PDHonline Course M378 (2 PDH)

HVAC – Practical Basic Calculations

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INTRODUCTION:

HVAC (pronounced either "H-V-A-C" or, occasionally, "*H-vak*") is an acronym for “*Heating, Ventilation and Air Conditioning*”. HVAC sometimes is referred to climate control as a process of treating air to control its temperature, humidity, cleanliness, and distribution to meet the requirements of the conditioned space.

The **HVAC** industry had been historically regulated by standards organizations such as, **ASHRAE, SMACNA, ARI, ACCA**, Uniform Mechanical Code, International Building Code, and **AMCA** established to support the industry and encourage high standards and achievements.

The term ventilation is applied to processes that supply air to or remove air from a space by natural or mechanical means. Such air may or may not be conditioned. An air conditioning system has to handle a large variety of energy inputs and outputs in and out of the building where it is used. The basic purpose of an **HVAC system** is to provide interior thermal conditions that a majority of occupants will find acceptable. This simply requires that the air be moved at an adequate velocity. However, occupant comfort will require that an **HVAC system** add or remove heat to or from building spaces.

HEAT AND TEMPERATURE:

• **Heat:** May be defined as the energy in transit from a high-temperature object to a lower-temperature object. This heat transfer may occur by the mechanisms of **conduction, convection and radiation**.

• **Sensible heat:** Kind of heat that increases the temperature of air. It is an expression of the molecular excitation of a given mass of solid, liquid, or gas.

• **Latent heat:** Heat that is present in increased moisture of air. It changes the matter from solid to liquid or from liquid to gas. Heat that is required to change solid to liquid is called latent heat of fusion, and that which is required to change liquid to gas is called latent heat of vaporization.

• **Enthalpy:** Sum of sensible and latent heat of a substance e.g. the air in our environment is actually a mixture air and water vapor. If the enthalpy of air is known, and the enthalpy of the desired comfort condition is also known, the difference between them is the enthalpy that must be **added** (by heating or humidification) or **removed** (by cooling or dehumidification).

• **Temperature:** A measure of the degree of heat intensity. The temperature difference between two points indicates a potential for heat to move from the warmer point to the colder point. Unit in English system is Fahrenheit, and in International System is Celsius.

• **Dry-bulb temperature (DB):** The dry-bulb temperature is the temperature of air measured by a thermometer freely exposed to the air but shielded from radiation and moisture. More specifically, it is a measure of the intensity of kinetic energy of the molecules in the air. It is one of "*the most important climate variables for human comfort and building energy efficiency*".

• **Wet-bulb temperature (WB):** The temperature registered by thermometer whose bulb is covered by a wetted wick and exposed to a current of rapidly moving air. It is the temperature air would have if part of its energy were used to evaporate the amount of water it would absorb to become fully saturated.

• **Dew point temperature:** The temperature at which condensation begins when the air is cooled.

• **Relative humidity (RH):** (actual vapor pressure of air-vapor mixture/pressure of water vapor when the air is completely saturated at the same dry-bulb temperature) x 100.

• **Vapor pressure:** Is the pressure exerted by the motion of molecules of water vapor. It is dependent on the amount of water vapor in the air and the temperature of the air.

THERMODYNAMICS BASIC CONCEPTS:

The biggest problem in **thermodynamics** is the student to learn and recognize **heat, work, force, energy, power** and other technical terms. So, it is very important to remember some concepts below:

Cal - Calorie: The **"Cal or Calorie"** is the standard unit of measurement for heat. The gram calorie, small calorie or calorie (cal) is the amount of energy required to raise the temperature of one gram of water from **14.5°C** to **15.5°C** under standard atmospheric pressure of **1.033 Kg/cm² (14.7 psi)**.

Btu - British Thermal Unit: The **"Btu"** is the standard unit of measurement for heat. The Btu is defined as the amount of energy needed to raise the temperature of one pound of water from **58.5°F to 59.5°F** under standard pressure of **30 inches of mercury (14.7 psi)**.

ENERGY UNITS CONVERSIONS:

Unit	Multiply	To obtain
1 Btu	0.252	kcal
	107.7	Kgf.m
	778.7	ft.lbf
1 Cal	0.00396	Btu
	0.00000116	kW.h
1 kcal	1000	cal
	3.9604	Btu

Unit	Multiply	To Obtain
1 Watt (W)	0.001	kW
	0.00134	hp
	0.0002387	kcal/s
	44.2	ft.lbf/min
	0.000948	Btu/s
	0.000284	ton (refrig.)

Unit	Multiply	To Obtain
1 Btu/s	0.3002	ton (refrigeration)
	1.055	kW
	1.435	hp
	106.6	kgf.m/s
	778.8	ft.lbf/s
1 joule/kilogram/K = J/(kg.K) = 1 joule/kilogram/°C = J/(kg.°C) =	0.001	kilojoule/kilogram/°C = kJ/(kg.°C)
	0.000239	kilocalorie /kilogram/°C = kcal/(kg.°C)
	0.000239	Btu/pound/°F = Btu/(lb.°F)
	0.000423	Btu/pound/°C = Btu/(lb.°C)
1 Btu/pound/°F = Btu/(lb°F)	1.8	Btu/pound/°C = Btu/(lb.°C)
	4186.8	joule/kilogram/°C = J/(kg.°C)
	4.1868	kilojoule/kilogram/°C = kJ/(kg.°C)
	778.2	pound-force.foot/pound/°R

Obs.:

1.0 Watt-Hour = 0.000948 (Btu/s) x 60 x 60 = **3.413 Btu/h**;
1.0 Btu/h = 0.293 Watt/h = 0.000293 kW/h **= 0.252 kcal/h**.

Temperature: Is a physical property of matter that quantitatively expresses hot and cold.

Celsius: Also known as **centigrade** is a temperature scale that is named after the Swedish astronomer Anders Celsius (1701–1744), who developed a similar temperature scale two years before his death. Then nominally, **0 °C** was defined as the freezing point of water and **100 °C** was defined as the boiling point of water, both at a pressure of one standard atmosphere **(1.033 Kg/cm²)**.

Fahrenheit: Is the temperature scale proposed in 1724 by, and named after, the physicist Daniel Gabriel Fahrenheit (1686–1736). On the Fahrenheit scale, the freezing point of water was **32 degrees** Fahrenheit (°F) and the boiling point **212 °F** at standard atmospheric pressure **(14.7 psi).**

Pressure: Is the **force per unit area** applied in a direction perpendicular to the surface of an object. Gauge pressure is the pressure relative to the local atmospheric or ambient pressure.

Unit	Pascal (Pa)	bar (bar)	atmosphere (atm)	Torr (Torr)	pound-force per square inch (psi)
1 Pa	1 N/m²	0.00001	0.000009867	0.0075006	0.000145
1 bar	100000	106 dyn/cm^2	0.9867	750	14.5
1 at	98066	0.980665	0.968	735.5	14.223
1 atm	101325	1.01325	**1 atm**	760	14.7
1 torr	133.322	0.013332	0.0013158	**1 mmHg**	0.0193
1 psi	0.006894	0.068948	0.068046	51.72	**1 lbf/in²**

TONS OF REFRIGERATION:

For commercial and industrial refrigeration systems most of the world uses the **kilowatt (kW)** as the **basic unit** refrigeration. Typically, commercial and industrial refrigeration systems are rated in **Tons of Refrigeration (TR)**. One Ton of Refrigeration was defined as the energy removal rate that will freeze **1 ton of water at 0 °C (32 °F)** in one day, or, the amount of heat required to melt **1 ton of ice in 24 hours**. The unit's value is approximately **11,958 Btu/h (~3.504 kW/h)**, redefined to be exactly:

1 Ton of Refrigeration = 12,000 Btu/h = 3.516 kW/h = 3.024 cal/h = 3,024 Kcal/h

METABOLIC RATE:

Metabolic rate is measured in **Met** units. A **Met** is the average amount of heat produced by a sedentary person (e.g. office work = **1 Met**). **1 Met** unit corresponds approximately: **360 Btu/h = 90.72 kcal/h = 90,720 cal/h**. Human beings are essentially constant-temperature creatures with a normal internal **body temperature of 98.6°F**. Heat is produced in the body as result of metabolic activity.

If the internal temperature rises or falls beyond its normal range, mental and physical operation is jeopardized or affected, and if the temperature deviation is extreme, then serious physiological disorders or even death can result.

COMFORT ZONE:

The comfort range of temperature during **summer varies between 70 to 76°F** dry bulb temperatures and **45 - 65% relative humidity**.

The comfort range during cold **winters** would be in the range of **65 to 68°F** dry bulb temperature and **relative humidity** of a minimum of **30%**.

DETERMINANTS OF THERMAL COMFORT:

Thermal Comfort Zone: It is an area plotted on the psychrometric chart. During **summer** the comfort range of temperature varies between **70 to 76°F** dry bulb temperatures and **45 - 65% RH**. During **cold winters** the comfort condition would be in the range of **65 to 68°F** dry bulb temperature and relative humidity of a minimum of **30%**.

Humidity: Density of water vapor per unit volume of air is expressed in units of **lbs. of water/ft³ of dry air**. Specific humidity = weight of water vapor per unit weight of dry air, expressed in **grains/lb**.

Relative Humidity (RH): Human tolerance to humidity variations: in winter is from **20 to 50%**; in summer, the range extends up to **60% @ 75ºF**. High humidity causes condensation problems and reduces body heat loss by evaporative cooling.

HEAT TRANSFER:

Conduction: Is the spontaneous transfer of thermal energy through matter, from higher temperature to lower temperature, and acts to equalize temperature differences. It is also described as heat energy transferred from one material to another by direct contact.

Convection: Is usually the dominant form of heat transfer in liquids and gases. Convection is circulation of a fluid or gas/air caused by temperature difference. Commonly an increase in temperature produces a reduction in density.

Evaporation: It is exclusively a cooling mechanism. Evaporative losses become a predominant factor when ambient temperatures are very high. When surrounding temperature is about **70°F**, most people lose sensible heat.

Radiation: Is the only form of heat transfer that can occur in the absence of any form of medium; it means heat transfers through a vacuum. Thermal radiation is a direct result of the movements of atoms and molecules in a material.

PSYCHROMETRICS CONCEPTS:

Psychrometrics or Psychrometry: Are terms used to describe the field of engineering concerned with the determination of physical and thermodynamic properties of gas-vapor mixtures. The term derives from the **Greek "***psuchron***"** that means **"cold"** and *"metron"* meaning **"means of measurement"**.

Thermodynamic properties of moist air are affected by atmospheric pressure. The standard **temperature is 59°F** and standard **atmospheric pressure is 29.921 in-Hg (14.697 psi)** at sea level.

The apparent molecular mass or weighted average molecular weight of all components, for **dry air is 28.9645, based on the carbon-12 scale.**

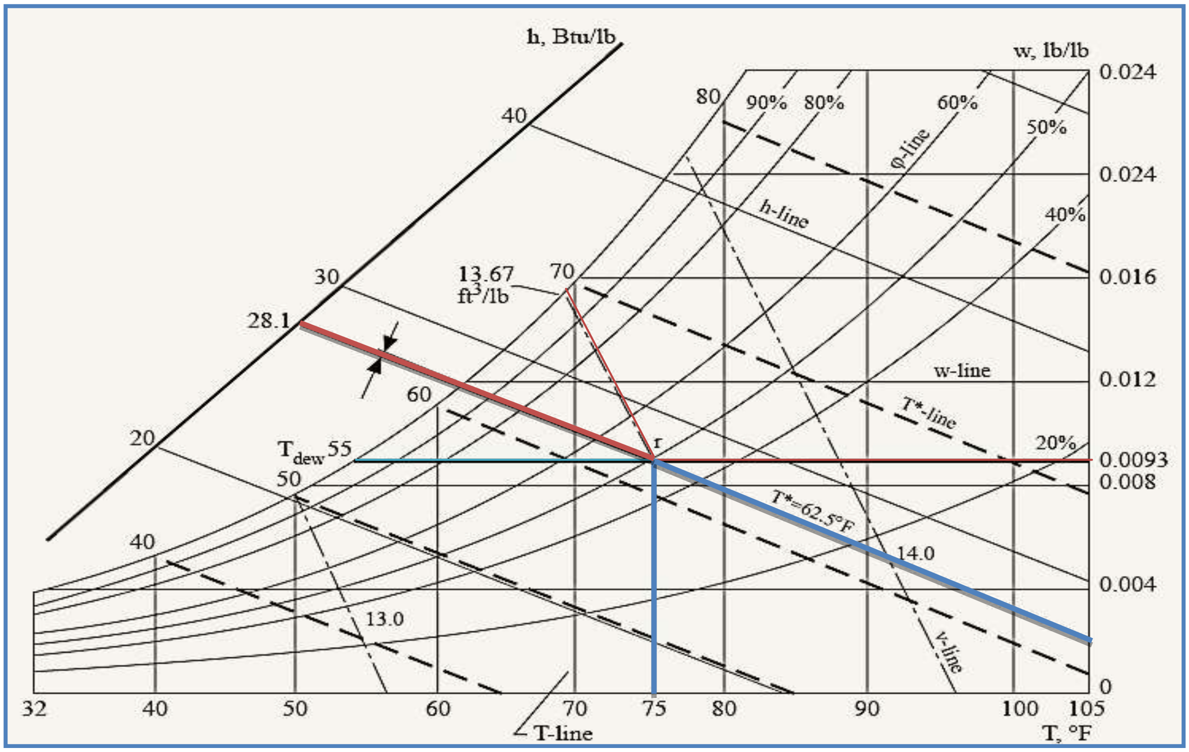
The gas constant for **water vapor is 1545.32 / 18.01528 = 85.778 ft-lb/lb°R**. The temperature and barometric pressure of atmospheric air vary with altitude as well as with local geographic and weather conditions. **Gravity** is also assumed constant at the standard value, **32.1740 ft/s^2**.

PSYCHROMETRIC CHART:

A **psychrometric chart** is a graphical presentation of the **thermodynamic properties** of moist air and various air-conditioning processes and air-conditioning cycles.

The most **common chart** is the **temperature - humidity ratio (w) chart**. The **Dry Bulb Temperature (DB)** appears horizontally as the abscissa and the **humidity ratios (w)** appear as the vertical axis.

Abridged sample of **psychrometric chart** is shown below:



Example: An air-conditioned room at sea level has an indoor design temperature of **75°F** and a relative humidity of **50%**. Determine the **humidity ratio, enthalpy, density, dew point, and thermodynamic wet bulb temperature** of the indoor air at design condition.

Solution:

Find the room temperature 75°F on the horizontal temperature base-line of the chart. **Draw a vertical line from the 75°F** temperature line and establish the point where it meets the relative humidity **curve** of **50% at point (r).** This point denotes the **state point** of room air.

• **Draw a horizontal line** to the **right** of the chart, toward the humidity ratio line from **point (r)**. This line meets the ordinate and thus determines the room air humidity ratio **w = 0.0093 lb/lb**.

• **Draw a line** from **point (r)** toward the enthalpy line at the left. This line determines the enthalpy of room air on the enthalpy scale, **h = 28.1 Btu/lb**.

• **Draw a line** from **point (r)** toward the moist volume line at the left of the chart, above. This line indicates **v = 13.67 ft^3/lb**.

• **Draw a horizontal line** to the left from **point (r)**. This line meets the saturation curve and determines the **dew point** temperature, **Tdew = 55°F**. Then, **draw a line** from **point (r)** parallel to the inclined dotted wet bulb line (from 0 to 60). This line indicates the **wet bulb** temperature **(WB) = 62.5°F**.

How to Read a Psychrometric Chart:

• **Dry Bulb Temperature (DB):** The verticals lines designate **DB**. A standard psychrometric chart for air conditioning applications has a temperature range of **32 to 120°F**.

• **Wet Bulb Temperature (WB):** The diagonals lines rising upward from left to right having negative slope slightly greater than that of the h-lines. A wet bulb line meets the DB line of the same magnitude on the saturation curve representing **100% RH**.

• **Dew Point Temperature (DP):** Follow the horizontal line from the point where the line from the horizontal axis arrives at **100% RH**, also known as the *saturation curve*. On a saturation curve the **dry bulb, wet bulb and dew point** temperature **(DP)** have the same value.

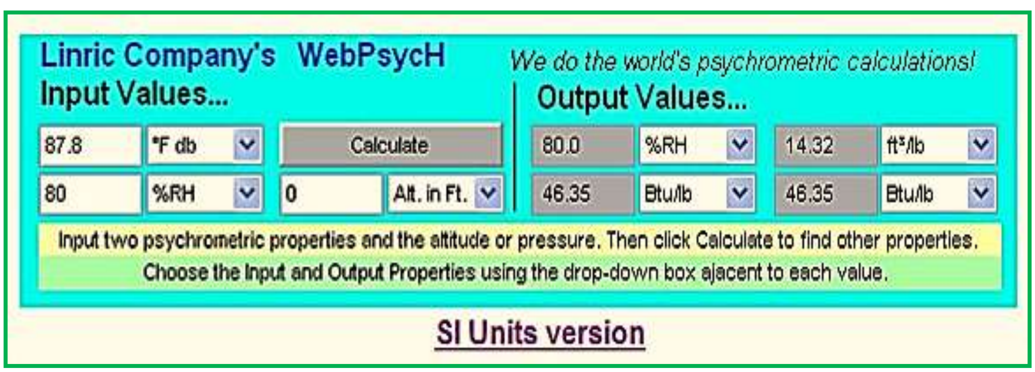
• **Relative Humidity (RH%):** Curved lines that radiate from lower left to upper right are **RH** lines. Horizontal line at the bottom represents **0% RH**; the uppermost curved line is **100% RH** line.

• **Humidity Ratio:** Humidity ratio or specific humidity w-lines are horizontal lines on the Y-axis, they range **from 0 to 0.28 lb/lb**. **Humidity** ratio **is dimensionless**, sometimes expressed **as grams of water per kilogram** of dry air or **grains of water/lb** of air.

• Specific Enthalpy (h): The enthalpy lines incline downward to the right-hand side (negative slope) at an **angle of 23.5°** to the horizontal line and have a range of **12 to 54 Btu/lb** expressed in **Btu/lb of air**.

• **Specific Volume (v):** The specific volume lines are represented by the diagonal lines close to 90º. The **moist volume** ranges from **12.5 - 15 ft^3/lb**, also called **Inverse Density**, which is the volume per unit mass of the air.

Basic Psychrometric Calculation: There are hundreds of **psychrometics charts** and calculation spreadsheets to be downloaded. For the examples below try http://www.linric.com/webpsy.htm.



Example 1: Calculate the air density, specific volume, and enthalpy **in US units** at the ambient conditions of **DB 87.8°F**, **RH 80%** and sea level.

Air Density = 0.0714 lb/ft^3;

Air Specific Volume = 14.32 ft^3/lb;
Air Enthalpy = 46.35 Btu/lb.

Example 2: Calculate the air density, specific volume, and enthalpy **in US units** at the ambient conditions of **DB 87.8°F, RH 0%** (Dry Air), and sea level.

Air Density: 0.0723 lb/ft^3;
Air Specific Volume: 13.8224 ft^3/lb;
Air Enthalpy: 21.1196 Btu/lb.

Example 3: Calculate the air density, specific volume, and enthalpy in **US units** at the ambient conditions of **DB 87.8°F, RH 80%**, and **1,000 feet** in altitude.

Air Density: 0.0688 lb/ft^3;
Air Specific Volume: 14.8824 ft^3/lb;
Air Enthalpy: 47.3494 Btu/lb.

Basic Air Conditioning Calculations: The air conditioning loads are the **Sensible Heat Loads + Latent Heat Loads** as explained below:

- **Sensible Heat Loads:** Sensible heat gain is directly added to the air-conditioned space by conduction, convection, and/or radiation. Sensible heat load is a total of:

a. Heat transmitted thru floors, ceilings, walls;
b. Occupant's body heat;
c. Appliance & Light heat;
d. Solar Heat gain thru glass;
e. Infiltration of outside air;
f. Air introduced by ventilation.

- **Latent Heat Loads:** Latent heat gain occurs when moisture is added to the space from internal sources or from outdoor air as a result of infiltration or ventilation to maintain proper indoor air quality. Latent heat load is a total of:

a. Moisture and outside air from Infiltration & Ventilation;
b. Occupant Respiration & Activities;
c. Moisture from Equipment & Appliances.

Obs.: Humidity ratio or **specific humidity -** is dimensionless, sometimes expressed **as grams of water per kilogram** of dry air or **grains of water/lb** of air.

1) Sensible Heat Loads:

A sensible heating process adds heat to the moist air in order to increase its temperature. The rate of heat transfer from the hot water to the colder moist air is often called **sensible heating**, in **Btu/h (kW)**, and is calculated from the equation:

Qsensible **= m x Cp (To – Ti) = [Btu/h]**

Where:

Q sensible = Sensible heat, (kcal/h) (Btu/h);
m = Mass flow rate of air, (kg/h) (lb/h);

Cp = Specific heat of air (see tables), **0.24 Btu/lb°F = 0.24 kcal/kg°C;**
ρair = Density of air, (kg/m³) (lb/ft³);
To, Ti = Moist air temperature at final/initial, (C°) (°F).

Note: Remember, **1.0 Btu/lb°F = 1.0 kcal/kg°C**. To maintain temperature requirements, the air inside a building keeps circulation through a cooling coil, empirically determined by:

Qsensible **= 1.08 x CFM (To – Ti) = [Btu/h] [kcal/h]**

Where:

CFM = Air circulation flow, CFM;
Ti = Inside air temperature, ºF;
To = Outside air temperature, ºF.

The sensible heat loss from can also be calculated as:

Qsensible **= 60 x CFM x ρair x C_p x (Ti – To) = [Btu/h] [kcal/h]**

Where:

Q = Heat loss (Btu/h);
CFM = Volumetric air flow rate (CFM);
ρair = Density of the air (Ib/ft³);
Cp = Specific heat of air (see tables), **0.24 Btu/lb°F = 0,24 kcal/h**;
Ti = Inside air temperature (°F);
To = Outside air temperature (°F).

2) Latent Heat Loads:

The most commonly used method of removing **water vapor** from air (dehumidification) is to cool the air below its dew point. The dew point of air is when it is fully saturated, at **100%** saturation. The **latent heat** to be removed is:

Qlatent **= m x hfg x (Wo - Wi) = [Btu/h] [kcal/h]**

Where:

Q = Cooling energy (kcal/h) (Btu/h);
m = Mass flow rate of air (kg/h) (lb/h);
hfg = Latent heat of vaporization of water (see tables), **1,060 Btu/lb (589 kcal/kg)**;
Wo, Wi = Moisture content of air (kg/kg) (lb/lb).

The amount of moisture added to the air must be removed through the cooling coil to maintain the humidity requirements, determined by:

Qlatent **= 4,840 x CFM (Wo – Wi) = [Btu/h] [kcal/h]**

Where:

CFM = Air circulation flow, CFM;
Wo = Outside moisture content of air (lb/lb);
Wi = Inside moisture content of air (lb/lb).

3) Humidity:

In a **humidifying** process, water vapor is added to moist air and increases the **humidity ratio** entering the humidifier if the moist air is not saturated. The humidifying capacity is given by:

$$H_m = CFM \times \rho \times (Ho - Hi) = [lb/min]$$

Where:

CFM = Volume flow rate of air, (CFM);
ρ = Density of air, (lb/ft³);
Ho, Hi = Moisture content of air at final and initial states, (Btu/lb).

Total heat loads are:

$$Q_{total} = 4.5 \times CFM \times (Ho - Hi) = [Btu/h]\ [kcal/h]$$

Where:

CFM = Volume flow rate of air, (CFM);
Ho, Hi = Moisture content of air at final and initial states, (Btu/lb).

Obs.: CFM (cubic feet per minute), amount of air that flows through a space in one minute. A typical HVAC system produces **400 CFM/ ton** of air conditioning. **1 CFM** is approximately **2 liters/s (l/s)**. The **constants** of the above formulas are:

Constant of 4.5 = **1 CFM** airflow, then, **60 CFM** = **1 ft³/h** = **4.5 lb of air**;
Constant of 1.08 = Specific heat of air = 0.24 Btu/lb/°F x 4.5 = **1.08 Btu/lb/ºF**;
Constant of 0.68 = Latent heat water vaporization, **1,060 Btu/h** = 1,060/7,000 x 4.5 = **0.68**;
Constant of 13.5 ft³/lb = Specific volume of moist air.

4) Design Volume Flow Rate:

The design **volume flow rate - V (Kg/m³) (CFM)** is calculated on the basis of the capacity to keep the space cooling load at summer in conditions to maintain the required temperature, T_r:

$$V = \frac{QTotal}{60 \times \rho air \times (Ho - Hi)} = \frac{QSensible}{60 \times \rho air \times (To - Ti)}$$

Where:

V = Design volume flow rate, (m³/h) (CFM);
QTotal, QSensible = Design cooling load, (kW) (Btu/h);
ρair = Air density - may vary with air systems (see tables), (kg/m³) (lb/ft³);
To = Room temperature - normally 75°F (24°C) - for comfort applications);
Ti = Air temperature leaving the cooling unit, (°F) (°C);
Ho = Air enthalpy, outside, (kcal/kg) (Btu/lb);
Hi = Air enthalpy, inside, (kcal/kg) (Btu/lb).

5) Total Refrigeration Load:

Since the sensible heat **Qsensible** and the latent heat **Qlatent** are known, the total R**efrigeration Load** can be determined by:

RL = CFH x ρair x (Ho – Hi) = [Btu/h] [kcal/h]

Where:

CFH = Air flow in ft^3/h (CFM x 60);
ρair = Air density = 0.075 lb/ft^3 at 70^oF;
Hi = Enthalpy of the air - inside temperature;
Ho = Enthalpy of the air – outside temperature.

6) Heat Loss by Conduction:

The different ways to calculate heat loss are: **"k"** values, **"C"** values, **"U"** values and **"R"** values.

a) k = Thermal Conductivity: Thermal conductivity means the rate of heat transfer through one inch thickness of a homogeneous material expressed in **Btu-in/h.ft².°F** or **Btu-ft/h.ft².°F.** Materials with **lower "k" values** are better **insulators**.

Q = k x A x ∆T / t =

Where:

k = Thermal conductivity of materials (see tables) (Btu-in/h ft² °F) or (Btu-ft/h ft² °F);
A = Area, ft²;
∆T = Average temperature difference across the material, (F°);
t = Thickness of a wall of some material (in).

Example:

Calculate the heat loss through a **3" thick** insulation board that has an area of **2 ft²** and has a **k-value** of **0.25**. Assume the average temperature difference across the material is **70°F**.

Q = k-value x A x ∆T / t =

$$Q = \frac{0.25\ (k) \times 2\ (ft^2) \times 70°F\ (\Delta T)}{3\ (in)} =$$

Q = 35 / 3 = **11.66 Btu/h**

Note: Most good **insulating** materials have a **"k" value** of approximately **0.25 or less**, and rigid foam insulations have been developed with **"k" factors** as low as **0.12 to 0.15**.

b) Specific Heat: is defined as the amount of heat energy needed to raise **1 gram of a substance 1°C** in temperature, or, the amount of energy needed to **raise one pound** of a substance **1°F** in temperature. Substances with **higher specific heats require more heat energy** to lower temperature than do substances with a low specific heat.

Q = m x Cp. (To – Ti) = [Btu]

Where:

Q = Heat energy needed (Joules) (Btu);
m = Mass of a substance (kg) (lb);
Cp = Specific heat of air (see tables), ~**0.24 Btu/lb°F = 0.24 kcal/kg°C**;
(To – Ti) = Dry Bulb temperature of air change (°C) (°F).

Example:

Using metric units and imperial units, how much energy is required to heat **350 grams (0.77 pounds)** of gold from **10°C (50°F) to 50°C (122°F)**.

Mass = 350 g = **0.35 kg** = **0.77 lb**

Specific heat of gold (see tables) = **0.129 J/(g.°C)** = 129 J/(Kg.°C) x 0.000239 = **0.0308 Btu/(lb.°F).**

Q = m x Cp. (To – Ti)

Metric Units:

Q = (0.35 kg) (129 J/(kg.°C) (50°C - 10°C) = **J**

Q = **1,806 J** (1,806 J / 1055 = 1.71 Btu)

Q = m x Cp. (To – Ti)

Imperial Units:

Q = (0.77 lb) (0.0308 Btu/(lb.°F) (122°F - 50°F) = **Btu**

Q = **1.71 Btu**

OBS: Greater **density (ρ)** means a smaller airflow rate **(kg/m³) (CFM)** for a given supply mass flow rate. Greater the cooling load or sensible heat, **Q Sensible**, higher will be the airflow rate **(kg/m³) (CFM)**.

1) ***C = Thermal Conductance:*** Thermal conductance is a specific factor or a heat transfer factor per inch of thickness. The **lower the "C" value (or k-value)**, the **better the insulator** and **the lower** is the heat loss.

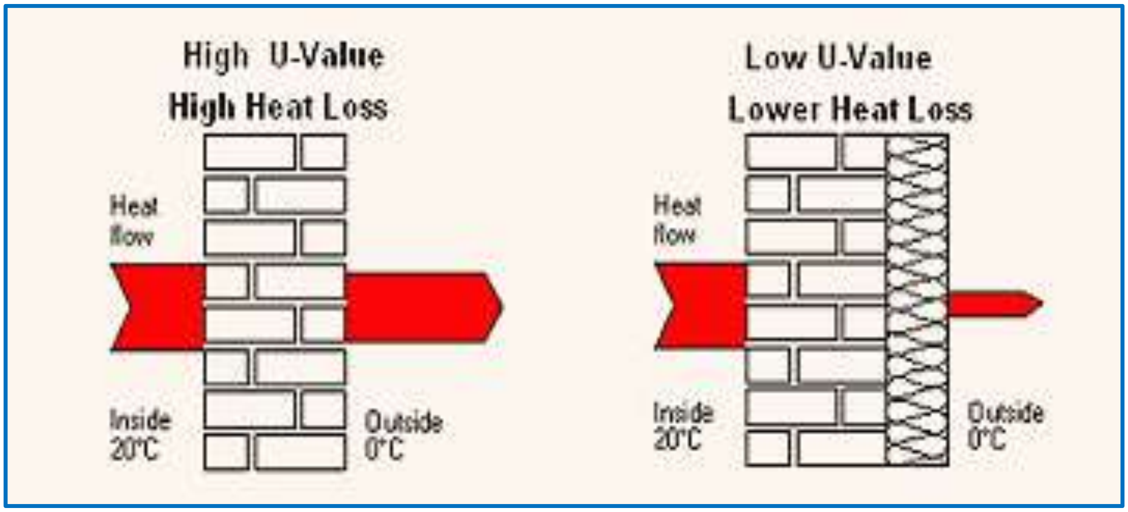
   Note: The overall **"C" value** must not be additive because **two insulating** materials with a **C-value** of **0.5** each, the result will be **1.0**.

2) ***U = Overall Coefficient of Heat Transmission:*** The **"U" value** is the rate of heat flow passing through a **square foot of a material per hour of each degree Fahrenheit difference in temperature** expressed in **Btu/h. ft².°F**.

   Note: The **"U" value** is the inverse of the **"R" value**, ("U" = 1/R) since ***the lower the "U" factor, the lower*** *is the heat loss.*

3) ***R = Thermal Resistance:*** The thermal resistance **"R" value** is a measure to retard the heat flow.

   Note: The thermal resistance is the reciprocal of a heat transfer coefficient, that is, the **"R" value** is the inverse of the **"C" value (R = 1/C)**, **"k" value (R = 1/k)**, and the **"U" value (U = 1/R)**.



Basic Calculations of Overall Coefficient of Heat Transmission - "U": The basic equation to calculate the Overall Coefficient of Heat Transmission (U) is:

U = 1/R Total = [Btu/h ft² °F]

Or

$$U = \frac{1}{Ri + R1 + R2 + ... Ro}$$

Where:

Ri = Resistance of a "boundary layer" on the inside surface;
R1, R2 …= Resistance of each component, according to thickness of the component;
Ro = Resistance of the "boundary layer" on the outside surface.

Example:

Calculate the heat loss through a **100 ft²** wall with an inside temperature of **65°F** and an outside temperature of **35°F**. The wall is composed of **2" thickness** bricks having a **"k" factor of 0.80**. The insulation is also **2" thickness** having a **"C" factor** of **0.16**.

Solution:

The **"R" value** is found as follows:

R total = 1/k + 1/C =
R total = 2"/0.80 + 2"/0.16 = **15.0**

U = 1/15.0 = **0.0666 Btu/h ft² °F**

Once the **"U" factor** is known, the heat loss can be calculated by the **basic heat transfer equation**:

Q = A x U x (Ti – To) = [Btu/h]

Q = 100 (ft²) x 0.0666 (Btu/h ft² °F) x [65 (°F) - 35 (°F)] = **(Btu/h)**

Q = 100 x 0.0666 x 30 =

Q = 342 Btu/h

Example:

Determine the **"U" value** and the **heat loss** through a **100 ft²** wall with a **70 °F** temperature difference for a layered wall. The construction is composed of plywood **0.75-inch thick (C = 1.25**, expanded polystyrene **2-inches thick (C = 4.00)** and hardboard **0.25-inches thick (C = 0.18)**.

The latent heat is assumed as **Ri = 0.68** (see constants)**;**
Outside air at 15 mph wind velocity is assumed as **Ro = 0.17.**

Solution:

Plywood, 0.75-inch thick - **(R1 = 0.75 X 1.25 = 0.94);**

Expanded polystyrene, 2-inches thick - **(R2 = 2" X 4.0 = 8.0);**

Hardboard, 0.25-inch thick - **(R3 = 0.25 x 0.18 = 0.045);**

$$U = \frac{1}{Ri + R1 + R2 + R3 + Ro}$$

$$U = \frac{1}{0.68 + 0.94 + 8.0 + 0.045 + 0.17}$$

$$U = \frac{1}{9.835}$$

U = 0.10 Btu/h ft² °F.

The heat loss **"Q"** for a **100 ft²** of wall with a **70°F** temperature difference will be:

Q = A x U x ∆T = 100 x 0.10 x 70 =

Q = 700 Btu/h

HEATING LOSS CALCULATIONS:

The heat loss in is divided into two groups:

1) **Conductive Heat Losses:** Through the building walls, floor, ceiling, glass, or other surfaces;
2) **Convective Infiltration Losses:** Through cracks and openings, or heat required to warm outdoor air used for ventilation.

The **heat loss** is determined by the **basic equation**:

Q = A x U x (To – Ti) = A x U x ∆ T = (Btu/h)

Where:

Q = Total hourly rate of heat loss through walls, roof, glass, etc. (Btu/h);
U = Overall heat-transfer coefficient of walls, roof, ceiling, floor, or glass (Btu/h.ft².°F);
A = Net area of walls, roof, ceiling, floor, or glass (ft²);
Ti = Inside design temperature (°F);
To = Outside design temperature (°F).
Δ**T** = To – Ti (°F).

Net Area (A):

The net area of each building section is determined from drawings or measurements considering the areas of the four walls, floor, and ceiling, doors and windows. Thus, we will also need to determine the volume of the building to estimate the rate of infiltration into the building measured in **air changes per hour (ACH)**.

Overall Coefficient of Heat Transfer (U):

The **U-value** measures how well a building component (wall, roof or a window), keeps heat inside a building. It is an indicator of how easy it is to keep the inside of the building cold. A house built with low **U-value** building components will use less energy and thus using less energy is good for the environment.

Note: The **inside design temperature** is traditionally taken as **65°F**. The temperature difference between the inside and outside of the building is the primary cause of heat loss in the winter months.

Outside Design Temperature (To):

The winter month heating load conditions are based on annual percentiles of 99.6 and 99%, which suggests that the outdoor temperature is equal to or lower than design data **0.4% and 1%** of the time respectively. Then, commonly the outside design temperature **(To)** is **4°F**.

Example:

What is the value of the **heat loss** for a **10 ft²** building with a single glass **[U-value of 1.13]** with an inside temperature of **70°F** and an outside temperature of **0°**:

Q = A (10) x U (1.13) x Δ T (70 - 0) = **791 Btu/h**

Heat Conduction and Thermal Resistance: Calculate the heat loss through each of the components separately and then add their heat losses together to get the total amount.

Q (wall) = Q (framed area) +Q (windows) +Q (door) =

The heat conducted calculation formula through a plane wall is:

$$Qw = \frac{k \times A\,(t1 - t2)}{L} \quad [Btu/h]$$

Where:

k = Thermal conductivity of the wall material, Btu-in/h ft² °F;
A = Area of the wall, ft²;
t1, t2 = Temperature difference of the wall, °F;
L = Wall thickness, inches;

The same equation in terms of thermal resistance is:

$$Qw = \frac{A\,(To - Ti)}{R} = A \times U\,(To - Ti) \text{ - Btu/h}$$

Heat Loss due Air Changes and Ventilation: To calculate this, you need to know how many times per hour the entire air in the building space is lost to outside referred to as **air changes per hour** or **ACH**. The infiltration can be considered to be **0.15 to 0.5 ACH** at winter design conditions.

1) Ventilation rate based on Air Change method:

V = ACH x A x H / 60 =

Where:

V = Ventilation air (CFM) (m^3/h);
ACH = Air changes per hour (ACH) – 0.15 to 0.5 CFM/ft^2;
A = Area of the space (ft^2) (m^2);
H = Height of the room (ft) (m).

2) Ventilation rate based on Crack method:

V = I x A =

Where:

V = Ventilation air (CFM) (m^3/h);
I = Infiltration rate usually 0.15 CFM/ft^2;
A = Area of cracks/openings (ft^2) (m^2).

3) Ventilation rate based on Occupancy method:

V = N x 20 =

Where:

V = Ventilation air, (CFM) (m^3/h);
N = Number of people in space - usually 1 person per 100 ft^2 (~9,0 m^2) office;
20 = Recommended ventilation rate is 20 CFM/person (0.5 m^3/h) - (ASHRAE 62 standard for IAQ).

Typical Concrete Frames:

For a **typical 2 x 4 concrete frame** wall with polystyrene insulation and drywall, there are **five thermal resistance layers** due to convection and radiation.

Ri = 6.0 Btu/h ft² °F - then, **1/Ri = 1/6.0 Btu/h ft² °F**;
Ro = 1.63 Btu/h ft² °F - then, **1/Ro = 1/1.63 Btu/h ft² °F**.

So, the **thermal resistance** equation is:

R = Ri + R1 + R2 + R3 + R4 + R5 + Ro =

Practical Example:

A building, **35.0 ft wide, 73.0 ft long and 8.0 ft high**, is constructed with concrete **4** in. **thick** and polystyrene insulation **2** in. **thick** on each side. The building has **4 windows** east and **16 windows** north measuring **2.5 ft by 4 ft.** There are **20** persons in office working. The conditions are:

Inside: (Ti)
Dry bulb temperature = **80 °F**
Relative Humidity = **50%**

Outside: (To)
Dry bulb temperature = **95 °F**
Dew Point = **75 °F DP (dew point)**

Ventilation:
Supply air = **65 °F -** Dry bulb temperature.
Air Handling Unit (AHU) = Assume **4,000 CFM per AHU**

Others:
Average electrical usage = **1.0 Watt/ft²**;
Human activity per person = **180 Btu/h**;
Infiltration rate, assume = **20 CFM**;
Air density (**ρair**) = **0.075 lb/ft³**, at **80°F**, sea level.

The Thermal Conductivities **"k"**, the Thermal Resistances **"R"**, and the Overall Heat Transfer Coefficient **"U"** are shown in table below:

Material	**k (Btu-in/ h ft² °F)**	**R (Btu/h ft² °F)**	**U (Btu/h ft² °F)**
Siding		1.0	
Polystyrene – wall side 1 (2.0 in)	**0.17**		
Polystyrene – wall side 2 (2.0 in)	**0.17**		
Concrete (4.0 in)	**10.0**		
Drywall		0.45	
Pine 2 x 4	0.8		
Insulation	0.28		
Sheathing (0.5 in)	0.8		
Glass			1.13
Framed roof and ceiling			0.23

Considering that for a **typical 2 x 4 concrete frame** wall:

Ri = 1 / Ri = 1 / 6.0 Btu/h ft² °F
Ro = 1 / Ro = 1 / 1.63 Btu/h ft² °F

The **thermal resistance** of a **4-inches concrete** wall with **2-inches insulation** is:

Rtotal = Ri + R1 + R2 + R3 + R4 + R5 + Ro =

$$\text{Rtotal} = \frac{1.0}{6.0} + \frac{1.0}{0.17} + \frac{2.0}{0.17} + \frac{4.0}{10} + 0.45 + \frac{1.0}{1.63} =$$

Rtotal = 26.0 Btu/h ft² °F

1) Sensible Loads:

The **heat** conducted through the wall area **minus the windows area** is:

$$Q_{windows} = \frac{A(To - Ti)}{R} = \frac{[(A_{building} - A_{windows}) \times (To - Ti)]}{R} =$$

East wall - **Qw** = [(8.0 x 35.0) - 4(2.5 x 4.0)] x (95 - 80) / 26 = **138 Btu/h**;
North wall - **Qw** = [(8.0 x 73.0) - 16(2.5 x 4.0)] x (95 - 80) / 26 = **245 Btu/h**;
Qwindows **= 383 Btu/h.**

There are **20 windows**, **10 ft² each**, the total window area is **200 ft²,** considering that the window glass is **U = 1.13,** the heat conducted through the glass is given by equation:

Qwindows **= A x U x (To – Ti)** =
Qwindows = 200 x 1.13 (95 - 80) = **3,390 Btu/h**

The infiltration of outside air through cracks around windows and doors, a leakage rate of **20 CFM** assumed. According to the **Qsensible** equation, the infiltration heat gain inside is:

Qsensible **= 1.08 x CFM (To – Ti)** =
Qinfiltration= 1.08 (20) (95 - 80) = **330 Btu/h**

For the medium size building considered here, the reference for average electrical usage is **1.0 Watt/ft².** The heat gain from electrical appliances and lights is:

Remember: 1 Watt-Hour = 0.000948 (Btu/s) x 60 x 60 = **3,412 Btu/h**

Qlight **= 3.412 x A**
Qlight = 3.412 x (35.0 ft x 73.0 ft) = **8,717 Btu/h**

The **sensible heat** according to be estimated for light activity is **200 Btu/h per person.** For **twenty people** in the building, this gives a heat gain of:

Qoccupancy = 20 (200) = **4,000 Btu/h**

The heat conducted through the frame ceiling (**U = 0.23** – see table above) is:

Qceiling = **A x U x (To – Ti) =**
Qceiling **=** (35.0 x 73) x 0.23 x (95 – 80) = **8,815 Btu/h**

Adding all the heat gains the **total Qsensible load** is:

Qsensible **=** 383 + 3390 + 8717 + 330 + 4,000 + 8,815 =
Qsensible **= 25,635 Btu/h**

2) Latent Loads:

For **light activity**, people produce a latent gain of about **180 Btu/h** per person. Kitchen **appliances** add latent heat to the building as estimated below:

Dishwater = 420 Btu/h; Gas Oven = 1,200 Btu/h; Coffee maker = 2 x 1,540 = 3,080 Btu/h, then:

Qlatent (persons) = 20 (180) = **3,600 Btu/h**

Qlatent (kitchen) **= 4,700 Btu/h**

The infiltration **humidity load** is determined by:

Qlatent **= 4,840 x CFM (Wo – Wi) =**

Using the **online WebPsych** can be found that for a dry bulb temperature of **80^{o}F and 50% RH**, as required, at sea level the air contains:

Inside: (Wi)

Dry bulb temperature = **80 °F**
Relative Humidity = **50%**

Wi = 76.8 gr/lb

The standard indicates that there are **7,000 grains of moisture per pound**, so we have:

Wi = $\frac{\mathbf{76.76}}{\mathbf{7,000}}$ **=** approximately **0.011 lb of moisture/lb of air** or pounds of moisture per pound of air.

Outside: (Wo)

Dry bulb temperature = **95 °F**
Dew Point = **75 °F**

Wo = 131.81 gr/lb

Using the same considerations above:

Wo = $\frac{\mathbf{131.81}}{\mathbf{7,000}}$ **=** approximately **0.019 lb of moisture/lb of air** or pounds of moisture per pound of air.

Since that a leakage rate of **20 CFM** is assumed, the resulting latent heat gain inside is:

Qlatent = 4,840 x CFM (Wo – Wi) =
Qlatent = 4,840 x 20 (0.019 – 0.011) **= 774 Btu/h**

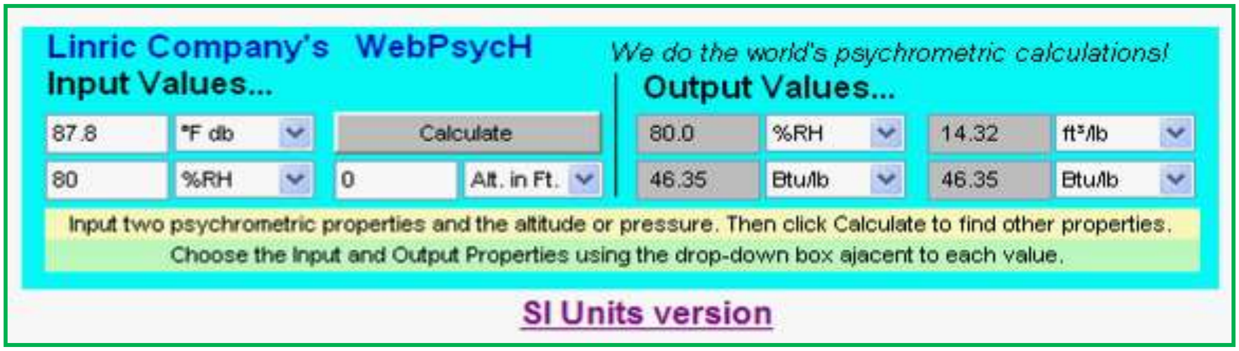
Adding all the heat gains the **total Qlatent load** is:

Qlatent **= 3,600 + 4700 + 774** = **9,074 Btu/h**

Calculate the **Refrigeration Load**:

RL = CFH x ρair (Ho – Hi) =

1) First find **Hi** and **Ho** enthalpies of air using the **online WebPsych**, as shown below:



Entering with the values:

Inside: (Ti)
Dry bulb temperature = **80 °F**
Relative Humidity = **50%**
Hi = 31.2 Btu/lb

Outside: (To)

Dry bulb temperature = **95 °F**
Dew Point = **75 °F**
Ho = 43.5 Btu/lb

2) Second find the **ventilation flow**:

Qsensible = 1.08 x CFM (To – Ti) =

Therefore,

$$\textbf{CFM} = \frac{\textbf{Qsensible}}{\textbf{1.08 (To – Ti)}}$$

$$\textbf{CFM} = \frac{25{,}635}{1.08\ (15)} = \textbf{1582}$$

CFH = 1,582 x 60 = **94,920 ft³/h**.

The **Refrigeration Load (RL)** is:

RL = CFH x ρair (Ho – Hi) =
RL = 94,920 x 0.075 (43.5 – 31.2) = **87,564 Btu/h**.

3) The **Total Heat Loads** is:

Qtotal = **4.5 x CFM x (Ho – Hi) [Btu/h]**
Qtotal = 4.5 x 1,582 x (43.5 – 31.2) = **87,564 Btu/h (= RL)**.

Considering the Total Heat Load (or Refrigeration Load) as Sensible Heat Load, the air conditioning loads are the **Sensible Heat Loads + Latent Heat Loads** as explained above, then:

Qload = **Q**sensible + **Q**Latent =
Qload = 87564 + 9074 = **96,638 Btu/h**

4) Calculating in **Tons of Refrigeration**:

$$\textbf{TR} = \frac{96{,}638}{12{,}000} = \textbf{8.0 tons}$$

The **ventilation** equipment size is based on the tons of cooling required, and a typical system produces **400 CFM/ ton of air** conditioning:

Since, **1 ton of cooling** = **12,000 Btu/h** = **400 CFM/ton,** as explained above:

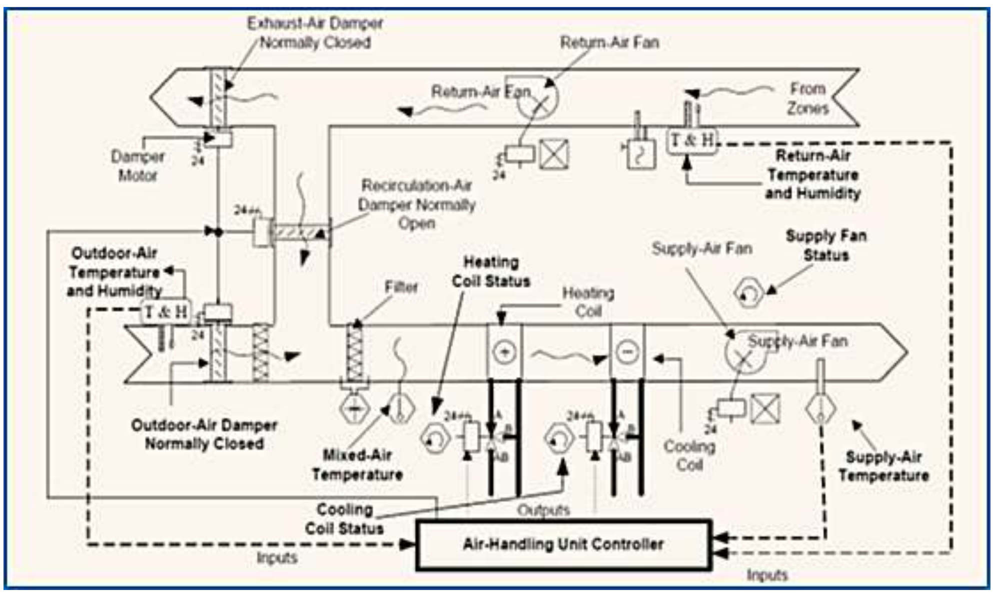
$$\textbf{CFM}(\text{ventilation}) = \frac{96{,}638 \times 400}{12{,}000} = \textbf{3,221 CFM}.$$

The system assumes **4,000 CFM** per Air Handling Unit (AHU), then:

$$\textbf{TR} = \frac{4{,}000 \text{ CFM}}{400 \text{ CFM/ton}} = \textbf{10 tons = 1 AHU Unit}.$$

$$\textbf{kW} = 10 \text{ TR} \times 3.517 = \textbf{\sim 35 kW}$$

Obs.: An **air handler**, or **air handling unit** (abbreviated to **AHU**), is a device used to condition and circulate air as part of a HVAC system. Air handlers usually are connected to ductwork, which distributes the conditioned air through the building and returns it to the **AHU**.



Cooling Load Concepts:

Design **cooling loads** take into account all the loads experienced by a building under a specific set of assumed conditions. The assumptions for cooling loads are as follows:

a. Weather conditions are selected from a long-term statistical database, representative of the location of the building. ASHRAE has tabulated such data;
b. The solar loads on the building are assumed on a clear day in the month for calculations;
c. The building occupancy is assumed to be at full design capacity;
d. The ventilation rates are assumed on air changes or maximum occupancy expected;

e. All building equipment and appliances are considered to be operating;
f. Lights and appliances are considered for a typical day of design occupancy;
g. Latent as well as sensible loads are considered.

CLTD/SCL/CLF METHOD OF LOAD CALCULATION:

CLTD Factors: Is a theoretical temperature difference for combined effects of inside and outside air temperature difference, daily temperature range, solar radiation and heat storage. It is affected by orientation, month, day, hour, latitude, etc. The CLTD factors: Are used for adjustment to conductive heat gains from **walls, roof, floor and glass**.

SCL Factors: Are used for adjustment of heat gains from **glass**.

CLF Factors: Is a radiant energy that enters the conditioned space at a particular time does not become a part of the cooling load instantly, calculated as functions of solar time and orientation and are available in the form of tables in ASHRAE Handbooks.

Obs.: The **CLF** factors are used for adjustment to heat gains from internal loads such as **lights, occupancy and power appliances**.

Basic Equations:

The basic conduction equation for heat gain is, **Q = U x A x ΔT**.

Where:

Q = Heat gain in Btu/h;
U = Coefficient of heat transfer in Btu/h.ft².°F;
A = Area of in ft²;
ΔT = Temperature difference in °F.

The **heat gain** is converted to **cooling load** using the functions (sol-air temperature) for light, medium and heavy thermal characteristics. The equation is modified as:

Q = (CLTD) x U x A =

Where:

CLTD = Cooling load temperature difference °F (from tables in AHSRAE Fundamentals Handbook);
Q = Cooling load, Btu/h;
U = Coefficient of heat transfer, Btu/hr.ft².°F;
A = Area, ft².

CLTD Corrected:

The **ASHRAE** tables provide hourly CLTD values for one typical set of conditions. Outdoor maximum temperature of **95°F** and mean temperature of **85°C** and daily range of **21°F**, the equation is adjusted to correction factors. The typical equation for roofs and walls are:

$$Q = U \times A \times CLTD_{Corrected} =$$

$$CLTD_{Corrected} = CLTD + (78 - TR) + (TM - 85) =$$

Where:

(78 – TR) = Indoor design temperature correction;
(TM – 85) = Outdoor design temperature correction;
TR = Indoor room temperature;
TM = Mean outdoor temperature = Tmax – $\frac{\text{(Daily Range)}}{2}$.

Example:

Estimate the cooling load using the Cooling Load Temperature Difference / Solar Cooling Load/ Cooling Load Factor (CLTD/SCL/CLF) method.

Given:

Type of building = **Office**;
Working = 8 h of working - **9.00 to 17.00 h**;
Room Length x Width = **16 ft x 15 ft**;
Room Height = **15 ft**;
Window area = **20 % of the wall area**;
Roof/Walls, U= **0.2 Btu/h.ft². ºF**;
Windows, U= **0.55 Btu/h.ft². ºF**;
Occupancy = **2 persons per room**.

Design Conditions:

Indoor temperature dry-bulb = **78 °F**;
Outdoor temperature dry-bulb = **90°F** (max);
Outdoor temperature wet-bulb = **75°F**;
Daily range temperature = **20 °F**.

Room Considerations – Roof and Walls:

Room area is (16 x 15) = **240 ft²**;
Window area for each wall is (16 x 15 x 0.2) = **48 ft²**;
Net area for each wall is: **240 ft² - 48 ft² (window)** = **192 ft²**.

Calculation of Room CLTD Correction:

$CLTD_C$ = CLTD + (78 – TR) + (TM – 85) =

TR = Indoor design temperature = **78°F**;
TM = Outdoor design dry bulb temperature - (Daily range / 2) = 90 - (20 / 2) = 90 - 10 = **80 °F**.

Therefore:

$CLTD_C$ = CLTD + (78 - 78) + (80 - 85) = (**CLTD – 5) =**

Calculation of Heat Load due to Conduction from 9.00 to 17.00 (see table below):

Given:

***CLTD** = from tables in AHSRAE Fundamentals Handbook
U = **0.2 Btu/h.ft^2.^{o}F**
A = **192 ft^2.**

Q = U x A x CLTDc = **(Btu/h)**

Time of Day	CLTD*	CLTDc = (CLTD – 5)	Q = U x A x CLTDc (Btu/h).
9.00	9	4	154
10.00	9	4	154
11.00	9	4	154
12.00	10	5	192
13.00	10	5	192
14.00	11	6	230
15.00	12	7	269
16.00	14	9	346
17.00	15	10	384

For calculation of Radiation Load through the Windows from 9.00 to 17.00 (use the following)**:**

Q = U x A x CLTDc = **(Btu/h)**
U = 0.55 Btu/h.ft^2 °F

Shading and **Solar** Load Factor (see table below) = **Q = A x SC x SCL = (Btu/h)**.

A = Glass area = **48 ft^2**;
SC = Shading Coefficient (according to ASHRAE Table 19-05F31.48);
SCL = Solar Cooling Load Factor (according to ASHRAE Table 36-89F26.41).

Time of Day	SCL	SC	Q = A x SC x SCL (Btu/h).
9.00	27	0.72	933
10.00	30	0.72	1037
11.00	33	0.72	1140
12.00	34	0.72	1175
13.00	35	0.72	1210
14.00	34	0.72	1175
15.00	32	0.72	1106
16.00	29	0.72	1002
17.00	29	0.72	1002

Obs.: Calculation of Internal Load for People (use the following)**:**

Q sensible **= N (number of people) x SHG (Btu/h) x CLF** (Btu/h);
Q latent **= N (number of people) x LHG (Btu/h)** (Btu/h).
SHG = Sensible heat gain;
LHG = Latent heat gain;
N = 2 persons per room;

PRACTICAL HVAC CALCULATION EXAMPLE:

Calculate the **U-values** and heat losses in a building with the following data:

Given:

- Dry-bulb temperature = **70 ºF**;
- Outside Temperature **= 22 ºF**;
- Dew point for the cooled air = **50 ºF**;
- Relative humidity = **40%**.

1) Horizontal Roof - Roof area = 1,200 ft²:

Built-up roofing, 0.375" thick - **R1 = 0.33 Btu/h.ft². ºF**;
3" extruded polystyrene insulation smooth skin surface – **R2 = 15 Btu/h.ft². ºF**;
3/4" plywood panels deck - **R3 = 0.93 Btu/h.ft².ºF**
3.5" air space (50ºF mean and 10ºF temperature difference) - **R4 = 0.93 Btu/h.ft². ºF**;
0.5" gypsum board – **R5 = 0.45 Btu/h.ft². ºF**;
0.5" acoustical ceiling tile – **R6 = 1.25 Btu/h.ft².ºF**.

2) Walls – Walls area = 1,000 ft²:

4" common face brick, density: 130 lb/ft^3 – **R1 = 0.56 Btu/h.ft². ºF;**
0.5" air space, (50ºF mean and 10ºF temperature difference) – **R2 = 2.54 Btu/h.ft². ºF;**
0.5" nail-base sheathing with bright aluminum foil to air space - **R3 = 1.06 Btu/h.ft².ºF;**
3.5"glass fiber insulation – **R4 = 12.98 Btu/h.ft². ºF;**
0.5" gypsum board – **R5 = 0.45 Btu/h.ft².ºF.**

And,

Outside air film (15 mph) – **Ri = 0.17;**
Inside air film (vertical surface) - **Ro = 0.68.**

Also,

Windows glasses, double pane, 0.5" air space, area 210 ft², **U-value** = **0.64 Btu/h.ft². ºF**;
Door, 1 3/4" solid core with metal, area 24 ft², **U-value** = **0.26 Btu/h.ft².ºF**.
Assume infiltration - Air change = **0.6** for building volume = **12,000 ft³**.
Assume 10 people in the building = **20 CFM per person**.

a) Using the **WebPsych** for **dry-bulb temperature 70ºF** and **relative humidity 40%** is found:

Wb = **55.76 °F**;
Hi = **23.60 Btu/lb**;
Dp = **44.60 °F**;
Wi = 43.66 gr/lb / 7000 = **0.0062 lb/lb.**

b) Using the **WebPsych** for **dry-bulb temperature 70ºF** and **dew point 50ºF** for cooled air is found:

Wb = **58.18 °F**;
RH = **49.02 %;**
Ho = **25.15 Btu/lb**;
Wo = 53.62 gr/lb / 7000 = **0.0076 lb/lb**.

3) Determination of the Roof (U-Value) R:

- Outside air film (15 mph) – **Ri = 0.17;**
- Built up Roofing (0.375") - 1/C = 1/3 - **R1 = 0.33;**
- 3" Extruded Polystyrene Insulation = 3" / 0.2 - **R2 = 15.00;**
- 3/4" plywood deck – 1 / 1.07 - **R3= 0.93;**
- 3.5" non-reflective air space (Tmean = 50 ºF, DT = 10 ºF) - **R4 = 0.93;**
- 0.5" gypsum board – 1 / 2.22 - **R5 = 0.45;**
- 0.5" acoustical tile – 1 / 0.8 – **R6 = 1.25;**
- Inside air film (vertical surface) - **Ro = 0.68.**

RroofTotal = 19.74

1 / RroofTotal = 1 / 19.74 = 0.0506 Btu/h.ft².ºF.

4) Determination of the Walls (U-Value) R:

- Outside air film – **Ri = 0.17;**
- 4" Common Face Brick – **R1 = 0.56;**
- 0.5" air space (Tmean = 50ºF, DT = 10ºF) – **R2 = 2.54;**
- 0.5" nail - base sheathing w/ aluminum foil – **R3 = 1.06;**
- 3.5" glass fiber insulation – **R4 = 12.98;**
- 0.5" gypsum board – **R5 = 0.45;**
- Inside air film (For a vertical surface) – **Ro = 0.68.**

RwallTotal = 18.44

1 / RwallTotal = 1 / 18.44 = 0.054 Btu/h.ft².ºF

5) Determination of Heat Loss through the roof - area of 1,200 ft²:

Ti = 70ºF, **To** = 22ºF, **A** = 1,200 ft²

Qroof = U x A x (Ti - To) =

Qroof = 0.0508 x 1200 x (48) = **2,926 Btu/h**.

6) Determination of Heat Loss through the walls - area of 1,000 ft²:

Ti = 70ºF, **To** = 22ºF, **A** = 1,000 ft²

Qwall = U x A x (Ti - To) =

Qwall = 0.054 x 1000 x (70 - 22) = **2,592 Btu/h**.

7) Determination of Heat Loss - windows clear glass, double pane, 0.5" air space:

Window area = 210 ft², **U-value** = 0.64 Btu/h.ft². ºF, **Ti** = 70ºF To = **22ºF**

Qwindow = U x A x (Ti - To) =

Qwindow = 0.64 x 210 x (48) = **6,451 Btu/h**.

8) Determination of Heat Loss - door, 1 3/4" solid core with metal:

Door Area = 24 ft², **U-value** = 0.26 Btu/h.ft². ºF, **Ti** = 70ºF, **To** = 22ºF

Qdoor = U x A x (Ti - To) =

Qdoor = 0.26 x 24 x (48) = **299 Btu/h**

9) Determination of heat loss by infiltration - Air change = 0.6, Building Area = 12,000 ft³:

a) Sensible Heat Loss:

The sensible heat formula is: **Qsensible = 1.08 x V x (Ti - To)**, then the air change volume is:

V = (0.6 x 12,000 ft^2) / 60 = **120 CFM**.

Qsensible = 1.08 x 120 x (70 - 22) = **6,220 Btu/h**.

b) Latent Heat Loss:

The latent heat formula is: **Qlatent. = 4,840 x V x (Wo - Wi) =** then the latent heat is:

Qlatent = 4,840 x 120 x (0.0076 – 0.0062) = **813 Btu/h**.

10) Determination of Heat Loss by Ventilation – 10 persons, 20 CFM per person:

V = 10 persons x 20 CFM = **200 CFM**.

a) Qsensible-vent. = 1.08 x V x (Ti - To) =

Qsensible-vent = 1.08 x 200 x 48 = **10,368 Btu/h**.

b) Qlatent-vent. = 4,840 x V x (Wi - Wo) =

Qlatent-vent = 4,840 x 200 x (0.0076 – 0.0062) = **1,355 Btu/h**.

11) Total Heat Loss through the Building:

Qroof = **2,926 Btu/h**;
Qwall = **2,592 Btu/h**;
Qwindow = **6,451** Btu/h;
Qdoor = **299 Btu/h**;
Qsensible = **6,220** Btu/h ;
Qlatent= **813. Btu/h**;
Qsensible-vent = **10,368 Btu/h** ;
Qlatent-vent = **1,355 Btu/h**.

Total Heat Loss = 31,026 Btu/h.

Note: Since, **1 ton. air** = **12,000 Btu/h** - Therefore, 31,026/12,000 = **2.56 tons** is necessary for thermal balance in the building. Select a **3.0 ton Air Handling Unit** (AHU) for this HVAC system.

BASIC HVAC DUCTS CALCULATION:

Temperature loss in ducts:

The heat loss from a duct can be expressed as:

Formula (a**) - H = A x k x (To + Ti) / (2 - Tr) =**

H = Heat loss – Btu (W);
A = Area of duct walls – in^2 (m^2);
Ti = Initial temperature in duct - ºF (ºC);
To = Final temperature in duct - ºF (ºC);
k(metric) - Heat Transfer Coefficient = (5.68 W/m^2 K, sheet metal ducts, 2.3 W/m^2 K, insulated ducts);
k(imperial) - Heat Transfer Coeffic. = (1.0 Btu/h.ft^2.ºF,sheet metal ducts, 0.4 Btu/h.ft^2.ºF,insulated ducts);
Tr = Surrounding room temperature - ºF (ºC).

The heat loss in the air flow can be expressed as:

Formula (b) **- H = q x cP x (To - Ti) =**

q = Mass of air flowing, (lb/s) (kg/s);
cP = Specific heat capacity of air, (Btu/lb. ºF) (kJ/kg K);

Formulae (a) and (b) can be combined to:

H = A x k x (To + Ti) / 2 - Tr) = q x C_p x (To - Ti) =

Sizing Ducts:

Air speed in a duct can be expressed as:

v = Q / A =

v = Air velocity, (ft/min) (m/s);
Q = Air volume, (CFM) (m^3/s);
A = Cross section of duct, (ft^2) (m^2);

The Velocity Method:

Proper air flow velocities for the application considering the environment should always be selected. The sizes of ducts are given by the continuity equation, as shown:

A = q / v =

A = Duct cross sectional area, (ft^2) (m^2);
q = Air flow rate, (CFM) (m^3/s);
v = Air speed, (ft/min.) (m/s);

Sizing ducts in Imperial units:

A_i = 144 x q_i / v_i =

A = Duct cross sectional area, (in²);
q_i = Air flow rate, (CFM);
v_i = Air speed, (FPM);

The velocity of air in a ventilation duct can also be expressed:

$$v_i = q_i / A_i = 576 \times q_i / (\pi \times d_i^2) = 144 \times q_i / (a_i \times b_i) =$$

v_i = Air velocity, (FPM);
q_i = Air flow (CFM);
A_i = Area of duct, (ft²);
d_i = Diameter of duct, (inches);
a_i = Width of duct (square or rectangle, inches);
b_i = Height of duct (square or rectangle, inches).

Sizing ducts in SI units:

$$v_m = q_m / A_m = 4 \times q_m / (\pi \times d_m^2) = q_m / (a_m \times b_m) =$$

v_m = Air velocity, (m/s);
q_m = Air flow, (m^3/s);
A_m = Area of duct, (m^2);
d_m = Diameter of duct, (m);
a_m = Width of duct, (square or rectangle, m);
b_m = Height of duct, (square or rectangle, m).

Pressure loss in ducts can be expressed as:

$$Dp_t = dp_f + dp_s + dp_c =$$

Dp_t = Total pressure loss in system, (psi) (Pa, kg/cm^2);
dp_f = Major pressure loss in ducts due to friction, (psi) (Pa, kg/cm^2);
dp_s = Minor pressure loss in fittings, bends etc., (psi) (Pa, kg/cm^2);
dp_c = Minor pressure loss in components as filters, heaters etc., (psi) (Pa, kg/cm^2).

Pressure loss in ducts due to friction per unit length can also be expressed as:

$$Dp_f = Pf \times l =$$

Pf = Duct friction per unit length, (psi, per feet of duct) (Pa, kg/cm^2, per meter of duct);
l = Length of duct, (inches) (cm, m).

Pressure loss in ducts due to friction can be expressed as:

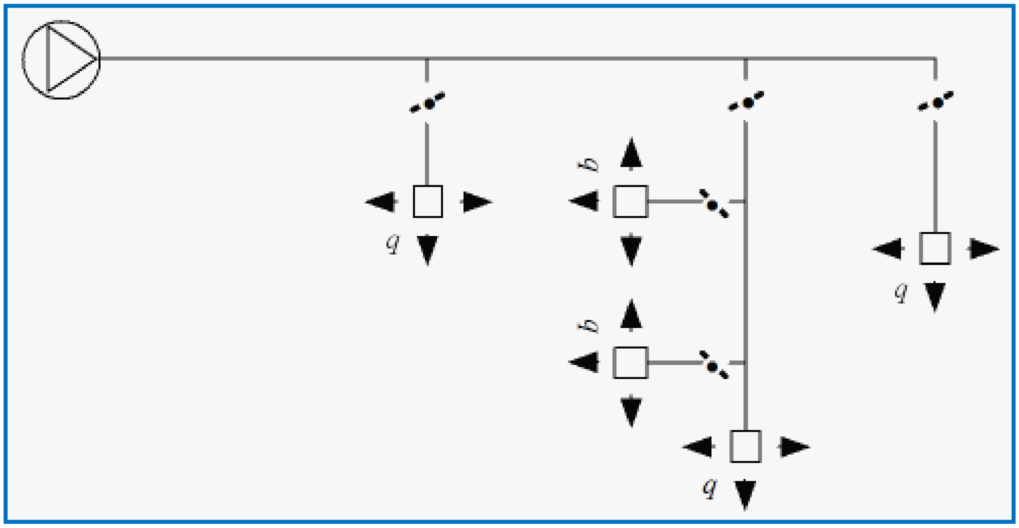
$$P_L = \lambda / D_h \times (\rho \times v^2 / 2) =$$

P_L = Pressure loss, (psi) (Pa, kg/cm^2);
λ = Friction coefficient (see tables);
D_h = Hydraulic diameter, (inches) (cm, m).

Note: The HVAC designer should know and always be **conscious** of the metric and imperial **conversions**. A correct and proper velocity depends on the application and the environment. The most commonly used **velocity limits** are shown below:

Type of Duct	Comfort Systems		Industrial Systems		High Speed Systems	
	m/s	ft/min	m/s	ft/min	m/s	ft/min
Main ducts	4 - 7	780 - 1380	8 - 12	1575 - 2360	10 - 18	1670 - 3540
Main branch ducts	3 - 5	590 - 985	5 - 8	985 - 1575	6 - 12	1180 - 2360
Branch ducts	1 - 3	200 - 590	3 - 5	590 - 985	5 - 8	985 - 1575

Obs.: High velocities close to outlets and inlets may generate unacceptable noise. Maximum air velocity in the ducts should be kept below certain limits to avoid unacceptable generation of noise.



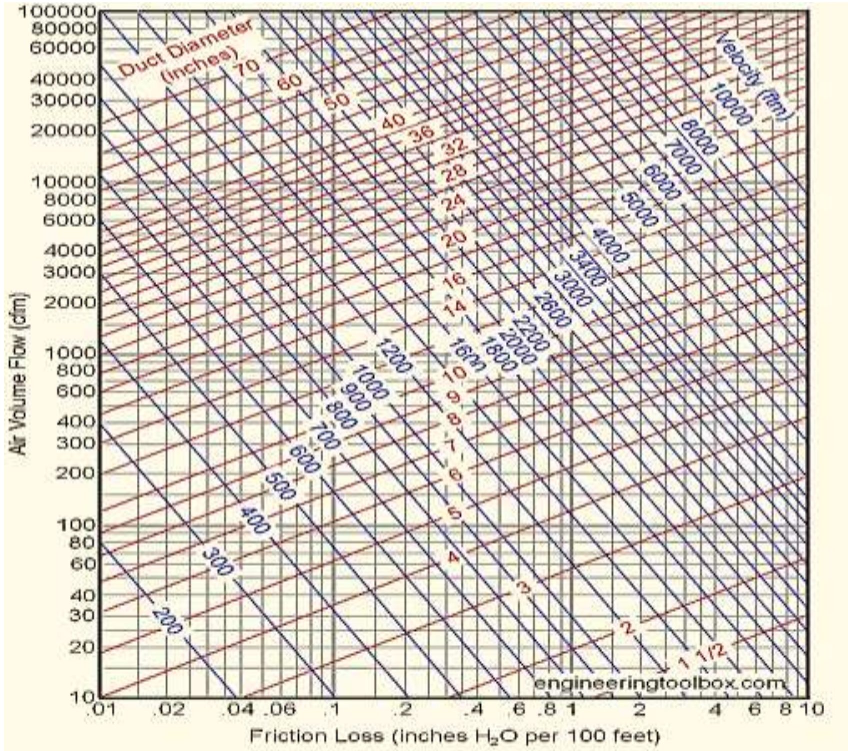
The values from the table below can be used to rough sizing of ducts in comfort, industrial and high speed ventilation systems. Commonly, the accepted duct velocities can be found in the table below:

Service	Velocity - *v*			
	Public buildings		Industrial plant	
	(m/s)	*ft/min*	*(m/s)*	*ft/min*
Air intake from outside	2.5 - 4.5	500 - 900	5 - 6	1000 - 1200
Heater connection to fan	3.5 - 4.5	700 - 900	5 - 7	1000 - 1400
Main supply ducts	5.0 - 8.0	1000 - 1500	6 - 12	1200 - 2400
Branch supply ducts	2.5 - 3.0	500 - 600	4.5 - 9	900 - 1800
Supply registers and grilles	1.2 - 2.3	250 - 450	1.5 - 2.5	350 - 500
Low level supply registers	0.8 - 1.2	150 - 250		
Main extract ducts	4.5 - 8.0	900 - 1500	6 - 12	1200 - 2400
Branch extract ducts	2.5 - 3.0	500 - 600	4.5 - 9	900 - 1800

Basic conversions:

1 inch water = 248.8 N/m² (Pa) = 0.0361 lb/in² (psi) = 25.4 kg/m² = 0.0739 in mercury;
1 ft³/min (CFM) = 1.7 m³/h = 0.47 l/s;
1 ft/min (FPM or ft/min.) = 0.00508 m/s.

Air Ducts Friction Loss Diagram:



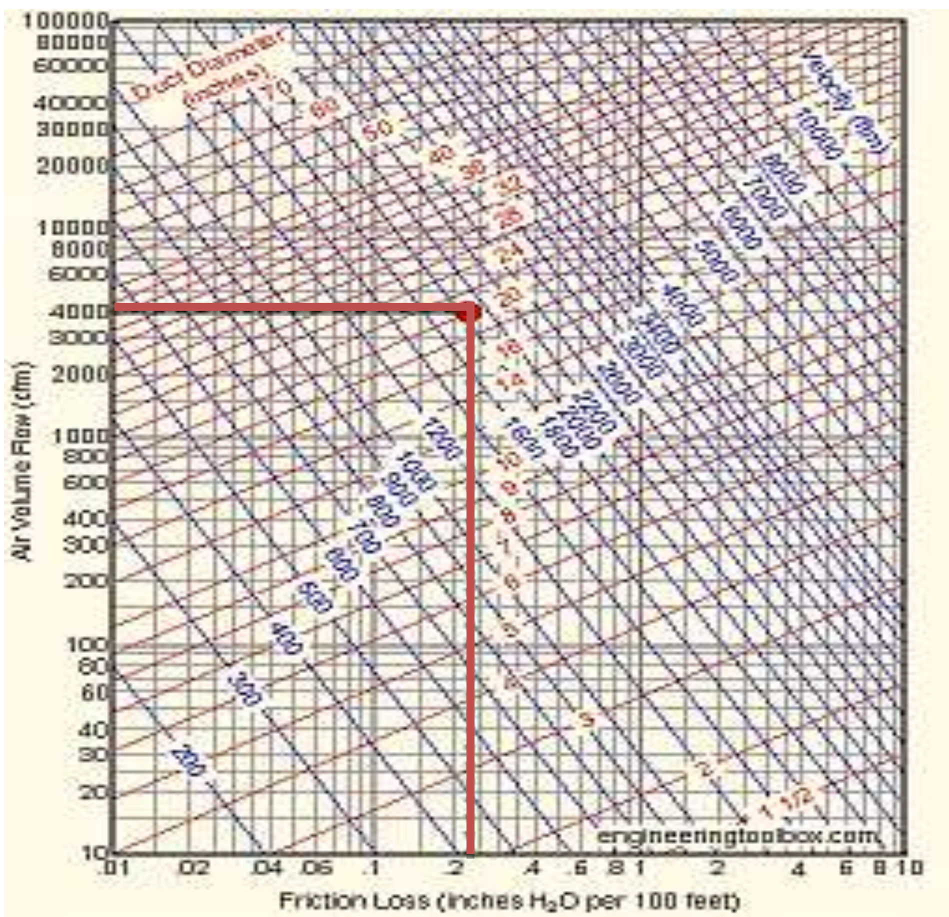


Diagram Example: Friction Loss in Air Duct: In this example there is a **20 inches duct** with air volume of **4,000 CFM.** The diagram estimated to approximately **0.23 inches per 100 feet duct of pressure loss**, as shown above. The air velocity estimated to approximately **1,850 FPM**. The diagram is based on **standard air 0.075 lb/ft³** in clean round galvanized metal ducts.

RULES OF THUMB FOR CALCULATIONS:

Property	Units	Water	Air
Heat Capacity	KJ/kg °C	4.2	1.0
	Btu/lb °F	1.0	0.239
Density	kg/m3	1000	1.29@STP (1 bar, 0°C)
	lb/ft3	62.29	0.075@STP (14.696 psia, 0°F)
Latent Heat	KJ/kg	1200 - 2100	
	Btu/lb	516 - 903	
Thermal Factors	W/m °C	0.55 - 0.70	0.025 - 0.05
	Btu/h ft °F	0.32 - 0.40	0.014 - 0.029
Viscosity	cP	1.8 @ 0 °C	0.02 - 0.05
		0.57 @ 50 °C	
		0.28 @ 100 °C	
		0.14 @ 200 °C	
Prandtl Number		1 - 15	0.7

CHILLERS AND AIR HANDLING (AHU):

Chillers provide cooling of chilled water, which is then used in the air cooling coils for air conditioning, while **AH Units provide cooling** by direct expansion of the refrigerant in the air cooling coils. **AH Units** are available in several categories, based on the type of the compressor and packaged or split design:

In general **AH Units** are used for **relatively small capacity** systems and **chillers** are used for relatively **large capacity systems**. Typically an AHU system is not used for systems **larger than 100 ton capacity.** Further variations of applications are as follows:

Chillers are package units on one skid, with the water piping system being external to the unit. The **package** unit includes **a compressor, condenser, evaporator and associated components.**

Reciprocating or scroll compressor package units (condenser, compressor & evaporator are on the same skid).

Reciprocating or scroll compressor split systems (condenser, compressor, evaporator are located at separate locations - many systems have the condenser + compressor on the same skid as condensing unit, and the evaporator is located separately)

The condenser for both AH Units and chillers can be air cooled or water cooled for relatively smaller sizes. For the **larger units the condenser** is typically water cooled.

Chiller & AH Unit Sizing Rules:

- **AH Unit Type – Reciprocating or Scroll:**

Capacity range for package units – 0.5 to 150 Tons
Capacity range for split units – 1 to 70 Tons
Power – 0.9 to 1.3 KW / Ton
Min Capacity Turndown capability – depends on number of cylinders

- **Chiller Type – Reciprocating:**

Capacity range – 15 to 100 Tons
Power – 0.9 to 1.3 KW / Ton
Min Capacity Turndown capability – depends on number of cylinders

- **Chiller Type – Scroll:**

Capacity range – 10 to 150 Tons
Power – 0.9 to 1.3 KW / Ton
Min Capacity Turndown capability – depends on number of cylinders

- **Chiller Type – Rotary Screw:**

Capacity range – 70 to 500 Ton
Power – 1 to 1.5 KW / Ton
Min Capacity Turndown capability – 25%

- **Chiller Type – Centrifugal:**

Capacity range – 200 Ton to 2,000 Ton
Power – 0.5 to 0.85 KW / Ton
Min Capacity Turndown capability – 10%

- **Chiller Type – Absorption:**

Capacity range – 100 Ton to 2,000 Ton
Heat – 12,000 Btu.h / Ton (gas/oil), 12,000 – 18,000 Btu.h / Ton (steam/hot water).
Min Capacity Turndown capability – 10%

Obs.: The air cooling coil in **AH Units** and the chilled water heat exchanger in chillers are also called an "Evaporator" since evaporations of the **liquid refrigerant** occurs in these components.

- **Centrifugal compressor chillers**: Used for medium to large capacity applications;
- **Screw compressor chillers**: Used for medium capacity applications;
- **Reciprocating compressor chillers**: Used for small to medium capacity applications;
- **Scroll compressor chillers**: Used for small to medium capacity applications;

HVAC REFRIGERANTS:

Refrigerant is a chemical that produces a cooling effect while expanding or vaporizing. A refrigerant is a substance, often a fluid, used in a refrigeration cycle to cool a space. In general the most common refrigerants used in the industry belong to the following three categories:

- **CFC:** Chlorofluoro Carbon refrigerants, such as R11, R12, R113, and R114, identified as the most **harmful to Ozone** layer by the Montreal Protocol, and were phased out in 2000. The **R12** is used commonly in the older cars for air conditioning.

- **HCFC:** Hydro Chlorofluoro Carbon refrigerants, such as R22, R123, etc., identified as **slightly harmful to the Ozone** layer by Montreal Protocol, and will be phased out by 2030. The **R22 refrigerant** is commonly used in most reciprocating type of compressors, while **R123** is used in centrifugal chillers as a temporary replacement for **R11**.

- **HFC:** These are the Hydrofluoric Carbon refrigerants, such as **R134a**, that **do not harm the Ozone** layer, and are being used in the newer machines to **replace the CFC and HCFC**. The **R134a** is now commonly used to replace either **R12 or R500**, and in all new cars air conditioning systems.

Refrigerant Analysis:

A periodic refrigerant analysis is important to detect and control contaminants in the refrigerant, which can result in degradation / failure of the various components, and cause inefficient operation of the unit. Refrigerants should be tested for the following contaminants:

Moisture:

Moisture is one of the primary causes of contamination-related problems in a refrigeration system which may cause damages to the chiller or AH Unit. The acceptable levels of moisture in new or reclaimed refrigerants are given in ARI 700. These levels are generally more demanding than what is typically feasible and acceptable in an operating system.

- Moisture, Acid; Particulate/solids, Organic matter – sludge, wax, tars, Non-condensable gases;
- Ice formation in evaporator, expansion valve or orifice;
- Degradation of lubricating oil due to hydrolysis;
- Acid formation due to hydrolysis of refrigerant in the presence of moisture and high temperature;
- Corrosion of metals;
- Copper plating.

Refrigerant	Allowable Moisture Level per ARI 700 (ppm by wt)	Normal Operating Moisture Levels (ppm by wt) (Ref. ASHRAE)
R11	20	0 – 30 (Centrifugal Chillers)
R12	10	0 – 25 (Centrifugal Chillers)
R22	10	0 – 56 (Recip.& Screw Chillers)
R113	20	0 - 30* (similar to R11)
R114	10	0 - 25* (similar to R12)
R134a	10	0 – 25* (similar to R12)
R500	10	0 – 25* (similar to R12)

* R113, R114, R134a, R500 data are not available in ASHRAE.

Obs.: There is extensive research going on to identify new refrigerants that can be used to replace the **CFC** and **HCFC** refrigerants. Currently **R134a is the most commonly** used new refrigerant.

LINKS AND REFERENCES:

ASHRAE: The American Society of Heating Air Conditioning and Refrigeration

- 2001 ASHRAE Handbook of Fundamentals;
- 1997 ASHRAE Handbook of Fundamentals;
- ASHRAE Cooling and Heating Load Calculation Manual.

NIST Standard Reference Database 69: NIST Chemistry Web Book;
University of Arkansas – School of Architecture;
Refrigerants Temperature/Pressure Table for common refrigerants;

Links:

http://www.engineeringtoolbox.com/sizing-ducts-d_207.html
www.engineeringtoolbox.com/air-psychrometrics-properties-t_8.html
www.linric.com/webpsy.htm
http://www.flycarpet.net/en/download.asp
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