4.4 CONDENSATION

- Condensation is the process of converting a gas or vapor to liquid.
- Any gas can be reduced to a liquid by lowering its temperature and/or increasing its pressure.
- Condensers are typically used as pretreatment devices.
- They can be used ahead of absorbers, absorbers, and incinerators to reduce the total gas volume to be treated by more expensive control equipment.
- Condensers used for pollution control are contact condensers and surface condensers
- In a contact condenser, the gas comes into contact with cold liquid.
- In a surface condenser, the gas contacts a cooled surface in which cooled liquid or gas is circulated, such as the outside of the tube.
- Removal efficiencies of condensers typically range from 50 percent to more than 95 percent, depending on Surface condenser Contact condenser.

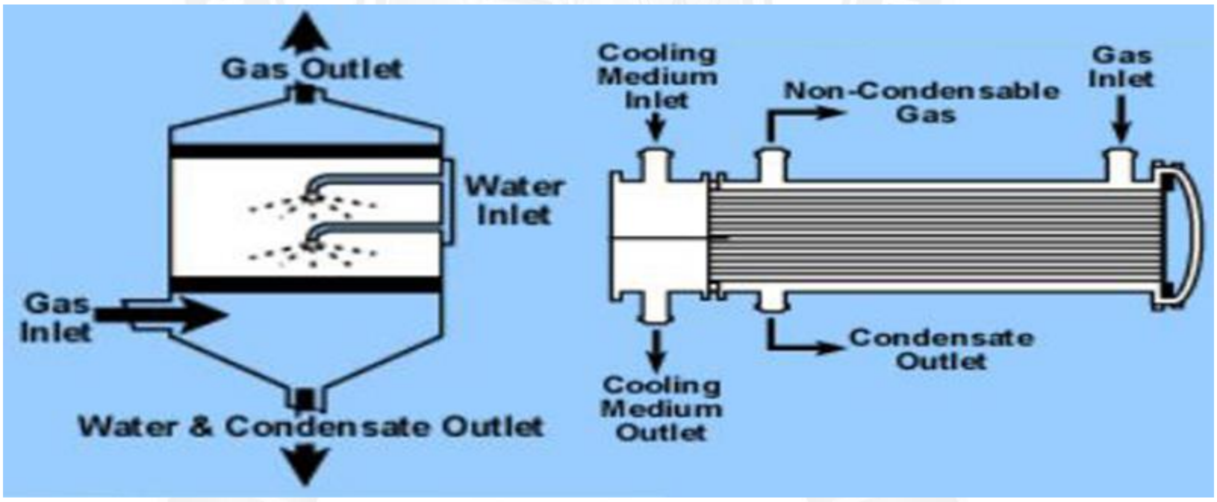

Figure 4.4.1 Contact and Surface Condenser

[Source:https://www.prakrriti.com/images/air-pollution-control-systems/condensation.jpg]

➢ REFRIGERATED CONDENSER

A refrigerated condenser is a control device that is used to cool an emission stream having organic vapors in it and to change the vapors to a liquid.

A refrigerated condenser condenses organic vapors just as moisture is condensed to water in an air conditioning system.

However, while condensed water from an air conditioning system is disposed of via a drain, condensed organic vapors can be recovered, refined, and might be reused, preventing their release to the ambient air.

- **Importance**

Nitrogen oxides (NOx, the x is used because there are five oxides) and VOC react with each other in ultraviolet (UV) light from the sun to produce tropospheric ozone.

Ozone in the troposphere (the air we breathe in the lower atmosphere) is the principle constituent of smog and is harmful to public health. Refrigerated condensers can reduce VOC emissions, which reduces the ozone generating potential of NOx. NOx reduction techniques are discussed in a separate CATC Technical Bulletin.

Many organic compounds have been designated as negligibly reactive with regard to ozone formation and are exempt from VOC regulations. Although some VOC maybe HAP, compounds exempt from VOC regulations also may be HAP and need to be controlled, in addition, stratospheric ozone depleting chemicals are not considered VOC or HAP, but still need to be controlled. Stratospheric ozone protects us from the harmful rays in sunlight.

- **Uses:**

A refrigerated condenser works best on emission streams containing high concentrations of volatile organic emissions. They are less effective on dilute streams (i.e., where there is much more air flow than organic vapor flow).

Example:

A paint spray booth requires a substantial amount of air flow through it to protect worker health and safety. As a result, most of the heat removed by a refrigerated condenser would come from air. The organic vapor content in a paint booth emission stream could be recovered by using .a refrigerated condenser, but it would be very costly per ton of organic compound recovered. In addition, to reuse the organic compound, moisture condensation would probably need to be removed.

A refrigerated condenser could be a viable control option for any source of evaporative organic emissions if:

- ❖ There is minimal air flow carrying the organic emissions (i.e., the air stream is saturated with the organic compound)
- ❖ The organic vapor containment system limits air flow
- ❖ Required air flow does not overload a refrigeration system with heat
- ❖ Only one organic compound is emitted (or the system is designed for the compound that is the most difficult to control)

Refrigerated condensers often are used in the following applications:

1.Dry Cleaning Industry :

It used to recycle dry cleaning fluid (perchlorethylene or petroleum- base solvent) with virtually no air flow. The vapors are usually condensed without air being used to transport them.

2.Degreasers using VOC or Halogenated Solvents :

Some air is mixed with vapors because the solvent is uncovered (i.e., exposed to the atmosphere). Preparation (degreasing/cleaning) of parts prior to powder coating is one example of this.

- ❖ Transfer of Volatile Organic Liquid (VOL) and Petroleum Products (e.g., bulk plants, bulk terminals, and similar transfer operations).
- ❖ Vapors from Storage Vessels/Tanks

➢ REFRIGERATION

All refrigeration units are basically "heat pumps," absorbing heat on the "cold side" of the system and releasing heat on the "hot side" of the system. All refrigeration systems have a hot side and a cold side. Some have a compressor.

The difference between refrigeration systems is whether the refrigerant is actually liquified within the apparatus and how low a temperature the "cold side"can reach.

Working of the Refrigerated Condensers:

- Each type of refrigeration system chills a heat exchanger surface in a condenser, and organic vapor condenses on the cold heat exchanger (or heat transfer) surface.

- Condensation of organic vapor causes it to lose volume.
- This loss of volume produces a lower concentration of vapor near the heat exchanger (i.e., the condensation) surface.
- This produces a concentration gradient that causes the flow of the emission stream toward the heat exchange surface.
- Condensation is assisted by turbulence in the emission stream that also brings the emission stream close enough for heat transfer and subsequent condensation of the organic vapors.

Only a negligible fraction of a percent escapes this combined action when the condenser is sized large enough and the refrigerant temperature is low enough. A finite vapor pressure is always present that allows some vapor to remain in the exhaust stream at all times.

➢ **Reverse Bravton Cycle Systems**

Reverse Brayton Cycle machines must be externally powered by an electric motor, a gas turbine, or an internal combustion (piston) engine. It is easier to reach the rotational speed of the turbine with either an electric motor or a gas turbine than with a piston engine.

Reverse Brayton Cycle turbines operate inversely from the normal operating cycle for gas turbines. Instead of converting heat to shaft horsepower, the Reverse Brayton Cycle system uses shaft horsepower to remove heat and reject it to the atmosphere.

As shown in Figure, it does this by first compressing the refrigerant air, then rejecting the heat of compression at an elevated temperature, and finally expanding the refrigerant air through a turbine to get useful work from it.

- As a result of the lack of heat input, temperature rise from compression, followed by dissipation of heat, and the work that the refrigerant air flow does on the expansion turbine, exhaust from the expansion turbine is very cold, reaching about -73°C (-100°F).
- The expansion turbine assists the external power source in spinning the compressor turbine.

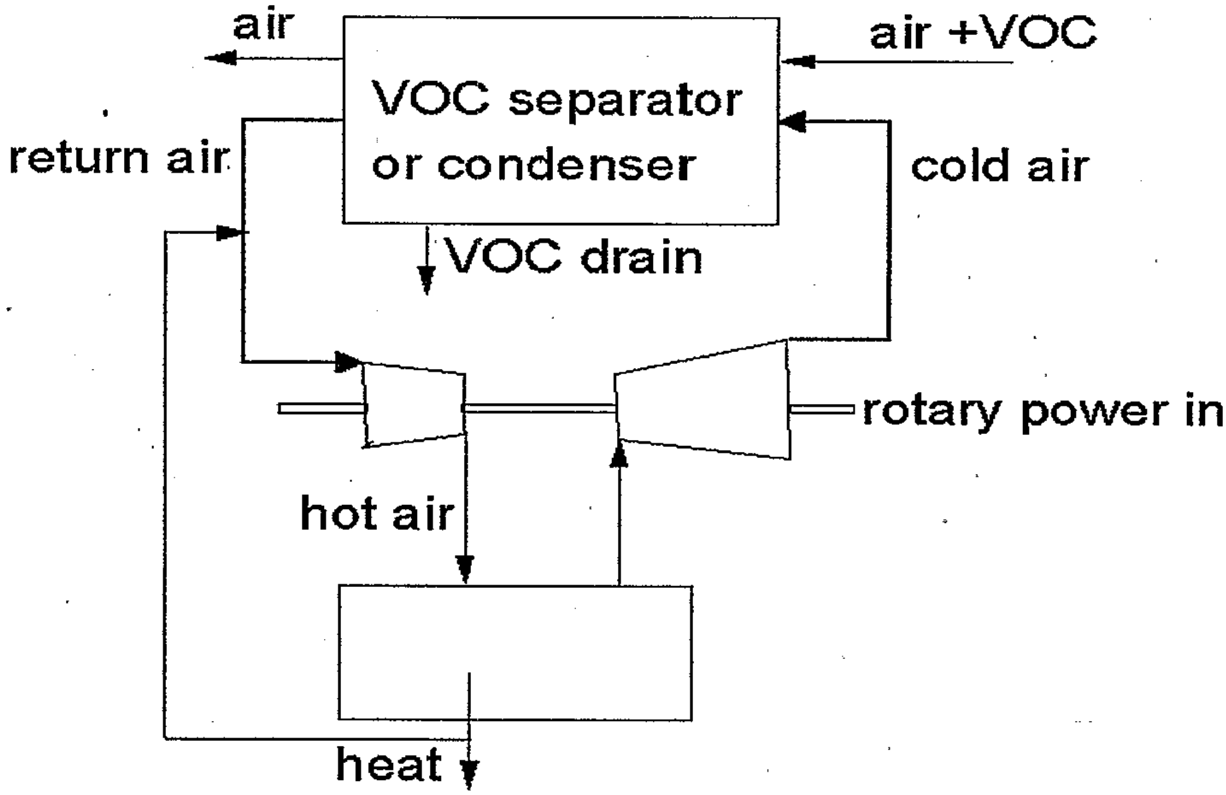

Figure 4.4.2 Reverse Brayton Cycle Refrigeration System

[Source:https://www.nuclear-power.net/wp-content/uploads/2017/04/reverse-Brayton-cycle-cooling-and-heat-pumps-min-259x300.png?ezimgfmt=ng:webp/ngcb49]

- The refrigerant air never liquefies in this cycle. Organic vapors may go through the Reverse Brayton Cycle along with the refrigerant air and no heat exchanger surface would then be required.
- Reverse Brayton Cycle machines cool the refrigerant air (and organic vapors if they are contained in the refrigerant air) to a very low temperature in what appears to be a single step, although it may actually be several steps in the expansion turbine.
- All of the vapors condense essentially together.
  - ❖ If the cold refrigerant air is used to chill a heat exchanger (surface condenser) as in Figure, the organic vapor can be condensed without going through the cycle.
  - ❖ When organic vapor is exposed only to a heat exchange surface, the heat exchanger can be like any other refrigerated condenser.
- The refrigerant air in a Reverse Brayton Cycle system does not contaminate the organic

compound, but several organic compounds may be mixed in the vapor state and therefore may be condensed together and mixed in a condensed liquid or slurry.

Reverse Brayton Cycle machines do not have a pre-cooling feature to separate moisture. To the extent that moisture is present in the vapor, it will be present in the condensed organic liquid. Some organic compounds can be separated by skimming, others require fractional distillation for purification.

After completing the Reverse Brayton Cycle, the refrigerant air can be either recycled or exhausted to the atmosphere. Because some organic compounds are actually frozen they should be separated as solid particles. To the extent that the refrigerant air recovers some of its heat before it is again compressed, or for some low melting point compounds, these organic compounds also maybe recovered as a liquid. Multiple filter channels can allow one compound to warm up for recovery, while the other is chilled by cleaning the cold refrigerant air flow. While frozen organic particles must be captured by a filter, organic droplets can be captured by inertia! impact or in a cyclone separator. In both cases the cut-off particle/droplet size depends on the design.

- **Cryogenic Cooling**

Cryogenic Cooling uses no power at the plant where it is used for cooling, but the air separation plant that generates liquid nitrogen usually is electrically powered. The truck used to deliver liquid nitrogen to the user's plant will also use fuel. The distribution of liquid nitrogen in a plant is self-powered by the pressure of the gaseous nitrogen that results from heat leakage which causes the liquid nitrogen to boil.

Cryogenic Cooling starts at an air separation plant. Air is compressed, cooled and then expanded to atmospheric pressure. This expansion cools some fraction of the compressed air to make it a liquid. The air that has become liquid is then allowed to boil to give off Argon, Nitrogen, Oxygen, etc. at their respective boiling point temperatures. Each gas is then collected and condensed again by compression and expansion just like the air originally was. This produces relatively pure liquid nitrogen that is used for cryogenic cooling.

Factors Affect The Performance Of Refrigerated Condensers:

Any refrigerant can be used to cool the surface of a heat exchanger. The only requirements are that the temperature is low enough and that the cooling capacity is sufficient. When organic compounds are recovered along with moisture and other contaminants, an impure organic compound may require too much effort to purify and might be destroyed by burning. However, recovery and recycling of the organic compound is the preferred outcome.

Each organic compound becomes liquid below its dew point, and becomes a solid "frost" below its freezing point. This "frost" must be removed from a condenser periodically, especially in cryogenic condensers because they are so cold, to allow free flow of the emission stream containing organic vapor and to permit heat transfer to occur as designed. The "frost" can be removed by flushing the condenser with the condensed organic compound in its liquid phase. However, the liquid organic compounds are always mixed in the frost and slurry, just as the organic vapors were mixed.

Cryogenic condensers can be the coldest and therefore are capable of the highest DRE. Fluctuations in heat load caused by fluctuations in emission stream flow and organic vapor concentration are offset by a thermostatically controlled valve modulating the nitrogen flow.However, if cryogenic cooling is operated at a temperature well above the boiling point of liquid nitrogen, there will be locations within the condenser that will be somewhat warmer than the thermostat setting because gaseous nitrogen has a low specific heat and is warming up as it passes through the shell of the condenser.

The DRE is limited by the amount of organic vapor that escapes with the exhaust from the condenser. The amount of organic vapor that escapes is determined by both the vapor pressure of the condensed liquid (i.e., the partial pressure of the organic vapors in the emission stream) and the amount of air present in the emission stream. We cannot always eliminate the air from the emission stream, but we can minimize both the amount of air in the emission stream and the vapor pressure of organic compounds. Therefore, condensation technology needs to:

1. Maximize the portion of the organic vapor that is affected by the cold surface in the condenser (i.e., make the residence time large enough and the flow sufficiently turbulent).

2. Minimize the partial pressure of the organic vapor after it comes in contact with the heat exchanger (i.e., make the condenser cold enough and the refrigeration capacity large enough).

3. Reduce the temperature of the organic compounds below the freezing point, if possible,because vapor pressure becomes a minimum when organic compounds are frozen. (This should be done even though frozen organic compounds must be removed periodically.)

4. Minimize the amount of air in the emission stream that contains organic vapors. Heat load is greater when you must chill a lot of air. Minimizing the amount of air mixed with the organic vapors will reduce the heat load and increase the useful cooling (i.e., the cooling available for condensation). Reducing the heat load will reduce the cost of refrigeration. Increasing the useful cooling will improve the DRE.