

Condensation

OBJECTIVES

Terminal Learning Objective

At the end of this chapter, the student will be able to identify the basics of condenser systems.

Enabling Learning Objectives

- 7.1 Distinguish among the various types of condenser systems.
- 7.2 Identify the principles of operation for condenser systems.
- 7.3 Determine the factors that influence the capability and sizing of a condenser system.

The concentration of organic compounds (VOC and air toxic compounds) in a gas stream can be reduced by condensation at low gas temperatures. Condensation begins at the dew point, the temperature at which the partial pressure becomes equal to the VOC vapor pressure and the gas is said to be saturated. The gas remains saturated as the temperature is further reduced and increasing amounts of VOC are condensed.

Condensation control systems can be divided into two general categories according to the operating temperatures that can be achieved. Conventional condensers operate in the 40°F to 80°F (4°C to 27°C) range using chilled water. Refrigeration and cryogenic systems operate in the range of -50°F to -150°F (-45°C to -65°C). In extreme cases, cryogenic units using liquid nitrogen can operate at temperatures as low as -320°F (-195°C). Because of the lower temperatures possible in refrigeration and cryogenic units, the removal efficiency is much higher than in conventional condensers; however, these units are considerably more complicated and expensive.

Condensation systems are usually applied to industrial sources where there is a significant economic value to the recovered VOCs. Usually only one or two VOCs are present in the inlet gas, since separating pure materials from a multi-component condensate is difficult. The gas streams treated in condensation systems should have low particulate loadings.

7.1 Types of Systems

Conventional Systems

Conventional condensers are simple, relatively inexpensive devices that normally use water or air to cool and condense the VOC. Because these devices are usually not capable of reaching very low temperatures (below 40°F or 4°C), high removal efficiencies are obtained only for organic vapors that condense in the temperature range of 40°F to 80°F (4°C to 27°C).

Conventional condensers fall into two basic categories: (1) direct contact condensers and (2) surface condensers. In a direct contact condenser, the coolant and gas stream are in physical contact. In a surface condenser, the coolant is separated from the gas stream by heat transfer surfaces. The coolant, the condensate, and the permanent gases leave by separate exits. Surface condensers are commonly called shell-and-tube heat exchangers or indirect condensers.

Direct Contact Condensers

Contact condensers are simple devices such as spray towers or water jet ejectors. These devices bring the coolant, usually water, into direct contact with the vapors as illustrated in Figure 7-1. If the vapor is soluble in the coolant, absorption also occurs, increasing the amount of contaminant that can be removed at the given conditions.

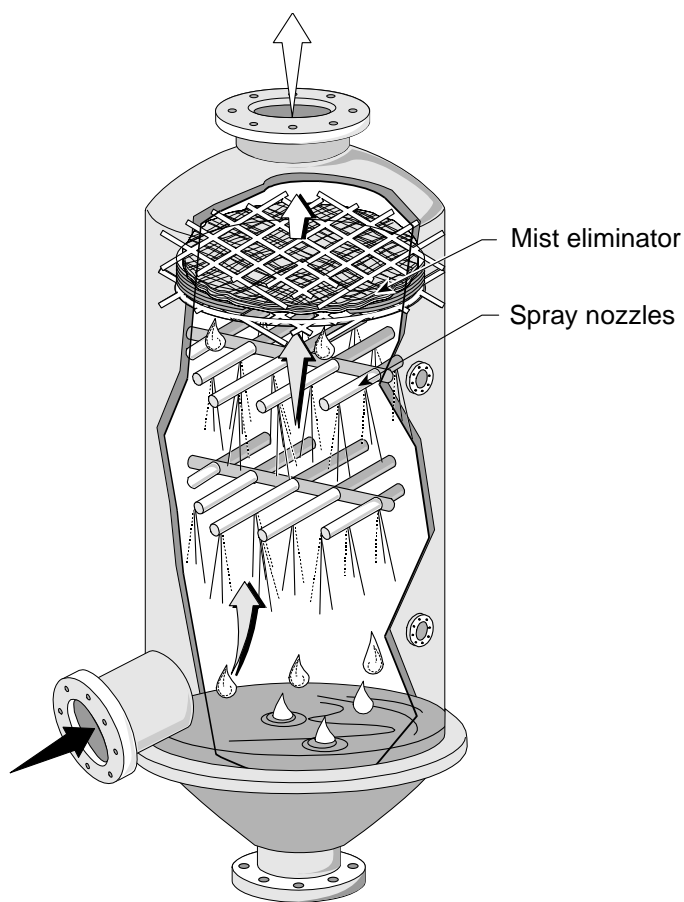


Figure 7-1. Direct contact condenser.

An ejector is a type of contact condenser. Ejectors use high-pressure liquid sprays to create suction for moving the VOC-laden gas stream and, therefore, do not need fans for gas movement. The coolant liquid is sprayed into the throat of the ejector, and organic vapors condense while passing through. Absorption can

also occur if the organic compound is soluble in the coolant fluid. An ejector condenser is illustrated in Figure 7-2.

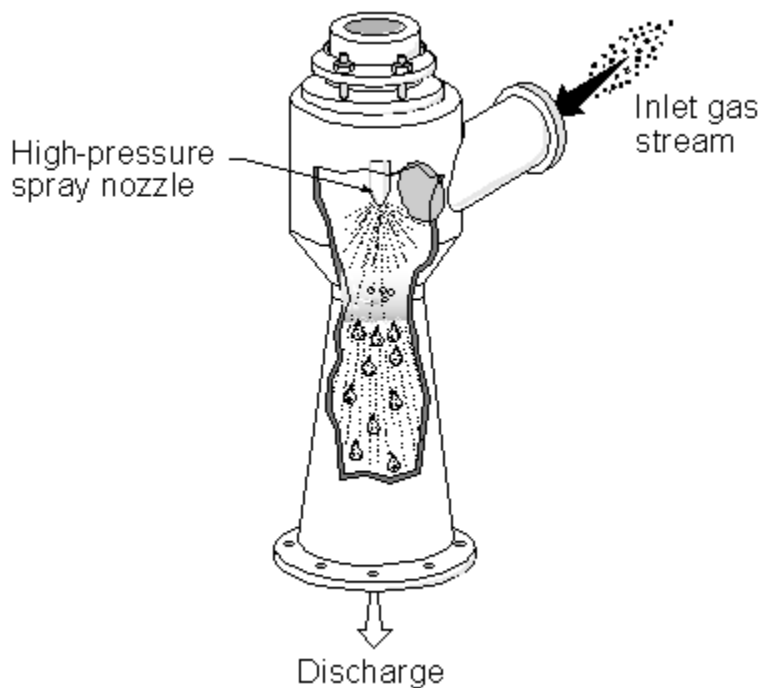


Figure 7-2. Ejector condenser.

The main advantages of contact condensers are their flexibility and low cost. The main disadvantage is the mixing of the water and the condensed VOC, which increases wastewater treatment costs and/or VOC recovery costs, particularly if the VOC is miscible in H₂O.

Surface Condensers

Surface condensers are usually in the form of shell-and-tube heat exchangers as shown in Figure 7-3. These devices consist of a cylindrical shell into which the gas stream flows while the coolant flows through numerous small tubes inside the shell. VOCs encounter the cool surface of the tubes, condense, and are collected. Permanent plus uncondensed VOCs exit the condenser and are emitted to the atmosphere.

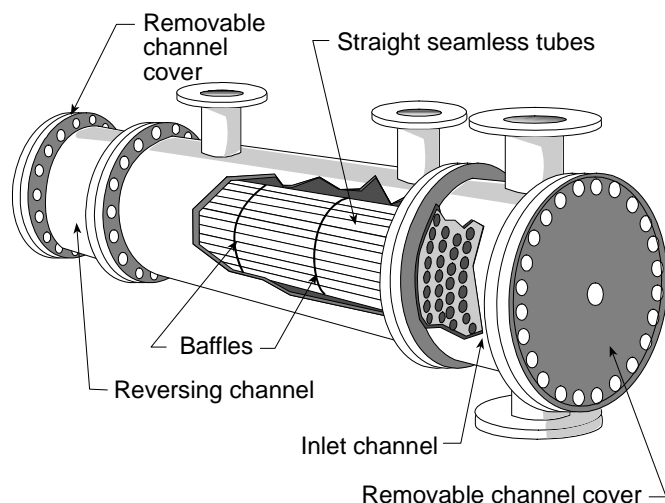


Figure 7-3. Single-pass condenser.

The system shown in Figure 7-3 is known as a single-pass condenser since both the coolant and gas streams flow in a single direction between entry and exit. This simple condenser is not usually used since improved heat transfer can be achieved with more complex systems that provide multiple passes, shorter tube lengths, and higher gas velocities. Figure 7-4 illustrates a 1-2 condenser. The first digit refers to the number of passes the gas makes on the shell side, while the second digit indicates the number of tube-side passes made by the coolant liquid. The addition of shell-side baffles increases the distance that the gas travels and the gas velocity. This design gives improved performance over the single-pass exchanger. A 2-4 heat exchanger (not shown) results in still higher gas velocities and better heat transfer than the 1-2 exchanger. However, adding more passes does have disadvantages: the exchanger construction is more complicated, friction losses are increased because of the higher velocities, and exit and entrance losses are multiplied.

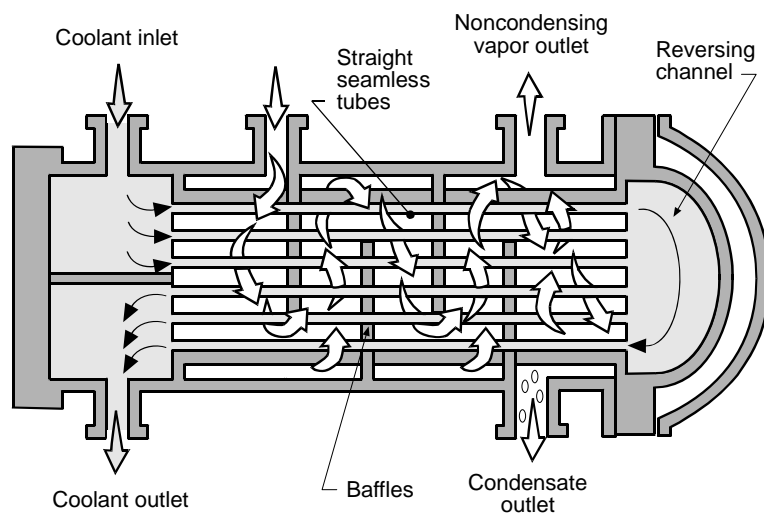


Figure 7-4. 1-2 pass shell-and-tube condenser.

Condensation applications normally involve large temperature differences between the gas and coolant. These temperature variances cause the tubes to expand or contract, and may cause the tubes to buckle or pull loose from the shell, destroying the condenser. Floating head construction is commonly used to avoid condenser expansion/contraction stress damage. In a floating head condenser, one end of the tube bundle is mounted so that, while sealed from the shell to prevent leakage, it is structurally independent and allows the tubes to expand and contract within the shell.

Air Condensers

Air condensers can be used in situations where water is not available, or treatment of the water stream is very expensive. Because of reduced heat transfer efficiency, condensers using air must be considerably larger than those using water.

Extended-surface air condensers may be used to increase the efficiency by conserving space and reducing equipment cost. In these units, the outside area of the tube is multiplied or extended by adding fins or disks, as shown in Figure 7-5, which illustrates two types of finned tubes. In extended-surface condensers, the VOC condenses inside the tubes while air flows around the outside in contact with the extended surfaces.

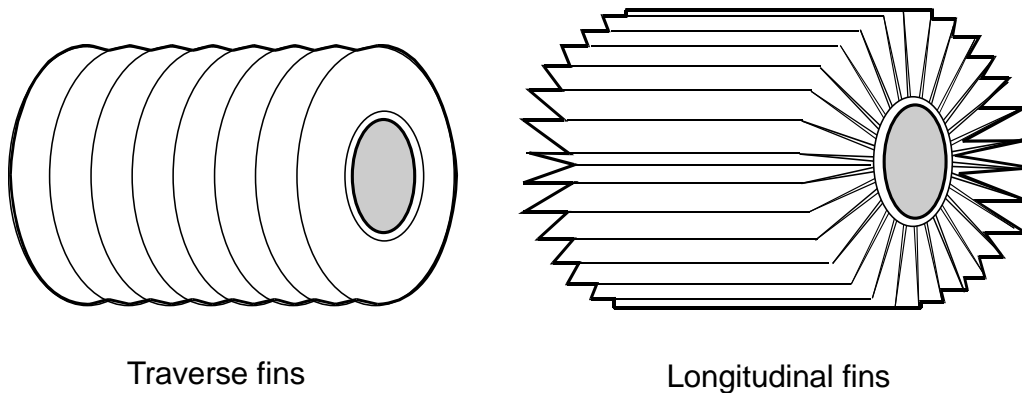


Figure 7-5. Extended surface tubes.

Refrigeration Systems

Refrigeration systems achieve low operating temperatures and are capable of increased VOC condensation. A simplified schematic of a refrigeration system is illustrated in Figure 7-6. Heat is removed from the VOC-laden gas stream in the evaporator section, causing condensation of a portion of VOC. The condensate and exhaust gas exit as separate streams. Heat removed from the gas stream is added to the refrigerant liquid, causing the refrigerant to vaporize. The refrigerant vapor leaving the evaporator section is then compressed to form a high-temperature, high-pressure vapor stream that is subsequently condensed in

an air condenser. The refrigerant liquid then passes through an expansion valve where the pressure is reduced to the level necessary for the evaporator. The overall operation is basically the same as a home air conditioning system.

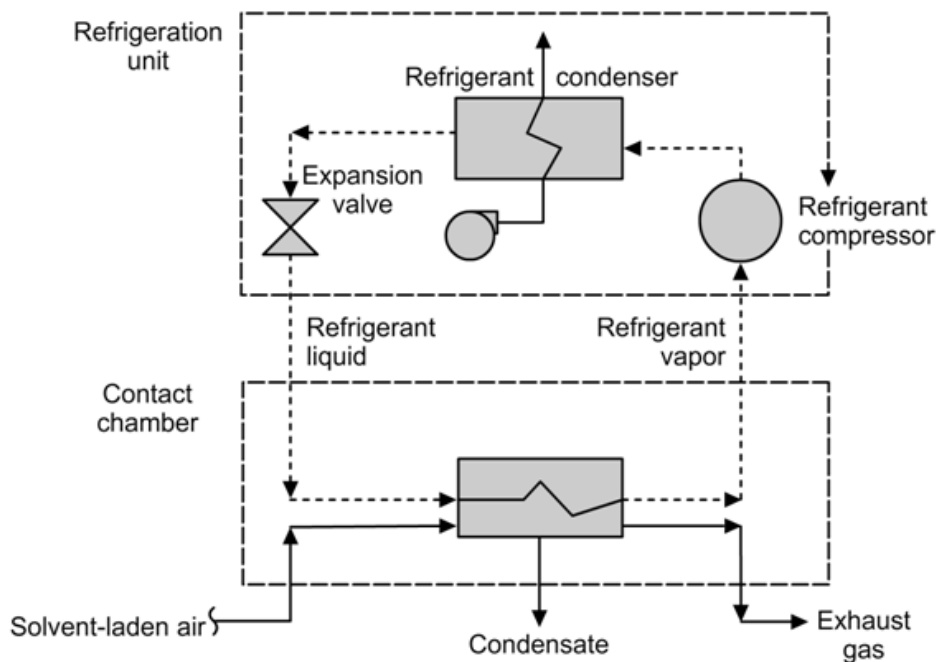


Figure 7-6. Basic refrigeration cycle.

The most common refrigerants used are chlorofluorocarbons (CFCs). A two-stage refrigeration system for VOC recovery from a gas stream that also contains appreciable amounts of water vapor is shown in Figure 7-7. The inlet gas stream enters a pre-condenser where it is cooled to approximately 40°F (4°C) in order to condense most of the water. The vapor pressure of water at 40°F is 0.12 psi, which corresponds to a water level of approximately 0.005 lb_m H₂O per lb_m air. By removing water vapor in the first stage, frost buildup on the heat exchange surfaces of the main chamber is minimized.

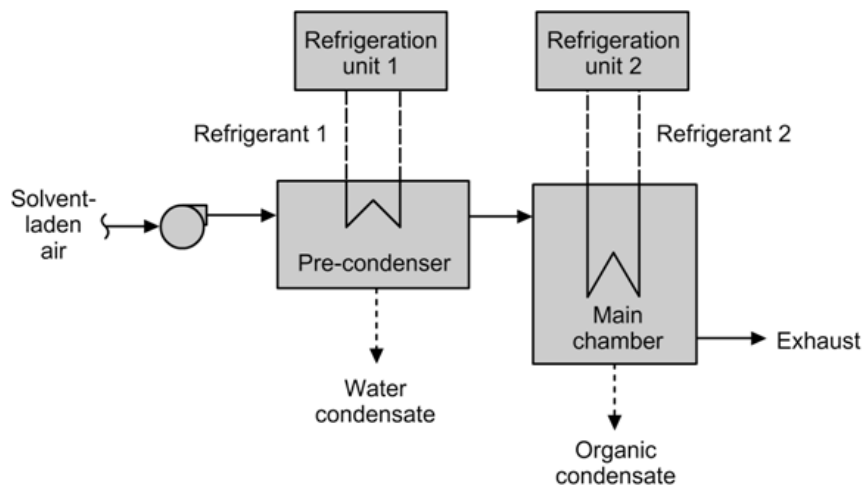


Figure 7-7. Simplified flowchart of a two-stage refrigeration system for organic vapor recovery.

The second stage (main chamber) operates at a lower temperature, ranging perhaps between -50°F to -150°F (-45°C to -100°C). Coolant for this chamber is supplied by a separate compressor system. Cascade-type systems are often used when extremely low temperatures are needed. The individual chambers are interconnected so that one unit can be used to expel the heat removed from another unit. Different coolants can be used in the various interconnected refrigeration units.

The treated gas stream leaving the main chamber is vented to the atmosphere. The condensate from the main chamber is collected in a storage tank and processed to remove water or other contaminants that would affect its reuse. The high water content condensate from the pre-condenser chamber is usually treated in a wastewater treatment system.

Cryogenic Systems

Cryogenic control systems use liquefied gases, such as nitrogen or carbon dioxide, to cool the waste gas streams to temperatures approaching the freezing point of the solvents. The extremely cold temperatures ranging from -100°F to -320°F (-70°C to -200°C) condense much larger amounts of VOCs. These systems are relatively simple because no refrigeration system is required, and the liquefied gas used for VOC control is simply vented to the atmosphere. Cryogenic systems do require a facility to receive and store the liquefied gas. There are three general types of cryogenic systems.

1. Indirect contact–single heat exchangers
2. Indirect contact–dual heat exchangers

3. Direct contact

Cryogenic systems are used primarily for single-component gas streams. To be economical, the organic vapor concentration must be greater than 500 ppm. As is the case with most condensation systems, cryogenic units are not tolerant of particulate matter that can accumulate on heat exchange surfaces.

Indirect Contact—Single Heat Exchanger Systems

A shell-and-tube heat exchanger is used for heat exchange between a liquefied gas and the VOC-containing gas stream. Liquefied nitrogen (N_2) at a temperature of -320°F (-200°C) is the most commonly used liquefied gas.^{1,2,3} The liquefied N_2 gas flows through the tubes of the heat exchanger while the waste gas passes through the shell side. A flowchart of an indirect contact—single heat exchanger system is shown in Figure 7-8.

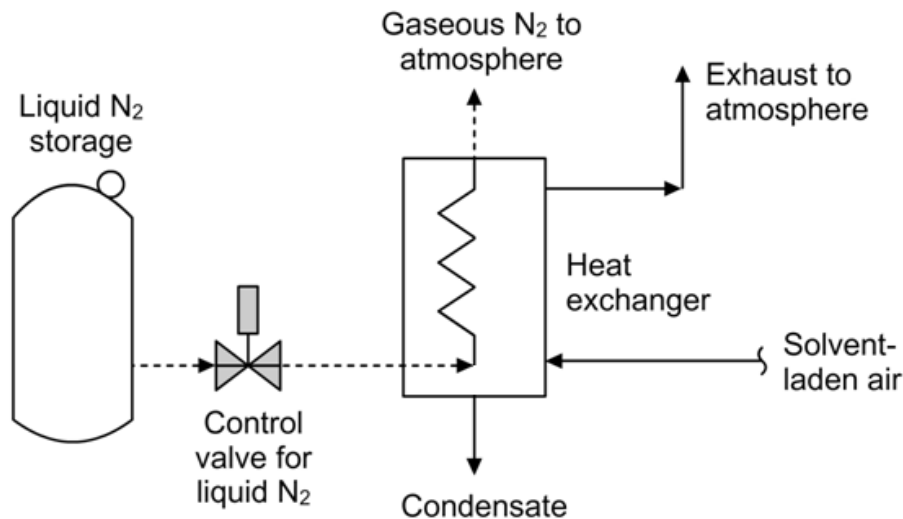


Figure 7-8. Single heat exchanger, indirect contact cryogenic system for organic vapor recovery.

Because of the extremely cold temperatures on the surface of the N_2 containing tubes, it is possible for the organic compounds to accumulate as frost on the exterior surfaces of the tubes.^{1,2,5} These layers can reduce heat transfer efficiency significantly and increase heat exchanger—static pressure drop.

To avoid this problem, it may be necessary to operate a parallel set of heat exchangers. One heat exchanger can be in a heat/defrost cycle while the other is in service for VOC condensation.

Cryogenic system shell-and-tube heat exchangers are not well-suited for large gas flow rates and are used primarily for small systems.

Indirect Contact–Dual Heat Exchanger Systems

The freezing problem inherent in an indirect contact–single heat exchange system can be avoided by the more complex dual system. As shown in Figure 7-9, the liquefied N₂ used in heat exchanger 1 cools a heat transfer fluid that, in turn, is used in heat exchanger 2 to condense VOC from the solvent-laden air.

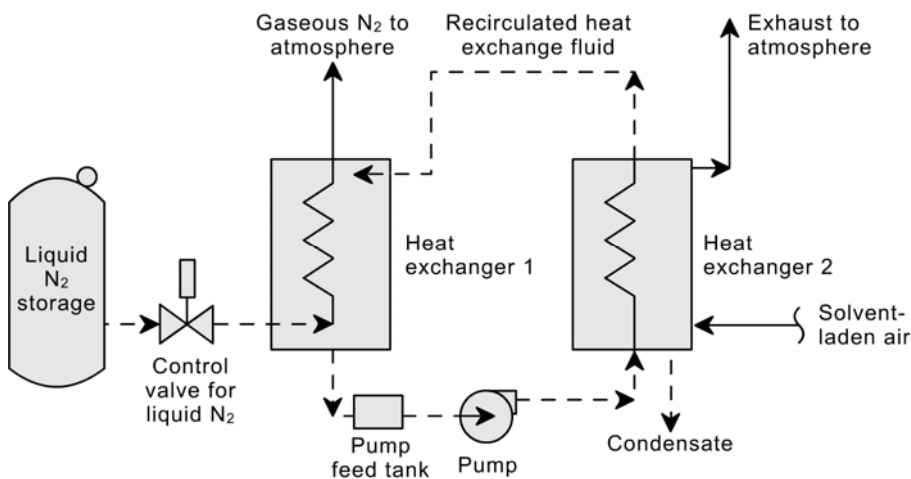


Figure 7-9. Dual heat exchange cryogenic system for organic vapor recovery.

The flow rate of the heat exchange fluid is controlled to maintain a VOC stream temperature just above the freezing point of the organic compound. This reduces the frequency of defrosting necessary to maintain adequate heat exchange efficiency, although occasional defrosting may still be needed because of the presence of moisture in the VOC-laden gas stream.

The capacity of the dual heat exchanger system is limited by the size of the heat exchanger. Dual heat exchanger systems are generally applicable to gas streamers less than 5,000 ACFM.

Direct Contact Systems

In direct contact systems, the VOC-laden gas stream comes into direct contact with a spray of liquid N₂ droplets. These systems avoid the frost buildup problem because there are no surfaces at extremely cold temperatures. The outlet gas temperature is controlled by the flow rate of liquefied gas. A typical flowchart is shown in Figure 7-10.

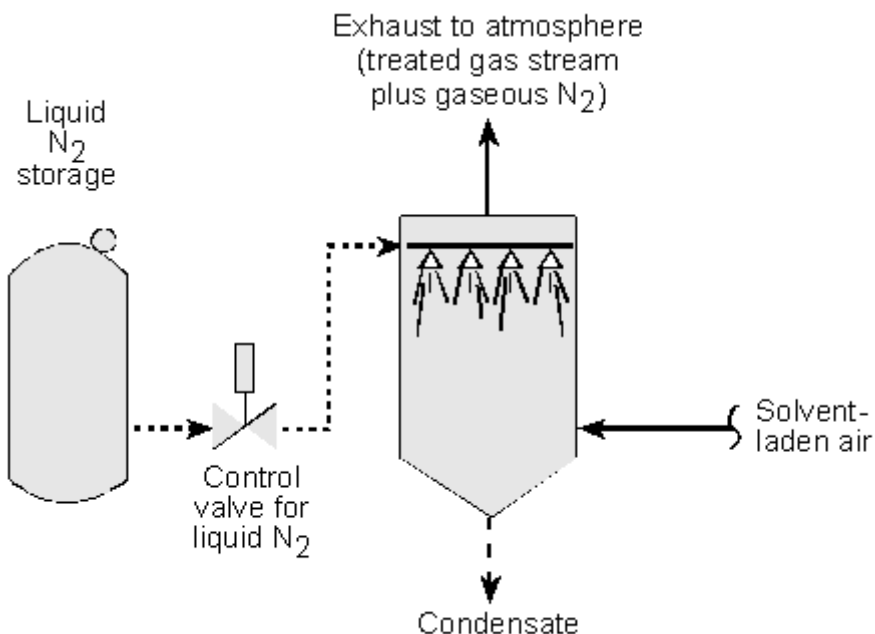


Figure 7-10. Direct contact cryogenic system for organic vapor recovery.

The liquid N₂ is dispersed using spray nozzles in the upper areas of the contacting chamber. The chamber is insulated to maintain the lowest possible gas temperatures. Heaters are included on the exterior sides of the chamber walls for the occasional removal of frost from the interior surfaces.

The outlet gas stream exhausted to the atmosphere includes the uncondensed compounds from the inlet gas stream and the vaporized nitrogen. The increased gas flow rate from the direct contact systems has a slight impact on its ability to remove organic vapor. The additional N₂ serves as a diluent and reduces the partial pressure of the VOC. Thus, a direct contact cryogenic condenser must operate at a lower temperature than an indirect contact condenser in order to achieve the same VOC removal efficiency.

The liquefied gas requirements for direct contact systems vary with the inlet concentration of the gas stream. At organic vapor concentrations less than 10,000 ppm, the liquefied gas requirement can be more than 20 pounds per pound of organic. As the concentration exceeds 100,000 ppm, the liquefied gas requirement drops to less than 5 pounds per pound of organic.^{1,2} For this reason, cryogenic systems are used primarily for vapor recovery applications in which the organic vapors are at high concentrations.

7.2 Operating Principles

Condensation can be caused by reducing the gas temperature, increasing the gas pressure, or a combination of both. Since it is not economical to compress the

large volumes of gas encountered in air pollution applications, temperature reduction is used.

As the temperature of the VOC-laden stream is reduced, both the volume occupied by the gas and the average kinetic energy of the gas molecules are reduced. Ultimately, the weak attractive forces (van der Waals' forces) between the molecules cause condensation to begin at the dew point temperature, where the partial pressure of the VOC is equal to the vapor pressure of the compound. As condensation begins, the partial pressure of the VOC decreases and further reductions in temperature are needed so that the vapor pressure of the VOC remains equal to the vapor pressure ion.

The gas stream leaving the condensation system will have a reduced VOC partial pressure. Because the condensate and the vapor are assumed to be in equilibrium, this outlet stream partial pressure will be equal to the vapor pressure of the organic compound. The reduction in vapor pressure with decreasing temperature is illustrated for a number of common VOCs in Figure 7-11.

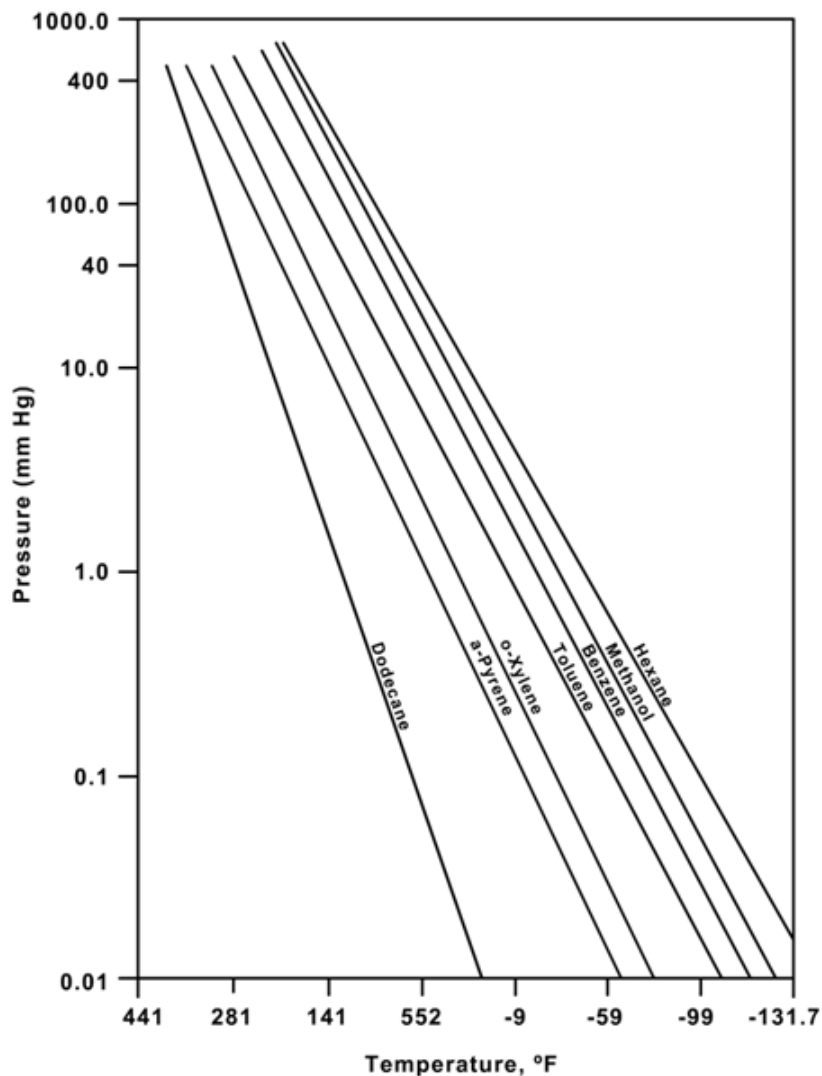


Figure 7-11. Vapor pressures of organic compounds.⁴

Problem 7-1 illustrates how the extent of VOC removal depends on the outlet temperature.

Problem 7-1

What is the maximum toluene removal efficiency possible in a refrigeration-type indirect contact condenser operating at -100°F and 760 mm Hg if the inlet concentration is 10,000 ppm? Use the toluene vapor pressure data provided in Figure 7-11.

Solution:

Step 1. Determine the outlet concentration of toluene by assuming that the outlet gas stream is in equilibrium with the toluene condensate. From Figure 7-11

Outlet partial pressure @ -100°F = 0.015 mm Hg (very approximate)

Step 2. Calculate the outlet concentration of toluene assuming $P_{\text{tol}} = P^*_{\text{tol}}$.

$$y_{\text{tol}} = P^*_{\text{tol}}/P = 0.015\text{mm Hg}/760\text{mm Hg} = 0.0000197$$

Multiply by 10^6 to convert to ppm: $0.0000197(10^6) = 19.7$ ppm

Step 3. Calculate the removal efficiency.

$$\eta = \frac{(\text{In} - \text{Out})}{\text{In}}(100\%) = \frac{10,000 - 19.7}{10,000}(100\%) = 99.8\%$$

Temperature is the only process variable that governs the effectiveness of a condenser. At the operating pressure of the system, the outlet temperature from the condenser determines the maximum removal efficiency. Condensers cannot be used in series like adsorbers or absorbers to further reduce outlet concentration unless the outlet temperature of the second condenser is lower than the previous one.

7.3 Capability and Sizing

Efficiency

The partial pressure of an organic compound leaving a condenser is assumed to be equal to the vapor pressure of that compound at the outlet gas temperature. Accordingly, the efficiency of a condenser can be estimated based on vapor pressure data for the specific compounds being removed. Vapor pressures for various organic compounds are often calculated using the Antoine Equation (Equation 7-1).

$$\text{(Eq. 7-1)} \quad \log_{10}(P^*) = A - \left[\frac{B}{C + t} \right]$$

Where: P^* = vapor pressure in mm Hg
 t = gas temperature in °C
 A, B, C = specific constants for each compound

Antoine constants for a number of compounds are tabulated in Table 7-1 and in standard reference texts such as *Chemical Properties Handbook* (1999), *Lange's Handbook* (1956), and *Hydrocarbon Processing*.

Table 7-1. Antoine constants.

Compound	Range (°C)	A	B	C
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Acetaldehyde	-0.2 to 34.4	8.00552	1600.017	291.809
Acetic acid	29.8 to 126.5	7.38782	1533.313	222.309
Acetone	-12.9 to 55.3	7.11714	1210.595	229.664
Ammonia	-83 to 60	7.55466	1002.711	247.885
Benzene	14.5 to 80.9	6.89272	1203.531	219.888
n-Butane	-78.0 to -0.3	6.82485	943.453	239.711
i-Butane	-85.1 to -11.6	6.78866	899.617	241.942
1-Butene	-77.5 to -3.7	6.53101	810.261	228.066
Butyric acid	20.0 to 150.0	8.71019	2433.014	255.189
Carbon tetrachloride	14.1 to 76.0	6.87926	1212.021	226.409
Chlorobenzene	62.0 to 131.7	6.97808	1431.063	217.55
Chlorobenzene	0 to 42	7.106	1500.000	224.000
Chloroform	-10.4 to 60.3	6.95465	1170.966	226.232
Cyclohexane	19.9 to 81.6	6.84941	1206.001	223.148
n-Decane	94.5 to 175.1	6.95707	1503.568	194.056
1,1-Dichloroethane	-38.8 to 17.6	6.97702	1174.022	229.06
1,2-Dichloroethane	-30.8 to 99.4	7.0253	1271.254	222.927
Dichloromethane	-40.0 to 40	7.40916	1325.938	252.615
Diethyl ether	-60.8 to 19.9	6.92032	1064.066	228.799
Dimethyl ether	-78.2 to -24.9	6.97603	889.264	241.957
Dimethylamine	-71.8 to 6.9	7.08212	960.242	221.667
Ethanol	19.6 to 93.4	8.1122	1592.864	226.184
Ethanolamine	65.4 to 170.9	7.4568	1577.67	173.368
Ethyl acetate	15.6 to 75.8	7.10179	1244.951	217.881
Ethyl acetate	-20 to 150	7.09808	1238.71	217.000
Ethyl chloride	-55.9 to 12.5	6.98647	1030.007	238.612
Ethylbenzene	56.5 to 137.1	6.9565	1423.543	213.091
Ethylene oxide	0.3 to 31.8	8.69016	2005.779	334.765
Formaldehyde	-109.4 to -22.3	7.19578	970.595	244.124
Glycerol	183.3 to 260.4	6.16501	1036.056	28.097
n-Heptane	25.9 to 99.3	6.90253	1267.828	216.823
i-Heptane	18.5 to 90.9	6.87689	1238.122	219.783
1-Heptene	21.6 to 94.5	6.91381	1265.12	220.051
n-Hexane	13.0 to 68.5	6.88555	1175.817	224.867
i-Hexane	12.8 to 61.1	6.86839	1151.401	228.477
1-Hexene	15.9 to 64.3	6.8688	1154.646	226.046
Hydrogen Cyanide	-16.4 to 46.2	7.52823	1329.49	260.418
Methanol	14.9 to 83.7	8.08097	1582.271	239.726
Methyl acetate	1.8 to 55.8	7.06524	1157.63	219.726
Methyl chloride	-75.0 to 5.0	7.09349	948.582	249.336
Methyl ethyl ketone	42.8 to 88.4	7.06356	1261.339	221.969

Nitrobenzene	134.1 to 210.6	7.11562	1746.586	201.783
Nitromethane	55.7 to 136.4	7.28166	1446.937	227.6
n-Nonane	70.3 to 151.8	6.93764	1430.459	201.808
1-Nonane	66.6 to 147.9	6.95777	1437.862	205.814
n-Octane	52.9 to 126.6	6.91874	1351.756	209.10
i-Octane	41.7 to 118.5	6.88814	1319.529	211.625
1-Octene	44.9 to 122.2	6.93637	1355.779	213.022
n-Pentane	13.3 to 36.8	6.84471	1060.793	231.541
i-Pentane	16.3 to 28.6	6.73457	992.019	229.564
1-Pentanol	74.7 to 156.0	7.18246	1287.625	161.33
1-Pentene	12.8 to 30.7	6.84268	1043.206	233.344
1-Propanol	60.2 to 104.6	7.74416	1437.686	198.463
2-Propanol	52.3 to 89.3	7.74021	1359.517	197.527
Propionic acid	72.4 to 128.3	7.71423	1733.418	217.724
Propylene oxide	-24.2 to 34.8	7.01443	1086.369	228.594
Styrene	29.9 to 144.8	7.06623	1507.434	214.985
Toluene	35.3 to 111.5	6.95805	1346.773	219.693
1,1,1-Trichloroethane	-5.4 to 16.9	8.64344	2136.621	302.769
1,1,2-Trichloroethane	50 to 113.7	6.95185	1314.41	209.197
Trichloroethylene	17.8 to 86.5	6.51827	1018.603	192.731
Water	0 to 60	8.10765	1750.286	235.000
m-Xylene	59.2 to 140.0	7.00646	1460.183	214.827
o-Xylene	63.5 to 145.4	7.00154	1476.393	213.872
p-Xylene	58.3 to 139.3	6.9882	1451.792	215.111

Problem 7-2

What is the vapor pressure of ortho-xylene at a temperature of -50°F?

Solution:

Step 1. Convert the temperature to °C.

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8 = -45.6^{\circ}\text{C}$$

Step 2. Calculate the vapor pressure using the Antoine Equation.

For ortho-xylene, A = 7.00154, B = 1476.393, C = 213.872

$$\frac{B}{C+t} = \frac{1476.393}{213.872-45.6} = 8.774$$

$$\log_{10}(\text{P}) = 7.002 - 8.774 = -1.772$$

$$P = 0.0169 \text{ mm Hg}$$

Sizing of Conventional Condensers

Coolant Flow Rate for Direct Contact Condensers

The first step in analyzing any heat transfer process is to set up a heat balance relationship. For a condensation system, the heat balance can be expressed as:

$$\begin{array}{rcccl} & \text{Heat in} & = & \text{Heat out} & \\ \\ \text{Heat required to} & & & & \text{Heat needed to} \\ \text{reduce vapors to} & + & \text{Heat required} & = & \text{be removed by} \\ \text{the final} & & \text{to condense} & & \text{the coolant} \\ \text{temperature} & & \text{vapors} & & \end{array}$$

This heat balance for an indirect contact condenser is written in equation form as:

(Eq. 7-2) $q = m_G C_{pG} (T_{G\text{initial}} - T_{G\text{final}}) + m_C \Delta H_v = LC_{pL} (T_{L\text{initial}} - T_{L\text{final}})$

- Where:
- q = heat transfer rate (Btu/hr)
 - m_G = mass flow rate of gas (lb_m/hr)
 - m_C = mass flow rate of condensate (lb_m/hr)
 - L = mass flow rate of liquid coolant (lb_m/hr)
 - C_p = average specific heat of a gas or liquid (Btu/lb_m °F)
 - T = temperature of streams: G for gas and L for liquid coolant (°F)
 - ΔH_v = heat of condensation or vaporization (Btu/lb_m)

In Equation 7-2, the mass flow rate (m_G) and inlet temperature of the gas stream ($T_{G\text{initial}}$) are set by the process exhaust stream. The temperature of the coolant entering the condenser ($T_{L\text{initial}}$) is also set. The average specific heats (C_p) of both streams and the heat of condensation (ΔH_v) can be obtained from chemistry handbooks. The final gas temperature ($T_{G\text{final}}$) can be calculated based on the required fractional VOC condensation. Only the amount of coolant (L) and its outlet temperature are left to be determined. If either one of these terms is set by process restrictions (i.e., only x pounds per hour of coolant are available, or the outlet temperature of coolant must be below a set temperature), then the other term can be solved for directly. Equation 7-2 may also be written in terms of molar flow rates in which case the specific heats and heat of condensation must also be on a molar basis.

Equation 7-2 has a number of limitations and should be used only for rough estimates. The specific heat of a substance is dependent on temperature, and the temperature throughout the condenser is constantly changing. The C_p of water varies only slightly between 32°F and 212°F (0°C to 100°C), and $C_p = 1$

Btu/lb_m °F is generally accurate enough for air pollution control work. When the concentration of VOC is small, the gas flow rate (m_G) is effectively constant. However, for high VOC concentration, m_G may decrease significantly as condensation increases.

Surface Area of Surface Condensers

In a surface (indirect) condenser, heat is transferred from the vapor stream to the coolant through a heat exchange surface. The rate of heat transfer depends on three factors: (1) total cooling surface available, (2) resistance to heat transfer, and (3) mean temperature difference between condensing vapor and coolant. This can be expressed mathematically by:

(Eq. 7-3)
$$q = U A \Delta T_m$$

- Where:
- q = heat transfer rate (Btu/hr)
 - U = overall heat transfer coefficient (Btu/°F · ft² · hr)
 - A = heat transfer surface area (ft²)
 - ΔT_m = mean temperature difference (°F)

The overall heat transfer coefficient, U, is a measure of the total resistance that heat experiences while being transferred from the hot body to the cold body. In a shell-and-tube condenser, cold water flows through the tubes, causing vapor to condense on the outside surface of the tube wall. Heat, which is always transferred from high to low temperature, is transferred from the vapor to the coolant. Figure 7-12 shows the typical contributions to heat transfer resistance in a shell-and-tube condenser.

Resistances (Figure 7-12) are associated with the condensate, any scale or dirt on the outside of the tube (outside fouling), the tube itself, with any scale or dirt on the inside of the tube (inside fouling), and with the cooling liquid. Each of these resistances must be combined to obtain an overall heat transfer coefficient. The overall heat transfer coefficients shown in Table 7-2 can be used for preliminary estimating purposes.

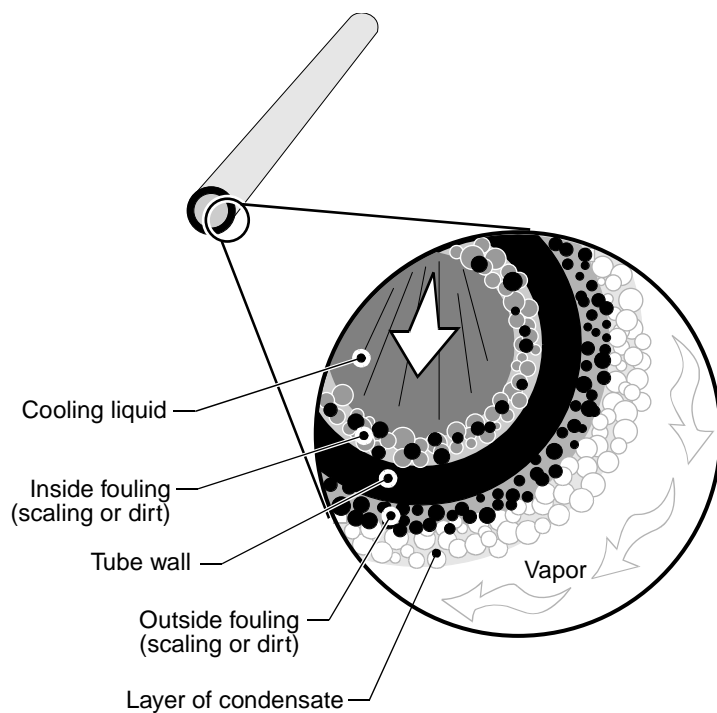


Figure 7-12. Heat transfer resistances.

Table 7-2. Typical overall heat transfer coefficients in tubular heat exchangers.		
Condensing Material (shell side)	Cooling Liquid	U Btu/°F ·ft ² ·hr
Organic solvent vapor with high percent of noncondensable gases	Water	20 - 60
High-boiling hydrocarbon vapor (vacuum)	Water	20 - 50
Low-boiling hydrocarbon vapor	Water	80 - 200
Hydrocarbon vapor and steam	Water	80 - 100
Steam	Feedwater	400 - 1000
Water	Water	200 - 250

In an indirect heat exchanger, the temperature difference between the hot gas and the coolant usually varies throughout the length of the exchanger; therefore, a mean temperature difference (ΔT_m) must be used. The log mean temperature difference can be used for the special cases when the flow of both streams is completely co-current, completely countercurrent, or the temperature of one of the fluids remains constant (as is the case in condensing a pure liquid). The temperature profiles for these three conditions are illustrated in Figure 7-13.

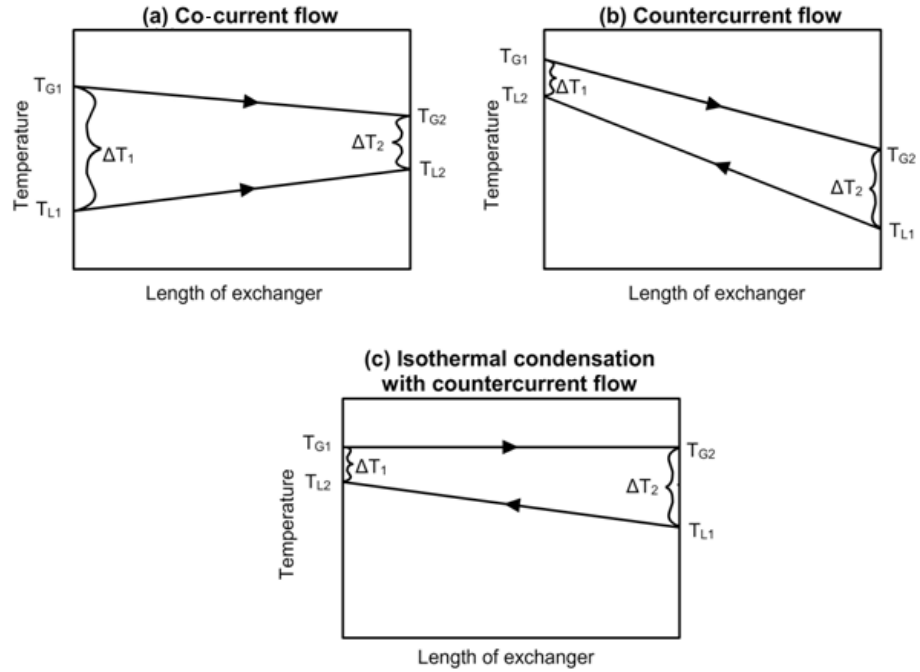


Figure 7-13. Temperature profiles in a heat exchanger for co-current flow, countercurrent flow, and isothermal condensation with countercurrent flow.

The log mean temperature for countercurrent flow can be expressed as:

$$(Eq. 7-4) \quad \Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)}$$

Where: ΔT_{lm} = log mean temperature difference

In co-current flow (Figure 7-13a), the temperature difference is a maximum at the inlet of the exchanger where the inlet gas temperature is a maximum and inlet coolant is a minimum. The temperature difference then decreases continually from the inlet to the outlet of the exchanger. In countercurrent flow (Figure 7-13b), the temperature difference is reasonably constant throughout the exchanger. The exit gas is opposite the inlet coolant liquid, and both temperatures are at their minimum values. At the other end of the exchanger, the inlet gas is opposite the outlet coolant, where both temperatures are at their maximum values. When the inlet gas is pure, the gas temperature does not change once the dew point temperature is reached, as condensation occurs isothermally.

The value calculated from Equation 7-4 is valid for single-pass heat exchangers. For multiple-pass exchangers, a correction factor for the log mean temperature must be included. Values of the correction factor may be found in most heat transfer textbooks. No correction factor is needed for the special case

of isothermal condensation when there is a single component vapor and the gas temperature is equal to the dew point temperature.

In order to size a condenser, Equation 7-3 must be rearranged to solve for the surface area.

(Eq. 7-5)
$$A = \frac{q}{U\Delta T_{lm}}$$

- Where:
- A = surface area of a shell-and-tube condenser (ft²)
 - q = heat transfer rate (Btu/hr)
 - U = overall heat transfer coefficient (Btu/°F · ft² · hr)
 - ΔT_{lm} = log mean temperature difference (°F)

If the incoming vapor stream is above its dew point (superheated), it must first be cooled to its dew point before condensation begins. It is generally considered conservative to size the condenser as if the entire heat load (de-superheating and condensing) were transferred to the condensate.³ In general, the condensate must be subcooled to ensure that it will not re-vaporize. This is accomplished by maintaining a condensate level that covers the bottom tubes in the condenser, a condition known as *flooding*.

Equation 7-5 gives the surface area required to cool the inlet gas and condense the VOC, but does not include subcooling. The area required for the subcooling section, which is generally small compared to the area for condensation, can be treated separately, and the total condenser area can be considered to be the sum of the areas required for condensing and subcooling.

Condensation from a gas containing multiple VOCs is a considerably more difficult problem and several cases may be encountered. In one case, all the components may condense at the final gas temperature. In other cases, some components may condense while others may not. Multicomponent condensation is always nonisothermal. Sensible heat removal or addition must be provided for both the liquid and vapor streams. The composition of both phases changes continually, all of which complicates the design.

In nearly all condensation applications related to air pollution control, the gas to be treated will contain one or more condensable VOCs and noncondensable gas components. Noncondensable gases offer resistance to the rate of condensation in terms of both heat and mass transfer, because the condensable vapor must diffuse to the cool surface. Air is usually the contaminant vapor, but other gases that do not condense or dissolve in the liquid can also affect heat transfer.

Problem 7-3 illustrates the design procedure for the special case in which the gas stream consists of pure acetone. In choosing a heat transfer coefficient, the smallest value should be used to allow as much overdesign as possible.

Problem 7-3

This is a special case in which a vapor stream of pure acetone at 120°C and 14.7 psia is fed to a condenser. The acetone exits the condenser as a subcooled liquid at 30°C. A single-pass, countercurrent-flow, indirect contact condenser is used. The cooling liquid is water that enters at a temperature of 20°C and exits at 40°C. The acetone feed rate is 10 kg/min. Calculate the required cooling water flow rate and estimate the required area of the exchanger. The following data for acetone and water are available:

For acetone:

Condensation temperature at 14.7 psia: 56°C
 Heat capacity of vapor: $C_p = 0.084 \text{ kJ/mol K}$
 Heat capacity of liquid: $C_p = 0.13 \text{ kJ/mol K}$
 Heat of condensation: $\Delta H_v = 25.1 \text{ kJ/mol K}$
 Molecular weight: $M = 58.1 \text{ kg/kmol}$

For water:

Heat capacity of liquid: $C_p = 0.0754 \text{ kJ/mol K} = 4.19 \text{ kJ/kg K}$

Heat transfer coefficients:

Cooling superheated acetone vapor: $U = 40 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F}$
 Condensing acetone: $U = 100 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F}$
 Subcooling acetone liquid: $U = 50 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F}$
 Conversion factor: $1 \text{ Btu/hr ft}^2 \text{ }^\circ\text{F} = 0.34 \text{ kJ/min m}^2$

Solution:

Step 1. Calculate the molar flow rate of acetone.

Molar flow rate:

$$\begin{aligned} m &= (10 \text{ kg/min}) / 58.1 \text{ kg/kmol} \\ &= 0.172 \text{ kmol/min} \\ &= 172 \text{ mole/min} \end{aligned}$$

Step 2. Calculate the total amount of heat that must be removed from the acetone in three steps: a) cooling the superheated vapor from 120°C to the saturation temperature of 56°C; b) condensing the acetone isothermally at 56°C; c) subcooling the liquid acetone from 56°C to 30°C.

$$\begin{aligned} q &= m [C_{pG}(120 - 56) + \Delta H_v + C_{pL}(56 - 30)] \\ &= 172 [0.084(64) + 25.1 + 0.13(26)] \\ &= 172 [5.4 + 25.1 + 3.4] \\ &= 5.83 \times 10^3 \text{ kJ/min} \end{aligned}$$

Step 3. Calculate the flow rate of water needed to absorb the total amount of heat to be removed from Step 2.

$$\begin{aligned}
 q &= mC_{pL}(40\text{K} - 20\text{K}) \\
 5.83 \times 10^3 \text{ kJ/min} &= m(4.19 \text{ kJ/kg K})(20 \text{ K}) \\
 m &= (5.83 \times 10^3 \text{ kJ/min}) / (4.19 \text{ kJ/kg K})(20 \text{ K}) \\
 &= 69.6 \text{ kg/min}
 \end{aligned}$$

To calculate the area of the exchanger, divide it into three parts:

Step 4. Calculate the area of the de-superheater.

Removal of superheat:

$$\begin{aligned}
 q &= mC_{pG}(120 - 56) \\
 &= 172(0.084)(120 - 56) \\
 &= 0.93 \times 10^3 \text{ kJ/min}
 \end{aligned}$$

Water temperature change over de-superheater:

$$\begin{aligned}
 \Delta T_{\text{H}_2\text{O}} &= q/m C_p \\
 &= 0.93 \times 10^3 / 69.6(4.19) \\
 &= 3.2 \text{ K}
 \end{aligned}$$

Log mean temperature difference:

$$\begin{aligned}
 \Delta T_{\text{lm}} &= (\Delta T_2 - \Delta T_1) / \ln(\Delta T_2 / \Delta T_1) \\
 &= [(120 - 40) - (56 - 36.8)] / \ln[(120 - 40) / (56 - 36.8)] \\
 &= (80 - 19.2) / \ln(80 / 19.2) \\
 &= 42.8 \text{ K}
 \end{aligned}$$

Area:

$$\begin{aligned}
 A &= q / U \Delta T_{\text{lm}} \\
 &= (0.93 \times 10^3) / (40)(0.34)(42.8) \\
 &= 1.6 \text{ m}^2
 \end{aligned}$$

Step 5: Calculate the area required for condensation.

Acetone condensation:

$$q = m\Delta H_v = 172(25.1) = 4.32 \times 10^3 \text{ kJ/min}$$

Water temperature change over condenser:

$$\begin{aligned}
 \Delta T_{\text{H}_2\text{O}} &= q/mC_p \\
 &= 4.32 \times 10^3 / 69.6(4.19)
 \end{aligned}$$

$$= 14.8 \text{ K}$$

Log mean temperature difference:

$$\begin{aligned}\Delta T_{lm} &= [(56 - 36.8) - (56 - 22)] / \ln[(56-36.8)/(56 - 22)] \\ &= (19.2 - 34) / \ln(19.2 - 34) \\ &= 26.2 \text{ K}\end{aligned}$$

Area:

$$\begin{aligned}A &= q / U \Delta T_{lm} \\ &= (4.32 \times 10^3) / (100)(0.34)(26.2) \\ &= 4.84 \text{ m}^2\end{aligned}$$

Step 6: Calculate the area of the subcooler.

Subcooling liquid:

$$\begin{aligned}q &= m C_{p,l}(56 - 30) \\ &= 172(0.13)(56 - 30) \\ &= 0.58 \times 10^3 \text{ kJ/min}\end{aligned}$$

Water temperature change over subcooler:

$$\begin{aligned}\Delta T_{H_2O} &= q / m C_p \\ &= 0.58 \times 10^3 / (69.6)(4.19) \\ &= 2 \text{ K}\end{aligned}$$

Log mean temperature difference:

$$\begin{aligned}\Delta T_{lm} &= [(56 - 22) - (30 - 20)] / \ln[(56 - 22)/(30 - 20)] \\ &= 19.7 \text{ K}\end{aligned}$$

Area:

$$\begin{aligned}A &= q / U \Delta T_{lm} \\ &= (0.58 \times 10^3) / (50)(0.34)(19.7) \\ &= 1.7 \text{ m}^2\end{aligned}$$

Step 7: Check overall H₂O temperature change.

$$\begin{aligned}\Delta T &= \Delta T_1 + \Delta T_2 + \Delta T_3 \\ &= 3.2 + 14.8 + 2 \\ &= 20\end{aligned}$$

Step 8: Calculate the total area.

$$\begin{aligned} A &= A_1 + A_2 + A_3 \\ &= 1.6 + 4.84 + 1.7 \\ &= 8.14 \text{ m}^2 \end{aligned}$$

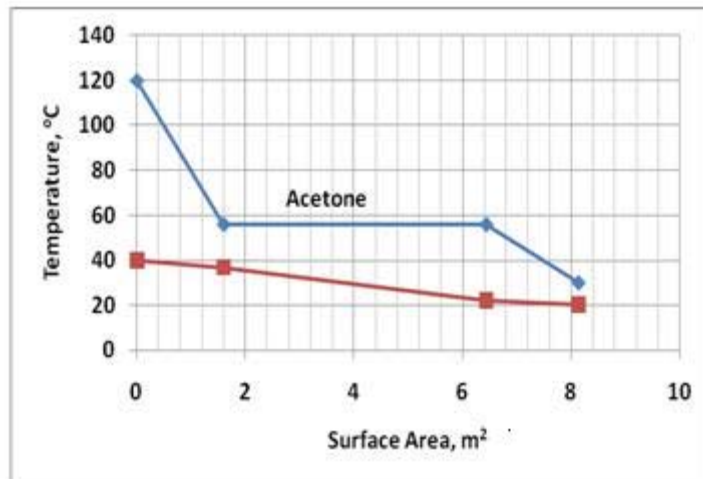


Figure 7-14. Graphical representation of Problem 7-3.

Review Exercises

Types and Components of Condensers

1. A shell-and-tube condenser using chilled water usually reduces the gas stream temperature to _____.
 - a. 80°F to 150°F
 - b. 40°F to 80°F
 - c. < -100°F
 - d. None of the above

2. A refrigeration condenser system usually reduces the gas stream temperature to _____.
 - a. < 40°F
 - b. < -50°F
 - c. < -320°F
 - d. None of the above

3. A precondenser is often used in refrigeration and cryogenic systems to _____.
 - a. prevent frost buildup on the heat exchanger surfaces of the main contacting chamber
 - b. minimize water-organic condensate separation problems
 - c. remove the organics prior to the removal of water vapor and other contaminants at high concentration
 - d. Answers a and b

4. A cryogenic condenser system usually reduces the gas stream temperature to _____.
 - a. -40°F to 80°F
 - b. -50°F to -100°F
 - c. -50 to -320°F
 - d. None of the above

Operating Principles of Condensers

5. The gas stream exiting a condensation system has an organic vapor partial pressure _____.
 - a. equal to the vapor pressure of the compound at the exit gas temperature

- b. equal to 10% of the partial pressure of the organic compound in the inlet gas stream
 - c. approximately 10% of the vapor pressure of the compound at the exit gas temperature
 - d. equal to the vapor pressure of water
6. Condensation systems are generally used for_____.
- a. low-concentration, multicomponent organic vapors
 - b. high-concentration, multicomponent organic vapors
 - c. low-concentration, single-component organic vapor
 - d. high-concentration, single-component organic vapor

Capability and Sizing of Condensers

7. Use the Antoine Equation to calculate the vapor pressure of ethyl acetate at 40°F, given the Antoine Constants $A = 7.09808$, $B = 1238.71$, and $C = 217.00$.
8. What is the maximum ethyl acetate removal efficiency in a direct contact condensation system operating at 40°F if the inlet concentration is 500 ppm?

Review Answers

Types and Components of Condensers

1. A shell-and-tube condenser using chilled water usually reduces the gas stream temperature to _____.
 - b. 40°F to 80°F
2. A refrigeration condenser system usually reduces the gas stream temperature to _____.
 - b. < -50°F
3. A precondenser is often used in refrigeration and cryogenic systems to _____.
 - a. prevent frost buildup on the heat exchanger surfaces of the main contacting chamber
4. A cryogenic condenser system usually reduces the gas stream temperature to _____.
 - c. < -50°F to -320°F

Operating Principles of Condensers

5. The gas stream exiting a condensation system has an organic vapor _____.
 - a. equal to the vapor pressure of the compound at the exit gas temperature
6. Condensation systems are generally used for _____.
 - d. high-concentration, single-component organic vapor.

Capability and Sizing of Condensers

7. Use the Antoine Equation to calculate the vapor pressure of ethyl acetate at 40°F, given the Antoine Constants $A = 7.09808$, $B = 1238.71$, and $C = 217.00$.

Solution:

Step 1. Convert the temperature to °C.

$$^{\circ}\text{C} = (^{\circ}\text{F} - 32) / 1.8 = 4.4^{\circ}\text{C}$$

Step 2. Calculate the $\log_{10} P$ using the Antoine Equation (Equation 7-1).

$$\log_{10} P^* = 7.09808 - \left[\frac{1238.71}{217.00 + 4.4} \right] = 1.5010$$

Step 3. Calculate the vapor pressure.

$$P^* = 10^{1.50} = 31.7 \text{ mm Hg}$$

8. What is the maximum ethyl acetate removal efficiency in a direct contact condensation system operating at 40°F if the inlet concentration is 500 ppm?

Solution:

Step 1. Use the vapor pressure for ethyl acetate at 40°F calculated in Review Exercise 7.

$$P^* = 31.7$$

Step 2. Determine the removal efficiency.

$$\eta = \left(\frac{\text{in} - \text{out}}{\text{in}} \right) 100\% = \left(\frac{500 - 31.7}{500} \right) (100) = 93.7\%$$

References

1. Barbour, W., et al. *OAQPS Control Cost Manual*, 4th ed., Supplement 2; EPA 450/3-90-006b; October 1992.
2. Bell, K.J.; Ghaly, M.A. *An Approximate Generalized Design Method for Multicompartment/Partial Condensers*; American Institute of Chemical Engineers Symposium Series; American Institute of Chemical Engineers: New York, 1972; Vol. 69, No. 131, pp 72-79.
3. Henzler, G.W.; Sameshima, G.T. *Cryogenic Vapor Recovery of VOC Emissions*; Paper 93-TP-51.02, presented at the 86th Annual Meeting and Exhibition of the Air & Waste Management Association, Denver, CO, June 13-18, 1993; Liquid Carbonic Industries Corporation: Northville, MI, 1993.
4. Perry, J.H., Ed. *Chemical Engineers Handbook*, 5th ed.; McGraw Hill: New York, 1973.
5. Spencer, R.J. *Cryogenic Condensation and Recovery of VOCs*; Paper 92-114.10, presented at the 85th Annual Meeting & Exhibition of the Air & Waste Management Association, Kansas City, MO, June 21-16, 1992; Liquid Carbonic Corporation: Chicago, 1992.