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Key design considerations for vacuum process condensers

The crude oil refining and petrochemical industries make extensive use of condensers that operate under vacuum (i.e., below atmospheric pressure). Distillation is the most common process using these condensers, either as a process precondenser ahead of an ejector system, or as an intercondenser within an ejector system.

Proper operation of a vacuum condenser is essential for distillation process throughput and/or fractionation. When these condensers perform poorly, it can become a major issue for the refiner or petrochemical plant because profit loss is significant when distillation product quality is inferior, or when throughput is scaled down to maintain process quality. Vacuum condenser design is challenging because available software for modeling performance is inadequate and unreliable. Therefore, reliance on know-how and proven experience from ejector and process vacuum technology providers is important.

Here, important considerations are proposed for developing purchase specifications, evaluating designs, selecting an appropriate supplier and considering what may be causing under-performance.

Vacuum condenser. Externally, a vacuum condenser may appear to be an ordinary shell and tube heat exchanger (S&THE). It has similar construction features that follow Tubular Exchanger Manufacturer Association (TEMA) or American Petroleum Institute (API) 660 guidelines; however, the internal configuration is different due to its operation under a vacuum, its condensing of vapors with noncondensibles and its handling of miscible condensates to ensure correct vapor-liquid equilibrium

and to permit continual extraction of noncondensibles (FIG. 1).

Several distinct differences between vacuum condensers and conventional S&THEs exist:

- Open areas above the tube bundle that permit flow distribution and reduce pressure loss
- Lack of conventional flow directing segmental or double-segmental baffling, which reduces pressure loss and appropriately manages vapor-liquid equilibrium
- Extraction of noncondensible gases within a tube bundle (FIG. 2).

Heat release data. To properly design a vacuum condenser, it is important to understand the compositional makeup of the process load and shape of the heat release curve (i.e., how condensing takes place as the process vapors are cooled). Often, the shape of the heat release curve informs the engineer designing or evaluating the design of a vacuum condenser about what elements are critical to ensure proper performance. The effect of noncondensible loading is always important.

Two important considerations should be taken into account for noncondensible



FIG. 1. Process vacuum condenser serving a distillation process for nylon intermediate production.



FIG. 2. Cross-section of a TEMA "X" shell vacuum condenser with a longitudinal baffle for venting noncondensibles.

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gas loading in a vacuum condenser. The first is suppression of efficient heat transfer caused by the gases that lower the overall heat transfer coefficient. The greater the percentage of noncondensible gases in the process load, the lower the overall heat transfer coefficient. As vapors condense along the heat release curve, the percentage of noncondensibles increases correspondingly.

Secondly, the presence of noncondensible gases will lower the effective log mean temperature difference (LMTD). For example, a pure component will condense isothermally and, therefore, will have a maximum effective LMTD. Alternatively, under the same conditions-but with 10% of the load being noncondensible gas, such as air-the LMTD is lower. Both a lower LMTD and overall heat transfer

coefficient result in greater surface area for the vacuum condenser.

FIG. 3 illustrates an example where pure steam is condensed, and the LMTD and overall heat transfer rate are compared under varying amounts of air loading. In a comparison of the case of pure steam without air loading, the required vacuum condenser surface area is 150 ft². A case with 750 pph of air load along with steam will require 275 ft².

Heat release data for crude oil refining processes—whether for vacuum distillation column, ultra-low-sulfur diesel (ULSD), lube oil fractionation or hydrodesulfurization service—are usually given with a grouping of lighterend cracked gases that are classified as noncondensible gases, steam (when stripping or fired heater velocity steam applies) and petroleum fractions or



FIG. 3. Effect on LMTD and heat transfer rate from increases in noncondensible loading. Chart shows 2,500 lb/hr of steam condensing with differing air loads. Pressure is 3 psia and cooling water is 80°F at inlet and 100°F at outlet.





pseudocomponents with varying normal boiling points.

An example for a ULSD process is detailed in TABLE 1. Inspection of the heat release curve (FIG. 4) infers that the pseudocomponent petroleum fractions condense along the cooling curve, as might be anticipated. A critical consideration is that vaporliquid equilibrium (and, therefore, heat release profile) assumes that the vapors and liquids remain in contact and at the same temperature throughout the heat exchanger. The pseudocomponents form miscible condensates. The amount of a pseudocomponent condensed at a given temperature along the cooling curve will depend on its partial pressure, which is a function of its vapor pressure and mole fraction in the condensate (i.e., Raoult's Law).

For lower-normal-boiling-point pseudocomponents with greater vapor pressures and generally lower molecular weights, a lower mole fraction in condensate will drive greater condensation. Therefore, it is imperative that the heat exchanger design permit the formed condensate and vapors to remain together throughout the cooling curve; otherwise, predicted vapor-liquid equilibrium will not be achieved. If the condensate is not kept in contact with the vapors due to baffling, which separates the vapors from condensate, then more pseudocomponents will remain in the vapor phase and will not be recovered as condensate, due to the mole fraction in the liquid being greater. This critical process equipment must condense the maximum amount of vapor.

Consider two condenser configura-

TABLE 1. Process loading to ULSD process vacuum precondenser Heat release curve Component Measurement, lb/hr Steam 300 Noncondensible gases 60 52,000 Pseudocomponents Normal boiling point breakdown 150°F-200°F 18,400 200°F-300°F 19,500 300°F-400°F 6,500 400°F-500°F 6,000 > 500°F 1,600

tions for the aforementioned ULSD service: a properly designed vacuum condenser keeping the vapors and condensate together in a TEMA "X" shell configuration; and a segmentally baffled unit with four cross-passes (TEMA "E" shell) where condensate is removed at each cross-pass and is no longer available in subsequent passes.

In the "E" shell case, condensate is removed at 250°F, 180°F and 150°F due to flow configuration. The objective is to condense the process load from 300°Fto 110°F.

Two important definitions for the method of condensation and vapor-liquid equilibrium include:

- **Integral condensation:** When vapors and condensate remain together throughout the heat release curve
- **Differential condensation:** When condensate is removed at intervals along the heat release curve and is no longer available in subsequent intervals.

Note: Process simulations regarding vapor-liquid equilibrium and heat release curves are based on integral condensation (TABLE 2). A rigorous stepwise analysis will be required for differential condensation. This analysis will apply when conventional baffling is used.

Note the variation in exit conditions between integral and differential condensation (FIG. 5). Differential, in this case, resulted in approximately three times the mass and volumetric flowrate exiting the condenser as vapor. Loading to an ejector downstream of the vacuum condenser is also changed by roughly three orders of magnitude.

Consider the effects if a vacuum condenser for the proposed case had been designed for optimum heat transfer using segmental or double-segmental baffling, where differential condensation is applied. Use of the process simulation heat release and vapor-liquid equilibrium information would cause incorrect performance. Process operating pressure would rise due to greater volumetric flowrate, causing higher pressure drop across the condenser. This would also result in higher vapor carried from the condenser to the ejector downstream. Heat transfer companies that specialize in optimum performance may not configure the condenser appropriately to balance **TABLE 2.** Vacuum condenser process conditions at inlet and outlet comparing integral to differential condensation

| | | Outlet conditions | | |
|---|--|-----------------------|---------------------------|--|
| Inlet conditions | _ | Integral condensation | Differential condensation | |
| Temperature, °F | 300 | 110 | 110 | |
| Steam, Ib/hr | 301 | 41 | 118 | |
| Noncondensible gas, lb/hr | 60 | 60 | 60 | |
| Pseudocomponents vapor phase, Ib/hr | 52,000 | 398 | 1,470 | |
| Pseudocomponents liquid phase, lb/hr | 0 | 51,602 | 50,530 | |
| | Total gas/vapor flowrate, lb/hr | 499 | 1,648 | |
| | Heat Exchange Institute water vapor equivalent, lb/hr | 310 | 980 | |
| | Volumetric flowrate, ft ³ /sec | 30.4 | 86.4 | |
| | | | | |

TABLE 3. Impact of pseudocomponent characterization on LMTD

| | Pseudocomponents, % | | | | |
|----------------------------|---------------------|-----------------------|------------------------|----------------------|--|
| Normal boiling point range | Design | Greater light ends | Greater middle ends | Typical breakdown | |
| 150°F-200°F | 35 | 40 | 9 | 15 | |
| 200°F-300°F | 37.5 | 33 | 64 | 25 | |
| 300°F-400°F | 12.5 | 12.5 | 12.5 | 25 | |
| 400°F-500°F | 11.5 | 11.5 | 11.5 | 25 | |
| > 500°F | 3 | 3 | 3 | 10 | |
| Effective LMTD, °F | 74 | 66 | 98 | 132 | |



FIG. 5. Schematic representation of differential and integral condensation.

efficient heat transfer with low pressure loss; nor may they be able to maintain vapors and liquid in contact throughout the cooling (condensing) curve. In cases where pressure rises above design, field operating measurements may appear to indicate that the process simulation is incorrect; however, in reality, the vacuum condenser configuration is incorrect.

Pressure drop is also important. It has a multiplier effect. Greater pressure drop will lower the LMTD, resulting in greater condenser surface area requirements. It will also reduce the amount of vapors

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Assessing

and

pseudocomponent breakdown of a

hydrocarbon mixture require diligence.

This breakdown is generally performed

via a distillation assay, where boiling

point range is determined in a lab for the

crude oil. Too often, this lab assessment

can be measurably off due to actual

distillation column performance caused

by stripping efficiency, vapor velocities

and crude slate variation. It is common

characterizing

condensed, thereby increasing the vapor loading to equipment downstream of the vacuum condenser. Consider the aforementioned example: if vapor side pressure drop is 0.3 psi, then the LMTD is 74°F, and 499 lb/hr exit the condenser as load to the downstream equipment. If the pressure drop were 1.2 psi, then the LMTD is 67°F, and 800 lb/hr exit the condenser as load to the downstream equipment.

TEMA "X" crossflow with longitudinal baffle Inlet vano Uncondensed vapor and noncondensible dases Condensate TEMA "X" crossflow with external separation Inlet vapor TEMA "E" shell Uncondensed vapor and With combination of large section for noncondensible gases cross and segmental baffling for final Uncondensed vapor and cooling and extraction of gases noncondensible gases Inlet vapor Condensate FIG. 6. Shell-side flow arrangements for vacuum condensers.

to observe that condensable hydrocarbon exiting a vacuum distillation column is meaningfully above design mass flowrate, and that a greater number of highernormal-boiling-point pseudocomponents are present than the design basis. TABLE 3 shows how variation in pseudocomponent distribution affects the LMTD as a result of changes to the heat release curve, using the ULSD example.

A similar situation can be found in petrochemical industries, where process loads are mixtures of petrochemicals, and where steam may form miscible, non-ideally miscible and immiscible condensates, or where chemical reactions occur. A common challenge is found in alcohols, acids, esters or urea processes, where the process load to the vacuum condenser requires integral condensation. Differential condensation, such as that which results from the use of baffling for improving heat transfer, will materially alter the heat release and vapor-liquid equilibrium results.

Considerations when specifying or evaluating process vacuum condensers include:

- 1. Conservatively estimate noncondensible gas load. This is particularly important for refining services where crude slate may vary, or where cracked gases from fired heaters cannot reliably be predicted. **Caution:** The most common cause of poor performance is incorrectly specifying noncondensible gas loading.
- 2. Understand the compositional makeup of the process load and assess:
 - Are condensates ideally miscible, immiscible or non-ideally miscible?
 - Are gases soluble in condensate, and to what degree should that be considered?
 - Are the chemical reactions between vapors, gases and condensate exothermic or endothermic?

In refining services, accurate process simulation of pseudocomponents is challenging due to the varied crude slates processed, as well as to the assumption of distillation column stripping efficiency. It is important to carefully and conservatively specify the condensable pseudocomponent loading:

- Use a molecular weight specific to each normal boiling point pseudocomponent. Do not use a constant and equal molecular weight for all pseudocomponents.
- 2. Run sensitivities to characterize the pseudocomponents and ensure the safest way to specify the pseudocomponents. A greater percentage of higher-normalboiling-point pseudocomponents will generally condense more quickly. Alternatively, a greater percentage of lower-normalboiling-point pseudocomponents will result in less condensing.
- 3. Bring the vacuum equipment supplier into the discussion early to understand how changes in characterization will impact design.
- 4. Evaluate the appropriateness of the condenser configuration to ensure that vapor-liquid equilibrium or chemical reaction equilibrium is achieved to match the process simulation for heat and material balance (heat release curve).
- 5. Provide at least two isobaric heat and material balance simulations, one at the inlet pressure to the condenser and another at

80%–90% of the inlet pressure.

- 6. Evaluate if condensate should be at the vapor outlet temperature.
- 7. Perform sensitivity analyses to understand how outlet compositional flow varies with outlet pressure and temperature. **Caution:** A process vacuum condenser is always part of an overall vacuum producing system. Never evaluate a process vacuum condenser in isolation. Evaluate the complete system, including interdependencies between the vacuum condenser and system components both upstream and downstream of it.
- 8. If commercially available software or software from research institutions is used, apply a rigorous analysis to validate pressure drop assumptions and outlet composition tied to flow arrangement. **Note:** At present, no reliable commercial software or software from research organizations are available.

Recommendations. Process vacuum condensers are specialized heat exchangers. How they are designed, and what factors should be kept

in mind to ensure that the vacuum system (including condensers and ejectors) performs properly, are key to successful operation.

These condensers are critical efficient and reliable process for performance. A first step toward successful integration of this type of heat exchanger into a refining or chemical industry process is respect for the important differences between vacuum condensers and process S&THEs. This integration should be followed by a rigorous and deliberate analysis of the design, where coupling heat transfer and mass transfer with low pressure loss configuration is paramount.

Process vacuum condensers are used successfully throughout the industry. However, when critical design considerations are not thoroughly analyzed, underperformance and economic loss are certain to result. **HP**



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