing the moisture content. Because we can easily sense this change in temperature, it is called 'sensible.' Sensible cooling is the removal of heat without removing moisture content of the air.

Latent Heat (Qlat), is the heat content of air due to the presence of water vapor. Latent heat is the heat required to evaporate this same amount of water (970 Btu/lb), also known as the latent heat of vaporization. As latent heat increases, moisture content increases.

Water can be heated to 212°F. If more heat is added, the water will vaporize but the temperature will not change.

Latent Cooling (Qlat), is the removal of latent eat from air without lowering the dry-bulb temperature. To retrieve 1 lb. of condensate, 970 Btu's would need to be removed. As latent heat decreased, moisture content decreases.

Latent Heat of Fusion is the heat required to change a liquid into a solid (144 Btu/lb. Water can be cooled to 32°F. If more heat is removed, it will cause ice to form. To retrieve 1 lb of water from ice, 144 Btu's must be added.

Sensible processes can be shown as horizontal paths on a psychrometric chart. Latent processes can be shown as vertical paths on a psychrometric chart. Most processes include both, resulting in an angled or diagonal path.

Sensible heat factor (SHF) is the measure of sensible heat to latent heat. Sensible heating only is 1.0. Equal proportions result in 0.5. SHF is generally higher than 0.5 because of the cooling processes that remove more sensible heat than latent heat.

INDUCTION

Induction is a flow that occurs as a result of the change in velocity pressure as a jet of air expands. The principals of induced air flow are based on the Venturi effect. The Venturi effect is a derivation of Bernoulli's principle and the continuity laws. In order to satisfy the fluid dynamic principles of continuity, a fluid's velocity must decrease as the flow expands; at the same time the static pressure of the flow must increase. The increase in static pressure balances the decreased velocity, thus maintaining the principles of conservation.

Benefits of Chilled Ceiling Systems

Chilled Ceiling Systems are designed to provide superior occupancy comfort. These systems require less energy to operate, operate more efficiently, and use less materials than conventional all air systems. Tempered and dehumidified air is supplied to the space to meet ventilation requirements and to handle the latent load. The majority of the sensible load is addressed with the chilled ceiling products. Decoupling the latent and sensible loads takes advantage of the superior volumetric heat capacity of water. The reduced volume of air that must be delivered to the space results in reduced air handler capacity and size, smaller duct sizes, and overall energy savings. A higher supply temperature contributes to increased occupancy comfort.

FIRST COST BENEFITS:

- Shallow unit profiles allow for reduced ceiling space requirements; typically require 60% less vertical space than conventional all air systems.
  - Reduced slab to slab spacing; reducing material costs per floor
  - Easily integrated into retrofit applications where space is limited
- Low volume of supply air required for active beams enables reduction of the total amount of air processed at the air-handler by an all air system up to 50%.
  - Reduced air-handler size/capacity, and duct work size

COMFORT AND IAQ BENEFITS:

- Active beams typically supply a constant volume of primary air, decreasing occurrences of dumping and changes to the air motion in the space; issues common to typical VAV systems
- When supplied with primary air from a dedicated outside air system (DOAS) 100% fresh air is supplied to the space
- Dry-coil sensible cooling, eliminates bacterial, fungal, or mold growth associated with fan coils and other unitary products with condensing coils
- Constant primary air volume ensures ventilation requirements are met and helps to maintain relative humidity levels in the space

ENERGY EFFICIENCY AND OPERATIONAL BENEFITS:

- Utilizing the heat transfer capacity of water also takes advantage of the superior operational efficiency of pumps as compared to fans.
  - A 1" diameter pipe can deliver the same cooling/heating capacity as an 18" x 18" duct
  - Reduction of fan energy by a factor of 7 to deliver the same cooling to the space
- Higher supply water temperatures compared to conventional systems allow for use of water side economizers.
  - Increased opportunities for free-cooling
- Significant reduction in maintenance costs and labor as compared to conventional all air systems
  - No moving parts - no blowers, motors, damper actuators to replace
  - Dry-coil operation - does not require regular cleaning and disinfecting of condensate pans
  - Recommend cleaning of coils once every 4 to 5 years, more frequently in hospitality rooms where linens are frequently changed (i.e. hospital patient rooms and hotel rooms)

Chilled Ceiling System Design

CHILLED CEILING APPLICATIONS

Chilled beam and radiant ceiling products are designed to handle high thermal loads in the space. They are also an effective solution in spaces where individual temperature control is desired. Ideal applications are spaces where the sensible heat ratio is greater than 0.75, meaning that 75% or more of the total heat gains in the space are sensible gains. These locations include computer/server rooms, condos/apartments/hotel guest rooms, libraries, and museums.

Use of chilled ceiling systems should be limited to applications where cooling loads are less than 40 BTUH/ft^2, and heating loads are lower than 15 BTUH/ft^2. More specifically, passive beam and radiant panel usage should be limited to applications where cooling loads are no more than 25 BTUH/ft^2, and active chilled beams are not recommended for use when cooling loads are more than 40 BTUH/ft^2. Chilled ceiling systems are not recommended in these applications since addressing the loads will likely create thermal comfort issues. In transitional spaces where thermal comfort is not critical, chilled ceiling products can be used to address higher loads.

Chilled beams and radiant ceiling systems should not be applied in buildings where relative humidity of the space is not easily maintained. This would include retrofit applications, lobbies, and entrances where there is excessive infiltration.

Chilled beams are best applied when installed no higher than 14 feet above the floor, but can remain effective with installation heights up to 20 feet. When installed above these heights it is difficult to effectively get heating and cooling into the occupied space.

PRACTICAL DESIGN GUIDELINES

There are guidelines that should be followed when considering a chilled ceiling system to ensure the design will create a comfortable environment for occupants and result in optimum energy efficiency.

The system should be designed to meet only the heating and cooling requirements of the actual space. Overdesigning the system will increase the cost of the project, and potentially result in decreased comfort.

Primary air must be adequately dehumidified, and supplied at a flow rate large enough to offset the latent loads of the space. This flow rate must also be high enough to meet the ventilation requirements outlined in ASHRAE standard 62.1.

When heating with chilled beams and radiant panels, care must be taken that the system is not oversized for heating. Entering water temperatures should be as low as possible to meet the heating requirements, and should never be over 140°F.

Condensation control strategies must be implemented to maintain optimum operating conditions, prevent bacterial, mold, and fungus growth, ensure damage to building does not occur.

When designing a chilled beam system it is best to limit the types and configurations of products used. This will help to make logistics during installation and building maintenance easier.

Room air temperature is maintained through regulation of 2-way control valves. Use of 2-way valves is preferred as they will minimize pumping costs.

Systems should be designed to take full advantage of free cooling and heating opportunities through economizers and heat recovery devices. Chilled beams and radiant panels are highly efficient products and offer energy savings over traditional systems. However, one of the biggest advantages these products offer is the additional energy savings that can be achieved in the rest of the system due to the unit operating conditions.

DESIGN METHODOLOGY

The design of chilled ceiling systems is an iterative process between selection of the equipment to be used and the inlet conditions for the system. This also includes placement/orientation. The iterative process enables the inlet conditions to be optimized so that the design results in a comfortable space for the occupant, and that the equipment is operating with the highest efficiency possible. This is true for all chilled ceiling systems, but is especially true for active chilled beams.

Equipment selection is based on the following items and must be balanced for creating an effective, efficient, and comfortable system:

- Total unit capacity
  - Size of units
  - Quantity of units
  - Unit Configuration
- Supply Air
  - Flow rate
  - Temperature
  - Relative humidity
  - Operating pressure
- Entering Water Conditions (cooling & heating)
  - Entering water temperature
  - Flow rate
  - Coil pressure drop
- Unit Placement
  - Throw patterns
  - Throw length
- Noise

Once the inlet conditions and equipment has been selected, the controls for the system are selected. The room control system must be designed to deliver the selected inlet parameters and maintain the energy efficiency of the design. The critical points to be maintained are the entering water conditions as well as the supply air conditions. After control of the critical points has been established, additional controls to compensate for changes in space dew point temperature and occupancy should be considered through a building management system.

This methodology is depicted in Figure 5, Chilled Ceiling Design Methodology.

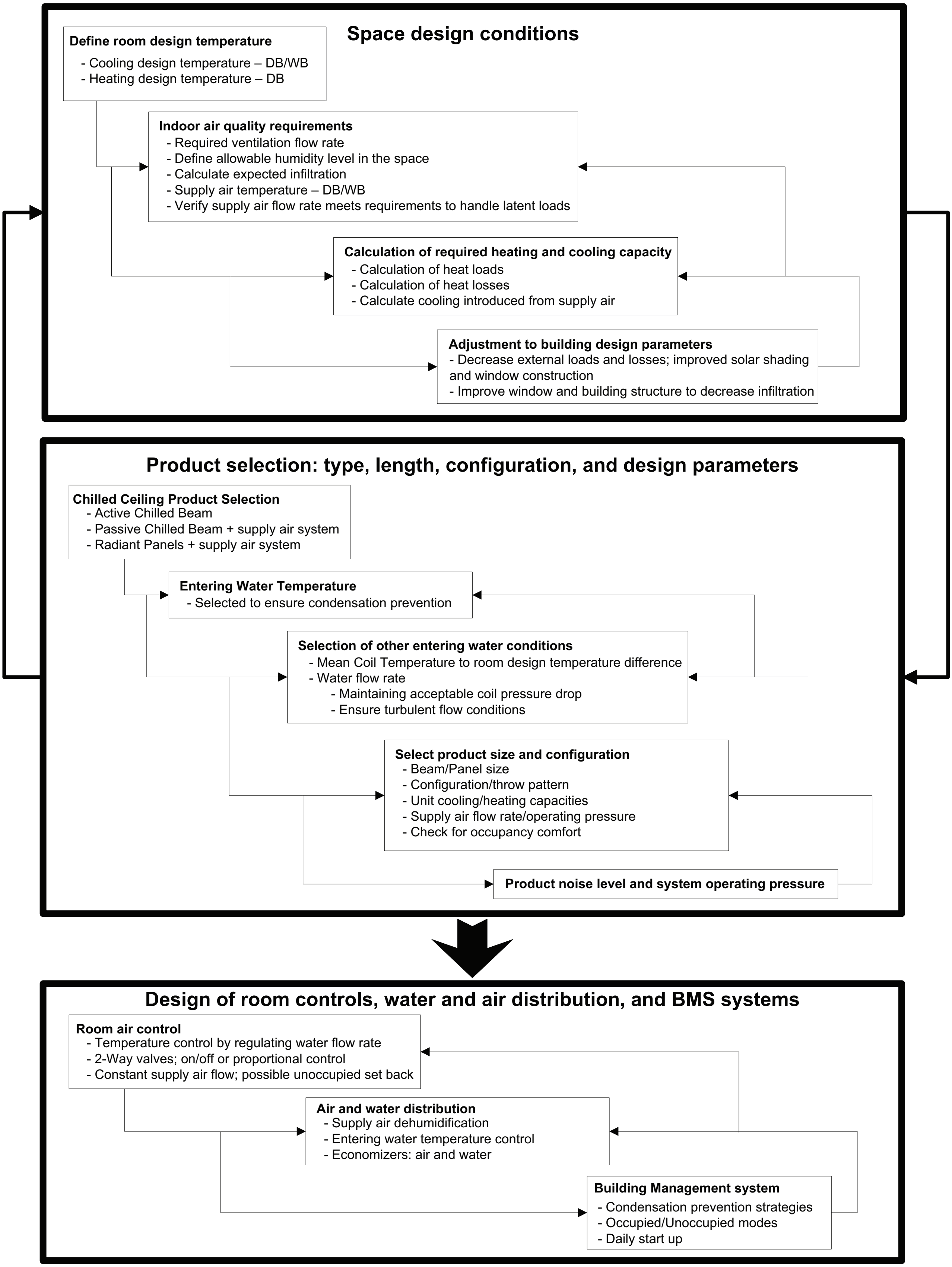
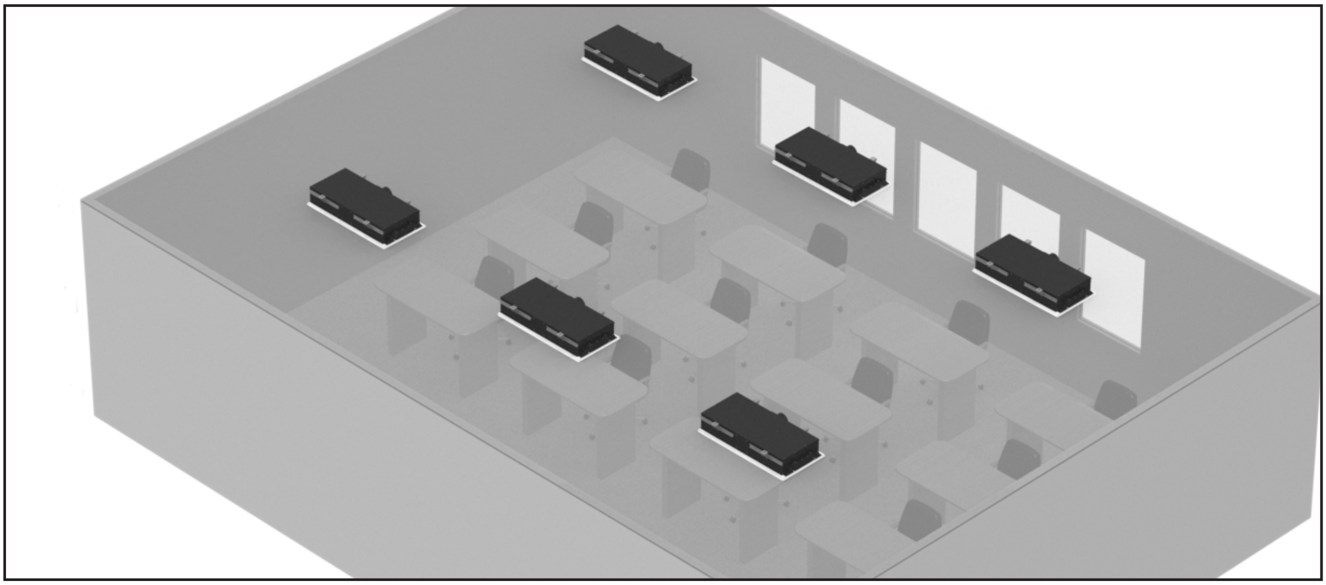


Figure 5. Chilled Ceiling Design Methdology



System Design Process

SPACE DESIGN CONDITIONS

The first step in determining the space design conditions is to define the design temperatures for both heating and cooling. This should be done by following the guidelines set in ASHRAE Standard 55 and the chapters on heating and cooling loads in the ASHRAE Fundamentals Handbook.

Once the design temperatures have been defined, an iterative process should be used to determine the indoor air quality requirements, calculating the required capacities to address the heating/cooling loads, and adjusting the building design/construction (if applicable).

The indoor air quality (IAQ) requirements include supply air flow rate, to meet both ventilation requirements and address the latent loads in the space, determining infiltration, and defining the maximum allowable humidity level.

Based on the building design and construction, anticipated infiltration should be calculated. Information on how to calculate infiltration and how to use infiltration when calculating heat loads and losses can be found in the ASHRAE Fundamentals Handbook. The heat loads and losses calculated associated with infiltration are used in determining the latent cooling requirements. This will affect the volume of supply air necessary to maintain the design humidity levels in the room.

Guidelines for determining the minimum ventilation requirements are given in ASHRAE Standard 62.1. Criteria for maximum relative humidity in the space, based on a humidity ratio of 0.012, is set in ASHRAE Standard 55; for a room design temperature of 75°F, the maximum relative humidity is 63.5%. Once the design conditions for room relative humidity have been determined the supply air flow rate necessary to maintain this level can be calculated. The required flow rate to meet the latent load can be determined by the following equation:

$$\dot{V} = \dot{q} \div [4840 \times (H_{Rr} - H_{Rp})]$$

$\dot{V}$ = the volumetric flow rate, CFM
$\dot{q}$ = latent heat gain in the space, BTU/H
H_{Rr} = room air humidity ratio, $lbs_{water}/lbs_{dry\ air}$
H_{Rp} = primary air humidity ratio, $lbs_{water}/lbs_{dry\ air}$

It follows that the required flow rate to maintain control of the humidity will rapidly increase as the difference between the room air and primary air humidity ratios decrease. As a result, designs seeking to maintain relatively low humidity ratios will need a high primary flow rate if the dew point temperature of the supply air is close to the design dew point in the room.

Comparing the required supply airflow rates for ventilation and to maintain the relative humidity of the space, the higher of the two flow rates will determine the minimum flow rate allowable for the space. If necessary the supply air flow rate can be increased to supplement the sensible cooling of the products selected.

After the IAQ requirements have been tentatively set, the required equipment capacities to meet the heat loads and losses can are determined. Care should be taken to design around actual loads/losses that will be experienced in the space. Overdesigning the system will increase installation and equipment costs, and could potentially cause thermal comfort issues. Once the capacity requirements have been calculated, either supply air conditions or building design/construction (if possible) can be adjusted to be more suited to chilled ceiling application.

PRODUCT SELECTION

The type of product to be used to is at the designer's discretion. However the recommended limitations of maximum capacity per square foot should not be exceeded where high levels of thermal comfort are required.

Once product type has been decided the entering water temperature should be selected such that condensation is prevented. The majority of chilled ceiling products do not include a means to collect or manage condensation. This means the temperature of the heat transfer surface, either water coil or panel/sail surface, must be higher than the dew-point temperature of the space to prevent the formation of condensation. However, to achieve the maximum cooling capacity the entering water temperature should be as low as possible. This can be difficult when trying to get the most capacity out of chilled ceiling products.

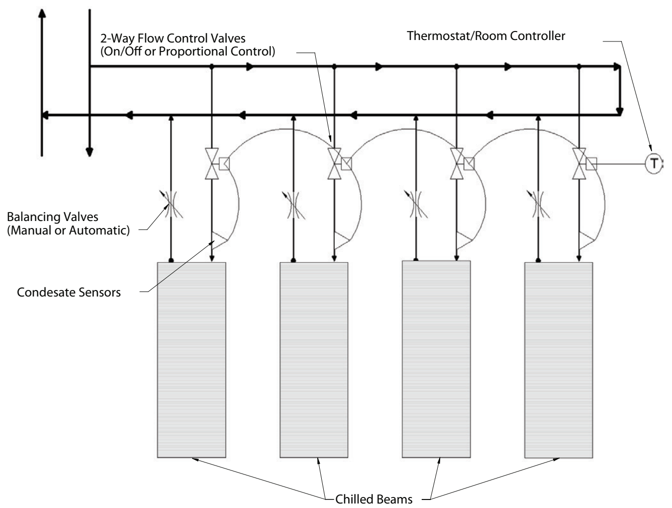
There are several ways to operate these products to prevent condensation. The primary step to preventing condensation is for the chilled water design supply temperature to be at least 1°F above the dew-point temperature of the space. Also, the supply air to the space must also be sufficiently dehumidified to maintain the design relative humidity conditions. The secondary measures are noted below:

- Properly insulated valves and piping
- Measures used to shut off chilled water flow
  - Condensation sensors installed on the supply water piping
  - Relative humidity/dew-point temperature sensor installed in the return air path
- Raising the chilled water supply temperature
  - Using a relative humidity sensor in conjunction with a room temperature system to determine moisture content and dew-point temperature of the space. Using this information the chilled water temperature can be adjusted upward to prevent condensation. This measure should only be used in the event that an entire building is at risk for condensation.

At this time the supply air temperature should be tentatively selected. Supply air temperature can be varied between cooling and heating, but most designs keep a fixed temperature as long as heating requirements can be met.

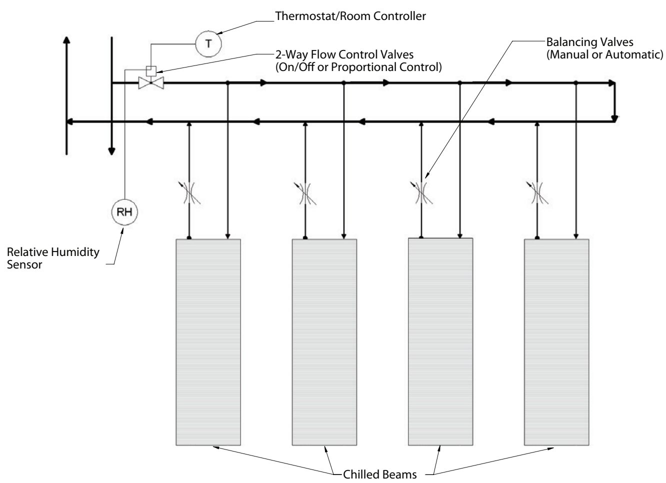
The size and configuration of products selected should be completed while adjusting the following parameters:

- Water flow rate: this should be selected to minimize pressure drop, should be no higher 10 ft w.g., while maintaining turbulent flow through the product
- Supply airflow rate: flow rate must be maintained above the minimum determined for IAQ requirements, but can be increased to offset the sensible cooling requirements of the product selected
  - Increasing the flow rate in active beams while maintaining the same nozzle geometry will result in an increase of operating pressure. The recommended operating range is typically between 0.2 in w.g. and 0.8 in w.g. Operating pressure in active beams will also directly impact the noise generated by the product during operation.
- Unit placement/Configurations:
  - Radiant panels and sails: These products should be installed so that no more than 75% of the available ceiling space is made up of active panels/sails. Panels models with perforated faces and backed with acoustic fleece insulation can be used to improve noise attenuation within the space.
  - Passive Beams: Passive beams should not be installed directly above occupants since the highest velocities occurring from the convection process will occur directly underneath the beam
  - It is critical to the operation of passive beams that adequate space is provided for air flow through the beam. When installed in a flush mount application, shadow gaps, perforated ceiling tiles, dummy beams, or return air grilles must be installed so that warm room air enter the air path for the passive beams. It is recommended that the total free area for the return air path be at least 50% of the passive beam surface area. In exposed applications, the beams should be installed with a minimum distance between the top surface of the beam and the ceiling that is equivalent to half of the beam width, see Figure 7.



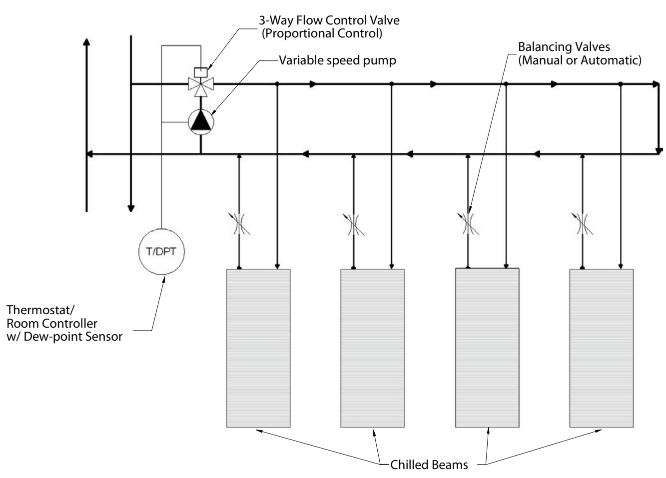
A) Condensate sensors installed on the chilled water supply shut down individual flow control valves when condesnation is detected.

Figure 6a. Condensation Prevention Strategies



B) Relative humidity sensor installed in return air path to shut down zone flow control valve when relative humidty reaches set point of the sensor.

Figure 6b. Condensation Prevention Strategies



C) Use of a 3-way proportional valve and variable speed pump to raise supply water temperature above the room dew-point temperature.

Figure 6c. Condensation Prevention Strategies

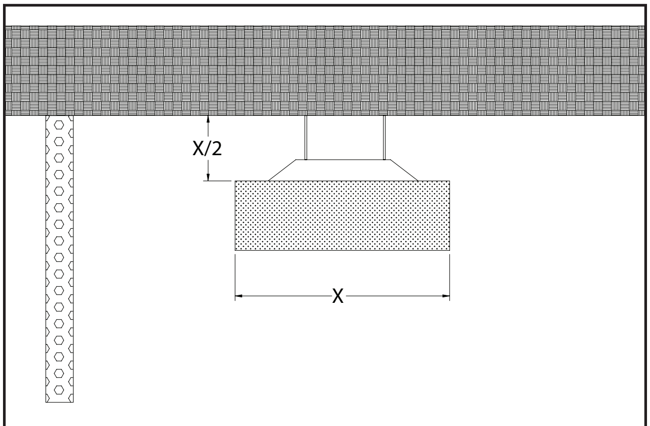


Figure 7. Passive beam mounting height

- Active Beams: With the different configurations available in active beams, 1, 2, and 4-way beams a design can be implemented to effectively create a comfortable space. In open office spaces as well as internal offices 2-way or 4-way beams are typically used. The flexibility provided by 2-way and 4-way beams, due to multiple sizes and nozzle configurations, allow them to be appropriately applied in most applications. 1-way beams are typically used in perimeter zones and small spaces such as individual offices and hotel rooms.

- After the throw pattern has been decided, placement of the beam within the space can be determined. Active chilled beams, because of their design, share throw characteristics with conventional slot diffusers. Placement and orientation of active beams is critical for thermal comfort due long throw values associated with active beams. In open office plans it is typically more cost effective to use several longer beams that are installed parallel to the long direction of conventional ceiling systems, instead of numerous smaller beams the length of the module division. (Figure 8, Open-office Active Beam Layout) However in an open office the number and size of beams used will be determined by balancing the cost per beam, cost of air side operating pressure, and water side pumping power to achieve optimum energy efficiency.

- When applying 2-way and 4-way beams in small offices and individual offices the recommended location is directly above the occupants. This will result in the lowest velocities within the occupied space. It is also recommended that 2-way beams are installed lengthwise in the space. This will allow for the use of longer beams, reducing the cooling requirements per linear foot which will in-turn lower total air flow per foot and the resulting velocities in the space ensuring occupancy comfort. If placement is required near a wall use of 1-way throw beams are recommended. 1-way beams can also be effectively used in perimeter zones for cooling applications; however they should be supplemented with baseboard heating to address window loads during the heating season. 2-way beams can be effectively applied in perimeter zones for both heating and cooling. Care must be taken if 2-way beams are installed parallel to windows. In intermediate seasons when internal cooling is required and window surfaces are cool an acceleration of the air can occur in the space creating drafts and potential discomfort.

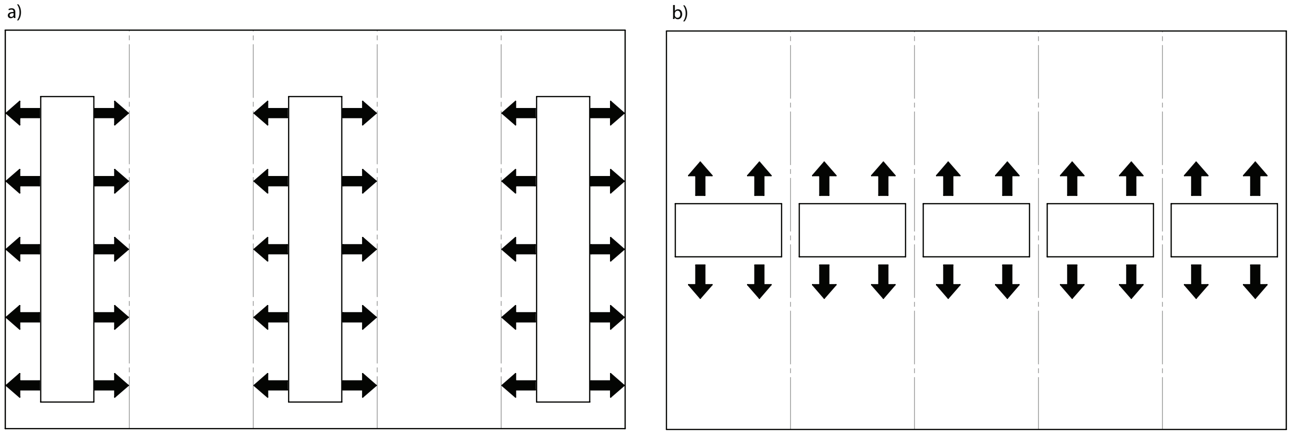
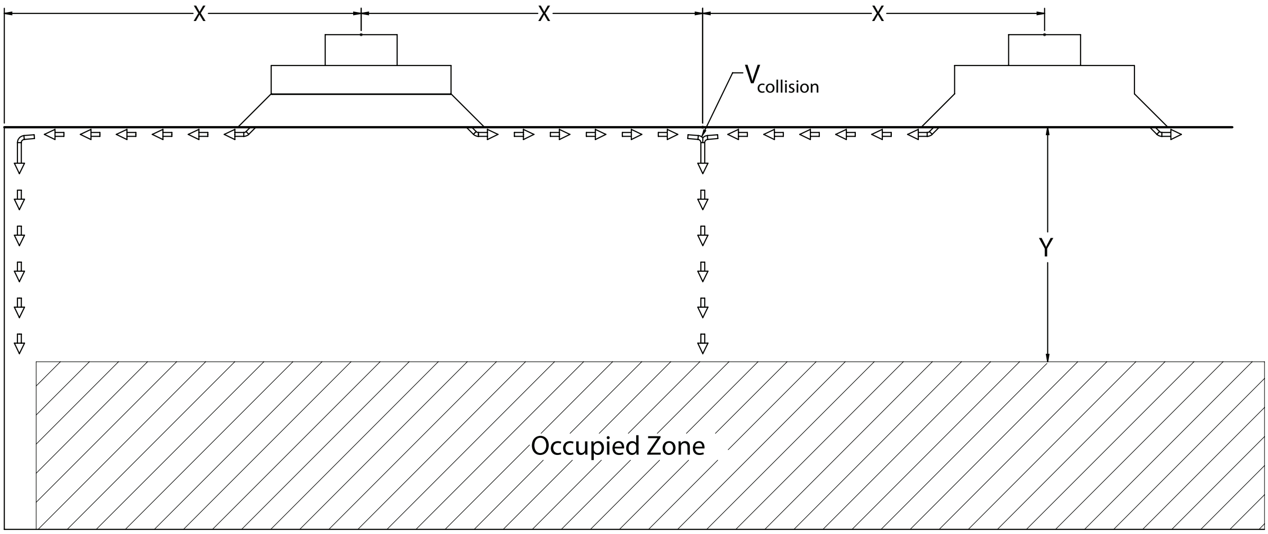


Figure 8 - Open-office Active Beam Layout: In lengthwise installations(a) there are less piping and duct connections than in crosswise installations(b). In crosswise installations, there is typically one beam per module. Even if the total cost for the beams in both layouts are the same, installation costs, additional valves, piping, and ductwork will prove to be more costly.



The minimum distance between units (2X) or minimum distance from a sidewall (X), can be determined by taking the difference between the diffuser's characteristic throw to 50 fpm (T_{50}) and the distance between the ceiling and the occupied zone (Y).

Figure 9. Local Velocity Diagram

- The ideal location for most active beams is directly above the occupant. This is because the lowest velocities in the space will occur in the induced air path. If it is desired to position an active beam close to a wall, a unit with an asymmetrical or 1-way throw pattern is recommended. As active chilled beams have throw characteristics similar to linear slot diffusers the same principles for determining thermal comfort conditions should be used. Location for final placement should take into consideration the allowable average air speed in the occupied space in accordance with ASHRAE Standard 55. Accounting for the air side sensible capacity will allow for reduced capacity requirements of the water coils in the beams. Designing with this in mind will reduce airflow requirements per linear foot, which will help to meet the requirements for thermal comfort. When placing two beams in the same space as shown in Figure 9, Local velocity diagram, care must be taken to ensure that the colliding air streams do not result in velocities over 50 fpm causing discomfort. A general guideline to achieve air velocities of 50 fpm or less in the occupied space is to ensure the velocities of colliding airstreams are below 100 fpm. If velocities at the point of collision are greater than 100 fpm, the distance from the ceiling for the air flow to slow to 50 fpm is noted in the equation below:

$$Y = T_{50} - X$$

Where:
Y = distance from the ceiling
X = half the distance to the adjacent diffuser
T_{50} *= diffuser characteristic throw to 50 fpm*

CONTROL OF CHILLED CEILING SYSTEMS

Very basic room controls can be used with chilled ceiling systems. This is due to the fact that most systems are designed to operate with a constant volume of supply air. Also, the large coil size, combined with relatively low velocities across the coils result in a fairly long response time.

With chilled beams or radiant systems, the most common method for controlling room temperature is regulating the water flow rate through the selected equipment. The alternative is to vary the supply water temperature.

The control of water flow rate is achieved through on-off, time proportional on-off, or modulating control valve actuators. The maximum flow rate should be limited by a balancing valve installed on each beam circuit. It is generally recommended for 2-way valves to be used to reduce pumping costs, but 3-way valves can be used when pump speeds are not variable. While on-off and modulating actuator control is straight forward, time proportional on-off systems are a bit more complex. These systems use a feedback control loop to open and close an on-off actuator such that the total time open is proportional to the percentage of flow that is requested by a modulated room controller. While control of this system is more complex, actuator first costs are greatly reduced.

Chilled beams should be connected in parallel so that each beam sees the same entering water temperature. For the greatest flexibility of control each beam should be fitted with an actuated control valve. With this setup, the flow rate can be modulated in each beam. And, in the event the entering water temperature reaches a point where condensation is a concern the flow rate to individual units affected can be shut down, so that the entire zone do not suffer a loss in sensible capacity. The alternative is one actuated control valve per zone. In either situation, each beam should be fitted with isolation valves on the both the supply and return.

Alternatively to varying water flow rate through the beam, the entering water temperature can be varied according to the load in the space. This requires more sophisticated control sequences. Varying the water temperature also requires a bypass loop, that can inject higher temperature water from the return loop of the chilled beams or main air handler into the supply water loop for the beams.

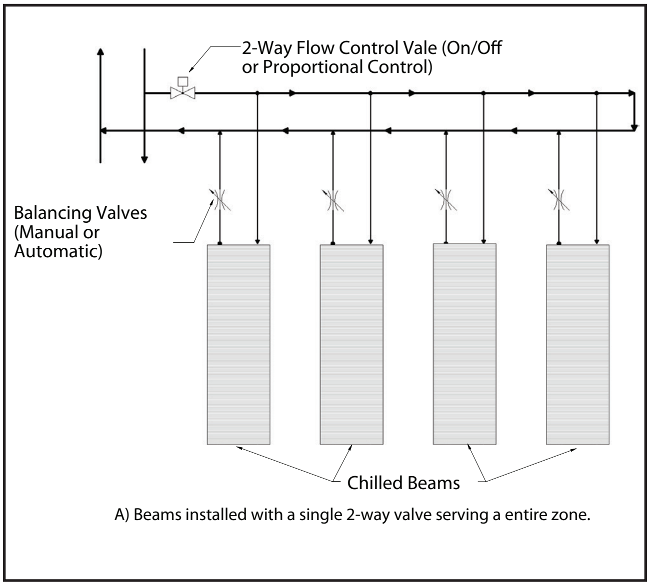


Figure 10a. Chilled beam zone control - Single flow control

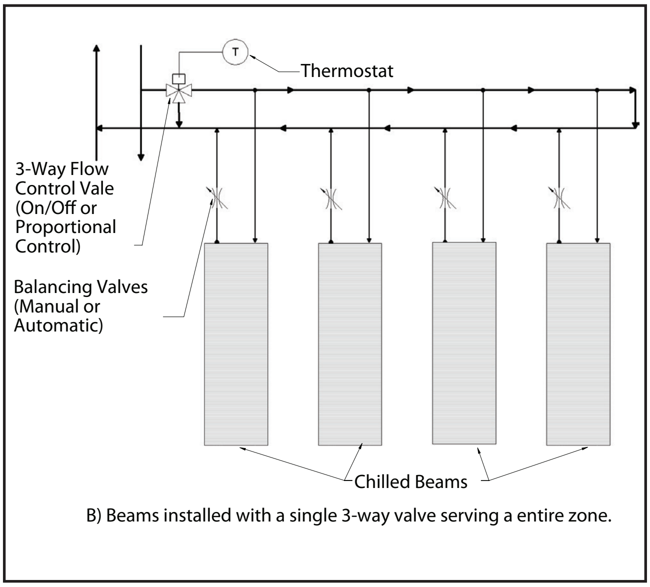


Figure 10b. Chilled beam zone control

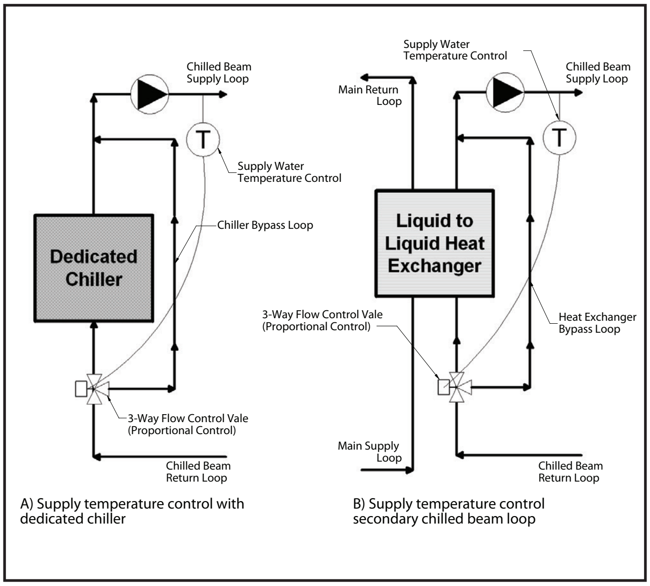


Figure 11a. Supply water temperature control with dedicated chiller;
Figure 11b. Supply water temperature control chilled beam loop

In order to control the supply water temperature a dedicated chiller and supply/return circuits can be used (see Figure 11a), or heat exchanger between the main air handler loop and chilled beam loop are acceptable (see Figure 11b).

When designing systems with occupied/unoccupied modes or with night set back set ups. It is critical to ensure the design relative humidity conditions are met prior any water based sensible cooling. In most cases, 30 minutes of dry-air ventilation will be enough to prevent any condensation during morning start-up and when returning to occupied modes. This can easily be achieved for night set back/morning start up by offsetting the time schedules for the air handlers and chilled beam system pumps.