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# Decreasing costs of distillation columns with vapor feeds

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## HIGHLIGHTS

- Total annual cost (TAC) for 2-enthalpy feed distillation compared to vapor feed.
- TAC significantly reduced for retrofitting to increase capacity.
- TAC significantly reduced for new and retrofit refrigerated systems.
- Retrofitting more economical when actual trays are used.
- 2-enthalpy feed distillation has better turndown performance than vapor feed.

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## ABSTRACT

The total annual cost is compared for standard vapor feed distillation and two-enthalpy feed distillation in which part of the feed is condensed and fed above the vapor feed. Total annual costs for new equipment are typically slightly, but not significantly, lower for two-enthalpy feed. Retrofitting from vapor feed to two-enthalpy feed increases capacity at lower total annual cost than building another vapor feed column. The two-enthalpy feed system has better turndown properties than vapor feed columns. If a less expensive coolant can be used for condensing feed than for condensing distillate, two-enthalpy feed distillation has significantly lower total annual costs than vapor feed for both new equipment and retrofits. The systems studied were binary separations of methanol and water, ternary separation of methanol, ethanol, and water, and separation of two five component mixtures of methane, ethane, propane, n-butane, and n-pentane.



## 1. Introduction

Distillation continues to be the most commonly used separation method in the chemical process industries, and is estimated to account for 90–95% of the separations (Humphrey and Keller, 1997). Because distillation is widely used and the scale of operation is often quite large, relatively small improvements in capital cost or energy use can have significant impact. There is significant interest in both new construction and in retrofitting existing equipment. Some of the most expensive distillation systems in industry are high-pressure columns processing vapor feeds that require refrigeration. Fortunately, 2-enthalpy feed (2-F) distillation is most effective for vapor feeds that require refrigeration.

Columns with vapor feeds typically have larger diameters than columns with liquid feeds, but the vapor feed columns use less energy in the reboiler. Wankat and Kessler (1993) introduced the 2-F system that divides the feed into two portions that are at the same composition but one part is vapor and the other is liquid. Soave et al. (2006) developed a 2-F process for refrigerated distillation systems using the cold distillate to condense part of the feed. When the fresh feed is a vapor, a 2-F system (Fig. 1) condenses a fraction $f_L$ of the feed while the remainder of the feed remains a vapor at the same composition (Wankat, 2007a). By restricting comparison of standard and 2-F distillation columns to identical purities and identical total cooling and heating loads, Wankat (2007a) showed the 2-F distillation can have a smaller column diameter, and do part of the condensation on the feed at a higher temperature than condensation of the distillate; however, more stages are required. The requirement of constant heating and cooling duties diminished the usefulness of the 2-F system for retrofitting to increase capacity, but this limitation was not realized at the time. The 2-F system for vapor feeds has been extended to rectifiers (Wankat, 2014, 2015) and 2-F applications with a liquid feed were explored for complete columns (Soave and Feliu, 2002; Wankat, 2007b) and strippers (Wankat, 2014).

Results for 2-F-rectifiers (Wankat, 2015) with low to modest feed concentrations of the more volatile component (MVC) showed that retrofitting a standard rectifier to a 2-F rectifier to

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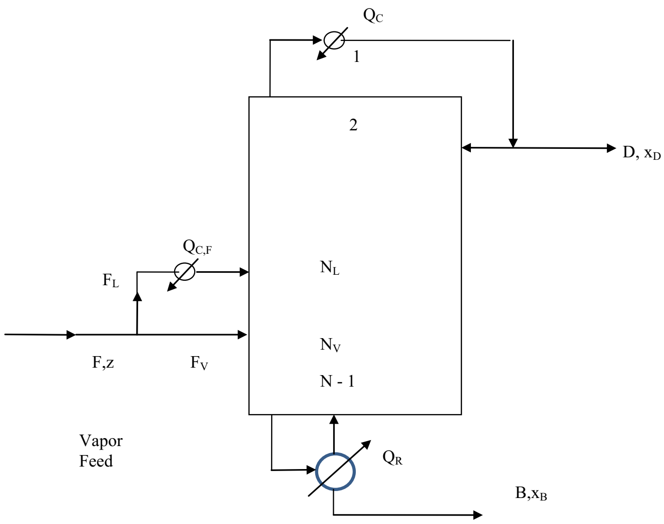


**Fig. 1.** Two enthalpy-feed distillation column (Wankat, 2007a). Copyright ACS, 2007. Reprinted with permission.

increase capacity had lower total annual costs (TAC) than building another standard rectifier. When a less expensive cooling medium could be used for condensing the feed instead of condensing distillate, the 2-F rectifier had economic advantages for both new construction and retrofits. Based on these positive results, I decided to revisit vapor feed distillation columns to include economic analysis of retrofits and refrigerated systems.

This paper presents cost comparisons and shows the economic advantages of retrofitting vapor feed columns to 2-F systems to increase capacity. The retrofitting examples use the same number of stages as the original vapor feed column, but with increased heating and total cooling duties to achieve the same purities. Since a significant portion of the condensation is done by condensing feed, 2-F systems have lower total annual costs than vapor feed columns for both new equipment and retrofits if condensation of the feed can use a less expensive cooling medium than condensation of the distillate. Improved vapor traffic and closer approach to the design percentage flooding of 2-F systems in the enriching section is shown for turndown operation.

## 2. Comparison of vapor feed to 2-enthalpy feed for new construction

For new construction the TAC values in US$ of standard vapor feed distillation columns were compared to TAC values of 2-F distillation columns with identical feed flow rates and feed compositions, either identical mole fractions of the MVC in the distillate and identical distillate flow rates or identical recoveries of the key components. The methods of Luyben (2013) and of Turton et al. (2012) for estimating capital costs are summarized in Table 1. TAC was calculated from Eq. (1).

Detailed Aspen Plus™ simulations assuming equilibrium stages were done with the NRTL VLE correlation for the separation of saturated vapor feeds of methanol–water with 10 mol%, 20 mol%, and 40 mol% methanol. The columns have partial reboilers and total condensers. Specific distillation details and calculated TAC values using Luyben's economic data for 10% methanol are shown in Table 2. The runs are coded as [identifier of feed – feed type (vapor, V, liquid, L, or 2-F) – number of stages]. Thus, M10VN50 is methanol at 10 mol% with a vapor feed and $N$ (Aspen notation)= 50. Later (Table 8) run HC1F50N36 is hydrocarbon feed 1–2-F with $f_L$ of 50% – $N$=36. Liquid feed columns involve condensing the entire feed and then use a standard liquid feed column. Designs were compared at identical feed rates and identical product purities. The results for a standard vapor feed column separating a 10 mol% methanol saturated vapor feed show a TAC minimum at a low multiplier of $(L/D)_{min}$. Details of additional runs to find the optimum conditions are not shown.

For new construction TAC values of the 2-F system for the 10 mol% feed (Table 2) range from 0.22% less than the liquid feed TAC value with zero steam cost to 5.15% less than the liquid feed for the \$5.00/GJ steam. For steam at \$7.78/GJ and \$10.0/GJ the 2-F TAC value is 5.09% and 4.6% less, respectively, than the TAC values for a vapor feed. The significance of these small differences in TAC depends on the uncertainties of the economic analyses and is discussed next.

The economic costs determined from Luyben's (2013) equations and the module approach of Turton et al. (2012) were compared for selected runs at 1 atm. For runs M10VN50 with a vapor feed and for 2-F run M10F50N50 (both in Table 2) the TAC values calculated from the two economic analyses are compared in Table 3. The estimates for TAC are clearly within the expected error for preliminary economic analyses.

To understand why TAC values in Table 2 for vapor feed and 2-F columns are relatively close to each other, the details of size and cost [based on Eqs. (1)–(3)] of run M10VN60, which is the optimum vapor feed column for steam at \$10/GJ, and run M10F90N80, which is the optimum 2-F column for the same steam cost, are compared in Table 4. Because the temperature difference for cooling the feed condenser is much larger than the temperature difference for the column condenser, the total condenser area (497 $m^2$) is 36.1% less for the 2-F system than for the vapor feed system. Despite this, the total cost of the 2-F condensers, \$524 000, is only 5.1% less than the vapor feed condenser. The reason is the cost exponent=0.65 in Eq. (2) makes smaller heat exchangers more expensive per $m^2$. Although both the total capital cost and the total energy costs for the 2-F system are less than for the vapor feed system, the TAC for the 2-F system is only 4.6% less than TAC for the vapor feed system.

For the 10% (Table 2), 20% (partial results shown later in Table 6), and 40% (results not shown) methanol feeds the 2-enthalpy feed system always had lower TAC values than using a vapor feed or condensing the vapor to form a liquid feed. As concentration of MVC in the feed increases TAC values for all the distillation processes are lower, the fraction of feed that should be condensed in a 2-F system is lower, the optimum number of stages is reduced, and the differences in TAC values of the 2-F process compared to a vapor or liquid feed are reduced. However, the advantages for new construction are small and are within the uncertainty of the economic analysis. Although there is no significant difference in TAC values for new construction, there are other advantages of 2-enthalpy feed systems that may add significant value. For example, when we compare retrofits, we will see much larger differences in TAC values.

## 3. Turndown

During turndown operation at feed rates lower than the design rate columns often operate at lower stage efficiencies or may cease to function entirely. Previous research showed that by reducing $f_L$ during turndown the vapor flow rates and percentage flooding of 2-F rectifiers could be kept fairly close to the values in the original design (Wankat, 2014, 2015).

Table 5 shows the vapor flow rates and percentages of flooding for separation of a 10% methanol–90% water feed in a distillation column for runs at the design conditions ($F$=1000, $D$=100) and at 50% turndown ($F$=500, $D$=50). The design and turndown runs are assumed to have equilibrium trays, which is undoubtedly not valid