313a Refrigeration and AC Study Guide

Comprehensive Easy Read Edition

Essential Concepts, Components, Formulas, and Operating Parameters

Prepared for HVAC/R Technicians
Date: June 2, 2025

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Chapter 1: Safety & Regulations

This chapter highlights **key safety guidelines** and **regulations** crucial for a **safe working environment** and **accident prevention**.

1.1 Ontario Health and Safety Act

Relevant regulations under the **Ontario Health and Safety Act (OHSA)** for construction and industrial establishments include:

- **O. Reg. 213/91: Construction Projects**
- **O. Reg. 851: Industrial Establishments**

1.2 Fire Extinguisher Classifications

Fire extinguishers are categorized by the **type of combustible material** involved:

- **Class A:** For **ordinary combustibles** (wood, paper, cloth).
    - **Agents:** Water, Foam, Monammonium Phosphate Dry Chemical (ABC).
- **Class B:** For **flammable and combustible liquids** (gasoline, oil, grease).
    - **Agents:** Foam, Dry Chemical (ABC or BC), Carbon Dioxide (CO2).
- **Class C:** For **energized electrical equipment**. Requires a **non-conductive agent**.
    - **Agents:** Dry Chemical (ABC or BC), Carbon Dioxide (CO2), Halocarbon.
- **Class D:** For **combustible metals** (magnesium, titanium, sodium). Requires **specific dry powder agents**.
    - **Agents:** Specific Dry Powder formulations.
- **Class K:** For **combustible cooking oils and fats** in commercial kitchens.
    - **Agent:** Wet Chemical.
- **Multi-Class Extinguishers:** Rated for **more than one class** (e.g., ABC dry chemical).

1.3 Refrigerant Cylinder Storage

Guidelines for **safe storage** of refrigerant cylinders:

- Store in a **cool, dry, well-ventilated area**.
- **Protect cylinders from physical damage**.
- Store **upright** and **secured** to prevent tipping.
- Keep **valve protection caps** in place when not in use.
- Store **away from direct sunlight and heat sources**.
- Do not expose to temperatures exceeding **52 degrees C (125 degrees F)** to prevent excessive internal pressure.
- **Segregate different types of refrigerants** to prevent accidental mixing.

Chapter 2: Fundamental Concepts & Formulas

This chapter covers **key definitions** and **fundamental formulas** used in thermal energy and refrigeration.

2.1 Key Definitions

- **Evaporator Approach:** The **temperature difference** between the **leaving air temperature** and the **saturated suction temperature (SST)**. A **lower approach** indicates **higher evaporator coil efficiency**.
  - **Formula:** Evaporator Approach = Leaving Air Temperature - SST
- **Condenser Approach:** The **temperature difference** between the **leaving refrigerant liquid temperature** (liquid line temperature) and the **saturated condensing temperature (SCT)**. A **lower approach** indicates **higher condenser coil efficiency**.
  - **Formula:** Condenser Approach = Liquid Line Temperature - SCT
- **Condenser Split:** The **temperature difference** between the **saturated condensing temperature (SCT)** and the **entering heat rejection medium temperature** (air or water).
  - **Formula (Air-Cooled):** Condenser Split = SCT - Entering Air Temperature
  - **Formula (Water-Cooled):** Condenser Split = SCT - Entering Water Temperature
- **Coil Delta T (Delta T):** The **temperature difference** between the **entering air temperature** and the **leaving air temperature** across the evaporator coil. Represents the **sensible cooling capacity**.
  - **Formula:** Coil Delta T = Entering Air Temperature - Leaving Air Temperature
- **Superheat:** The amount of **sensible heat added** to the **refrigerant vapor** above its saturation temperature at a given pressure, measured at the evaporator outlet. **Ensures complete vaporization** and **prevents liquid floodback** to the compressor.
  - **Formula:** Superheat = Suction Line Temperature - SST
- **Subcooling:** The amount of **sensible heat removed** from the **refrigerant liquid** below its saturation temperature at a given pressure, measured at the condenser outlet (liquid line). **Ensures a solid column of liquid refrigerant** enters the metering device.
  - **Formula:** Subcooling = SCT - Liquid Line Temperature

2.2 Thermal Energy and Refrigeration Formulas

- **Temperature Conversions:**
  - **Fahrenheit to Celsius:** Degrees C = (Degrees F - 32) / 1.8
  - **Celsius to Fahrenheit:** Degrees F = (Degrees C * 1.8) + 32
  - **Celsius to Kelvin:** K = Degrees C + 273.15
  - **Fahrenheit to Rankine:** Degrees R = Degrees F + 460
- **Specific Heat (c):** Heat required to raise the temperature of a unit mass by one degree.
  - **Water:** approx **1 BTU/lb degrees F**
  - **Steam:** approx **0.5 BTU/lb degrees F**
  - **Ice:** approx **0.5 BTU/lb degrees F**
- **Latent Heat:** Heat absorbed or released during a **phase change** at constant temperature.
  - **Fusion (ice to water):** approx **144 BTU/lb**
  - **Vaporization (water to steam):** approx **970 BTU/lb**
- **Specific Volume of Standard Air:** Approximately **13.33 cubic feet per pound**.

- **Sensible Heat Transfer (Air):**
  - **Formula:** Q_sensible (BTUH) = CFM * 1.08 * Delta T (degrees F)
  - **Example:** If you have **1000 CFM** of air and the temperature changes by **20 degrees F**: Q_sensible = 1000 * 1.08 * 20 = **21,600 BTUH**.
- **Sensible Heat Transfer (Water):**
  - **Formula:** Q_sensible (BTUH) = GPM * 500 * Delta T (degrees F)
  - **Example:** If you have **10 GPM** of water and the temperature changes by **15 degrees F**: Q_sensible = 10 * 500 * 15 = **75,000 BTUH**.
- **Total Heat Transfer (Air):**
  - **Formula:** Q_total (BTUH) = CFM * 4.5 * Delta h (BTU/lb) (where Delta h is the change in enthalpy)
  - **Example:** If you have **1000 CFM** of air and the change in enthalpy (Delta h) from a psychrometric chart is **10 BTU/lb**: Q_total = 1000 * 4.5 * 10 = **45,000 BTUH**.
- **Basic Heat Transfer Equation:**
  - **Formula:** Q = m * c * Delta T (where Q is heat, m is mass, c is specific heat, Delta T is temperature change)
  - **Example:** If you have **50 pounds** of water (c = 1 BTU/lb degrees F) and its temperature changes by **30 degrees F**: Q = 50 * 1 * 30 = **1500 BTU**.
- **Density of Water:** Approximately **62.4 pounds per cubic foot**.
  - **Example:** To find the mass of **10 cubic feet** of water: Mass = 10 ft^3 * 62.4 lb/ft^3 = **624 lb**.
- **Mass Flow Rate of Refrigerant:**
  - **Formula:** Mass Flow Rate (lb/min) = (200 BTU/min/ton) / NRE (BTU/lb)
  - **Note: 1 ton of refrigeration = 12,000 BTUH = 200 BTU/min**.
  - **Example:** If a system has **5 tons** of cooling capacity (5 * 200 = 1000 BTU/min) and the **Net Refrigeration Effect (NRE)** for the refrigerant is **80 BTU/lb**: Mass Flow Rate = 1000 / 80 = **12.5 lb/min**.
- **Flash Gas Calculation:** Fraction of liquid refrigerant that vaporizes when pressure is reduced across the metering device.
  - **Formula:** Flash Gas (%) = ((enthalpy of liquid at inlet - enthalpy of vapor at outlet) / (enthalpy of vapor at outlet - enthalpy of liquid at outlet)) * 100%

h_liquid, inlet (BTU/lb)	h_saturated liquid (BTU/lb)	h_saturated vapor (BTU/lb)	Output (Flash Gas %)
30	25	75	10%

2.3 Gas Laws

Fundamental laws describing **ideal gas behavior** under varying conditions. **Absolute temperature scales** (**Kelvin** or **Rankine**) must be used.

- **Boyle's Law:** At **constant temperature**, **pressure** and **volume** are **inversely proportional**.
  - **Formula:** P1 * V1 = P2 * V2
  - **Example:** A gas in a container has a pressure of **10 psi** and a volume of **5 cubic feet**. If you increase the pressure to **20 psi** without changing the temperature, the new volume is (10 * 5) / 20 = **2.5 cubic feet**.

- **Charles's Law:** At **constant pressure**, **volume** is **directly proportional to absolute temperature**.
  - **Formula:** V1 / T1 = V2 / T2
  - **Example:** A gas has a volume of **10 cubic feet** at a temperature of **500 degrees R** (absolute). If you heat it to **600 degrees R** at the same pressure, the new volume is (10 / 500) * 600 = **12 cubic feet**.

- **Gay-Lussac's Law:** At **constant volume**, **pressure** is **directly proportional to absolute temperature**.
  - **Formula:** P1 / T1 = P2 / T2
  - **Example:** A gas in a sealed container with a pressure of **100 psi** at a temperature of **500 degrees R** (absolute). If you heat it to **600 degrees R**, the new pressure is (100 / 500) * 600 = **120 psi**.
- **Combined Gas Law:** Combines **Boyle's**, **Charles's**, and **Gay-Lussac's** laws.
  - **Formula:** (P1 * V1) / T1 = (P2 * V2) / T2
  - **Example:** A gas has a pressure of **10 psi**, a volume of **5 cubic feet**, and a temperature of **500 degrees R**. If the pressure changes to **20 psi** and the temperature changes to **600 degrees R**, the new volume is ((10 * 5) / 500) * (600 / 20) = **3 cubic feet**.

2.4 Units and Conversions

Common **units** and **conversion factors** in **HVACR**:
- **Pressure Units:** Pa, bar, kPa, MPa, psi, kg/cm^2, inHg, atm.
  - **1 bar** = 100,000 Pa = 100 kPa = 0.1 MPa, approx 14.5 psi, approx 1.02 kg/cm^2, approx 29.53 inHg.
  - **1 atm** = 101.325 kPa.
- **Common Conversions:**
  - **1 inch** = 25.4 mm
  - **1 meter** approx 3.281 feet
  - **1 kilogram** approx 2.205 pounds
  - **1 kW** approx 1.341 hp approx 0.284 tons of refrigeration (TR)
  - **1 L/s** approx 2.119 cfm

2.5 Pressure Nomenclature

- **Operating Pressure:** Refrigerant pressure under **normal running conditions** (e.g., suction pressure, discharge pressure).
- **Test Pressure: Higher pressure** used to verify **structural integrity** and **leak-tightness**.
- **Maximum Component Pressure: Maximum pressure** a component is designed to **safely withstand**. High-side components have higher ratings.

Chapter 3: Psychrometrics: Properties of Moist Air

Psychrometrics is the study of **thermodynamic properties of gas-vapor mixtures**, primarily **moist air** in HVACR.

3.1 Key Properties of Moist Air

- **Psychrometric Chart:** A **graphical representation** of moist air properties at specific atmospheric pressure. **Essential** for analyzing and designing air conditioning processes. Standard charts typically cover **32 degrees F to 120 degrees F**.
- **Dry-Bulb Temperature (DB):** Air temperature measured by a **standard thermometer**. Represented by **vertical lines** on the chart.
- **Wet-Bulb Temperature (WB):** Temperature air reaches when water evaporates into it. Measured by a thermometer with a **wet wick**. Represented by **diagonal lines** sloping downwards from left to right.
- **Dew-Point Temperature (DP):** Temperature at which **moisture in the air begins to condense**. Determined by following a **horizontal line** from the state point to the saturation curve.
- **Relative Humidity (RH):** Ratio of **actual water vapor** to **maximum possible** at same temperature and pressure, as a percentage. Represented by **curved lines** radiating from the lower left. The **saturation curve is 100% RH**.
- **Humidity Ratio (Absolute/Specific Humidity): Mass of water vapor per unit mass of dry air**. Represented by **horizontal lines**, scale typically on the right vertical axis.
- **Enthalpy (Specific Enthalpy): Total heat content of air** (sensible + latent) per unit mass of dry air. Represented by **diagonal lines** sloping downwards from left to right.
- **Specific Volume: Volume occupied by a unit mass of dry air** and its associated water vapor. Represented by **diagonal lines** sloping downwards from left to right.

3.2 Psychrometric Chart and Its Lines

- **Dry-Bulb Temperature (DB): Vertical lines**.
- **Wet-Bulb Temperature (WB): Diagonal lines** sloping downwards from left to right. Adiabatic lines (constant enthalpy) are nearly parallel.
- **Dew-Point Temperature (DP): Horizontal lines**. Read on the saturation curve.
- **Relative Humidity (RH): Curved lines** radiating from the lower left.
- **Humidity Ratio: Horizontal lines** (right vertical axis scale).
- **Enthalpy: Diagonal lines** sloping downwards from left to right (often outside the chart).
- **Specific Volume: Diagonal lines** sloping downwards from left to right.
- **Saturation Curve:** The **left boundary of the chart**, representing **100% RH**, where DB=WB=DP.

3.3 Applications of Psychrometrics

Psychrometrics is used for:

- Analyzing and designing **air conditioning processes** (heating, cooling, humidification, dehumidification).
- Determining the **Comfort Zone** (acceptable ranges of temperature and humidity for human comfort).
  - **Summer comfort: 70-76 degrees F DB**, **45-65% RH**.
  - **Winter comfort: 65-68 degrees F DB**, min **30% RH**.
- Plotting and analyzing **air treatment cycles** on the psychrometric chart.
- Determining the **sensible heat ratio** from the slope of a process line.
- Analyzing **coil performance** based on **Apparatus Dew Point (ADP)** and coil contact factor.
- Guiding **air treatment methods** and optimizing **energy efficiency**.
- Performing **psychrometric calculations** (e.g., heat removal/addition).
- Requires initial air properties (e.g., DB and WB) measured by instruments like a **sling psychrometer**.

3.4 Mixed Air Calculations

Air entering an air conditioning plant is often a **mixture of return air and outside air**. This is commonly controlled by an **economizer circuit** for ventilation and free cooling. The **mixed airstream condition** can be found graphically or by calculation. **No heat or moisture is gained or lost during mixing**. Calculations use a **weighted average** based on **mass flow rates**.

- **Mixed Air Dry Bulb Temperature:**
  - **Formula:** Mixed DB = [(Mass Flow Stream 1 * DB Stream 1) + (Mass Flow Stream 2 * DB Stream 2)] / (Total Mass Flow)

Stream	Mass Flow (lb/min)	DB (degrees F)
1	8000	75
2	2000	20
Total	10000	
Output	Mixed DB	64 degrees F

- **Mixed Air Moisture Content:**
  - **Formula:** Mixed Moisture = [(Mass Flow Stream 1 * Moisture Content Stream 1) + (Mass Flow Stream 2 * Moisture Content Stream 2)] / (Total Mass Flow)

Stream	Mass Flow (lb/min)	Moisture Content (kg/kg)
1	8000	0.012
2	2000	0.003
Total	10000	
Output	Mixed Moisture	0.0102 kg/kg

Chapter 4: Refrigeration Cycle Components

This chapter details the various **components of a refrigeration system**, outlining their **functions** and **operational characteristics**.

4.1 Refrigerant Information and Classification

Properties and safety classifications of refrigerants.

- **Refrigerant Classification (ASHRAE Standard 34):** Based on **toxicity** and **flammability**.
  - **Toxicity (Letter): A** (lower), **B** (higher).
  - **Flammability (Number): 1** (no flame propagation), **2L** (lower flammability), **2** (flammable), **3** (higher flammability).

Toxicity / Flammability	1 (No Flame Propagation)	2L (Lower Flammability)	2 (Flammable)	3 (Higher Flammability)
A (Lower)	A1	A2L	A2	A3
B (Higher)	B1	B2L	B2	B3

- **Refrigerant Designation (ASHRAE 34):** Numbering system indicating chemical composition.
  - **R-700 series: Inorganic compounds** (R-717 Ammonia, R-744 CO_2, R-718 Water).
  - **R-400 series: Zeotropic blends** (temperature glide).
  - **R-500 series: Azeotropic blends** (no temperature glide).
- **DOT/Transport Canada:** Regulatory bodies for refrigerant cylinder transportation in Canada.

4.2 Refrigerant Circuit Flow

The sequence of components in a **vapor-compression refrigeration cycle**:

1. **Compressor Discharge:** High pressure, high temperature **superheated vapor**.
2. **Condenser: Desuperheating**, **condensing** to high pressure liquid, **subcooling**.
3. **Liquid Line:** High pressure, **subcooled liquid**.
4. **Metering Device (Expansion Device): Pressure reduction**, flashing to low pressure, low temperature **liquid/vapor mixture**.
5. **Evaporator: Absorption of heat** from the load, **boiling** to low pressure, low temperature **superheated vapor**.
6. **Suction Line:** Low pressure, **superheated vapor** returning to the compressor.

4.3 Refrigeration Temperature Regimes & Recommended Superheat

Typical **saturated suction temperature (SST)** ranges and corresponding recommended evaporator superheat settings for different applications:

- **High Temperature Refrigeration: 35 degrees F to 50 degrees F SST** (e.g., A/C, produce).
  - **Recommended Evaporator Superheat: 8 degrees F to 12 degrees F**.
- **Medium Temperature Refrigeration: 0 degrees F to 35 degrees F SST** (e.g., dairy, meat).
  - **Recommended Evaporator Superheat: 4 degrees F to 8 degrees F**.
- **Low Temperature Refrigeration: -20 degrees F to 0 degrees F SST** (e.g., ice cream, holding freezers).
  - **Recommended Evaporator Superheat: 2 degrees F to 4 degrees F**.
- **Ultra-Low Temperature Refrigeration: Below -20 degrees F SST** (e.g., medical freezers).
  - **Recommended Evaporator Superheat: 2 degrees F to 6 degrees F**, precise control is critical.
- **Total System Superheat (TSH):** Evaporator Superheat + Suction Line Temperature Rise.

4.4 Compressor Types

Compressors increase the pressure of a gas by reducing its volume. They draw low-pressure, low-temperature refrigerant vapor from the evaporator and compress it to high-pressure, high-temperature vapor for the condenser. Categorized into **positive displacement** and **dynamic** types.
Positive Displacement Compressors Increase pressure by trapping a fixed amount of refrigerant vapor and forcing it into a smaller volume.

- **Reciprocating Compressors:**
  - **Operation:** Use **pistons** moving back and forth within cylinders, drawing in low-pressure vapor and compressing it.
  - **Construction Style:**
    - **Hermetic: Sealed welded shell**, no internal servicing. Motor cooled by suction gas. Common in residential units.
    - **Semi-Hermetic: Bolted housing**, can be opened for servicing. Widely used in commercial refrigeration. Motor typically cooled by suction gas.
    - **Open: Separate compressor and motor**, connected by shaft/coupling or belt. Requires shaft seal. Common in large industrial systems.
  - **Characteristics:** Wide range of conditions/refrigerants. Robust, can handle varying loads. Can be noisy and vibrate.
- **Rotary Compressors:**
  - **Operation:** Use a **rotating mechanism** (e.g., rolling piston with a sliding vane) to trap and compress vapor.
  - **Construction Style:** Almost exclusively **Hermetic**.
  - **Characteristics:** Compact, quiet, efficient for smaller capacities. Less vibration. Used in room AC and small heat pumps.

- **Scroll Compressors:**
  - **Operation:** Two **interleaved spiral scrolls** (one fixed, one orbiting) progressively squeeze vapor towards the center.
  - **Construction Style:** Primarily **Hermetic**. Some larger commercial may be semi-hermetic.
  - **Characteristics:** High efficiency, quiet, smooth, vibration-free. Fewer moving parts, higher reliability. Widely used in residential and light commercial AC/heat pumps.
- **Screw Compressors:**
  - **Operation:** Two **helical (screw-shaped) rotors** mesh, trapping and continuously compressing vapor along their length.
  - **Construction Style:** Most commonly **Semi-Hermetic** or **Open**.
  - **Characteristics:** Handle **large volumes**. High efficiency, smooth operation, excellent part-load performance. Used in medium to large commercial/industrial refrigeration/AC (e.g., chillers). Can tolerate some liquid refrigerant return.

Dynamic Compressors Increase pressure by imparting velocity to refrigerant vapor and then converting that velocity energy into pressure energy.

- **Centrifugal Compressors:**
  - **Operation:** High-speed rotating **impeller** accelerates vapor radially, converting kinetic energy to static pressure in a diffuser and volute casing.
  - **Construction Style:** Typically **Open** or **Semi-Hermetic**.
  - **Characteristics:** Best for **very large capacity** (e.g., large chillers). Highly efficient at full load, can lose efficiency at part loads. Require specific low molecular weight refrigerants. Sensitive to pressure/flow changes.

4.5 Evaporator Types and Defrost Methods

Evaporators are **heat exchangers** that absorb heat from the conditioned space or medium, causing low-pressure liquid refrigerant to boil and change into vapor.

Evaporator Types

- **Bare Tube Evaporator:**
  - **Description:** Simple coils of tubing without fins. Heat absorbed directly from surrounding air or product.
  - **Application:** Significant frost buildup, very low-temperature freezers, ice machines, direct product contact.
  - **Characteristics:** Less efficient for air-to-refrigerant heat transfer due to smaller surface area, but easier to defrost.
- **Finned Tube Evaporator:**
  - **Description:** Most common type. Tubes with thin metal fins to increase surface area for heat transfer.
  - **Application:** Widely used in residential/commercial AC, walk-in coolers, medium-temperature refrigeration.
  - **Characteristics:** Highly efficient for air-to-refrigerant heat transfer.
  - **Draw-Through:** Fan after coil, pulls air through. Uniform airflow.
  - **Blow-Through:** Fan before coil, pushes air through. Simpler, but less uniform airflow.

- **Plate Evaporator:**
    - **Description:** Two metal plates pressed/welded to create internal refrigerant channels. Heat exchanged directly through plate surfaces.
    - **Application:** Direct contact cooling/freezing (plate freezers), beverage coolers, some types of ice makers.
    - **Characteristics:** Efficient heat transfer through direct contact. Easy to clean on product side.
- **Shell and Tube Evaporator:**
    - **Description:** Cylindrical shell containing a bundle of tubes. Refrigerant typically in tubes, fluid being cooled in shell.
    - **Application:** Larger refrigeration systems, chilling liquids in industrial processes or large commercial AC (e.g., water chillers).
    - **Characteristics:** Robust and efficient for liquid-to-refrigerant heat transfer. Tube bundle often removable for cleaning.

Evaporator Defrost Methods (for Low-Temperature Applications) Frost buildup on low-temperature evaporator coils acts as an insulator, reducing efficiency. Defrosting removes this ice.

- **Off Cycle Defrost:**
    - **Operation:** Compressor and sometimes evaporator fan turn off. Warmer space temperature or ambient air melts frost.
    - **Application:** Medium-temperature refrigeration (e.g., display cases, walk-in coolers above **32 degrees F**) where box temperature is warm enough.
    - **Characteristics:** Energy-efficient (uses ambient heat), but only suitable if coil temperature can rise above freezing.
- **Electric Defrost:**
    - **Operation:** Electric heating elements within/around coil are energized. Compressor and fan off. Heat melts frost.
    - **Application:** Common in low-temperature freezers where box temperature is always below freezing.
    - **Characteristics:** Effective and reliable. Energy-intensive as it adds heat to the refrigerated space, requiring more work after defrost.
- **Hot Gas Defrost:**
    - **Operation:** Hot, high-pressure refrigerant vapor from compressor discharge (or condenser outlet) is diverted into the evaporator. Condenses, releasing latent heat to melt frost.
    - **Application:** Highly efficient for low-temperature applications, especially larger systems, uses waste heat.
    - **Characteristics:** More energy-efficient than electric defrost. Can be complex, requiring additional valves. Evaporator acts as a condenser during defrost.
- **Evaporator Film Factor (Film Effect):** At low air velocities, a **stagnant air layer** forms on the coil surface, acting as an insulator and reducing heat transfer efficiency.

4.6 Condenser Types and Head Pressure Control

Condensers are **heat exchangers** that reject heat from high-pressure, high-temperature refrigerant vapor, causing it to condense back into a liquid.
Condenser Types

- **Air-Cooled Condenser:**
  - **Description:** Uses **ambient air** as heat rejection medium. Hot refrigerant flows through finned tubes, fan moves air over them.
  - **Operation:** Heat transfers from hot refrigerant vapor to cooler ambient air. Refrigerant desuperheats, condenses, and often subcools.
  - **Types of Airflow:**
    - **Natural Draft:** Relies on natural convection. Limited capacity/efficiency.
    - **Fan-Assisted Draft (Forced or Induced):** Uses fans.
      - **Forced Draft:** Fan before coil, pushes air. Common, simpler.
      - **Induced Draft:** Fan after coil, pulls air. More uniform airflow.
  - **Application:** Most common for residential and light commercial AC/refrigeration due to simplicity and lower cost.
  - **Characteristics:** Efficiency depends on ambient air temperature. Higher ambient temps lead to higher condensing temps/pressures, reducing efficiency.
  - **Condenser TD (Temperature Difference):** Difference between SCT and entering ambient air temperature.
    - **Standard Efficiency: ~30 degrees F TD**.
    - **High Efficiency: 5-10 degrees F TD**.
  - **Design Consideration:** Condensing temperature should be as close to ambient as possible for optimal efficiency.
- **Water-Cooled Condenser:**
  - **Description:** Uses **water** as heat rejection medium. Water is more effective than air, allowing compact designs and lower condensing temperatures.
  - **Operation:** Hot refrigerant vapor flows through one side, cooler water through the other, absorbing heat.
  - **Types:**
    - **Shell and Tube:** Refrigerant in shell, water in tubes. Tube bundle often removable for cleaning.
    - **Tube-in-Tube (Coaxial):** One tube inside another. Refrigerant in one, water in other (often counter-flow).
    - **Shell and Coil:** Refrigerant in shell, water in coil inside shell. Chemically cleaned.
  - **Application:** Larger commercial/industrial AC/refrigeration (e.g., chillers), where cool water source is available.
  - **Characteristics:** More efficient than air-cooled, leading to lower condensing pressures and improved performance. Requires **water treatment** and often a **cooling tower**.
  - **Rule of Thumb: ~3 GPM of water per ton of refrigeration**.
  - **Water Temperature Split:** Typically designed for a **10 degrees F temperature rise** across water circuit.
  - **Designed Water Cooled Inlet Temperature:** Often **~85 degrees F**.

- **Evaporative Condenser:**
    - **Description:** Combines **air-cooled and water-cooled**. Refrigerant tubes wetted by recirculated water, ambient air drawn over them. Cooling from water evaporation.
    - **Operation: Latent heat of water vaporization** provides effective cooling. Water evaporation absorbs heat from refrigerant tubes, allowing lower condensing temperatures.
    - **Application:** Large commercial/industrial refrigeration where high efficiency is critical and water usage is manageable.
    - **Characteristics: Most efficient type**. Achieves lower condensing temperatures/pressures, higher system efficiency. Requires **water treatment** and regular maintenance.

Head Pressure Control (Low Ambient Operation) In cold ambient conditions, air-cooled condensers can become too efficient, causing condensing pressure (**head pressure**) to drop too low. This leads to issues like insufficient pressure differential across the metering device, poor oil return, and short-cycling. **Head pressure control methods** maintain adequate condensing pressure.

- **Flooded Condenser Valves (Head Pressure Control Valves):**
    - **Description:** Valves in liquid line or discharge line that regulate liquid refrigerant flooding a portion of the condenser coil. Reduces effective surface area.
    - **Types:**
        - **ORI Valve (On Rise of Inlet pressure):** Inlet pressure regulating valve. Closes as condensing pressure drops, backing up liquid, raising pressure.
        - **ORD Valve (Opens on Rise of Differential pressure):** Pressure differential valve. Bypasses hot gas to receiver or liquid line to maintain pressure.
    - **Operation:** Overcharge condenser with liquid, reducing surface area, raising condensing pressure.
- **Condenser Splitter Valve (or Condenser Fan Cycling/Speed Control):**
    - **Description:** For systems with multiple coils/fans.
    - **Operation:**
        - **Splitter Valve:** Directs refrigerant flow to only a portion of coils in cold weather.
        - **Fan Cycling/Speed Control:** Turns off fans or reduces speed as ambient temperature drops, reducing airflow and maintaining head pressure. Common and energy-efficient.
- **Receivers (as part of head pressure control):**
    - **Description:** Liquid refrigerant storage tank in liquid line between condenser and metering device.
    - **Operation:** Stores excess liquid refrigerant (e.g., during pump-down). Essential for flooded condenser head pressure control, holding excess liquid that backs up into condenser. Typically has a **King valve** on outlet.

- **Pump Down Procedure:**
  - **Description:** Service procedure to **isolate refrigerant charge** in receiver/condenser for low-pressure side maintenance.
  - **Operation:** Close liquid line service valve (King valve). Run compressor to pump refrigerant from low-pressure side to high-pressure side (condenser/receiver). Monitor suction pressure; shut off compressor when safe (e.g., slightly above **0 PSIG**). Close suction line service valve.
  - **Purpose:** Safe and efficient service of low-side components without losing entire charge.

4.7 Refrigerant Metering Devices

Metering devices (expansion devices) reduce liquid refrigerant pressure entering the evaporator, causing temperature drop. They also control flow rate to match heat load, ensuring efficient operation and preventing liquid floodback.

- **Thermostatic Expansion Valve (TXV/TEV):**
  - **Description:** Precision modulating valve controlling liquid refrigerant flow into evaporator based on **superheat of vapor leaving evaporator**. Adjusts flow to maintain **constant superheat**.
  - **Operation:** Balances three forces on a diaphragm:
    - **Bulb Pressure (P_Bulb): Opening force**. Sensing bulb on suction line expands with increasing superheat, pushing valve open.
    - **Evaporator Pressure (P_Evap): Closing force**. Evaporator pressure acts on underside of diaphragm, tending to close valve.
    - **Spring Pressure (P_Spring): Closing force**. Spring below diaphragm pushes to keep valve closed. Adjustable.
  - **Adjustment (Superheat Adjustment):** Turning **clockwise** (tightening spring) **increases spring pressure**, increasing superheat setting. Turning **counter-clockwise** (loosening spring) **decreases spring pressure**, decreasing superheat setting. Adjust in small increments (**1/4 to 1/2 turn**), stabilize for **15-30 minutes**.
  - **Types of TXVs:**
    - **Internally Equalized TXV:** Senses evaporator pressure at valve outlet. For single-circuit evaporators with **low pressure drop** (approx **2 psig or less**).
    - **Externally Equalized TXV:** Senses evaporator pressure in suction line after coil. Required for coils with **significant pressure drop** or larger, multicircuited evaporators. External equalizer line compensates for pressure drop.
  - **Sensing Bulb Placement:** For suction lines > **7/8 inch**, place at **4 or 8 o'clock**. For < **7/8 inch**, place at **12 o'clock**.
  - **Operational Considerations:** Responds well to load changes, not affected by high ambient. Can starve (underfeed) or flood (overfeed) evaporator. **"Hunting"** (cycling above/below set point) can occur.

- **Electronic Expansion Valve (EEV):**
  - **Description:** Uses an **electronic stepper motor** for precise valve opening control. Receives signals from a controller monitoring system parameters (superheat, pressures, ambient temp).
  - **Operation:** Controller uses algorithms to determine optimal flow, sends pulses to stepper motor for precise adjustments.
  - **Advantages:** More **precise and rapid superheat control** than TXVs, improving efficiency, temperature control, and wider operating ranges.
  - **Adjustment:** Electronically through control panel/software.
- **Fixed Orifice / Piston Type:**
  - **Description:** Simplest, least expensive. Small, **fixed-size opening** or piston with fixed hole.
  - **Operation:** Creates pressure drop by restricting liquid refrigerant flow. Flow rate depends on pressure difference and refrigerant density. **Does not actively regulate superheat**.
  - **Adjustment:** None. Size is fixed.
  - **Application:** Residential AC/heat pumps, small self-contained units.
  - **Characteristics:** Simple, reliable, and inexpensive. Less efficient than a TXV, especially when the system load varies significantly, as it cannot adjust refrigerant flow to maintain optimal superheat. This can lead to higher superheat at low loads or liquid floodback at high loads.
- **Capillary Tube:**
  - **Description:** A **long, narrow tube** with a very small internal diameter.
  - **Operation:** Creates a pressure drop by providing a **fixed resistance** to refrigerant flow due to friction along its length. The length and internal diameter are carefully selected during design.
  - **Adjustment:** There is **no adjustment**. Its metering characteristic is fixed by its physical dimensions.
  - **Application:** Primarily used in **small, self-contained refrigeration systems** like domestic refrigerators, freezers, and small room air conditioners. Can also be found feeding distributors in larger multi-circuit evaporators, though a primary metering device (like a TXV) would still be upstream.
  - **Characteristics:** Very simple, inexpensive, and reliable (no moving parts). It eliminates the need for a liquid receiver as it allows the pressures to equalize during the off cycle, reducing compressor starting torque requirements. Less efficient under varying loads.

- **Automatic Expansion Valve (AXV):**
  - **Description:** A modulating valve that maintains a **constant pressure in the evaporator**.
  - **Operation:** The AXV has a spring (opening force) and evaporator pressure (closing force). It modulates to balance these, keeping evaporator pressure constant.
  - **Adjustment:** The evaporator pressure setting can be adjusted by tightening or loosening the spring. Clockwise (tightening) increases pressure setting; counter-clockwise (loosening) decreases it.
  - **Application:** Used in specialized applications where a **constant evaporator pressure is critical**, regardless of the load, such as some dehumidifiers or certain industrial processes.
  - **Characteristics:** Simple and effective at maintaining constant evaporator pressure. However, it **does not regulate superheat**. At low loads, it can cause the evaporator to "starve" (high superheat). At high loads, it might allow liquid floodback. This limits its use in most general HVAC/R systems.
- **Low Side Float Valve:**
  - **Description:** A metering device that maintains a **constant liquid refrigerant level** in a **flooded evaporator**.
  - **Operation:** A float mechanism senses the liquid level. As level drops, float falls, opening valve to add more liquid. As level rises, float rises, closing valve.
  - **Adjustment:** Adjustment is typically limited to the **float level setting**, usually factory-set.
  - **Application:** Primarily used in **large industrial flooded evaporators** (e.g., large chillers, ice rinks) where the evaporator is designed to be completely filled with liquid refrigerant for maximum heat transfer efficiency.
  - **Characteristics:** Provides excellent heat transfer efficiency by ensuring the evaporator is fully wetted. However, it is complex, bulky, and requires a large refrigerant charge. It does not control superheat directly, as the evaporator is designed to be flooded.
- **Distributors:**
  - **Description:** A component used in **multi-circuit evaporators** to ensure that the refrigerant from the metering device is **evenly distributed** to each individual circuit of the evaporator coil.
  - **Operation:** Takes a single stream of refrigerant (liquid/vapor mixture) and divides it into multiple, equal streams for each circuit. This ensures all parts of the coil receive adequate refrigerant.
  - **Adjustment:** Distributors themselves are **not adjustable**. Their design (number and size of nozzles) is fixed.
  - **Application:** Essential for all **multi-circuit evaporators**, especially larger finned-tube coils in AC and commercial refrigeration systems.
  - **Characteristics:** Helps maintain proper superheat across the entire evaporator by ensuring even refrigerant distribution. Causes a slight pressure drop, which must be accounted for in the system design.

4.8 Refrigerant Driers

Components containing **desiccant** to remove **moisture and contaminants** from the refrigerant.

- **Desiccants: Silica Gel**, **Molecular Sieve**, **Activated Alumina** (for burnout cleanup).

4.9 Brazing and Soldering Techniques

Joining processes for refrigerant tubing.

- **Soldering:** Filler metal melts **below 840 degrees F (450 degrees C)**. Lower strength, not for high-pressure lines.
- **Brazing:** Filler metal melts **above 840 degrees F (450 degrees C)**. Higher strength, suitable for high-pressure refrigerant lines.

4.10 Brazing Alloy Designations

Filler metals used for brazing.

- **BAG Alloys: Silver brazing alloys** (contain silver, copper, zinc). Requires flux for dissimilar metals.
- **BCuP Alloys: Copper-Phosphorus brazing alloys**. **Self-fluxing** on copper-to-copper. Not for ferrous metals.
- **Welding Rod (ER70S-2):** Mild steel welding rod designation.

4.11 Capacity Control

Capacity control in HVAC/R systems is crucial for **maintaining efficiency** and **protecting equipment** when the system operates below its maximum design load. It helps control the amount of work a compressor can perform, extends run time, prevents damage under low-load conditions, and reduces energy consumption while increasing overall efficiency.
Here are common methods for capacity control:

- **Compressor Unloading:** Reduces a compressor's capacity by **preventing suction vapor from entering some cylinders**. This lowers the electrical current drawn and is activated when suction pressure drops (low load). Helps prevent short cycling and overheating.
- **Variable Frequency Drives (VFDs):** Control the **speed of the compressor motor** by changing the frequency of the electrical power supply. Allows **precise and energy-efficient adjustment** of capacity, especially for centrifugal and rotary vane compressors.
- **Multiple Compressors (Parallel Rack Systems):** Uses **several compressors** for a single load. Capacity is managed by turning individual compressors **on or off** as demand changes. Offers significant control and energy savings, common in large refrigeration systems (e.g., supermarkets).
- **Hot Gas Bypass:** Diverts **hot discharge gas** from the compressor back into the low-pressure side (suction line or evaporator inlet). This **artificially increases the load** on the compressor, helping to maintain a minimum suction pressure. Prevents low compression ratios and excessive heat, useful in low-temperature applications.

- **Condenser Control:** Methods that regulate heat rejection from the condenser can indirectly affect system capacity. This includes **reducing airflow** over air-cooled condensers (e.g., fan speed, cycling fans, dampers) or restricting water flow in water-cooled systems.
- **Metering Devices:** Some metering devices offer capacity control. **Electronic Expansion Valves (EEVs)** provide precise and wide-ranging control. **Pressure Limiting TXVs (MOP valves)** restrict refrigerant flow during high-load startups to prevent compressor overload. **Evaporator Pressure Regulators (EPRs)** maintain a constant evaporator pressure, allowing multiple evaporators at different temperatures to work with one compressor.
- **Stepping Control:** Adjusts system capacity in **distinct, incremental steps**. Often seen in multi-compressor systems (units cycled on/off) or through floating controls that sequence capacity stages.
- **Air/Water Flow Control in Air Handling Units:**
    - **Constant Air Volume systems:** Face and bypass dampers control airflow over heating or cooling coils.
    - **Variable Air Volume (VAV) systems:** Adjust the **quantity of air supplied** to a space based on demand.
- **Capacity Control in Chillers:** Chillers use various methods, often integrated into compressor design or system controls. Examples include varying compressor motor speed (for centrifugal chillers) or using hot gas bypass valves to prevent evaporating temperature from dropping below freezing.
- **Compound Systems and Intercoolers:** In multi-stage compression systems (for very low temperatures), **staging compressors on or off** acts as capacity control. Intercoolers, while primarily for efficiency, are integral to these systems.
- **Suction Pressure Regulation (LP Control, CPR, EPR):**
    - **Low Pressure (LP) controls:** Shut off the compressor if suction pressure falls too low.
    - **Crankcase Pressure Regulators (CPRs):** Prevent compressor overload by restricting suction vapor flow during hot pull-downs.
    - **Evaporator Pressure Regulators (EPRs):** Maintain a constant evaporator pressure, allowing multiple evaporators at different temperatures to operate with the same compressor.

Chapter 5: Electrical Concepts

This chapter covers **fundamental electrical principles** and **components** relevant to HVACR systems, including **motor types** and **starting methods**.

5.1 Fundamental Electrical Concepts and Formulas

Basic principles and calculations for electrical circuits in HVACR.

- **Charge: Coulomb (C)**.
- **Current (I): Flow of charge**, measured in **Amperes (A)**.
  - **Conventional flow:** + to -.
  - **Electron flow:** - to +.
  - An **Ampere** is **one coulomb per second**.
  - One **coulomb** contains **6.25 x 10^18 electrons**.
- **Voltage (V or E): Electrical potential difference**, measured in **Volts (V)**. Also known as **electromotive force (EMF)** or **electrical pressure**.
- **Resistance (R): Opposition to current flow**, measured in **Ohms (Ohm)**.
  - **Factors determining resistance:** diameter, material, length, temperature.
  - **Conductors:** Easy path for electron flow (e.g., silver, copper, gold).
  - **Insulators:** Do not permit electrons to flow easily (e.g., wood, ceramic, rubber).
- **Conductance (G): Reciprocal of resistance**, measured in **Siemens (S)**.
  - **Formula:** G = 1 / R
  - **Example:** If a wire has a resistance of **10 Ohms**, its conductance is 1 / 10 = **0.1 Siemens**.
- **Power (P): Rate of energy transfer**, measured in **Watts (W)**.
  - **Formula:** P = V * I
  - **Example:** A heating element has **240 Volts** across it and draws **10 Amperes** of current. The power consumption is 240 * 10 = **2400 Watts**.
  - **Formula:** P = I^2 * R
  - **Example:** A resistor has a resistance of **5 Ohms** and has **5 Amperes** of current flowing through it. The power being used is 5^2 * 5 = **125 Watts**.
  - **Formula:** P = V^2 / R
  - **Example:** A heating element has **120 Volts** across it and a resistance of **10 Ohms**. The power consumption is 120^2 / 10 = **1440 Watts**.
- **Ohm's Law:** Links **Voltage (V)**, **Current (I)**, and **Resistance (R)**.
  - **Formula (Voltage):** V = I * R
  - **Example:** If a circuit has **2 Amperes** of current flowing through a resistor with **6 Ohms** of resistance, the voltage across the resistor is 2 * 6 = **12 Volts**.
  - **Formula (Current):** I = V / R
  - **Example:** If a circuit has **24 Volts** applied across a resistor with **8 Ohms** of resistance, the current flowing through the resistor is 24 / 8 = **3 Amperes**.
  - **Formula (Resistance):** R = V / I
  - **Example:** If a heating element has **120 Volts** across it and draws **12 Amperes** of current, its resistance is 120 / 12 = **10 Ohms**.

- **Kirchhoff's Laws:**
    - **Current Law:** Sum of currents entering a junction **equals sum of currents leaving**.
    - **Voltage Law:** Sum of voltage drops around a closed loop **equals total voltage source**.
- **Series Circuits:** Components in a **single path**.
    - **Current** is **constant**.
    - **Total voltage** is **sum of individual voltages**.
    - **Total resistance** is **sum of individual resistances**.
    - **Formula (Total Resistance):** R_total = R1 + R2 + R3 + ...
    - **Example:** Three resistors with resistances of **5 Ohm**, **10 Ohm**, and **15 Ohm** are connected in series. The total resistance is 5 + 10 + 15 = **30 Ohm**.
    - **Total Voltage in a Series Circuit:**
        - **Formula:** V_total = V1 + V2 + V3 + ...
        - **Example:** Three components in a series circuit have voltage drops of **5 V**, **10 V**, and **9 V**. The total voltage supplied to the circuit is 5 + 10 + 9 = **24 V**.
- **Parallel Circuits:** Components in **separate branches**, multiple paths.
    - **Voltage** is **constant** across each branch.
    - **Total current** is **sum of branch currents**.
    - **Total resistance** found using reciprocal formula.
    - **Formula:** 1 / R_total = 1 / R1 + 1 / R2 + 1 / R3 + ...
    - **Example:** Two resistors with resistances of **10 Ohm** and **20 Ohm** are connected in parallel. The total resistance is 1 / (1/10 + 1/20) approx **6.67 Ohm**.
    - **Total Current in a Parallel Circuit:**
        - **Formula:** I_total = I1 + I2 + I3 + ...
        - **Example:** Three branches in a parallel circuit have currents of **2 A**, **3 A**, and **4 A**. The total current flowing into the circuit is 2 + 3 + 4 = **9 A**.
- **Inductive Reactance:**
    - **Formula:** X_L = 2 * pi * f * L
    - **Example:** A coil has an inductance (L) of **0.1 Henrys** and is connected to an AC power source with a frequency (f) of **60 Hertz**. Its inductive reactance is 2 * 3.14159 * 60 * 0.1 approx **37.7 Ohm**.
- **Voltage Unbalance (Three-Phase):** Unequal phase voltages.
    - **Formula:** Voltage Unbalance (%) = (Largest Deviation from Average Voltage / Average Voltage) * 100%

Phase Voltage 1 (V)	Phase Voltage 2 (V)	Phase Voltage 3 (V)	Average Voltage (V)	Largest Deviation (V)	Output (Unbalance %)
235	240	242	239	4	~1.67%

- **Overload:** A condition where **too much current** flows through a circuit, potentially causing **damage or overheating**.
    - **Overload protectors** (or overload relays) are designed to protect motors or motor circuits from damage due to overload conditions.
    - Most overload relays **sense heat**. An electric heater element in series with the motor senses the motor current; excessive current heats the element, which triggers a mechanism to open contacts.
    - There are two basic types of industrial overload units: **solder-melting type** and **bimetal strip type**.

        - **Solder-melting type:** Uses solder around a tube; excessive current melts the solder, allowing a shaft to turn and open contacts. They use a **eutectic alloy** with a low, sharp melting point. These require **manual reset**. Their contacts are small auxiliary contacts in series with the motor starter coil.
        - **Bimetal strip type:** Uses a bimetal strip that warps from excessive heat and allows a spring to open contacts. They must cool down before resetting. Bimetal types can often be adjusted for **manual or automatic reset**.
    - Small **automatic reset overloads** are typically for single-phase motors. These can have a separate heater or the bimetal strip itself can act as the heater, snapping contacts open to interrupt motor current.
    - Overload units have a **heater section** (in series with the motor) and a **contact section** (in series with the motor starter coil for industrial types).
    - Since they sense heat, overload units are **affected by ambient temperature**.
    - **Motor starters** are contactors with overload relays. Overloads in a starter are selected based on voltage and the motor's **RLA (Rated Load Amperage)**.
- **Electrical Overload Sizing:**
    - Overload units are generally designed to open their contacts when the motor current reaches **115% to 125% of the motor's full-load current (FLA)**. This is based on the **National Electrical Code (NEC)**.
    - **Incorrect sizing** can lead to nuisance tripping (too small) or motor damage (too high).
    - For **hermetically sealed compressors**, **NEC Article 440** covers sizing requirements for conductors, disconnecting means, controllers, fuses, and overload protection. **NEC Section 440.6(A)** specifies using the **RLA (Rated-Load Current)** marked on the equipment nameplate for determining these ratings.
- **Standard Fuse: Fuses** are safety devices for circuit protection, protecting against excessive current by melting a metal link to open the circuit. They are considered **over-current protectors**.
    - Fuses are rated by **voltage** and **current (ampere)**.
        - **Voltage rating:** Indicates the voltage the fuse can interrupt without arcing. Common HVAC field ratings are **250V** and **600V**.
        - **Current rating:** The maximum current the device is designed to withstand.
    - Standard ampere ratings for fuses are listed in **NEC Section 240.6(A)**. These include ratings like **1, 3, 6, 10, 15, 20, 25, 30**, up to **6000 amperes**, plus **601 amperes**.
    - If a calculated fuse size isn't standard, generally use the **next smaller standard size**.
    - For air conditioning and refrigeration equipment, fuses are typically sized at **175% of the motor's FLA**.
    - Compressors can be fused up to **225% of their FLA** if needed to allow the motor to start. This oversizing handles the high **starting current (Locked Rotor Amperage or LRA)**, which can be much higher than FLA (commonly five times higher).
    - Fuses primarily protect against **short circuits** and are generally **not used to protect the motor from overloads**; overload relays or dual-element time delay fuses provide motor overload protection.
    - **To test a fuse:** Remove power, take the fuse out, set an ohmmeter to **R x 1**, and check continuity. Good fuses have **zero resistance**; burnt open fuses have **infinite resistance**. Use an **insulated fuse puller** for safety.

- **Slow Blow Fuse (Time Delay Fuse): Time delay fuses**, also called **slow blow fuses**, are designed to withstand **temporary overcurrents**, such as the high starting current of motors, without immediately opening the circuit.
    - The fuse link in a time delay fuse allows a **degree of overload for a short duration**.
    - **Dual-element time delay fuses** offer both **short circuit protection** (quick-acting fuse link) and **overload protection with a time delay** (solder link). The solder link takes time to melt, allowing motor starting; a spring then separates the link.

5.2 Single-Phase Induction Motor Types

Single-Phase motors need assistance to start. A **start winding** creates a phase shift to initiate rotation. Once the motor reaches **~75% synchronous speed**, the start winding disconnects.

- **Operating Principle:** Stator windings typically **180 degrees apart**. Start winding creates phase shift for initial rotation.
- **Motor Windings:**
    - **Run Winding:** Main winding, **thicker wire**, **lower resistance**, **higher inductance**. In circuit during full operation. (T1 and T4).
    - **Start Winding:** Helps motor start, **thinner wire**, **higher resistance**, **lower inductance**. Only in circuit during startup. (T5 and T8).
    - Run and start windings are wired in **parallel**.
- **Synchronous Speed (N_s):** Speed of AC motor's rotating magnetic field.
    - **Formula:** N_s (RPM) = (120 * frequency) / Number of Poles
    - **Example:** A **two-pole motor** on a **60 Hz** line has a synchronous speed of (120 * 60) / 2 = **3600 RPM**. A **four-pole motor** has a synchronous speed of (120 * 60) / 4 = **1800 RPM**.
- **Types of Single-Phase Motors (Lowest to Highest Starting Torque):**
    - **Split-Phase Motor (Resistance-Start Induction-Run):** Inductive run winding, resistive start winding. **Weak rotating field**, **low starting torque**. No capacitors. Start winding disconnected by **centrifugal switch**, current relay, or solid-state relay.
    - **Permanent Split Capacitor (PSC) Motor:** Capacitor permanently in series with start winding. **Lower starting torque** than capacitor-start, but better than basic split-phase. Capacitor improves running efficiency/power factor.
    - **Capacitor-Start Induction-Run Motor (CSIR):** Starting capacitor in series with start winding. Capacitor causes start winding current to lead voltage, **increasing starting torque significantly**. Start winding/capacitor disconnected by centrifugal switch or potential relay.
    - **Capacitor-Start, Capacitor-Run Motor (CSR or Two-Value Capacitor Motor): Two capacitors**. Larger starting capacitor for high starting torque. Smaller running capacitor remains in circuit for efficiency/power factor. **Highest starting torque**.

Starting Relays: Disconnect start winding in hermetically sealed motors.

- **Current Relay:**
  - **Definition:** A **current-sensing relay** with a coil designed to carry the **full motor start winding current**. It operates based on the **high inrush current** drawn by the motor during startup.
  - **Circuit Orientation:** The **coil** of the current relay is wired in **series with the run winding** of the motor. Its **normally open (NO) contacts** are wired in **series with the start winding/capacitor**. When the motor starts, the high current through the run winding energizes the relay coil, closing its contacts to bring in the start winding. Once the motor speeds up and current drops, the relay de-energizes, opening its contacts and taking the start winding out of the circuit.
- **Potential Relay:**
  - **Definition:** A **voltage-sensing relay** that operates based on the **voltage (back EMF)** generated across the start winding as the motor approaches running speed.
  - **Circuit Orientation:** The **coil** of the potential relay is wired in **parallel with the start winding** of the motor. Its **normally closed (NC) contacts** are wired in **series with the start winding/capacitor**. During startup, the voltage across the start winding builds up. When this voltage reaches a certain level (indicating the motor is near running speed), the relay coil energizes, opening its contacts to remove the start winding from the circuit.

- **Solid-State Starting Relay:** Electronic component (thermistor) replacing current-type relay.
- **Dual-Voltage Single-Phase Motors:** Operate on **two different voltages** (e.g., 120/240V). Multiple run and sometimes start windings. **Series connection for higher voltage**, **parallel for lower**.
- **Reversing Direction of Rotation:** Change connections of **either run winding leads or start winding leads**, but not both.
- **Testing:** Stator windings generally tested with **ohmmeter** for open or grounded windings.

5.3 Three-Phase Motor Starting Methods

5.3.1 Three-Phase Part Winding Start

- **Purpose:** Reduces **starting current** of large three-phase squirrel-cage motors.
- **Motor Requirement:** Motor must have **two separate stator windings**, each rated for line voltage.
- **Operating Principle:** At startup, **only one winding is energized**, reducing starting current. After a delay, the **second winding is energized**, connecting both in parallel for normal operation.
- **Dual-Voltage Motors:** Can be used for part winding if connected to their low voltage rating.

- **Sequence of Operation (Basic Example):**
    1. When the thermostat contact closes, power is supplied to **coil 1C** and **timer TR**.
    2. All **1C contacts close**, connecting terminals **T1, T2, and T3** to the power line. This energizes the first stator winding.
    3. After the time delay (e.g., **3 seconds**), the normally open **TR contact** connected in series with **coil 2C** closes.
    4. **Coil 2C energizes**, causing all **2C contacts** to close.
    5. The **2C load contacts close**, connecting terminals **T7, T8, and T9** to the power line. This energizes the second stator winding.
    6. With both windings energized, the motor is now running with its stator windings connected in parallel.

5.3.2 Three-Phase Wye-Delta Start

- **Purpose:** Reduces **inrush current** during starting of three-phase squirrel-cage motors.
- **Operating Principle:** Stator windings connected in **wye (Y) configuration** during starting (reduces voltage across each winding by factor of **1.732**), reducing current and torque. After acceleration, switches to **delta (Δ) configuration** for normal running.
- **Motor Requirements:**
    - Motor designed to operate in **delta** during normal run.
    - All stator winding leads accessible at terminal box (**T1-T6 for single voltage, T1-T12 for dual**).
- **Overload Protection:** Overload heaters sized for **phase current**, not line current.
- **Sequence of Operation (Basic Example):**
    1. When the thermostat contact closes, power is supplied to **coil S** and **timer TR**.
    2. All **S contacts change position**. The normally open **S load contacts close**, connecting the motor leads (**T1, T2, T3, T4, T5, T6**) in a **wye configuration** for starting. The normally open **TR contact** in series with **coil 1C** closes, but coil 1C is not yet energized because the normally closed S contact in series with it is open.
    3. After the time delay (e.g., **3 seconds**), the normally closed **TR contact** connected in series with **coil S opens**, de-energizing coil S.
    4. All **S contacts return to their normal position**. The normally closed **S contact** connected in series with **coil 2C** recloses, providing a current path to coil 2C. The normally open **TR contact** connected in series with **coil 2C** (which closed in step 2) is now providing power.
    5. **Coil 2C energizes**, causing all **2C contacts** to change position.
    6. The **2C load contacts close**, reconnecting the motor stator windings in a **delta configuration** for running. A normally closed **2C contact** connected in series with **coil S opens**, providing interlocking protection.

5.4 Solid State Electronic Components

Semiconductor devices used for **control and switching**.

- **Semiconductors:** Materials (**Si, Ge**) with conductivity between conductors and insulators.
- **Doping:** Adding impurities to alter conductivity (**N-type:** excess electrons, **P-type:** holes).
- **PN Junction:** Boundary between P and N type semiconductors.
- **Diode:** Two-terminal device allowing **unidirectional current flow** (anode to cathode).
- **SCR (Silicon Controlled Rectifier):** Three-terminal **unidirectional switch**, triggered by gate signal. Conducts when anode positive relative to cathode and gate signal applied.
- **TRIAC (Triode for Alternating Current):** Three-terminal **bidirectional switch**, controls AC current flow in both directions, triggered by gate signal.

5.5 Rectifier Circuits

Convert **AC to DC power** using diodes or other solid-state switches.

- **Half-Wave Rectifier:** Uses **one diode**, passes half of AC waveform. **Pulsating DC** output.
- **Full-Wave Rectifier:** Converts **both half-cycles to DC**. Smoother DC output.
  - **Types:** Center-Tapped (2 diodes, transformer), Bridge (4 diodes).
  - **Bridge Rectifier:** Common full-wave configuration using **four diodes**. Does not require a center-tapped transformer.

5.6 Basic Electricity Fundamentals

5.6.1 The Atom

Basic building block of the universe.

- Composed of **electrons** (negative charge), **protons** (positive charge), and **neutrons** (no charge).
- **Nucleus** contains protons and neutrons.
- Electrons orbit nucleus in **shells**.
- **Valence electrons:** Electrons in outermost shell, key to electrical theory.

5.6.2 The Flow of Electricity (Current)

- Electricity is composed of **electrons**.
- **Electric current** is the **flow of electrons**.
- Electrons flow from **negative terminal**, through load, to **positive terminal** (electron flow theory).
- Conventionally, current flows from **positive to negative**.
- Current is measured in **Amperes (Amps)**.
- An **Ampere** is **one coulomb per second**.
- A **coulomb** is **6.25 x 10^18 electrons**.
- **Water system analogy:** Amperage is like **gallons per minute (GPM)**, representing flow rate.

5.6.3 Electrical Force (Voltage)

- **Voltage** is the **force that pushes electrons** through a circuit.
- Also known as **electromotive force (EMF)** or **electrical pressure**.
- Greater difference in electrons between terminals = greater force (voltage).
- Higher voltage = greater push.
- Voltage cannot flow; it's the force causing current.
- Voltage is measured in **Volts (V)**.
- **Water system analogy:** Voltage is like **pressure**, pushing water through a pipe.

5.6.4 Opposition to Flow (Resistance)

- **Resistance (R)** is how much a material fights against current flow.
- Measured in **Ohms (Ohm)**.
- **Four factors determine resistance of a wire:** diameter, material, length, temperature.
- **Larger cross-sectional area** = less resistance. **Longer wires** = more resistance.
- **Conductors:** Easy path for electron flow (e.g., silver, copper).
- **Insulators:** Do not permit electrons to flow easily (e.g., wood, rubber).
- **Water system analogy:** Resistance is like **pipe restrictions** impeding water flow.

5.6.5 The Relationship: Ohm's Law

Most important electrical formula. Links **Voltage (V)**, **Current (I)**, and **Resistance (R)**.
- **Formulas:**
  - $V = I * R$
  - $I = V / R$
  - $R = V / I$

5.6.6 How They Work Together in Circuits (Basic Concepts)

Electrical circuits: **series**, **parallel**, and **combination**.
- **Series Circuits: Single path** for current.
  - **Current** is **same everywhere**.
  - **Sum of voltage drops** equals applied voltage.
  - **Total resistance** is **sum of individual resistances**.
  - Opening any point **stops current**.
- **Parallel Circuits: Multiple branches**, more than one path for current.
  - **Voltage** is **constant** across each branch.
  - **Total current** is **sum of branch currents**.
  - **Total resistance** found using reciprocal formula ($1/R_{Total} = 1/R1 + 1/R2 + ...$).
- **Ohm's Law** applies to individual components and total circuit.

5.7 Normally Open (NO) and Normally Closed (NC) Contacts

5.7.1 Understanding Normally Open (NO) and Normally Closed (NC) Contacts

Components drawn in **deenergized position**.

- **Normally Open (NO) contacts: Open** (no electrical connection) when component is deenergized. Used for **"start" functions**, wired in parallel.
- **Normally Closed (NC) contacts: Closed** (complete electrical circuit) when component is deenergized. Used for **"stop" functions**, wired in series.

5.7.2 Lock-Out Protection Circuits

Used to **disconnect compressor from line** if there's a problem.

- Involves a **high-impedance lock-out relay (LOR)** in series with compressor contactor coil.
- **LOR coil** is in parallel with normally closed safety switches (high-pressure, low-pressure, low evaporator temperature).
- **Normal operation:** Safety switches closed, LOR coil bypassed, remains deenergized.
- **Fault occurs:** Safety switch opens, LOR coil becomes series with contactor coil. Most voltage drops across LOR, energizing it.
- When LOR energizes, its normally closed contact (in series with contactor coil) opens, breaking circuit and **locking out compressor**.
- Normally open LOR contact typically closes to activate a **fault indicator light**.
- Circuit remains locked out until **control power is interrupted (resetting LOR)**.

Chapter 6: Variable Frequency Drives (VFDs)

Electronic devices controlling **AC motor speed** by varying frequency and voltage. Also known as **ASD, VSD, AFD, Frequency Converter, Inverter**.

6.1 Principle of Operation

- **Principle:** AC input -> DC conversion -> Variable frequency/voltage AC output.

6.2 Functional Blocks

- **Rectifier (Converter):** Converts **AC input to DC** (e.g., 3-phase diode bridge).
- **DC Link (DC Bus):** Filters and stores **DC voltage** (capacitors, inductors).
- **Inverter:** Converts **DC to variable frequency/voltage AC** using switching elements (**IGBTs**).
- **Control Unit: Microprocessor-based logic**, interprets inputs, generates control signals (**PWM**).
- **User Interface:** Keypad, touchscreen for configuration and monitoring.

6.3 Pulse Width Modulation (PWM)

PWM: Technique used by inverter to **simulate AC output** by rapidly switching DC voltage on/off. **Duty cycle** controls average voltage.

- **Motor Speed (rpm):**
  - **Formula:** (Frequency (Hz) * 120) / Number of Poles
  - **Example:** A **4-pole motor** is controlled by a VFD supplying power at **45 Hz**. The motor speed is (45 * 120) / 4 = **1350 RPM**.

6.4 Applications in HVAC

Fans, pumps, air handlers, chillers, compressors. Beneficial for **variable flow/capacity systems** (VAV, cooling towers, chilled water).

6.5 Benefits of VFDs

Energy Savings (primary), **precise control**, reduced mechanical/thermal stress (**low inrush start**), user-friendly, high power factor, voltage sag alleviation.

6.6 Selection Considerations

Motor nameplate data (**V, FLA, Hp**), motor type (**Inverter-duty**), control I/O requirements, enclosure type.

6.7 Commissioning and Troubleshooting

Parameter setting, fault history, status display.

6.8 Harmonics

Current distortion at **multiples of fundamental frequency**.

- **Mitigation:** Multi-pulse VFDs (**12, 18, 24 pulse**), **Active Front End (AFE) VFDs**.

Chapter 7: System Calculations

This chapter provides **methodologies** and **formulas** for various system calculations.

7.1 Heat Load Calculation Methodology

Determining the **total heat gain** to a conditioned space or product.

- **Sources of Heat Gain (Refrigerated Box): Transmission Gains** (walls, floor, ceiling), **Infiltration Gains** (air leakage), **Product Load** (cooling product, respiration), **Miscellaneous Gains** (lights, motors, people), **Safety Factor** (typically **10%**).
- **Thermal Resistance (R-value): Resistance to heat flow**. Higher R-value = better insulation.
  - **Formula:** R = r * thickness
- **Thermal Conductivity (k-value): Ability to conduct heat**. Lower k-value = better insulator.
  - **Formula:** C = k / thickness
- **Heat Transfer Equation:**
  - **Formula:** Q = U * A * Delta T
  - **Example:** A wall has an overall heat transfer coefficient (U) of **0.05 BTU/hrft^2degrees F**, an area (A) of **200 square feet**, and a temperature difference (Delta T) across it of **40 degrees F**. The heat transfer rate is 0.05 * 200 * 40 = **400 BTUH**.
- **Overall Heat Transfer Coefficient (U):**
  - **Formula:** U = 1 / R_t
  - **Example:** A wall has a total thermal resistance (R_t) of **20 ft^2degrees Fhr/BTU**. Its overall heat transfer coefficient (U) is 1 / 20 = **0.05 BTU/hrft^2degrees F**.
- **Total Thermal Resistance: Sum of individual resistances**.
  - **Formula:** R_t = R1 + R2 + R3 + ...
  - **Example:** A wall is made of drywall (R1 = **0.5**), insulation (R2 = **19**), and siding (R3 = **0.2**). The total thermal resistance is 0.5 + 19 + 0.2 = **19.7**.
- **Relationship between Thermal Resistance and Conductance:**
  - **Formula:** R = 1 / C
  - **Example:** A material has a thermal conductance (C) of **0.2 BTU/hrft^2degrees F**. Its thermal resistance (R) is 1 / 0.2 = **5 ft^2degrees Fhr/BTU**.

7.2 Refrigerant Piping Design Considerations

Selecting appropriate line sizes for **refrigerant flow velocity** and **pressure drop**.

- **Recommended Velocities:**
  - **Vapor Lines (Suction/Discharge):** Minimum **750 FPM** (horizontal), **1500-3500 FPM** (vertical rise) for oil return.
  - **Liquid Lines: 100-300 FPM** to minimize flash gas.
  - **Condensate Lines:** approx **100 FPM**, typically **one size larger** than liquid line.
- **Maximum Allowable Pressure Drop:** Typically limited to **2 degrees F Equivalent Pressure Drop (FEPD)** in the suction line.

7.3 Miscellaneous System Formulas

- **Belt Length:**
  - **Formula:** L = 2C + 1.57 * (D + d) + (D - d)^2 / (4C)

Input (C)	Input (D)	Input (d)	Output (L)
30 inches	12 inches	6 inches	88.56 inches

- **Volumetric Efficiency (%):**
  - **Formula:** (Volume of Vapor Pumped / Compressor Displacement) * 100
  - **Example:** A compressor has a theoretical displacement of **10 CFM**, but it actually pumps **8 CFM** of vapor under certain conditions. The volumetric efficiency is (8 / 10) * 100 = **80%**.
- **Theoretical Reciprocating Compressor CFM:**
  - **Formula:** CFM = (pi * r^2 * L * N * RPM) / 1728

Input (r)	Input (L)	Input (N)	Input (RPM)	Output (CFM)
1 inch	2 inches	1	1750	~6.36 CFM

- **Electrical Schematics:** Diagrams illustrating electrical connections.

Chapter 8: Control Systems

This chapter covers **fundamental techniques** used in HVAC control systems for **signal processing** and **control logic**.

8.1 Control System Fundamentals

In HVAC control systems, **interpolation** and **scaling** are fundamental concepts that ensure optimal system operation. While control systems often utilize data tables internally, these concepts can be effectively illustrated using charts or tables.

Interpolation

Interpolation is a technique employed by smart control systems to determine appropriate actions for values that fall between discrete data points within a table or dataset. It leverages known data points to estimate values for intermediate inputs.

Consider a control system using a data table (similar to a chart) to define optimal settings:
Data Table (Example)

Outdoor Air Temperature (°F)	Optimal Chiller Supply Water Setpoint (°F)
65	43
70	44

- **Purpose:** To calculate the ideal chiller supply water temperature when the outdoor temperature lies between the table's specified values.
- **Problem:** The outdoor air temperature is **68°F**. The control system needs to determine the corresponding chiller supply water setpoint.
- **Data Table Application (Chart Concept):** The system recognizes that **68°F** is between **65°F** and **70°F** in the table. It uses the points (**65°F, 43°F**) and (**70°F, 44°F**) to estimate the setpoint for **68°F**.
- **Interpolation Formula:** Linear interpolation calculates the intermediate output (y) for a given input (x) using two known points (x1, y1) and (x2, y2):y = y1 + ((x - x1) / (x2 - x1)) * (y2 - y1)Where: x1 = **65 deg F**, y1 = **43 deg F**, x2 = **70 deg F**, y2 = **44 deg F**, and x = **68 deg F**
- **Calculation:**
    1. y = 43 + ((68 - 65) / (70 - 65)) * (44 - 43)
    2. y = 43 + (3 / 5) * 1
    3. y = 43 + 0.6 * 1 y = 43 + 0.6
    4. **y = 43.6 deg F**
- **Answer:** The control system calculates an optimal chiller supply water temperature of approximately **43.6°F** for an outdoor air temperature of **68°F**.

Scaling

Scaling is the process of translating a signal from a sensor into a value the controller understands (e.g., converting a voltage into a temperature) or translating a controller command into a signal the equipment can use (e.g., converting a percentage into a voltage for a valve). It involves mapping a value from one defined scale or range to another defined scale or range. Consider scaling a temperature sensor signal using a data table:

Data Table (Example)

Input (Voltage V)	Output (Temperature °F)
0	50
10	90

- **Purpose:** To convert a voltage signal received from a temperature sensor into a corresponding temperature value that the control system can use.
- **Problem:** A temperature sensor outputs a voltage between **0V** and **10V**, which corresponds to a temperature range of **50°F** to **90°F**. The system receives a signal of **5.5V**. What temperature does this represent?
- **Data Table Application (Chart Concept):** The table shows the voltage-temperature relationship, with minimum (**0V, 50°F**) and maximum (**10V, 90°F**) points.
- **Scaling Formula:** Linear scaling maps an input value from its range to the equivalent position in the output range:Output = Output_min + ((Input - Input_min) / (Input_max - Input_min)) * (Output_max - Output_min)Where: Input = **5.5V**, Input_min = **0V**, Input_max = **10V**, Output_min = **50 deg F**, Output_max = **90 deg F**
- **Calculation:**
    1. Output = 50 + ((5.5 - 0) / (10 - 0)) * (90 - 50)
    2. Output = 50 + (5.5 / 10) * 40
    3. Output = 50 + 0.55 * 40 Output = 50 + 22
    4. **Output = 72 deg F**
- **Answer:** The control system interprets the **5.5V** sensor signal as a temperature of **72°F**.

These examples illustrate how interpolation and scaling, applied to data points (often in tables), enable control systems to determine intermediate values and convert signals, ensuring precise control.

Linear Interpolation

- **Formula:** y = y1 + ((x - x1) / (x2 - x1)) * (y2 - y1)
- **Example 1: Chiller Setpoint Control:**

Parameter	Value
Outdoor Air Temp (x1)	65 degrees F
Chiller Setpoint (y1)	43 degrees F
Outdoor Air Temp (x2)	70 degrees F
Chiller Setpoint (y2)	44 degrees F
Input Outdoor Air Temp (x)	68 degrees F
Output Chiller Setpoint (y)	43.6 degrees F

* **Example 2: Fan Speed Estimation:**

Parameter	Value
Airflow (x1)	5000 CFM
Fan Speed (y1)	40%
Airflow (x2)	8000 CFM
Fan Speed (y2)	75%
Input Airflow (x)	6500 CFM
Output Fan Speed (y)	57.5%

* **Example 3: Heating Coil Capacity:**

Parameter	Value
Entering Water Temp (x1)	140 degrees F
Capacity (y1)	"50,000 BTUH"
Entering Water Temp (x2)	180 degrees F
Capacity (y2)	"85,000 BTUH"
Input Entering Water Temp (x)	165 degrees F
Output Capacity (y)	71875 BTUH

8.2 Control System Fundamentals: Scaling

Transforming a signal from one range to another.

- **Linear Scaling Formula:**
  - **Formula:** Output = Output_min + ((Input - Input_min) / (Input_max - Input_min)) * (Output_max - Output_min)
- **Example 1: Temperature Sensor Signal:**

Parameter	Value
Input Range (min)	0 Volts
Input Range (max)	10 Volts
Output Range (min)	50 degrees F
Output Range (max)	90 degrees F
Input Signal	5.5 Volts
Output (Temperature)	72 degrees F

* **Example 2: Valve Control Output:**

Parameter	Value
Input Range (min)	0%
Input Range (max)	100%
Output Range (min)	2 Volts
Output Range (max)	10 Volts
Input Signal	60%
Output (Voltage)	6.8 Volts

* **Example 3: Static Pressure Sensor:**

Parameter	Value
Input Range (min)	4 mA
Input Range (max)	20 mA
Output Range (min)	0 in. w.c.
Output Range (max)	2 in. w.c.
Input Signal	12 mA
Output (Pressure)	1.0 in. w.c.

Chapter 9: Diagnostic and Operational Tips

9.1 Quick Reference Tips

- Understand the **system's function** and **components**.
- Trace the **refrigerant circuit** for diagnosis.
- Utilize **Pressure-Temperature charts** for refrigerant state analysis.
- Assess **Superheat** and **Subcooling** for charge and metering device performance.
- Verify **adequate airflow** over heat exchangers.
- Prioritize **electrical system checks**.
- Employ **sensory observation** (sound, temperature).
- Adhere strictly to **safety protocols** (refrigerants, electrical, fire).

9.2 Thermodynamic Charts: Pressure-Enthalpy (P-H) Chart Concepts

A **graphical tool** for visualizing the **thermodynamic state changes** of a refrigerant during the refrigeration cycle.

- **Enthalpy (h): Total heat content** (x-axis).
- **Pressure (P): Absolute pressure** (y-axis).
- **Saturation Curve:** Boundary between liquid, liquid-vapor mixture, and vapor phases.
    - **Bubble Point Line (left):** Saturated liquid.
    - **Dew Point Line (right):** Saturated vapor.
    - **Inside Dome:** Liquid-vapor mixture.
- **Critical Point:** Apex of the saturation curve.
- **Superheat:** Region to the **right of the dew point line** (vapor above saturation temperature).
- **Subcooling:** Region to the **left of the bubble point line** (liquid below saturation temperature).

Chapter 10: Comprehensive Formula Reference

This chapter consolidates all formulas with examples for quick reference.

10.1 Refrigeration Cycle Formulas

- **Evaporator Approach**
  - **Formula:** Evaporator Approach = Leaving Air Temperature - SST (Saturated Suction Temperature)
  - **Example:** If the air leaving the evaporator coil is **50 degrees F** and the refrigerant boiling temperature (SST) is **40 degrees F**: Evaporator Approach = 50 - 40 = **10 degrees F**.
- **Condenser Approach**
  - **Formula:** Condenser Approach = Liquid Line Temperature - SCT (Saturated Condensing Temperature)
  - **Example:** If the liquid line temperature leaving the condenser is **95 degrees F** and the refrigerant condensing temperature (SCT) is **90 degrees F**: Condenser Approach = 95 - 90 = **5 degrees F**.
- **Condenser Split (Air-Cooled)**
  - **Formula:** Condenser Split = SCT (Saturated Condensing Temperature) - Entering Air Temperature
  - **Example:** If the refrigerant condensing temperature (SCT) is **105 degrees F** and the outside air temperature entering the condenser is **80 degrees F**: Condenser Split = 105 - 80 = **25 degrees F**.
- **Condenser Split (Water-Cooled)**
  - **Formula:** Condenser Split = SCT (Saturated Condensing Temperature) - Entering Water Temperature
  - **Example:** If the refrigerant condensing temperature (SCT) is **90 degrees F** and the water temperature entering the condenser is **85 degrees F**: Condenser Split = 90 - 85 = **5 degrees F**.
- **Coil Delta T (Delta T)**
  - **Formula:** Coil Delta T = Entering Air Temperature - Leaving Air Temperature
  - **Example:** If the air entering the cooling coil is **75 degrees F** and the air leaving the coil is **55 degrees F**: Coil Delta T = 75 - 55 = **20 degrees F**.
- **Superheat**
  - **Formula:** Superheat = Suction Line Temperature - SST (Saturated Suction Temperature)
  - **Example:** If the temperature of the suction line near the evaporator outlet is **48 degrees F** and the refrigerant boiling temperature (SST) is **40 degrees F**: Superheat = 48 - 40 = **8 degrees F**.
- **Subcooling**
  - **Formula:** Subcooling = SCT (Saturated Condensing Temperature) - Liquid Line Temperature
  - **Example:** If the refrigerant condensing temperature (SCT) is **90 degrees F** and the temperature of the liquid line leaving the condenser is **85 degrees F**: Subcooling = 90 - 85 = **5 degrees F**.

- **Net Refrigeration Effect (NRE)**
  - **Formula:** NRE = Enthalpy Leaving Evaporator - Enthalpy Entering Evaporator
- **Heat of Compression**
  - **Formula:** Heat of Compression = Enthalpy Leaving Compressor - Enthalpy Entering Compressor
- **Refrigerant Quality (%)**
  - **Formula:** Quality = ((Enthalpy - Enthalpy of Saturated Liquid) / (Enthalpy of Saturated Vapor - Enthalpy of Saturated Liquid)) * 100%
- **Coefficient of Performance (COP)**
  - **Formula:** COP = Net Refrigeration Effect / Heat of Compression
- **Compression Ratio**
  - **Formula:** Compression Ratio = High Side Absolute Pressure / Low Side Absolute Pressure

10.2 Thermal Energy & Refrigeration Formulas

- **Fahrenheit to Celsius Temperature Conversion**
  - **Formula:** Degrees C = (Degrees F - 32) / 1.8
  - **Example:** Convert **68 degrees F** to Celsius: (68 - 32) / 1.8 = **20 degrees C**.
- **Celsius to Fahrenheit Temperature Conversion**
  - **Formula:** Degrees F = (Degrees C * 1.8) + 32
  - **Example:** Convert **25 degrees C** to Fahrenheit: (25 * 1.8) + 32 = **77 degrees F**.
- **Fahrenheit to Rankine Temperature Conversion**
  - **Formula:** Degrees R = Degrees F + 460
  - **Example:** Convert **70 degrees F** to Rankine: 70 + 460 = **530 degrees R**.
- **Celsius to Kelvin Temperature Conversion**
  - **Formula:** K = Degrees C + 273.15
  - **Example:** Convert **20 degrees C** to Kelvin: 20 + 273.15 = **293.15 K**.
- **Sensible Heat Transfer (Air)**
  - **Formula:** Q_sensible (BTUH) = CFM * 1.08 * Delta T (degrees F)
  - **Example:** If you have **1000 CFM** of air and the temperature changes by **20 degrees F**: Q_sensible = 1000 * 1.08 * 20 = **21,600 BTUH**.
- **Sensible Heat Transfer (Water)**
  - **Formula:** Q_sensible (BTUH) = GPM * 500 * Delta T (degrees F)
  - **Example:** If you have **10 GPM** of water and the temperature changes by **15 degrees F**: Q_sensible = 10 * 500 * 15 = **75,000 BTUH**.
- **Total Heat Transfer (Air)**
  - **Formula:** Q_total (BTUH) = CFM * 4.5 * Delta h (BTU/lb)
  - **Example:** If you have **1000 CFM** of air and the change in enthalpy (Delta h) from a psychrometric chart is **10 BTU/lb**: Q_total = 1000 * 4.5 * 10 = **45,000 BTUH**.
- **Basic Heat Transfer Equation**
  - **Formula:** Q = m * c * Delta T
  - **Example:** If you have **50 pounds** of water (c = 1 BTU/lb degrees F) and its temperature changes by **30 degrees F**: Q = 50 * 1 * 30 = **1500 BTU**.
- **Density of Water**
  - **Formula:** Approximately **62.4 lb/ft^3**
  - **Example:** To find the mass of **10 cubic feet** of water: Mass = 10 ft^3 * 62.4 lb/ft^3 = **624 lb**.

- **Mass Flow Rate of Refrigerant**
  - **Formula:** Mass Flow Rate (lb/min) = (200 BTU/min/ton) / NRE (BTU/lb)
  - **Example:** If a system has **5 tons** of cooling capacity (5 * 200 = 1000 BTU/min) and the Net Refrigeration Effect (NRE) for the refrigerant is **80 BTU/lb**: Mass Flow Rate = 1000 / 80 = **12.5 lb/min**.
- **Flash Gas Calculation:** Fraction of liquid refrigerant that vaporizes when pressure is reduced across the metering device.
  - **Formula:** Flash Gas (%) = ((enthalpy of liquid at inlet - enthalpy of vapor at outlet) / (enthalpy of vapor at outlet - enthalpy of liquid at outlet)) * 100%
- **Alternative Flash Gas Calculation:**
  - **Formula:** Flash Gas (%) = ((Theoretical Latent Heat of Vaporization - Actual Latent Heat) / Theoretical Latent Heat of Vaporization) * 100%

h_liquid, inlet (BTU/lb)	h_saturated liquid (BTU/lb)	h_saturated vapor (BTU/lb)	Output (Flash Gas %)
30	25	75	10%

10.3 Gas Law Formulas

- **Boyle's Law**
  - **Formula:** P1 * V1 = P2 * V2
  - **Example:** You have a gas in a container with a pressure of **10 psi** and a volume of **5 cubic feet**. If you increase the pressure to **20 psi** without changing the temperature, the new volume is (10 * 5) / 20 = **2.5 cubic feet**.
- **Charles's Law**
  - **Formula:** V1 / T1 = V2 / T2
  - **Example:** You have a gas with a volume of **10 cubic feet** at a temperature of **500 degrees R** (absolute). If you heat it to **600 degrees R** at the same pressure, the new volume is (10 / 500) * 600 = **12 cubic feet**.
- **Gay-Lussac's Law**
  - **Formula:** P1 / T1 = P2 / T2
  - **Example:** You have a gas in a sealed container with a pressure of **100 psi** at a temperature of **500 degrees R** (absolute). If you heat it to **600 degrees R**, the new pressure is (100 / 500) * 600 = **120 psi**.
- **Combined Gas Law**
  - **Formula:** (P1 * V1) / T1 = (P2 * V2) / T2
  - **Example:** You have a gas with a pressure of **10 psi**, a volume of **5 cubic feet**, and a temperature of **500 degrees R**. If the pressure changes to **20 psi** and the temperature changes to **600 degrees R**, the new volume is ((10 * 5) / 500) * (600 / 20) = **3 cubic feet**.

10.3.1 Pressure Conversions

- **psia vs psig**
  - **Formula:** psia = psig + 14.7
  - **Formula:** psig = psia - 14.7 (Using **14.7 psi** as standard atmospheric pressure)
- **Kilopascals (kPa) to psi**
  - **Formula:** psi = kPa * 0.145038
- **psi to Kilopascals (kPa)**
  - **Formula:** kPa = psi * 6.89476

10.4 Electrical Formulas

- **Conductance from Resistance**
  - **Formula:** G = 1 / R
  - **Example:** If a wire has a resistance of **10 Ohms**, its conductance is 1 / 10 = **0.1 Siemens**.
- **Power from Voltage and Current**
  - **Formula:** P = V * I
  - **Example:** A heating element has **240 Volts** across it and draws **10 Amperes** of current. The power consumption is 240 * 10 = **2400 Watts**.
- **Power from Current and Resistance**
  - **Formula:** P = I^2 * R
  - **Example:** A resistor has a resistance of **5 Ohms** and has **5 Amperes** of current flowing through it. The power being used is 5^2 * 5 = **125 Watts**.
- **Power from Voltage and Resistance**
  - **Formula:** P = V^2 / R
  - **Example:** A heating element has **120 Volts** across it and a resistance of **10 Ohms**. The power consumption is 120^2 / 10 = **1440 Watts**.
- **Ohm's Law (Voltage)**
  - **Formula:** V = I * R
  - **Example:** If a circuit has **2 Amperes** of current flowing through a resistor with **6 Ohms** of resistance, the voltage across the resistor is 2 * 6 = **12 Volts**.
- **Ohm's Law (Current)**
  - **Formula:** I = V / R
  - **Example:** If a circuit has **24 Volts** applied across a resistor with **8 Ohms** of resistance, the current flowing through the resistor is 24 / 8 = **3 Amperes**.
- **Ohm's Law (Resistance)**
  - **Formula:** R = V / I
  - **Example:** If a heating element has **120 Volts** across it and draws **12 Amperes** of current, its resistance is 120 / 12 = **10 Ohms**.
- **Total Resistance in a Series Circuit**
  - **Formula:** R_total = R1 + R2 + R3 + ...
  - **Example:** Three resistors with resistances of **5 Ohm**, **10 Ohm**, and **15 Ohm** are connected in series. The total resistance is 5 + 10 + 15 = **30 Ohm**.
- **Total Voltage in a Series Circuit:**
  - **Formula:** V_total = V1 + V2 + V3 + ...
  - **Example:** Three components in a series circuit have voltage drops of **5 V**, **10 V**, and **9 V**. The total voltage supplied to the circuit is 5 + 10 + 9 = **24 V**.

- **Parallel Circuits:** Components in separate branches, multiple paths.
  - **Voltage** is **constant** across each branch.
  - **Total current** is **sum of branch currents**.
  - **Total resistance** found using reciprocal formula.
  - **Formula:** 1 / R_total = 1 / R1 + 1 / R2 + 1 / R3 + ...
  - **Example:** Two resistors with resistances of **10 Ohm** and **20 Ohm** are connected in parallel. The total resistance is 1 / (1/10 + 1/20) approx **6.67 Ohm**.
  - **Total Current in a Parallel Circuit:**
    - **Formula:** I_total = I1 + I2 + I3 + ...
    - **Example:** Three branches in a parallel circuit have currents of **2 A**, **3 A**, and **4 A**. The total current flowing into the circuit is 2 + 3 + 4 = **9 A**.
- **Inductive Reactance**
  - **Formula:** X_L = 2 * pi * f * L
  - **Example:** A coil has an inductance (L) of **0.1 Henrys** and is connected to an AC power source with a frequency (f) of **60 Hertz**. Its inductive reactance is 2 * 3.14159 * 60 * 0.1 approx **37.7 Ohm**.
- **Voltage Unbalance (Three-Phase):** Unequal phase voltages.
  - **Formula:** Voltage Unbalance (%) = (Largest Deviation from Average Voltage / Average Voltage) * 100%

Phase Voltage 1 (V)	Phase Voltage 2 (V)	Phase Voltage 3 (V)	Average Voltage (V)	Largest Deviation (V)	Output (Unbalance %)
235	240	242	239	4	~1.67%

- **Synchronous Speed of a Motor**
  - **Formula:** N_s (RPM) = (120 * frequency) / Number of Poles
  - **Example:** A motor is connected to a **60 Hz** power source and has **4 poles**. Its synchronous speed is (120 * 60) / 4 = **1800 RPM**.
- **Number of Poles of a Motor**
  - **Formula:** Number of Poles = (120 * Frequency) / Synchronous RPM
  - **Example:** A motor runs at a synchronous speed of **3600 RPM** on a **60 Hz** power source. It has (120 * 60) / 3600 = **2 poles**.
- **Three-Phase Wye Connection: Line Voltage from Phase Voltage**
  - **Formula:** V_line = 1.732 * V_phase
  - **Example:** In a Wye-connected system, the voltage across one phase (V_phase) is **120 Volts**. The voltage between two lines (V_line) is 1.732 * 120 approx **207.84 V**.
- **Three-Phase Delta Connection: Line Current from Phase Current**
  - **Formula:** I_line = 1.732 * I_phase
  - **Example:** In a Delta-connected system, the current flowing through one phase (I_phase) is **10 Amperes**. The current in the line (I_line) is 1.732 * 10 = **17.32 A**.
- **VFD Motor Speed**
  - **Formula:** Motor Speed (rpm) = (Frequency (Hz) * 120) / Number of Poles
  - **Example:** A **4-pole motor** is controlled by a VFD supplying power at **45 Hz**. The motor speed is (45 * 120) / 4 = **1350 RPM**.
- **Power (3-Phase)**
  - **Formula:** P = V * I * sqrt(3) * PF (Where **PF** is Power Factor)
- **Transformer Maximum Current Output**
  - **Formula:** Maximum Amps = VA / V (Where **VA** is the transformer's volt-ampere rating and **V** is the secondary voltage)

- **Electrical Sizing Guidelines**
  - **Typical Voltage Tolerance:** Electrical loads should operate within **+/- 10%** of their designed voltage.
  - **Fuse Sizing (AC/Refrigeration):** Fuses are typically sized at **175% of the motor's FLA**, and up to **225% of FLA** for compressors to handle starting current.
  - **Wire Sizing:** Determined using the **Canadian Electrical Code (CEC)** and manufacturers' specifications. **Circular mils** are used for wire area.

10.5 System Calculation Formulas

- **Heat Transfer Equation**
  - **Formula:** Q = U * A * Delta T
  - **Example:** A wall has an overall heat transfer coefficient (U) of **0.05 BTU/hrft^2degrees F**, an area (A) of **200 square feet**, and a temperature difference (Delta T) across it of **40 degrees F**. The heat transfer rate is 0.05 * 200 * 40 = **400 BTUH**.
- **Overall Heat Transfer Coefficient from Total Resistance**
  - **Formula:** U = 1 / R_t
  - **Example:** A wall has a total thermal resistance (R_t) of **20 ft^2degrees Fhr/BTU**. Its overall heat transfer coefficient (U) is 1 / 20 = **0.05 BTU/hrft^2degrees F**.
- **Total Thermal Resistance**
  - **Formula:** R_t = R1 + R2 + R3 + ...
  - **Example:** A wall is made of drywall (R1 = **0.5**), insulation (R2 = **19**), and siding (R3 = **0.2**). The total thermal resistance is 0.5 + 19 + 0.2 = **19.7**.
- **Relationship between Thermal Resistance and Conductance**
  - **Formula:** R = 1 / C
  - **Example:** A material has a thermal conductance (C) of **0.2 BTU/hrft^2degrees F**. Its thermal resistance (R) is 1 / 0.2 = **5 ft^2degrees Fhr/BTU**.
- **Belt Length Calculation**
  - **Formula:** L = 2C + 1.57 * (D + d) + (D - d)^2 / (4C)

Input (C)	Input (D)	Input (d)	Output (L)
30 inches	12 inches	6 inches	88.56 inches

- **Volumetric Efficiency (%):**
  - **Formula:** (Volume of Vapor Pumped / Compressor Displacement) * 100
  - **Example:** A compressor has a theoretical displacement of **10 CFM**, but it actually pumps **8 CFM** of vapor under certain conditions. The volumetric efficiency is (8 / 10) * 100 = **80%**.
- **Theoretical Reciprocating Compressor CFM:**
  - **Formula:** CFM = (pi * r^2 * L * N * RPM) / 1728

Input (r)	Input (L)	Input (N)	Input (RPM)	Output (CFM)
1 inch	2 inches	1	1750	~6.36 CFM

- **Electrical Schematics:** Diagrams illustrating electrical connections.
- **Heat Load Calculation (Area-based)**
  - **Formula:** Q = Area (sq ft) * Heat Load Factor (BTU/hr per sq ft)
- **CFM based on Room Size**
  - **Formula:** CFM = (Room Volume * Air Changes per Hour) / 60
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- **CFM from Air Velocity**
  - **Formula:** CFM = Area (sq ft) * Air Velocity (ft/min)
- **Round Duct Area**
  - **Formula:** Area = pi * radius^2
  - **Formula:** Area = pi * (diameter/2)^2
- **Fan Pulley Calculation**
  - **Formula:** Fan Pulley Diameter = (Motor RPM * Motor Pulley Diameter) / Fan RPM
- **Blower External Static Pressure (Residential/Light Commercial):** Typically **0.5 WC (Water Column)**

10.6 Control System Formulas

- **Linear Interpolation**
  - **Formula:** y = y1 + ((x - x1) / (x2 - x1)) * (y2 - y1)
  - **Example 1: Chiller Setpoint Control:**

Parameter	Value
Outdoor Air Temp (x1)	65 degrees F
Chiller Setpoint (y1)	43 degrees F
Outdoor Air Temp (x2)	70 degrees F
Chiller Setpoint (y2)	44 degrees F
Input Outdoor Air Temp (x)	68 degrees F
Output Chiller Setpoint (y)	43.6 degrees F

* **Example 2: Fan Speed Estimation:**

Parameter	Value
Airflow (x1)	5000 CFM
Fan Speed (y1)	40%
Airflow (x2)	8000 CFM
Fan Speed (y2)	75%
Input Airflow (x)	6500 CFM
Output Fan Speed (y)	57.5%

* **Example 3: Heating Coil Capacity:**

Parameter	Value
Entering Water Temp (x1)	140 degrees F
Capacity (y1)	"50,000 BTUH"
Entering Water Temp (x2)	180 degrees F
Capacity (y2)	"85,000 BTUH"
Input Entering Water Temp (x)	165 degrees F
Output Capacity (y)	71875 BTUH

10.7 Mixed Air Formulas

- **Mixed Air Dry Bulb Temperature**
  - **Formula:** Mixed DB = [(Mass Flow Stream 1 * DB Stream 1) + (Mass Flow Stream 2 * DB Stream 2)] / (Total Mass Flow)

Stream	Mass Flow (lb/min)	DB (degrees F)
1	8000	75
2	2000	20
Total	10000	
Output	Mixed DB	64 degrees F

- **Mixed Air Moisture Content**
  - **Formula:** Mixed Moisture = [(Mass Flow Stream 1 * Moisture Content Stream 1) + (Mass Flow Stream 2 * Moisture Content Stream 2)] / (Total Mass Flow)

Stream	Mass Flow (lb/min)	Moisture Content (kg/kg)
1	8000	0.012
2	2000	0.003
Total	10000	
Output	Mixed Moisture	0.0102 kg/kg