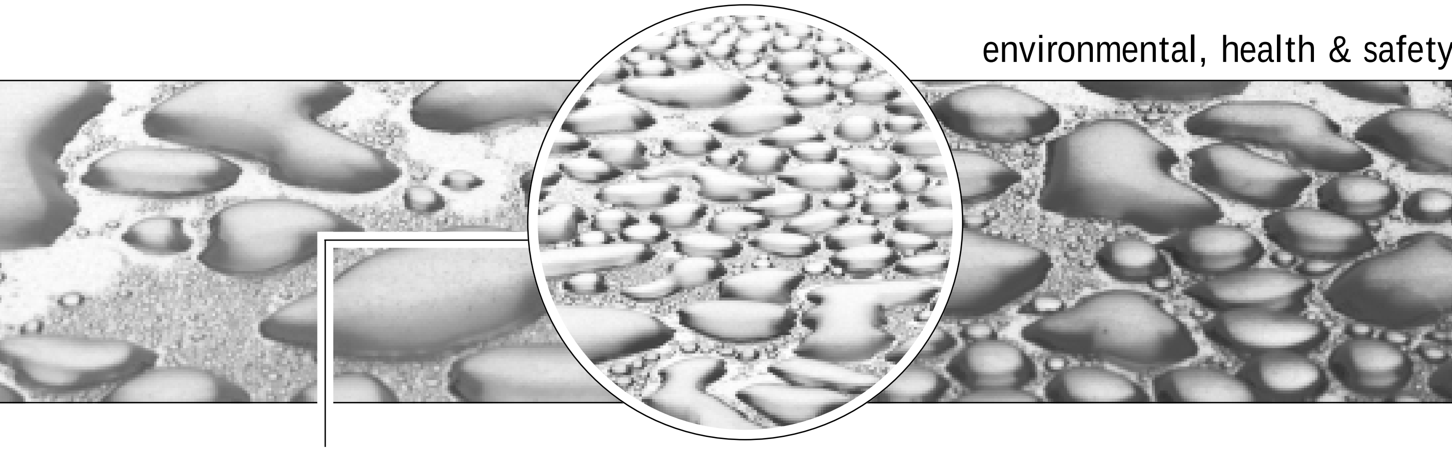

Condensers control and reclaim VOCs

Technological advances increase recovery of costly product

By J.R. Lines and A.E. Smith

Condensation is one technology used to reduce volatile organic compound (VOC) emission rates. Its use has been driven in part by the Clean Air Act Amendments of 1990, which state acceptable rates for VOC emissions. Condensation technology allows reclamation of VOCs, providing an economic incentive when costly product is reclaimed as a condensate.

Condenser operation

Condensation in a condenser is a phase change operation in which a vapor contacts a heat transfer surface maintained below the dewpoint temperature of that vapor. A liquid film, known as a condensate, forms on the heat transfer surface. This condensate can be compared to the moisture that develops on the inside of a window in a home on a cold winter day. The window temperature is below the dewpoint temperature; therefore, moisture in the air is condensed onto the cold surface.

When a vent stream consists of a single VOC and no non-condensible gas, then condensation occurs isothermally, that is, at a constant temperature. When non-condensibles or other VOCs with varied volatilities are present, condensation will occur along a temperature change. As the outlet temperature gets colder, more of the VOCs are converted from vapor to liquid.

Non-condensible gases

The most common condenser applications involve a VOC stream that includes non-condensible gases. Non-condensible gases may be air, nitrogen or any other gas that will not condense at the operating temperatures within a condenser. Because of the presence of non-condensible gases, there always is an associated VOC saturation component. The colder the gas/vapor stream, the lower the amount of VOCs that saturate the non-condensible component. The amount of VOCs that saturate the non-condensible gases at the operating temperature and pressure of a condenser may be calculated in a number of ways. The method used depends on the assumptions of ideal gas behavior and that the condensate and gas/vapor are at the same temperature. In actual practice, equal gas/vapor and condensate temperature rarely occurs because the condensate temperature typically is lower than the average gas/vapor temperature.

Dalton's Law of Partial Pressures is used to calculate the amount of VOCs that will saturate non-condensible gas, and the basic calculation may take one of three forms, depending on condensate behavior. Practical application of Dalton's Law uses the vapor pressure of a condensible VOC at the operating temperature as its partial pressure. For example, the vapor pressure of methylene chloride at -40°F is 12.7 torr.

Ideal gases and immiscible condensate:

$$pph_{VOCi} = \left(\frac{Ync * VPi * MWi}{\text{total pressure} - \sum_{i=1}^{n} VPi} \right)$$

Equation (1)

Ideal gases and ideally miscible condensate:

$$pph_{VOCi} = \left(\frac{Ync * Xi * VPi * MWi}{\text{total pressure} - \sum_{i=1}^{n} Xi * VPi} \right)$$

Equation (2)

Ideal gases and non-ideally miscible condensate:

$$pph_{VOCi} = \left(\frac{Ync * \gamma i * Xi * VPi * MWi}{\text{total pressure} - \sum_{i=1}^{n} \gamma i * Xi * VPi} \right)$$

Equation (3)

where Ync is the mole-based flowrate of non-condensible gases, VP is the vapor pressure of a component at a specified temperature, MW is molecular weight, total pressure is system operating pressure, X is mole fraction in condensate, γ is an activity coefficient and pph is mass flowrate.

An example of an immiscible condensate mixture is oil and water. When oil and water are placed in the same container, they do not mix. In contrast, an example of a miscible condensate mixture is water and ethylene glycol (radiator fluid). Miscible condensate will mix in all proportions.

Example

Determine the amount of methylene chloride and water vapor that will saturate 200 lb/hr of nitrogen at a temperature of 40°F and a pressure of 14.7 psia. The molecular weight of methylene chloride is 85 lb/lb-mole and has a vapor pressure of 3.24 psia at 40°F. Water vapor has a molecular weight of 18 lb/lb-mole and a vapor pressure of 0.122 psia at 40°F. Methylene chloride and water are immiscible.

VOC condensation is dependent on non-condensible gas mass flowrate and molecular weight, operating temperature, operating pressure, VOC vapor pressure, characteristics of other condensible components and pressure drop across the heat exchanger. Generally:

- the greater the non-condensible flowrate, the lower the reclamation;
- the lower the operating pressure or the greater the pressure drop across the condenser, the lower the reclamation;
- the greater the vapor pressure of a VOC, the lower the reclamation;
- the greater the concentration of other VOCs, the lower the reclamation;
- the colder the temperature, the lower the vapor pressure and the greater the reclamation.

Tank vent condensers

Vent condensers are used on storage tanks to reclaim the valuable product contained in the tank and to control the harmful emissions that escape from the tank to atmosphere. During the day, the sun heats the fluid and vapors contained in the tank. This temperature increase causes the vapors to expand. Also, more vaporization of the volatile components results from the increasing fluid temperature. The vapor concentration increases in the tank, which causes the internal pressure of the tank to increase. Because the tank is exhausting to atmosphere, this increase in the tank's internal pressure provides a driving force to vent the VOCs.

In addition to venting caused by concentration changes, vapors are exhausted to the atmosphere as the tank is refilled. Typically, the condenser will experience its greatest duty when the tank is being filled. By installing a vent condenser on the tank, the condensible vapors are refluxed back into the storage tank, recovering valuable product for future use.

Spiral-tube vent condensers are available in three different designs. Each of the three designs is unique and excels in different applications.

A vent condenser on nozzle (VCON) style is shown in Figure 1. This condenser is installed directly on a tank's nozzle, and does not require additional supports. The endplate of the casing or shell

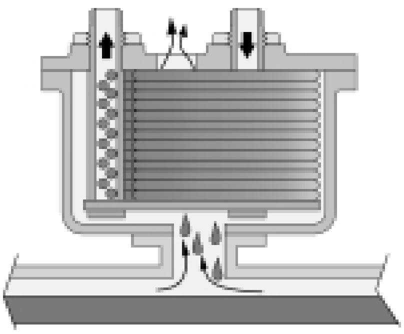

Figure 1. A VCON-style condenser is mounted on a nozzle.

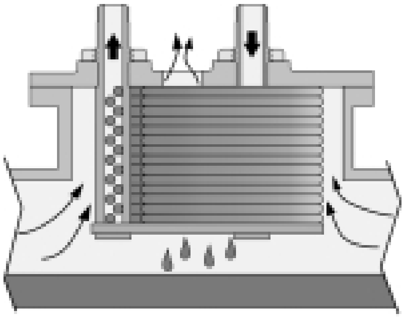

Figure 2. A VCIN-style condenser is installed inside the tank's nozzle.

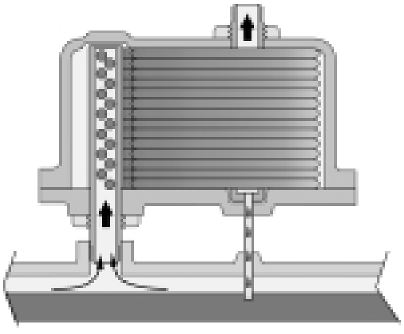

Figure 3. A VCT-style condenser accomplishes condensation on the tube side.

is tapped and studded to any desired flange diameter. Typically, VCON units are installed on existing tanks where the nozzle diameters cannot be changed.

The vent condenser in nozzle (VCIN) style, Figure 2, is similar to the VCON model, except it is mounted inside the tank's nozzle. This eliminates the need for a casing. This unit is more economical than the VCON because it has fewer components. Typically, VCIN units are installed in new tanks where the user and supplier can work together to properly size the nozzle diameter. As with the VCON, the VCIN style will not require additional supports.

The vent condenser tube side (VCT) style, Figure 3, is used when the condensed fluids require exotic materials of construction or to ensure the vapors remain in intimate contact with the condensate, which may be necessary in certain applications. Because the condensation occurs on the tube side, the casing can be constructed of cast iron or carbon steel, minimizing costs. This design requires additional supports for the condenser.

Case study

A spiral-tube heat exchanger was installed on a methylene chloride tank at a chemical storage company. The company distributes virgin chemicals and processes hazardous waste. The methylene chloride in the tank was the highest-vapor-pressure chemical the company handled; thus, the most difficult to reclaim.

The specifications required 95 percent of the methylene chloride to be recovered from the vent stream. However, because the laws eventually will require a 98 percent reclamation rate, the specification requested the condenser be able to meet future requirements.

The methylene chloride liquid in the tank ranged in temperature from approximately 70°F in the summer to approximately 45°F in the winter. As shown in Figure 4, methylene chloride has a relatively high vapor pressure. To achieve 95 percent VOC recovery, a cryogenic coolant was needed for the condenser.

For a constant non-condensible flowrate and one vapor component, the following equation can be used to determine the percent recovery and/or the desired vapor outlet temperature:

$$\%\ \text{Recovery} = \left(100 - \frac{(Tp - Vp_1)Vp_2}{(Tp - Vp_2)Vp_1}(100)\right)$$

Equation (4)

where Tp is the tank pressure, Vp_1 is the vapor pressure of the VOC at the fluid temperature, and Vp_2 is the vapor pressure of the VOC at the outlet temperature.

By rearranging Equation 4, we can solve for the required outlet vapor pressure and determine the corresponding temperature. For this particular case, Vp_2 was based on 45°F, Tp is 785 mmHgA and percent recovery was 95. Therefore, Vp_2 is 12.7 mmHgA, which corresponds to a -40°F vapor outlet temperature.

Because a cryogenic coolant is required, the tank must be purged with nitrogen to displace the air and its associated moisture from the tank. This ensures the moisture in the air does not freeze on the tube walls. To ensure atmospheric air does not enter the tank from the vapor outlet of the condenser, a check valve is installed. Again, this prevents freezing of the saturation moisture on the tube walls.

Liquid nitrogen (LN_2) flow is regulated by a temperature controller that monitors the vapor outlet temperature. In this case, the temperature controller was set to regulate the outlet vapor temperature at -40°F. When the tank is being filled or heated by the sun, the control will sense an increase in the outlet temperature and actuate the LN_2 valve. This valve must be equipped with a cryogenic extension to ensure the actuator does not freeze.

It also is important to place a pressure-indicating controller on the tank. During the day, the sun heats the tank, causing the methylene chloride to evaporate and the internal tank temperature to rise. At night, the reverse occurs, and a portion of the vapors in the tank condenses. Because there is a check valve on the vapor outlet, nitrogen must be bled into the tank to guarantee the vacuum breaker is not actuated.

After the vent condenser was installed, an independent testing company confirmed the condenser was reclaiming at least 95 percent of the methylene chloride contained in the vent stream. Because the largest heat duty occurs when the tank is being charged, the test was conducted while the tank was being filled. U.S. Environmental Protection Agency Method 25A, "Determination of Total Gaseous Organic Concentrations using a Flame Ionization Analyzer," was used to determine the VOC concentration before and after the condenser. For the emissions test, the temperature controller was set to -65°F to check the maximum recovery rate achievable without freezing the methylene chloride to the tube walls. The vent condenser can recover 98.8 percent of the methylene chloride at -65°F. Based on these test results, the customer was satisfied the spiral tube vent condenser could meet present and future requirements.

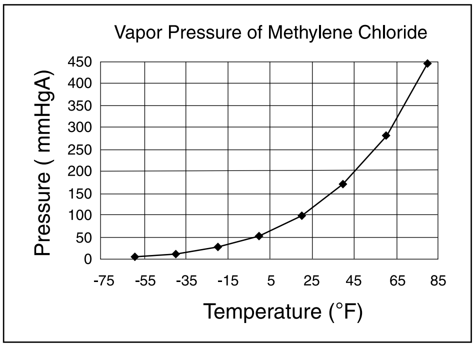

Figure 4. Methylene chloride has a high vapor pressure.

Freeze condensation

Technology has progressed to the point where freeze condensation techniques are being used to strip VOCs from vent streams. Freeze condensation is a deposition phenomena whereby the heat transfer surface is maintained at such a cold temperature that the VOC vapor stream passes from the gas phase to the solid phase without necessarily going through a liquid phase.

The heat transfer characteristics of the condenser are different from conventional applications. A frost or ice layer often builds up continuously on the heat transfer surface. This continued buildup of product on the heat transfer surface tends to impede heat transfer, with the buildup acting as an insulator, and the pressure drop increasing across the condenser.

Normally, pressure drop rises faster than outlet temperature increases. To ensure reliable VOC reclamation, two freeze condensers are used. One is operating while the other waits on standby. As operation progresses, inlet pressure to the operating condenser is sensed. As operating pressure increases above a preset value, a set of automatic control valves switches flow to the standby unit. Pressure rises in the operating unit because ice forms, reducing cross-sectional flow area. That unit needs to undergo defrosting so it will be ready to return to reclamation operation.

Another important aspect of freeze condenser design is gas/vapor velocity. Velocity must be maintained relatively low to avoid entrainment of droplets or buoyant snowflake-like material. Velocity concerns exist for conventional condensers as well.

To achieve deposition or required reclamation levels, the use of a cryogen as a cooling media is becoming commonplace. A typical cryogen is liquid nitrogen at -275°F to -300°F. To conserve nitrogen consumption, it is vaporized and superheated within the condenser. Here again, thermal design takes on a new level of sophistication. The temperature differentials result in suppression of the boiling coefficient because it is in the film-boiling regime instead of the preferable nucleate regime. The excessive temperature gradient induces pressure fluctuations or surging in the nitrogen supply line if upstream piping is not properly configured.

Conclusion

The desire to recover VOCs and reduce emission rates has fostered the technological advance of vent condenser design. The heat transfer community has stepped up to the challenge and embarked on research and development to understand thermal hydraulic and vapor/liquid equilibrium characteristics of these seemingly universal condensers.

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