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Note: Two-Enthalpy Feed for Distillation with Vapor Feed and Refrigerated Condenser

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Abstract: The use of two-enthalpy feed, which involves splitting the feed, condensing part of it, and sending both the liquid and vapor streams to the distillation column, is explored for columns that have a vapor feed and require refrigeration in the column condenser. The use of two-enthalpy feed can reduce both capital and operating costs compared to condensing all the feed. Compared to use of partial cooling and use of a two-phase feed, two-enthalpy feed reduces the condenser heat duty, but the feed cooling occurs at a lower temperature.

Keywords: Distillation, refrigeration, two-enthalpy-feed

INTRODUCTION

When distilling systems that contain compounds with low boiling points it is common to operate at elevated pressures to raise the temperature in the condenser and allow use of a less expensive coolant. Despite this, refrigeration is often required in the condenser. When refrigeration is required, it is common to totally or partially condense the entire feed to reduce the condenser cooling load Q_c (1,2). However, this procedure increases both the reboiler heat duty Q_R and the total cooling load $(Q_c + Q_{F,cond})$, although much of the cooling load $Q_{F,cond}$ used to condense the feed is done at a higher temperature than the reflux and therefore is less expensive

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than condensing the reflux. In this note we will show that when the fresh feed is a vapor and refrigeration is required in the condenser use of the two-enthalpy feed system, which splits the feed before condensing part of it and then feeds the liquid and vapor to different stages in the column (3–5), saves both operating and capital costs compared to condensing all the feed. Compared to cooling the feed to a two-phase mixture, the two-enthalpy feed reduces the condenser duty significantly, but cooling the liquid portion of the two-enthalpy feed occurs at a lower temperature. Previously, we showed that the two enthalpy feed can be very favorable with liquid feeds when the reboiler operates at a high temperature (3), with vapor feeds when the diameter is largest at the top of the column (4), and with liquid feeds when the diameter is largest at the bottom of the column (5). This note explores a case for use of two-enthalpy feed that was not considered in detail previously (3–5).

DISTILLATION SYSTEMS

To simplify the discussion, we will assume that feed enters the feed condenser as a saturated vapor. This assumption is easily relaxed. The base case distillation system with a refrigerated partial condenser, a partial reboiler, and condensation of all or part of the vapor feed is shown in Fig. 1.

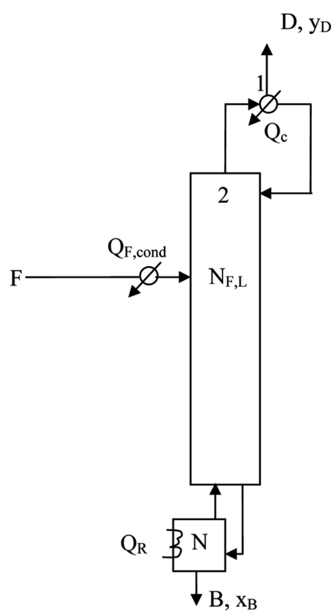

Figure 1. Base cases condensing all or part of the vapor feed.

The energy balance for Fig. 1 is,

$$Fh_F + Q_{F,cond} + Q_c + Q_R = DH_D + Bh_B \tag{1}$$

H and h are vapor and liquid enthalpies, respectively.

In the two-enthalpy feed system the feed is split and only part of the feed is condensed (Fig. 2). For binary systems it is easy to show that the liquid feed should be located above the vapor feed as shown in Fig. 2 (3). Simulations for multicomponent systems agree with this placement of the feeds (4,5). If the feed, distillate, and bottoms purities are identical in Figs. 1 and 2, then the enthalpy values H_D, h_B, and h_F (z_i, T_{cond}) will be identical for Figs. 1 and 2. Then the energy balance for the two-enthalpy feed system in Fig. 2 is,

$$\begin{aligned} Fh_F + Q_{F,cond,2\text{-Enth-F}} + Q_{c,2\text{-Enth-F}} \\ + Q_{R,2}\text{-Enth-F} = DH_D + Bh_B \end{aligned} \tag{2}$$

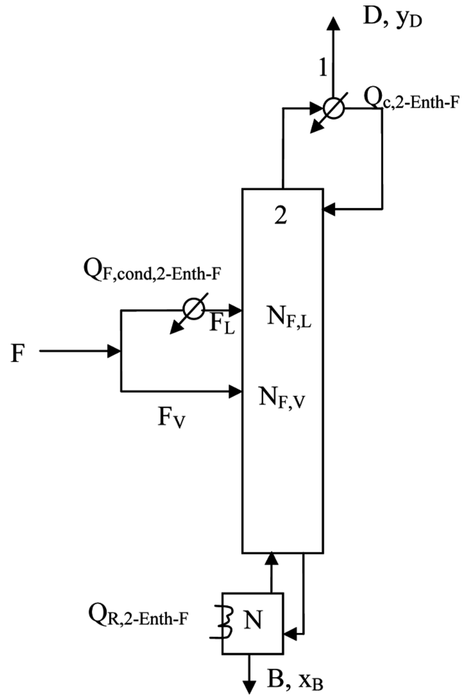

Figure 2. Two-enthalpy feed system for vapor feed.

where

$$Q_{F,cond-Enth-F} = -f_{liq}F[H_F(y_i = z_i, T_{vap}) - h_F(x_i = z_i, T_{cond})] \quad (3)$$

Where z_i is the mole fraction in the feed and f_{liq} is the fraction of the feed that is liquefied in the feed condenser.

For a binary system it is easy to show that for an equilibrium curve without any inflection points there is a pinch at the liquid feed location in Fig. 1 and there are two possible pinch points for Fig. 2 (3,4). If f_{liq} is not too far from 1.0, the controlling pinch for Fig. 2 will remain at the liquid feed stage. For small values of f_{liq} the controlling pinch switches to the vapor feed stage. Although more complicated, multicomponent systems also keep the controlling pinch unchanged for values of f_{liq} near 1.0. Thus, for values of f_{liq} near 1.0 the minimum external reflux ratio $(L/D)_{min}$ will be the same for total condensation of the feed and for the two-enthalpy feed. If we operate at the same multiplier of the minimum reflux ratio, then L/D values will be the same and $Q_c = Q_{c,2\text{-Enth-F}}$. If f_{liq} is reduced too much, the pinch point switches to the vapor feed and the reflux ratio and $|Q_{c,2\text{-Enth-F}}|$ both increase. Since the purpose of the operation is to reduce the required refrigeration, this is undesirable. Appropriate values for f_{liq} to keep $Q_{c,2\text{-Enth-F}}$ constant can easily be determined by simulation. If the feed is cooled to form a two-phase mixture, the column pinch point changes and $|Q_{c,2\text{-phase-F}}|$ increases compared to the total condensation of the feed.

The calculated column diameter almost always varies along the column, and often the largest calculated diameter is at the bottom of the column. In this case, the column diameter can usually be reduced by boiling up less vapor in the bottom of the column and adding vapor higher up the column. This is exactly what the two-enthalpy feed system in Fig. 2 does (5). Use of a two-enthalpy feed system will normally result in more stages (3–5) than with total condensation of the feed, but the column volume and cost will usually decrease because a smaller column diameter is required.

RESULTS

Sample calculations were done for a distillation column separating HCl from vinyl chloride and dichloroethane, which is part of a process to produce vinyl chloride (1). The column operates at 12.0 atm., and has a partial reboiler and a partial condenser producing a vapor distillate. The simulations were done with Aspen Plus using the NRTL correlation for

VLE. The optimum feed stages were determined by maximizing distillate purity with a constant total number of stages N at a constant value of Q_c. Either Q_c or N were varied to obtain the desired HCl purity in the distillate of $y_{D,HCl} = 0.99978$ or better. Simulations for total condensation of the feed and for the two-enthalpy feed systems were done with $Q_c = Q_{c,2\text{-Enth-F}} = -1156$ kW which corresponds to $L/D = 0.423$. The simulations with a vapor feed and with two-phase feeds (Table 1) had to use larger values of $|Q_{c,2\text{-phase-F}}|$ to obtain the desired distillate purity. The feed

Table 1. Results for base cases (Fig. 1) and two-enthalpy feed (Fig. 2). Pressure is 12.0 atm, partial condenser is stage 1 and the partial reboiler is stage N. The optimum feed stages are: N_F = single feed, $N_{F,L}$ = liquid feed, and $N_{F,V}$ = vapor feed. Distillate flow rate = 1600 lbmol/hr. Minimum value of $y_{D,HCl} = 0.99978$. Q_c, Q_R, and $Q_{F,cond}$ are energy loads in the condenser, reboiler, and feed cooler/condenser, in kW. Notation: dia = maximum calculated diameter, m; tray = tray at which maximum diameter occurred; A = maximum calculated column area, m^2; Vol = column volume, $m^3 = A(N–2 + 1)$(tray spacing) where N–2 is the number of trays, +1 is for disengagement space for liquid and vapor, and tray spacing of 24 inch = 0.6096 m

Base cases: All liquid, two-phase and all vapor feeds ($y_{D,HCl} = 0.99978$):

f_{liq}	N_F	N	dia	A	Vol	tray	Q_R	Q_c	$Q_{F,cond}$	T_f, K
1.0	5	10	2.34	4.31	23.7	9	7255	−1156	−15,152	278.1
.7037	5	10	1.98	3.08	16.9	5	4846	−2080	−11819	301.9
.5	5	10	1.82	2.59	14.2	5	3404	−3750	−8707	330.0
.5	6	11	1.81	2.59	15.8	6	3114	−3460	−8707	330.0
.3276	5	10	2.03	3.23	17.7	5	2656	−5800	−5910	358.6
0	5	10	2.56	5.16	28.3	4	1997	−11050	0	403.8

Two-enthalpy feeds ($Q_{c,2\text{-Enth-F}} = -1156$ kW, $T_{F,liq} = 278.1$ K, $T_{F,vap} = 403.8$ K) [Decrease in column volume and $|Q_{F,cond,2\text{-Enth-F}}|$ are compared to liquid base case ($f_{liq} = 1$)]:

f_{liq}	$N_{F,L}$	$N_{F,V}$	N	dia	A	Vol	tray	Q_R	$Q_{F,cond,2\text{-Enth-F}}$	$y_{D,HCl}$	Vol decr (%)	$Q_{F,cond,2F}$ decr (%)
.9	5	7	11	2.13	3.55	21.6	10	5741	−13,637	0.99986	8.6	10
.8	5	7	11	1.88	2.77	16.9	10	4225	−12,122	0.99981	28.7	20
.78	5	7	11	1.82	2.61	15.9	10	3921	−11,819	0.99978	32.8	22
.75	5	7	12	1.74	2.38	16.0	11	3468	−11,364	0.99984	32.4	25
.70	5	8	12	1.81	2.57	17.3	8	2709	−10,607	0.99978	27.0	30
.65	5	8	14	1.72	2.33	18.5	8	1953	−9,849	0.99981	22.0	35
.60	Not possible with $Q_c = -1156$ kW. Obtain $y_{D,HCl} = 0.99489$ with 50 stages.											

consisted of 1600 lbmole/hr of HCl, 1600 lbmole/hr of vinyl chloride, and 1067 lb moles/hr of dichloroethane for a total feed of 4267 lbmole/hr. The fresh feed was a saturated vapor at 403.8 K while the totally condensed feed leaving the feed condenser was a saturated liquid at 278.1 K. The two-phase feeds were in-between these two temperatures (Table 1). Column diameters are calculated at 80% of flooding and a tray spacing of 24 inch = 0.6096 m with the method developed by Fair (6). The pressure drop across the trays is assumed to be negligible. The operating conditions and results for the distillation systems are given in Table 1.

The base cases in Table 1 have $N = 10$, which is 8 equilibrium stages, a partial condenser, and a partial reboiler. The partial condenser operates at 247.3 K, which is 30.8 K less than the feed condenser when the entire feed is condensed. The reboiler, which contains mainly vinyl chloride, $x_{B,VC} = 0.59980$, and dichloroethane, $x_{B,dichloro} = 0.40007$ is at 367 K. When all of the feed is condensed, $f_{liq} = 1.0$, $|Q_c|$ is a minimum but the total cooling load $|Q_c + Q_{F,cond}|$ is at a maximum. The smallest column volume was obtained with a two-phase feed with $f_{liq} \sim 0.5$. With the two-phase feeds as f_{liq} decreases cooling the feed is done at higher temperatures, but $|Q_{c,2\text{-phase-F}}|$ increases significantly.

With the two-enthalpy feed we have assumed that the vapor is a saturated vapor at 403.8 K and the liquid is a saturated liquid at 278.1 K. The condenser heat load, which is cooled to 247.3 K, is kept constant at the minimum value $Q_{c,2\text{-Enth-F}} = -1156$ kW. Starting with total condensation of the feed, as we reduce the fraction of feed that is liquefied f_{liq} the amount of energy required to condense the feed $|Q_{F,cond,2\text{-Enth-F}}|$ is reduced by the same percentage as the decrease in f_{liq}. For constant purity products and constant $Q_{c,2\text{-Enth-F}}$ Eq. (2) implies that $Q_{F,cond,2\text{-Enth-F}} + Q_{R,2\text{-Enth-F}}$ is constant. Thus, the value of $Q_{R,2\text{-Enth-F}}$ must decrease proportionally as f_{liq} increases. When the two-enthalpy feed system is used, the number of stages required increases slowly while the calculated diameter at the bottom of the column can decrease quite rapidly. Thus, the column volume decreases until it reaches a minimum at $f_{liq} = 0.78$. The column volume first becomes larger when f_{liq} becomes less than 0.78 because an additional stage is required to achieve the desired separation. For example, at $f_{liq} = 0.75$, despite a decrease in diameter, the column volume increases because the number of stages had to be increased. At $f_{liq} = 0.70$ the vapor feed stage (#8) has the largest calculated diameter because the vapor flow rate at this point is significantly greater than at the bottom of the column and the diameter increases compared to $f_{liq} = 0.75$. Once the diameters at the feed stage and the bottom of the column become equal, the rate of reduction in the diameter is controlled by the change in diameter at the feed plate, which is much slower than the rate when diameter is controlled at the bottom of the column. At

$f_{liq} = 0.65$ the diameter decreases, but the volume increases because more stages are required to obtain the desired separation. Compared to the use of a vapor feed, at $f_{liq} = 0.65$ the two-enthalpy feed system has slightly lower values of $Q_{R,2\text{-}Enth\text{-}F}$ and $|Q_{c,2\text{-}Enth\text{-}F} + Q_{F,cond,2\text{-}Enth\text{-}F}|$, a lower column volume, and a significantly lower value of $|Q_{c,2\text{-}Ehtn\text{-}F}|$. When f_{liq} is reduced to 0.6, the desired separation is not possible with the minimum value of $Q_{c,2\text{-}Enth\text{-}F} = -1156\,kW$. The vapor feed stage is now the controlling pinch point and we need to increase the reflux ratio to obtain the desired separation. Since our goal is to keep $Q_{c,2\text{-}Enth\text{-}F}$ constant, we stop the reduction in f_{liq} at this point.

DISCUSSION AND CONCLUSIONS

If we are trying to minimize the column condenser cooling and the cost of the column simultaneously, then a two-enthalpy feed system with $f_{liq} = 0.78$ is probably the optimum for this separation (see Table 1). The minimum total capital costs and operating cost per year for the two-enthalpy feed may be at a somewhat lower value of f_{liq} (0.7 to 0.65) because $|Q_{F,cond,2\text{-}Enth\text{-}F}|$ and $Q_{R,2\text{-}Enth\text{-}F}$ and thus the areas of the feed condenser and the reboiler continue to drop as f_{liq} decreases. The optimum operating conditions will depend on the economics of the particular system.

This particular case—a vapor feed when refrigeration is required for the column condenser—is favorable for the use of a two-enthalpy feed system. In other cases (3–5), additional heat exchangers are required. Here, because a feed condenser will be employed anyway, the two-enthalpy feed allows it to be smaller compared to total condensation which automatically reduces costs. Since the largest calculated diameter was at the bottom of the column, adding some of the vapor at the vapor feed instead of at the bottom of the column reduces the diameter, the column volume and hence the cost. If the largest calculated diameter is not at the bottom of the column (4,5), then the two-enthalpy feed will still result in reductions in $|Q_{F,cond,2\text{-}Enth\text{-}F}|$ and $Q_{R,2\text{-}Enth\text{-}F}$, but because the diameter is not reduced, column costs will go up and the optimum value for f_{liq} will probably be closer to 1.0.

Comparison of two-enthalpy feed with use of two-phase feed is not quite as clear-cut. The most important factors in comparing the two-phase and two-enthalpy systems are probably the condenser cooling cost and the cost of cooling the feed. Because the two-phase feed is condensed at a higher temperature than the liquid portion of the two-enthalpy feed system, cooling the two-phase feed may be less expensive than cooling a two-enthalpy feed, but column condenser cooling costs are significantly higher because the cooling load is more than three times as large for the two-phase feed than for the two-enthalpy feed. To a modest extent $|Q_{c,2\text{-phase-F}}|$ can be reduced by increasing N (compare the entries with $f_{liq} = 0.5$ in Table 1), but the column volume increases. Note that the cooled portion of the two-enthalpy feed system does not have to be entirely condensed which will result in a higher temperature for the feed heat exchanger. When the column condenser cooling is the controlling cost, the two-enthalpy feed will be less expensive. In other cases a detailed economic analysis will be required.

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