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Distillation Cascades Based on Differential Vaporization and Differential Condensation Stages. II. Four- and Six-Stage DCDV Cascades and Hybrid Cascades Containing DV Reboilers and DC Condensers

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ABSTRACT

The conceptual design for N-stage cascades based on the differential condensation (DC), and differential vaporization (DV) processes is presented. Four and six stage "no-mix" and constant recycle DCDV cascades have been modeled to separate an arbitrary binary feed. The study suggests that cascades based on the differential processes could be significantly more efficient than cascades based on equilibrium stages (ordinary distillation). In no-mix DCDV cascades, all stage separation factors are equal and significantly greater than the equilibrium stage separation factors (i.e., relative volatility). In constant recycle DCDV

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cascades, the DV reboiler and DC (partial) condenser stages have stage separation factors much higher than the relative volatility and are significantly greater than the separation factors for the interior DCDV stages, although the stage separation factors for the interior stages are still higher than the relative volatility. Constant recycle hybrid cascades containing DV reboilers and DC condensers coupled with equilibrium interior stages are more efficient than constant recycle ordinary distillation cascades containing the same number of stages, especially for systems with higher relative volatility that require fewer stages. For systems with lower relative volatility (greater number of stages) the difference in performance between the hybrid and ordinary distillation cascades is less pronounced.

Key Words: Countercurrent differential distillation cascades; Hybrid cascades; Equilibrium-stage distillation.

INTRODUCTION AND BACKGROUND

In part I, the equations for the differential stage separations were developed, and applied to the conceptual design of two-stage cascade consisting of a differential vaporization (DV) reboiler and a differential condensation (DC) condenser.[1] The two-stage recycle DCDV cascades can theoretically make any desired separation of a binary mixture with relative volatility $\alpha^* > 1$, but very high recycle ratios would be required, with $\alpha^* < \approx 3$. The study suggested that the two-stage DCDV process might be useful for the separation of air ($\alpha^* = 4 - 6$ depending on pressure) for hypersonic flight applications.

The present study considers only special cases of four- and six-stage DCDV cascades and hybrid cascades, but it is believed that N-stage DCDV cascades can be designed to make any desired separation using significantly fewer stages and lower recycle ratios, compared with conventional (equilibrium stage) distillation, because the DC, DV, and DCDV stage separation factors can be significantly higher than the equilibrium stages. It is also shown that theoretically, in some cases, a hybrid cascade with DV reboiler and DC condenser coupled with equilibrium interior stages can be significantly more efficient than conventional distillation cascades with equilibrium reboiler and condenser.

CONCEPTUAL CASCADE MODELS FOR DCDV DISTILLATION

For a binary system in which all stage separation factors are greater than 1, any desired separation can theoretically be obtained in a countercurrent recycle cascade provided the cascade is properly designed with respect to interstage flow rates (stage recycle ratios), and number of stages [2,3]. Just as with ordinary distillation, to carry out a specified separation, many cascade designs are possible based on the DCDV processes, with the cascades ranging from "constant recycle" (constant molal overflow), to "no-mix" cascades in which mixing of streams of different compositions does not occur in the stage, to (possibly) ***ideal*** cascades that would require the minimum total interstage flow to make the desired separation. It is not known if ideal cascade theory applies to the DCDV cascades. Some of the no-mix and ideal cascade requirements have been discussed by Herbst and McCandless [4]. Experience to date shows that calculation procedures for the DCDV cascades are considerably more complicated than for ordinary distillation column design, and so the "easier" cascades are considered first. First considered was the two-stage no-mix process, which contains a DV stage as the "reboiler" and a DC stage as a (partial) condenser, as reported in part I. For the present study, only four- and six- stage no-mix, and four-stage constant recycle DCDV cascades have been modeled. In general, the modeling of these cascades require multiple iterative (trial and error) calculations, and MathCad (Mathsoft Engineering & Education, Inc., Cambridge, MA, USA) has been used for convenience, although other computational methods may also be used.

The conceptual design for a 4-stage DCDV cascade is presented schematically in Fig. 1. Note that the cascade consists of a DV partial reboiler for stage 1, and a DC partial condenser for stage N, Whereas the interior stages in the cascade consist of separate DC and DV sections. The flow patterns in (a) are identical, but in (b), it is assumed the energy provided by stage (DC) condensation would provide for stage (DV) vaporization. Figure 1b presents schematic diagrams for four-stage DCDV, hybrid, and OD cascades (see previous).

In developments that follow, the stage **heads** stream designated by **H** is the one enriched in the more volatile component, the stage **tails** stream designated by **T** is the one depleted in the more volatile component (enriched in the least volatile component), whereas the stage feed stream is designated by **F**; with Y, X, and Z designating the respective mole fractions of the more volatile component, with 1-Y, 1-X, and 1-Z representing the compositions of the least volatile material. The **cut** or **stage cut** designated by θ is defined as the ratio of heads flow to feed flow. In distillation, H is vapor, T is liquid, and F may be either vapor or liquid.

In the DC stage, the liquid tails stream being removed in small portions is depleted in the more volatile component, whereas the remaining vapor heads stream becomes progressively enriched in this component.

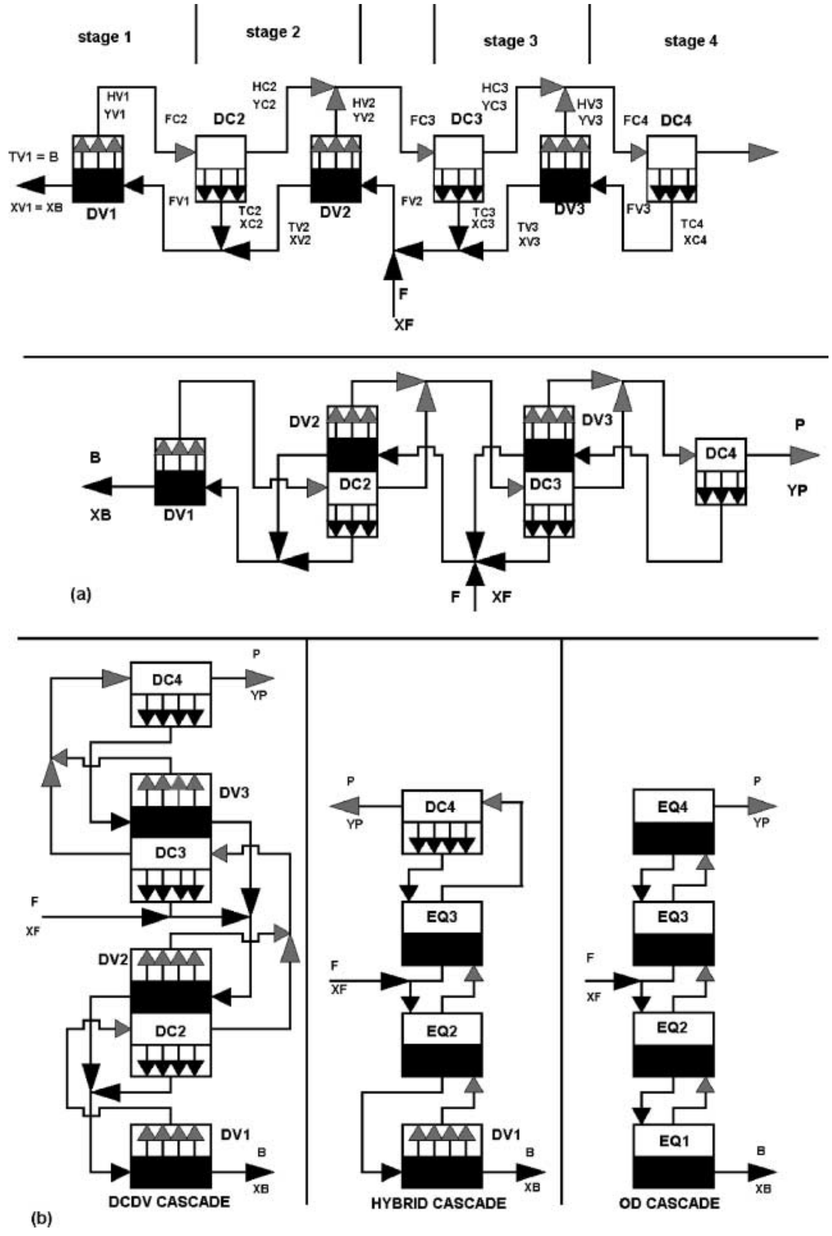

Figure 1. (a) Conceptual design for a four-stage DCDV distillation cascade and (b) schematic diagrams of four-stage DCDV, hybrid, and OD cascades.

In the DV stage, the vapor heads stream being removed in small portions is enriched in the more volatile component, whereas the remaining liquid tails stream becomes progressively depleted in this component.

In the DC and DV stages it is assumed that, at any point, X* is related to Y* by the local (or "point") separation factor which is defined as:

$$\alpha^* = \frac{Y^*/(1-Y^*)}{X^*/(1-X^*)}$$

$$X^* = \frac{Y^*}{Y^* + \alpha^*(1-Y^*)} \tag{1}$$

Y* and X* are the compositions of vapor and liquid phases in thermodynamic equilibrium, and α^* is the relative volatility of conventional distillation.

The stage separation factor is defined as:

$$\alpha S = \frac{YS(1-XS)}{XS(1-YS)} \tag{2}$$

where XS and YS are the compositions of the two (separated) streams leaving a stage.

By definition the stage cut is:

$$\theta \equiv \frac{H}{Z} \tag{3}$$

The "equilibrium" equations for the DC and DV stages were derived in part I, and are presented here for convenience. The "equilibrium" equation for the DC stage is:

$$\left(\frac{1-Y}{1-Z}\right)\theta = \left[\left(\frac{Y}{Z}\right)\theta\right]^{\alpha} \tag{4}$$

whereas the equilibrium equation for the DV process is:

$$\left(\frac{X}{Z}\right)(1-\theta) = \left[\left(\frac{1-X}{1-Z}\right)(1-\theta)\right]^{\alpha} \tag{5}$$

Note that the DC equation relates the residual vapor (heads stream) composition, resulting from a vapor feed, to the stage feed composition and cut (i.e., the ratio of residual vapor to feed), whereas the DV equation relates the residual liquid (tails stream) composition, from a liquid feed, to the feed composition, and (1-θ). These are the equations for the so-called Rayleigh distillation and condensation.

These equations can be used to determine the separation characteristics of either type of process or a combination of the two processes.

FOUR-STAGE "NO-MIX" AND "CONSTANT RECYCLE" DCDV CASCADES

The four-stage DCDV cascade is shown schematically in Fig. 1. For these cascades α^*, F, XF, and either one internal recycle ratio for the no-mix cascade or P for the constant recycle cascade are specified, with YP and XB being calculated by the cascade model.

For the no-mix design, the compositions of the heads and tails streams from the DC and DV processes in each (interior) stage are assumed equal, and the composition of the combined tails stream from stage 3 is assumed to be equal, and equal to that of the feed:

$$\mathrm{XV3} = \mathrm{XC3} = \mathrm{XF}$$

$$\mathrm{XV2} = \mathrm{XC2}$$

$$\mathrm{YC2} = \mathrm{YV2}$$

$$\mathrm{YC3} = \mathrm{YV3}$$

A specific liquid rate to stage 2 is also specified, which, in effect fixes the recycle rates to all stages.

For the four-stage constant recycle DCDV cascade, cascade recycle ratio is defined as:

$$RR = \frac{TC4}{P} \tag{5}$$

and, in this design, for specified α^*, F, XF, and P, with the assumption of "constant molal overflow," fixing the cascade RR fixes all stage heads and tails rates:

$$\mathrm{TC4} = \mathrm{FV3} = \mathrm{RR(P)}$$

$$\mathrm{TC3} + \mathrm{TV3} = \mathrm{RR(P)}$$

$$\mathrm{FV2} = \mathrm{RR(P)} + \mathrm{F}$$

$$\mathrm{TC2} + \mathrm{TV2} = \mathrm{FV1} = \mathrm{RR(P)} + \mathrm{F}$$

$$\mathrm{HV1} = \mathrm{FC2} = \mathrm{HC2} + \mathrm{HV2} = \mathrm{FC3} = \mathrm{HC3} + \mathrm{HV3} = \mathrm{FC4} = (\mathrm{RR} + 1)\mathrm{P}$$

with TC2, TC3, TV2, TV3, HC2, HC3, HV2, HV3, and all stream compositions being fixed by equilibrium and material balance requirements. Note that, with the assumption of constant molal overflow, HV2 $=$ TC2 and HV3 $=$ TC3

The iterative MathCad method was used to simultaneously solve the stagewise equilibrium and material balance equations. These calculations yield all external and internal flow rates and compositions (i.e., the separation that would result from that "no-mix" or "constant recycle" cascade design).

For the constant recycle case, there appears to be more than one solution to the set of linear material balance equations and the nonlinear equilibrium equations that represent the constant recycle model, some with $\alpha S < \alpha^*$ or $\alpha S < 1$. Solution of the equation set with the constraints that all $\alpha Si > 1$ resulted in the desired solution.

The results of some of the preliminary four and six-stage cascade calculations for a system with $\alpha^* = 2.5$, XF $=$ 0.5, F $=$ 100, are presented in Table 1. Note that many other four and six stage no-mix and constant recycle designs are possible, which would require different stage heads and tails rates, and result in different separations.

As can be seen from Table 1, good separations can be obtained in the four- and six- stage no-mix cascades with $\alpha^* = 2.5$ using relatively low recycle ratios. For the cascade designs considered, all αS are constant and equal to 6.07 and 6.51. Note that for the no-mix design αSDV $=$ αSDC $=$ αS, whereas αS is different for each stage in the constant recycle cascade, and significantly higher than α^*. For the four-stage constant recycle DCDV cascade with RR $=$ 5, a separation slightly better than for the four-stage no-mix (FV2 $=$ 300) is obtained, but all stage recycle ratios (RRi) are greater in the constant recycle design. With the constant RR $=$ 5 design, the resulting stage separation factors are αS1 $=$ 15.41, αS2 $=$ 4.30, αS3 $=$ 3.93, and αS4 $=$ 13.26.

The disadvantage of the no-mix design is that heat input for vaporization and heat removal for condensation is required at each interior stage, with different energy requirements for vaporization and condensation. Because of this, the no-mix design may not, in general, be practical. However, it may be possible to design "constant recycle" DCDV cascades in which the energy added in the reboiler is "reused" from stage to stage, just as in an ordinary distillation cascade. This would require the flow pattern in Fig. 1b for the four-stage cascade.

Table 1. Four- and six-stage no-mix DCDV and four-stage constant recycle cascades to produce 98%–99% products.*

Stage #	yS	xS	HS	TS	RRS	αS
Six-Stage No mix, $\alpha^* = 2.5$ F = 100, XF = 0.5 FV3 = 300						
6	0.990 = YP	0.943	49.76 = P	81.24	1.63	6.07
5	0.961	0.803	131.00	118.76	2.39	6.07
4	0.859	0.5	168.52	200 + F	4.02	6.07
3	0.598	0.197	249.76	180.97	2.19	6.07
2	0.267	0.0565	130.73	134.11	2.70	6.07
1	0.0817	0.014 = XB	83.87	50.24 = B		6.07
Four-Stage No-Mix, $\alpha^* = 2.5$ F = 100, XF = 0.5 FV2 = 300						
4	0.967 = YP	0.818	49.22 = P	100.00	2.03	6.51
3	0.867	0.5	149.22	200 + F	4.06	6.51
2	0.592	0.182	249.22	160.79	3.26	6.51
1	0.245	0.047 = XB	110.02	50.78 = B		6.51
Four-Stage Constant Recycle, $\alpha^* = 2.5$ F = 100, XS = 0.5, RR = 5, P = 50						
4	0.976 = YP	0.755	50 = P	250	5	13.26
3	0.792	0.492	300	250 + F	5	3.93
2	0.573	0.238	300	350	7	4.30
1	0.274	0.024 = XB	300	50 = B		15.41

*Rates and compositions of heads and tails streams from each stage with resulting RRS and αS.

EFFECT OF RECYCLE RATIO ON THE FOUR-STAGE CONSTANT RECYCLE DCDV CASCADE SEPARATION

For the comparison of the different four-stage cascade designs, the same (hypothetical) system characterized by $\alpha^* = 2.5$, $F = 100$, and $XF = 0.5$ is assumed, with the cascades designed to produce $P = 50$. These are the same parameters used to calculate the four-stage no-mix cascade, except in that case P is calculated by material balance.

The effects of interstage flow (i.e., the specified RR) in terms of stage separation factors, product compositions, and extent of separation, for the four-stage constant RR DCDV cascade designs are presented in Figs. 2a and b. As can be seen, the resulting αSi vs RR are not "smooth," but show some deviations from smooth curves. This is probably because of round-off errors associated with the simultaneous solution of the large set of linear material balance and non-linear equilibrium equations used to model the DCDV cascades.

For the constant recycle DCDV cascade, the stage separation factors for the DV reboiler and the DC condenser are significantly higher than for the interior stages, which are greater than α^* but significantly smaller than αS1 and αS4. This suggests that it may be possible to improve the efficiency of ordinary distillation by using DV reboilers and DC condensers. Calculations for the constant recycle hybrid and OD cascades are easily carried out, and the results for the calculation for the four-stage cascades are presented in Fig. 3. Figure 3d compares YP for the four-stage DCDV, hybrid, and OD cascades.

As can be seen from Figs. 2 and 3 for this system, the separation in the hybrid cascade is significantly better than for the OD cascade, but not as good as for the more complex constant RR (T_{i+1}/P) DCDV cascade.

More comparisons between hybrid and OD distillation cascades are presented in the following section.

COMPARISON OF FOUR-STAGE CASCADES USING McCABE-THIELE PLOTS

Figure 1b presents the schematic diagrams for the different four-stage cascades. McCabe-Thiele type plots for the four-stage no-mix DCDV, constant recycle DCDV, hybrid, and OD cascades are presented in Fig. 4. These plots present the equilibrium curves for the different stage separation factors that result for the specific designs considered. Together with the curve for $\alpha^* = 2.5$, the relative volatility. Also shown are

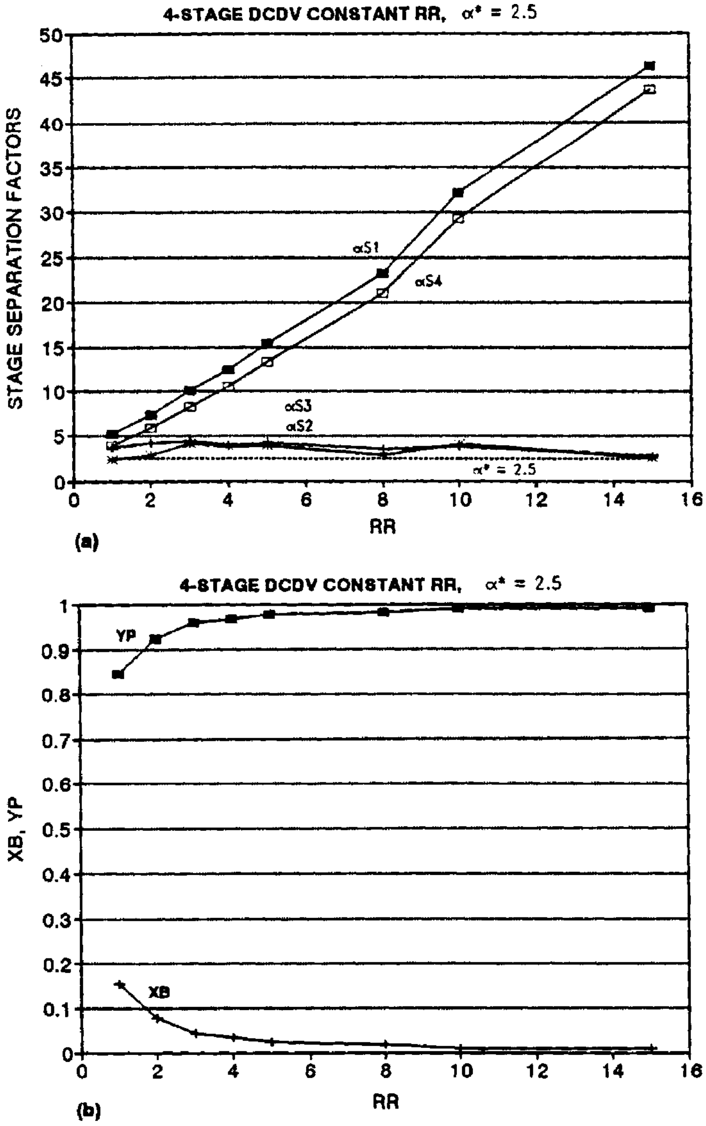

Figure 2. Separation characteristics of four-stage constant RR DCDV cascade designs with α* = 2.5. (a) Stage separation factors as a function RR and (b) YP, XB as a function of RR.

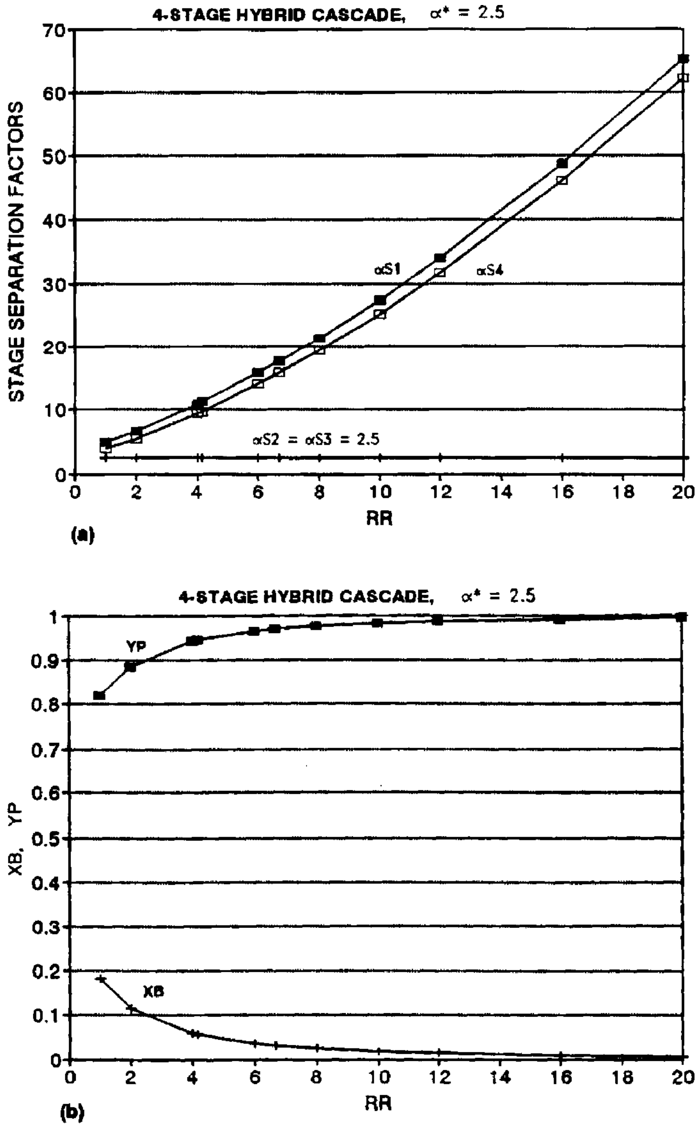

Figure 3. Comparison of four-stage constant RR hybrid cascade designs with ordinary distillation designs for $\alpha^* = 2.5$. (a) Hybrid stage separation factors as a function of RR; (b) hybrid YP, XB as a function of RR (c) ordinary distillation YP, XB a function of RR; (d) YP as a function of RR for the DCDV, hybrid, and OD cascades.

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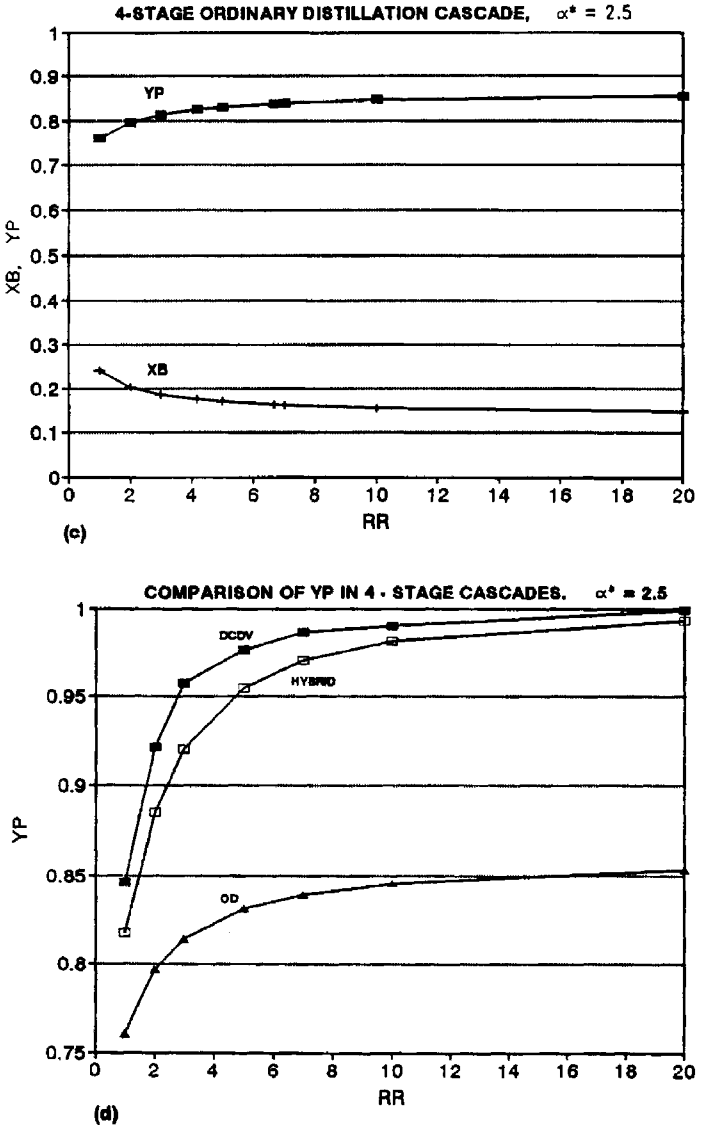

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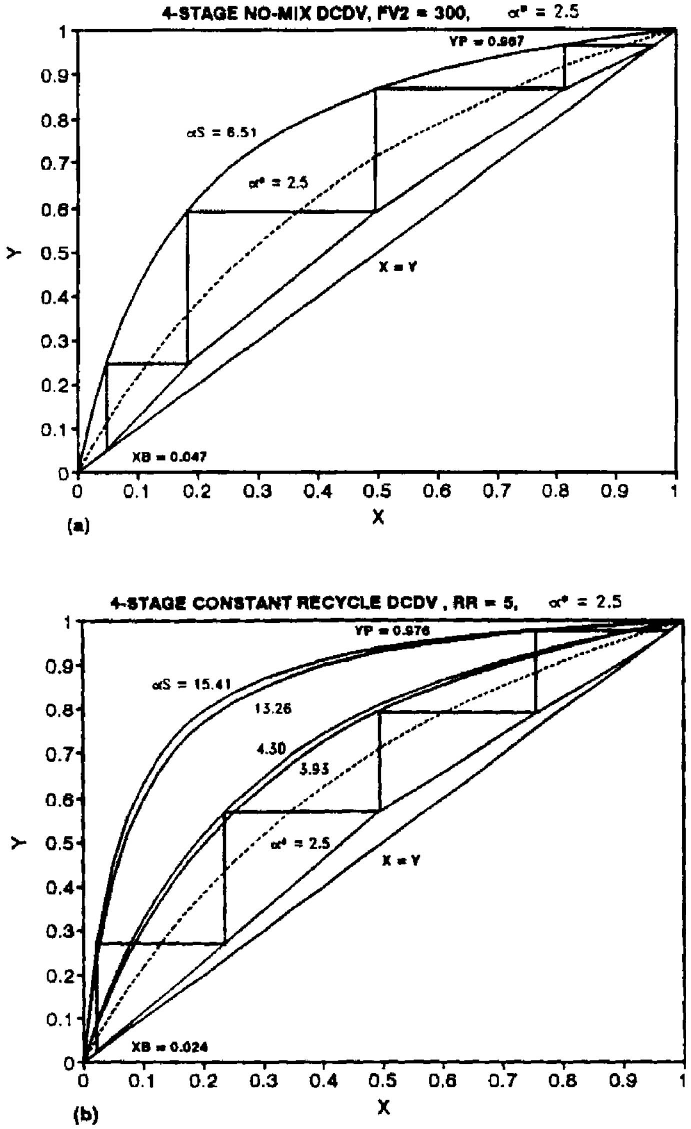

Figure 4. McCabe-Thiele plots for some four-stage cascade designs, α* = 2.5. (a) No-mix DCDV with FV2 = 300; (b) constant RR DCDV, RR = 5; (c) constant RR hybrid; RR = 5; (d) constant RR ordinary distillation, RR = 5.

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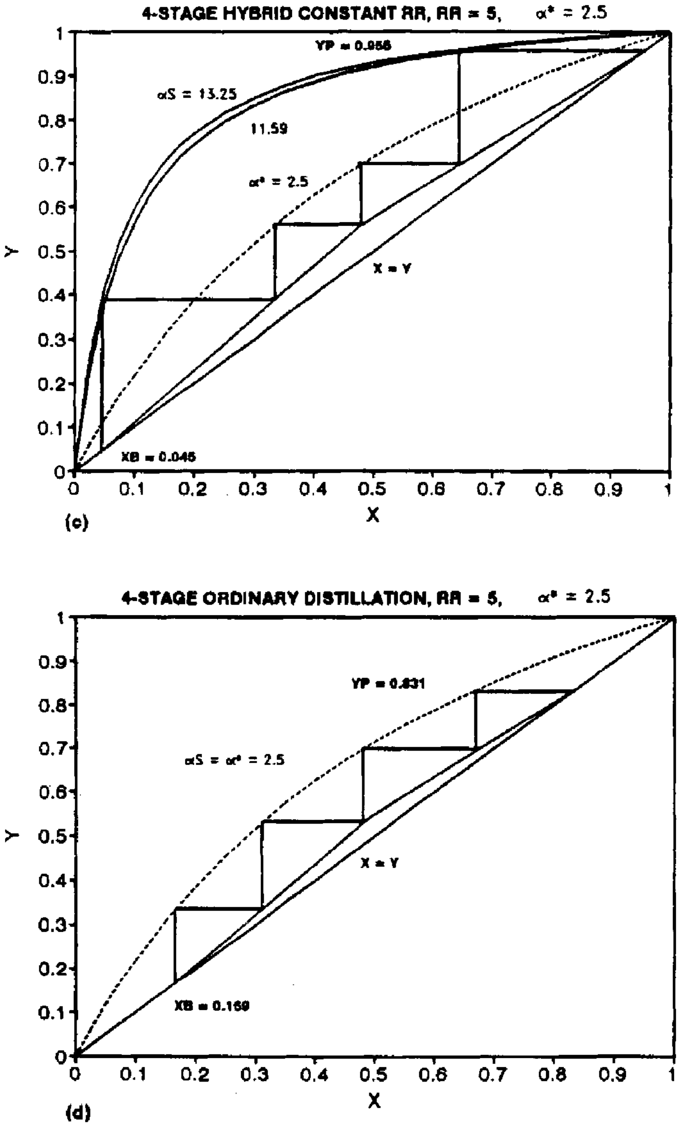


Figure 4. Continued.

the "operating lines" and the lines that represent the four-stage separations. The no-mix DCDV cascade is for the case with FV2 = 300, whereas the constant recycle DCDV, hybrid, and ordinary distillation designs are all for RR = 5. The no-mix design requires a different RR at each stage, and as a result, the "operating line" for this case is a curve rather than two straight lines.

These plots graphically show the possible advantages of DCDV or hybrid distillation cascades.

COMPARISON OF SOME HYBRID AND OD CASCADES

A detailed investigation comparing the separation in "optimized" hybrid cascades, with "optimized" ordinary distillation cascades may be made in the future, but here a preliminary look at cascades that might be used to separate systems with $\alpha^* = 2.0$ (cyclopentane/methyl-cyclopentane) and 1.56 (iso-butane/n-butane) are made, assuming (arbitrarily) N = 10 and 16 for the system with $\alpha^* = 2$, and N = 24, 30, and 44, for the system with $\alpha^* = 1.56$. The results of these calculations are shown in Figs. 5 and 6.

The separation in the hybrid cascade continues to increase with increasing design RR, whereas the maximum separation in the OD cascades is limited to the separation that could be obtained in the N-stage cascade designed for total reflux. This behavior is, of course the result of the behavior of the DV reboiler and DC condensers in which αs10 and αS1 are greater than α^*, and increase with increasing RR. αS1 and αSN vs. RR or resulting YP are shown in Figs. 5(a) and 6(a) for the hybrid cascades for the different cases considered.

For the simple system considered in this study, YPmaxOD for the ordinary distillation is easily calculated from the Fenske-Underwood equation:

$$Nmin = \frac{\ln\left(\left(\frac{YPmaxOD}{1-YP\text{max}OD}\right)^2\right)}{\ln(\alpha^*)} \tag{7}$$

with Nmin = N.

Also shown in Figs. 5 and 6 are more detailed comparisons in terms of RR required to make the same separation, the ratio RRH/RROD, and the total interstage heads rate (TIHR) as a function of YP. TIHR is proportional to the "**size**" of the cascade required to make the separation.[2,3]

Figures 5 and 6 clearly show the limitations of the OD designs. The OD designs are limited to YPmaxOD, whereas the hybrid design with the same

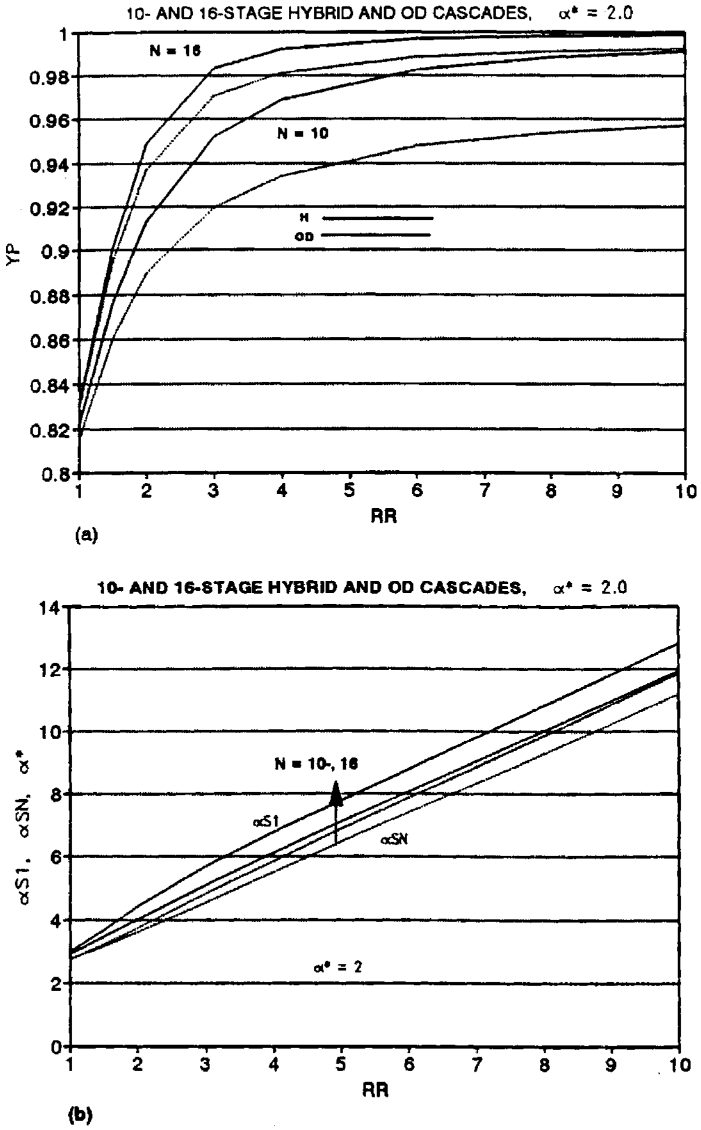
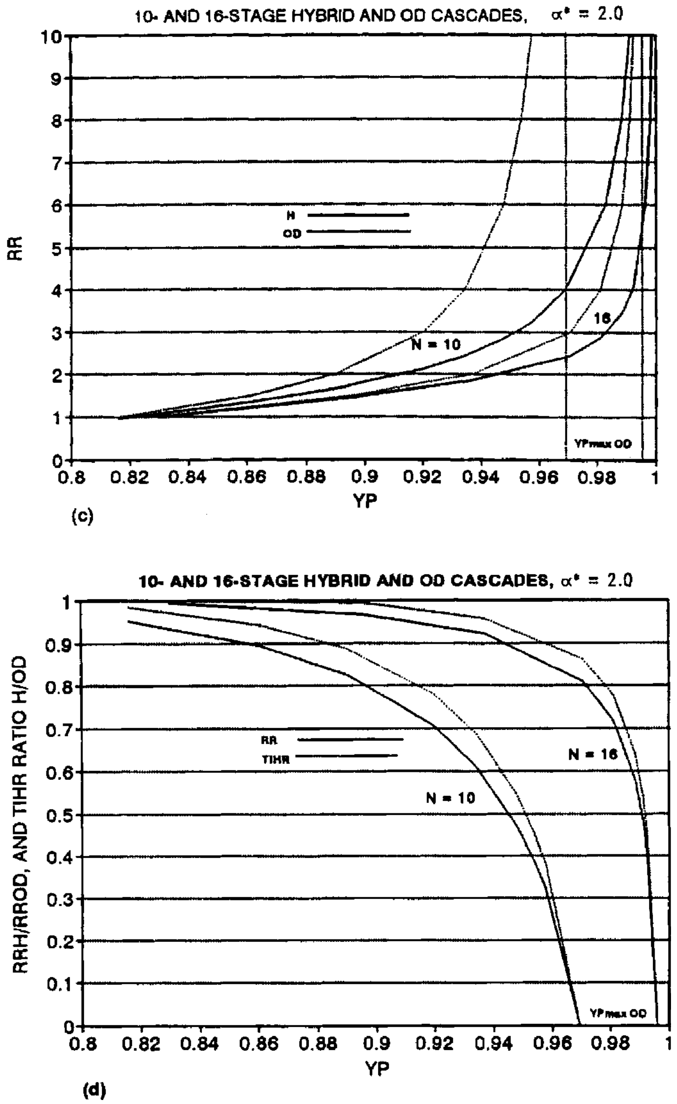


Figure 5. Comparison of 10- and 16-stage constant RR hybrid and ordinary distillation designs, α* = 2. (a) YP as a function of RR; (b) αS1, αS2 as a function of RR; (c) RR required to produce YP for the hybrid and OD designs; (d) the ratio RRH/RROD and the ratio TIHR H/OD to produce YP < YPmaxOD as function of YP.

(*continued*)



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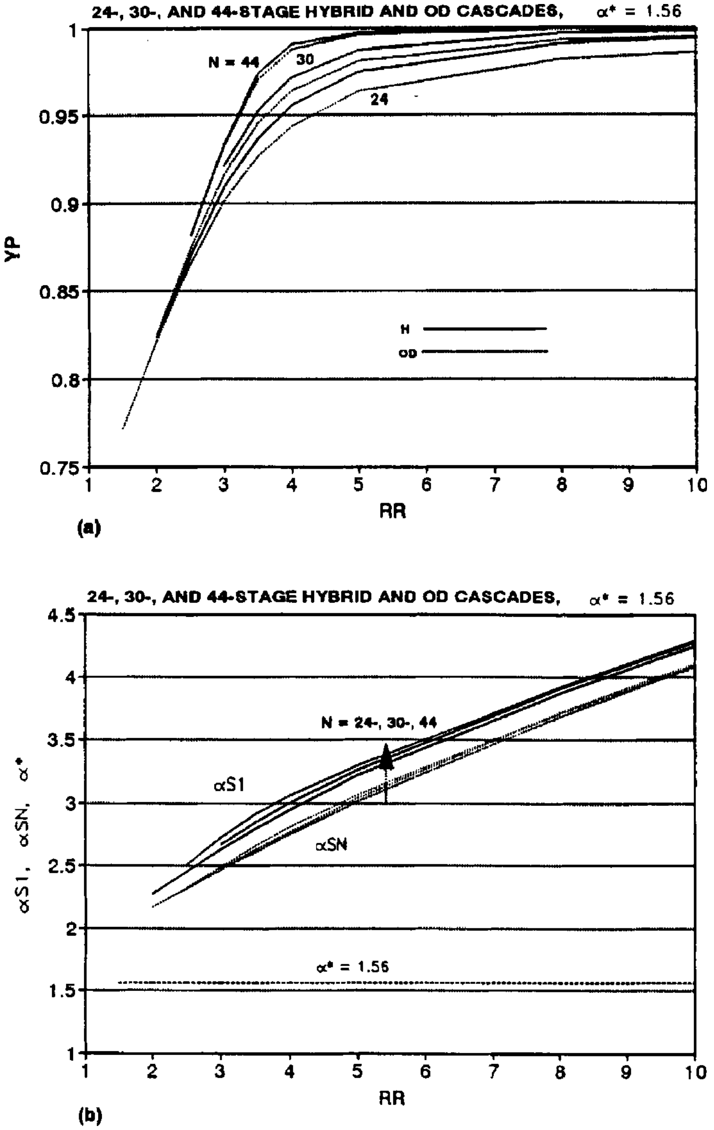

Figure 6. Comparison of 24-, 30-, and 44-stage hybrid and OD cascades for the system $\alpha^* = 1.56$. (a) YP as a function of RR; (b) αS1, αSN as a function of YP; (c) RR required to produce YP as a function of YP; (d) ratio RRH/RROD and ratio TIHR H/OD as a function of YP.

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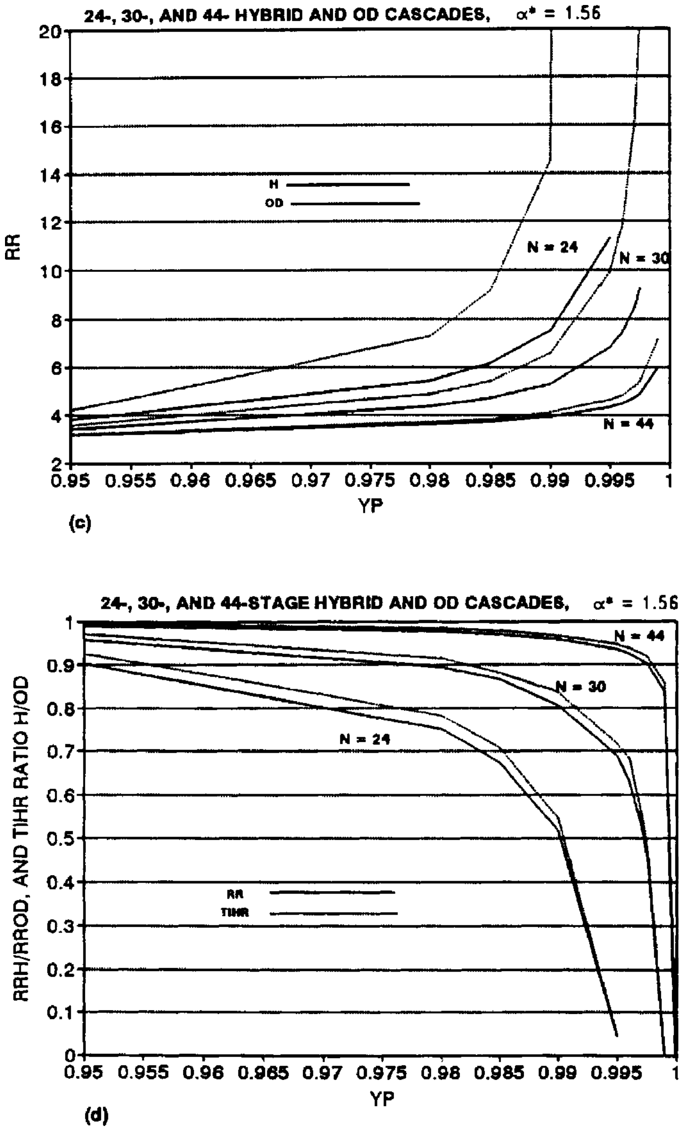


Figure 6. Continued.

number of stages can produce YP $>$ YPmaxOD. The hybrid design requires a lower RR to produce all YP $<$ YPmaxOD, with RRH/RROD → 0 as YP → YpmaxOD. Again, in the hybrid designs, there.are no theoretical limitations on YPmaxH, although very large RR may be required compared with optimized hybrid or OD designs requiring more stages.

Intuitively, it would be expected that the difference in performance between the hybrid and ordinary distillation would be less pronounced for systems with smaller α^* (i.e., systems that require a greater number of stages to achieve the desired separation). These preliminary calculations (Fig. 6) show that this is true because the incremental increase in separation of the hybrid design compared with ordinary distillation at comparable α^* and RR is less as N is increased for systems with smaller α^*.

GENERAL DISCUSSION AND CONCLUSIONS

For all of the countercurrent recycle cascades considered in this study, the design engineer has considerable freedom in choosing N, RRi ($>$RRimin), and feed stage location to achieve a specified separation for a system with fixed XF and α^*. For fixed N with all αS $=$ α^* (i.e., OD), infinite RR is required to achieve YpmaxOD, whereas there is not theoretical limitation on YP that can be achieved with increasing RR in the DCDV and hybrid cascades. In the DCDV cascades, all αS $>\alpha^*$: therefore, to make the same separation, fewer stages and lower RR are required compared with the hybrid and OD designs. In the constant recycle hybrid designs, αS1 and αSN vary with RR and are greater than α^*. As a result, fewer stages and lower RR are required than for the OD designs, but the incremental benefits are more pronounced for systems with higher α^*, systems requiring fewer stages and lower RR in any case.

The RRimin required for stagewise (Stage 1) separation in countercurrent recycle cascades is a function of αSi, stage compositions, and XB or YP. It is a maximum at the feed stage, becoming smaller at the two ends of the cascade where Yi → YP, and Xi → XB.[2,3] For example, for the enriching section:

$$RR\min = \left[\frac{Ti+1}{P}\right]\min = \frac{YP[1+(\alpha Si-1)(Xi)]-(\alpha Si)(Xi)}{(\alpha Si-1)(Xi)(1-Xi)}$$

$$= \frac{(YP-Yi)[Yi+(\alpha Si)(1-Yi)]}{(\alpha Si-1)(Yi)(1-Yi)} \tag{8}$$

To produce the same YP, RRimin is essentially the same for the OD and hybrid designs because all interior αSi $=$ α* in both cases; and N $\rightarrow \infty$ for constant recycle cascades designed for RR $\rightarrow$ RRimin. Note that RRi is defined in terms of the (recycle) tails rate from the next higher numbered stage, and so there is no RRNmin

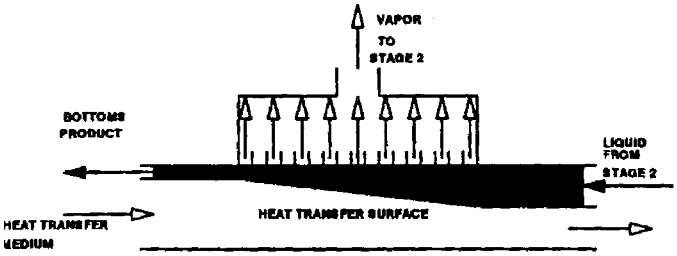
The amount of energy required to make the specified separation is a very important dependent variable in distillation cascade design. The required energy input to the cascade is proportional to the maximum RRi used in the cascade design, and the design engineer has great latitude in choosing N, with concomitant RR. Normally for a constant recycle cascade, a RR $>$ RRimin at the feed stage is selected and the cascade is designed using the same value throughout the enriching and stripping sections of the cascade although cascades designed for smaller RR (possibly with more stages) would suffice toward the two product ends. In the hybrid cascades αS1and αSN $>$ α* (in the region where RR requirements are a minimum), and so, intuitively, probably more benefit in terms of reduced RR (and energy) requirements could be obtained with other hybrid designs that incorporate DCDV stages near the feed stage. Maximum benefit in terms of lower RR requirements would be obtained for the full DCDV designs where all αSi $>$ α*, but the no-mix DCDV cascade requires a different RR (partial reboilers and condensers) at each stage.

In (adiabatic) ideal ordinary distillation, the energy that is added in the reboiler is reused from stage to stage. This is possible because the vapor and liquid feed streams to all interior stages are directly mixed. Indeed, perfect mixing must take place for the ideal OD stage heat transfer and separation to take place. A temperature gradient in the cascade is established as the system tends toward stage-wise thermodynamic equilibrium, and in the ideal ordinary distillation stage the two streams leaving the stage are in thermodynamic equilibrium and at the same temperature. For a specified separation the same overall temperature gradient must exist in the different cascade designs. In the hybrid designs, the heads and tails streams leaving the DV reboiler and DC condenser stages will be at different temperatures, and there will be temperature gradients in the streams undergoing the differential processes. In the DCDV cascades, the four streams leaving a general DCDV stage will be at different temperatures and there will be temperature gradients in the two countercurrent vapor DC and liquid DV streams, presumably with local temperature differences between the two streams necessary to achieved the desired heat transfer, with the energy necessary for DV coming from the DC condensation. In any DC, DV, or DCDV stage the two streams undergoing heat transfer will probably have to be separated by a high conductivity heat transfer surface, which would tend to work against the attainment of the DC and DV temperature gradients. As a result of these requirements, it will probably be very difficult to achieve conditions necessary for the DC, DV, or DCDV stages. Intuitively, it should be easier to achieve conditions approaching the DC and DV processes separately, that is, it would probably be easier to design equipment to carry out the DV reboiler process and DC condenser processes than for the general DCDV stage. Thus although theoretically the no-mix and constant RR DCDV cascades would be more efficient than the hybrid cascades, from a practical standpoint it is believed that it would be much easier to achieve the conditions necessary for the hybrid cascade design.

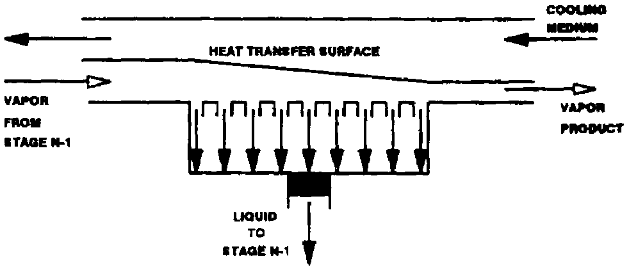
Apparently hardware has not been developed or manufactured to carry out the DC and DV processes, and assuming that these processes can be developed, the DC condensers and DV reboilers would probably be more expensive than for the OD condensers and reboilers. During the era of cheap energy, it was assumed that the use of differential condensers could not be justified. It was found to be more satisfactory and cheaper to obtain added separation by adding more stages[5]. Even today, for new distillation columns it may be better (cheaper) to design the cascade with more stages for more separation rather than use the DC condenser and DV reboiler processes, except (possibly) for situations where cascade size (TIHR) may be important. On the other hand, it may be possible to retrofit DC condensers and DV reboilers to existing OD columns to economically increase energy efficiency if reliable hardware can be developed.

It can be shown that ***simple cascades***[3] containing a relative few number of equilibrium flash condensation or vaporization stages can approach the performance of the DC and DV processes, and this comparison may be useful to guide the development of hardware to carry out the two processes. The concepts for simple cascade DC condensers and DV reboilers and an experimental DC condenser are shown schematically in Fig. 7.

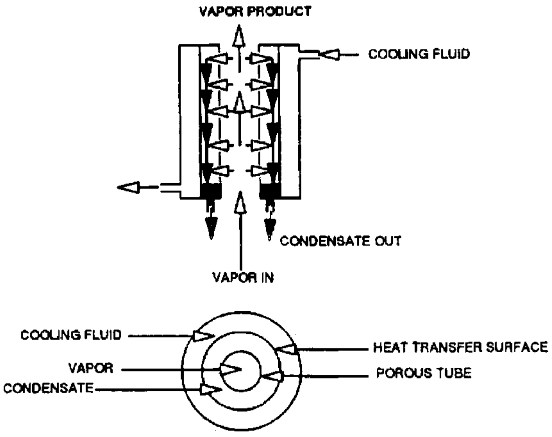
A detailed comparison of optimized ordinary distillation with optimized hybrid, or DCDV cascades for some industrially important separations would be necessary to establish possible economic benefits, but was beyond the scope of this.preliminary investigation. The present study was limited to DCDV cascades with six stages or less because of limitations on the MathCad iterative solver. DCDV cascades with more stages will be significantly more difficult to model because a very large set of linear material balance and nonlinear equilibrium relationships must be solved simultaneously at each stage, consistent with overall cascade material balance requirements. The set of model equations can have several solutions and the iterative solver requires good initial guesses to result in meaningful solutions to the DCDV cascade model equations.



(a) DV REBOILER



(b) DC CONDENSER



(C) CONCEPT FOR AN EXPERIMENTAL DC CONDENSER

Figure 7. Diagrams showing the concept for (a) DV reboilers f and (b) DC condensers in terms of simple cascades; (c) concept for an experimental DC condenser.

Based on the present study it is concluded that, theoretically, hybrid and DCDV cascades can be more efficient than ordinary distillation with concomitant energy savings, and provides the incentive to continue the theoretical DCDV and hybrid cascade investigation, and to conduct research to try to develop hardware to carry out, or at least approach, the conditions necessary for DC condensation and DV vaporization and the DCDV stage processes.

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