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THE ENERGY SAVING EFFECTS OF COMPLEX HEAT-INTEGRATED DISTILLATION CONFIGURATIONS

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Abstract—The distillation of a ternary BTX mixture was studied to evaluate three potential energy saving methods: optimal configuration structuring, heat integration and heat pumping. Ten heuristics, in two categories, were induced and arranged in order of priority.

Separation-technique heuristics: (1) Favor heat flux exchange between units by direct stream contact (thermal coupling). (2) Favor separations with initial splits between extremes in volatility (prefractionation). (3) Favor heat integration if flexibility and operability are satisfactory. (4) Favor operation under lower pressures if the cost involved is reasonable. (5) Favor heat pumping with a product stream as the working medium.

Separation-system heuristics: (1) Favor the PET configuration. (2) Favor the PF configuration if various feeds are anticipated. (3) Favor the SS configuration for very low concentrations of the most or least volatile components. (4) Favor the R heat integration form. (5) Favor the OHP heat pumping form.

INTRODUCTION

Distillation is a unit operation that has been around for a long time, and continues to be the primary and most widely practiced method of separation in the chemical and petrochemical industries. Its strength is contributed to its ability to handle and separate, easily and satisfactorily, almost all kinds of chemical mixtures.

Unfortunately, however, distillation's weak technical foundation and meager amounts of data available for design, usually result in unprecise units with low reversibility measures. It is no surprise, therefore, that distillation is a monster energy consumer which accounts for a considerable fraction of the total capital and operating costs of chemical plants.

Rising energy costs and short supplies in the last decade have spurred conservation programs from homes to government and industry. It suddenly became imperative that energy usage must be carefully monitored and reduced.

Distillation has, since then, become a prime target for energy conservation and saving. In the mid 70s, most of the improvements were achieved through better operation and maintenance practices, while more recently through investment projects primarily of a retrofit nature. These energy conservation projects compete on their own merits against other capital expenditures, particularly as the prices of energy and power continue to escalate at faster rates than the remainder of the economic sector.

Energy conservation and saving efforts in any process should be directed in order of priority, towards: (1) Eliminating energy demands, (2) Reusing waste energy to replace virgin input, and (3) Machinery-aided waste energy recovery.

Applied in distillation, these efforts were classified differently. The classification presented in this article follows the general process trend comprehended, in order of priority, as: (1) Optimal configuration structuring, (2) Heat integration, and (3) Heat pumping.

Focus, on the other hand, must not be strictly on energy conservation and saving. Capital, controlability, safety and operability are equally critical; they must be effectively analyzed to produce reliable systems.

Besides, this must be done against the background of the entire process. The target is a system, not just a collection of units. This system can include more than one step, the relationship among which must also be taken into account.

Additional process equipments are almost always required. The economic tradeoff between the incremental costs for extra capital and the resulting energy savings must always be made to determine whether the addition of new equipment is economical.

This article discusses the various potential energy saving methods used in distillation. It should serve as a guide to indicate whether or not such methods are cost-effective, and under what conditions.

REVIEW

Many energy saving methods have been known for a long time, although their use was limited to a relatively few applications. They were reviewed by King [1], and Stephanson and Anderson [2].

Different classifications of these methods were presented by Mix et al. [3], Rush [4], and Cheng and Luyben [5].

The objectives were different. Gomez and Seader [6], and Luyben et al. [5,7-9] presented economic objectives. While Tedder and Rudd [10], Linnhoff et al. [11-15], Umeda et al. [16,17], Naka et al. [18], Seader [19], Hindmarsh et al. [20], and Andrecovich and Westerberg [21] presented thermodynamic objectives.

The approaches were also different. Petlyuk et al. [22], Stupin and Lockhart [23], Tedder and Rudd [10] and Luyben et al. [5,7-9] persued selective approaches. While Hendry and Hughes [24], Rathore et al. [25], Rodrigo and Seader [26], Gomez and Seader [6], Linnhoff et al. [11-15], Umeda et al. [16,17], Naka et al. [18], and Westerberg [28] persued synthesis. The selective approaches employed different heuristic and evolutionary rules, while synthesis employed different search algorithms, composite diagrams and flow cascades.

1. Optimal configuration structuring

Separation problems based on distillation technology have an enormous variety of alternate solutions. Optimal configuration structuring is to select the best, by eliminating energy demands at the design level.

The general techniques for determining the optimal sequence have included heuristic, algorithmic and evolutionary methods, as well as combinations of two or all three methods.

Much of the experience obtained so far has been embedded in different heuristic rules. The earliest efforts were by Lockhart (1947), Harbert (1957) and Heaven (1969) [10]. Others were by Nishimura and Hiraizumi [29], Rudd et al. [30], Tedder and Rudd [10], and King [1]. Armed with these heuristics, one can often write down very quickly reasonable sequences that can prove to be close to the best sequence.

Another approach is to set up the three of alternatives and search for the best sequence algorithmically. Several search algorithms were used by Thompson and King [31], Hendry and Hughes [24], Westerberg and Stephanopoulos [27], Rodrigo and Seader [26], Gomez and Seader [6], and Andrecovich and Westerberg [21].

Another, is to use evolutionary methods such as the composition diagrams presented by Hohmann and Sander [32].

Heuristic search with evolution also proved to be effective, and three papers report on it, those by Seader and Westerberg [19], Nishida et al. [33], and Nath and Motard [34].

Among the configurations that attract attention for the separation of ternary mixtures are: LOF, HOF, PF, SS, PET, SRS and SRR. The LOF and HOF are simple configurations, where components are separated sequentially in descending or ascending orders of volatility, respectively. The PF is a complex configuration, where initial splits are between extremes in volatility (prefractionation). The SS is a complex configuration, where components are separated in only one step. The PET, SRS and SRR are complex configurations, where the heat flux is utilized in more than one unit and the coupling between units is by direct flow of material (thermal coupling).

Tedder and Rudd [10], and Doukas and Luyben [7] studied the complex PF and SS configurations, and compared them with the simple LOF and HOF configurations. Alatiqi and Luyben [8] focussed on the SS configuration and presented the SRS configuration. Many others discussed the PET, SRS and SRR configurations, originally introduced by Brugma (1937, 1942), and Cahn and Di Miceli (1962) [22]. Some of these were, Petlyuk et al. [22], Stupin and Lockhart [23], and Glinos et al. [35].

2. Heat integration

Only rarely are distillation columns operated singly in production processes. Chemical plants consist of many operating units, each of which typically includes several columns performing successive separations. Optimising the design of individual columns in isolation from the rest of a process may sometimes have a counter-productive effect, spoiling opportunities for better energy conservation and therefore adversely affecting the energy consumption of the entire process. Heat integration is to select the best energy exchange between different units of a process, by reusing waste energy from one unit to replace virgin input to another.

The basic feature of heat integration is the utilization of the heat content of the overhead vapor of one column to supply the heat required in the reboiler of another. In order to provide the necessary temperature difference, the columns must always be operated under different pressures. The overhead vapor of the high pressure column should generate a reasonable temperature difference from the reboiler of the low pressure column so that heat transfer areas would not be excessive.

Heat integration is practiced in three forms: forward, reverse and multiple effect. Forward heat integration utilizes the waste heat from the former columns in the latter ones. The operating pressures of the consecutive columns, therefore, decrease in the direction of flow. In reverse heat integration, the operating pressures increase in the direction of flow. In the case of multiple effect, also called split column, the feed is split into two or more portions. One portion is separated in a high pressure column, and the other in a low pressure one. Split columns are particularly useful in low temperature distillation, when sufficient temperature difference is available and high reflux ratios are required.

As can be derived from the above discussion, the operating pressure is crucial to heat integration. The pressure chosen to operate a distillation column influences many important design parameters, e.g., relative volatility, vapor density, shell thickness, and heating and cooling levels.

The use of extreme values of pressure in distillation makes the cost very high, and leads to thermal degradation [37]. High pressures are undesirable particularly in hydrocarbon separations where relative volatilities decrease with increasing pressures, making the separations more difficult. As a rule of thumb, heat duties are reduced by 1% for every 2% reduction in operating pressures [37]. Reverse heat integration gives the lowest pressure in the high pressure column. If relative volatilities are strong functions of pressure, this can result in a considerable reduction in the total energy requirement.

The general problem of heat integration in process networks is complex and to date not fully understood. Its conjunction with the optimal configuration structuring problem, is approached either simultaneously or sequentially. The simultaneous approach leads to very large formulations, and was implemented mainly by Rathore et al. [36]. While the sequential approach was implemented by Umeda et al. [16] and Naka et al. [18].

Linnhoff et al. [11], and Andrecovich and Westerberg [21] extended the principles of overall process heat integration, established for heat exchanger networks, to cover distillation.

Heat integration is an effective energy saving tool. Yet, the more sophisticated a system becomes due to its application, the more complicated its operation becomes.

3. Heat pumping

At one time heat pumping was considered primarily for systems which would have otherwise required refrigeration, but now with higher energy costs it is attracting attention for other systems. It can reduce energy consumption significantly, but at the expense of capital and simplicity. Savings as high as 25% in energy requirement were reported by Robertson [38] and Null [39]; 10-15% by Kenny [40]; and 50% by Davidson and Campagne [41].

There are several forms in which a heat pump can be applied to a distillation column. The most common, is the compression heat pump. Its main concept is the reuse of overhead vapor from a column, in its reboiler. The adverse quality difference is overcome by adding compression work to the vapor, to raise its pressure and condensing temperature.

The great disadvantage of this method, however, is that it requires the heat pump to operate over the total temperature difference across the system. This is not only thermodynamically inefficient, but imposes practical limitations on the application of the technique if the temperature difference to be overcome is large. If the heat pump could be applied over a smaller temperature difference, it would become more feasible. However, this means increasing the heat transfer areas of the reboiler and/or condenser, and consequently the capital cost.

Compression heat pumping eliminates the cooling water limitation on tower pressure, which can as a result be lowered to improve the relative volatility and reduce the reflux. This, in turn, leads to more reduction in the energy requirement. In addition, the need for refrigeration in low-temperature applications is eliminated.

The compression medium can either be an external working fluid or a product stream. The case of the external working fluid imposes an additional thermodynamic inefficiency, due to the temperature difference between the condensing tower vapor and the vaporizing working fluid. If the fluid in the distillation column is itself a fairly good refrigerant, it is possible to improve the performance by utilizing this fluid as the compression medium. By so doing, it is possible to increase the limit of allowable temperature difference. At the same time, one heat exchanger may also be eliminated and capital cost reduced.

Three other types of heat pumps proved to be promising when applied to distillation. All of which, however, are yet at the stage of being high-investment low-efficiency systems. The first, is the absorption heat pump introduced by Davidson and Campagne [41]. The second, is the secondary reflux and vaporization heat pump introduced by King [1]. The third, is the

Table 1. Column design specifications

Case	Unit	N_t	N_f	N_s	F_o	F_s	R
1A1	1	19	13	—	0.007	—	7.2
	2	22	12	—	0.038	—	1.8
1A2	1	21	12	—	0.045	—	1.6
	2	20	14	—	0.007	—	5.1
1A3	1	25	17	—	0.027	—	1.5
	2	35	6/26	8	0.007	0.038	12.0
1A4	1	40	21	14	0.007	0.038	18.2
1B1	1	17	14	—	0.018	—	5.1
	2	20	11	—	0.035	—	1.9
1B2	1	21	12	—	0.053	—	1.3
	2	17	11	—	0.018	—	2.9
1B3	1	20	12	—	0.027	—	1.3
	2	34	3/25	10	0.018	0.035	4.0
1B4	1	30	11	9	0.018	0.035	20.7
1B5	1	20	1/#	1/20	—	0.052	—
	2	30	5/25	5/§	0.018	0.025/*	5.0
1B6	1	25	6/15	6	0.018	0.073	7.0
	2	17	1	1	—	0.039	—
1B7	1	27	7/18	18	0.018	0.041	5.0
	2	5	5	5	0.035	0.007	0.2

#: 12/20
§: 15/25
*: 0.035/0.052

organic Rankine heat pump introduced by O'Brien [37].

EVALUATION

The criteria for evaluation include: (1) Capital investment, (2) Operating cost, (3) Operating conditions, (4) Feed and product specifications, and (5) Degree of irreversibility.

The compromise, between the saving in the consumption of utilities and the corresponding increase in capital investment, must be carefully handled. This is incorporated in the term for the total annual separation cost, being the sum of the annual operating cost and the annual capital cost.

The equation is as follows:

$$C_t = C_{op} + C_{cp}$$

The annual operating cost is mainly the annual cost of utilities.

The equation is as follows:

$$C_{op} = (10.015\ Q_c + 24.572\ Q_r) + (420\ W)$$

First term: Swartz and Stewart [42]

Second term: O'Brien [37]

The annual capital cost is the return on capital investment at an estimated rate value of 15%.

The equation is as follows:

$$C_{cp} = (N_t + 2)(11.875 + 36.020D + 36.810D^2 - 0.144D^3 + 2.878D^4) + 300A + 90W^{0.82}$$

First term: Swartz and Stewart [42]

Second term: Dryden and Furlow [43], scaled by a factor of 3.2

Third term: Null [39], scaled by a factor of 1.6.

The degree of irreversibility helps to locate systems where energy conservation and integration are needed, as well as pinpoint unreliable systems. It is measured by many different techniques, one of which is the lost work analysis. Lost work arises from all potential gradients or discontinuities within a system whether they be temperature, pressure, chemical potential, or any combination of these. It is calculated using the availability function, and heat and work exchanged.

The work presented in this article is divided into three parts. The first is devoted to optimal configuration structuring, the second to heat integration and the third to heat pumping. The feed under focus is a mixture of benzene, toluene and m-xylene (BTX).

The design parameters and consumption rates of utilities are the result of simulation runs on the DESIGN II simulation package, copyright by ChemShare Corporation [44].

The objectives are to determine the total annual separation cost and lost work of all configurations in each part, compare them, and induce a set of heuristics as a guide.

General assumptions and design specifications are:

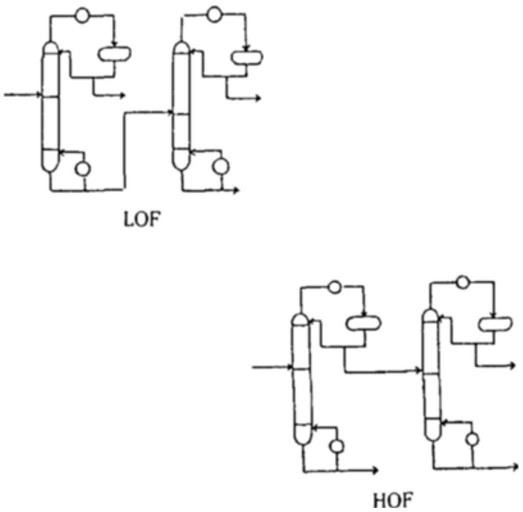


Fig. 1. Simple configurations.

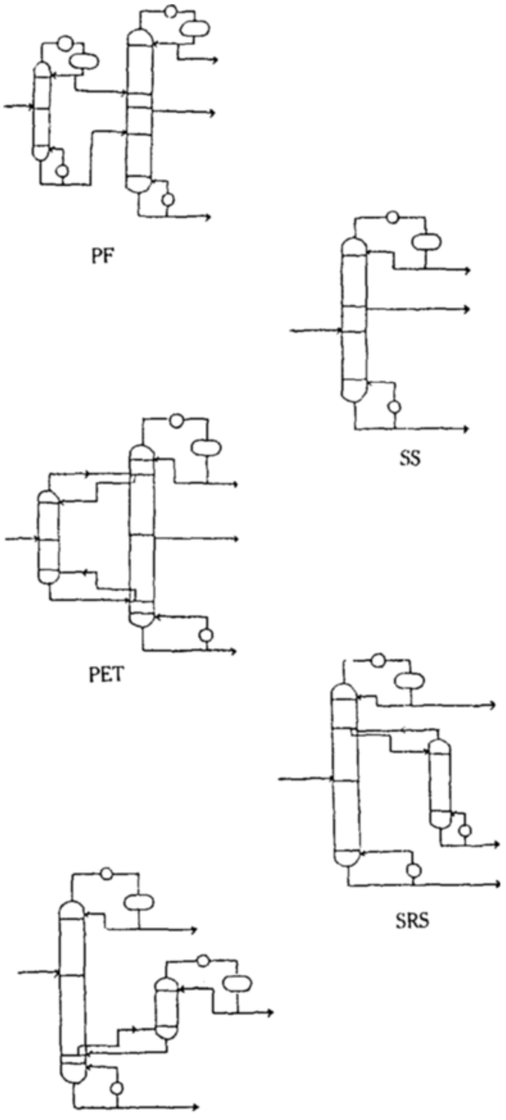


Fig. 2. Complex configurations.

(1) Ideal gas and liquid behavior for vapor/liquid equilibrium, (2) Tray efficiency of 100%, (3) Saturated liquid reflux, and (4) Total condensers and partial reboilers.

PART ONE

The purpose of part one is to explore the performance of different simple and complex configurations in two sections, A and B of different feed compositions.

Configurations in section A are: Case 1A1. LOF, Case 1A2. HOF, Case 1A3. PF, and Case 1A4. SS.

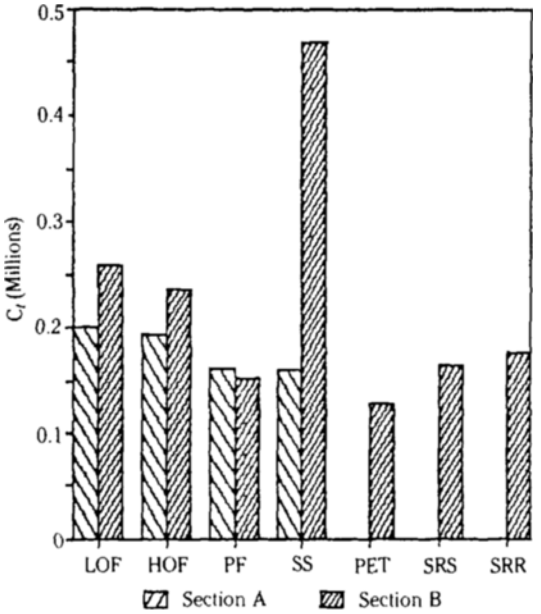


Fig. 3. Cost analysis.

Configurations in section B are: Case 1B1. LOF, Case 1B2. HOF, Case 1B3. PF, Case 1B4. SS, Case 1B5. PET, Case 1B6. SRS, and Case 1B7, SRR.

Special assumptions and design specifications are: (1) Condenser/reboiler minimum temperature difference of 10K, (2) Operating pressure of 101.3 kPa, (3) No pressure drop across trays or condensers, (4) Feed rate of 0.083 kgmol/s, (5) Feed temperature of 389K (section A) or 383K (section B), (6) Feed composition of benzene of 10 mol% (section A) or 20 mol% (section B), with that of toluene and m-xylene equal, and (7) Product purity of 95, 90 and 95 mol% of benzene, toluene and m-xylene, in their respective product streams.

Conclusions

Configurations which are more reversible, are more economical and less energy consuming.

Thermal coupling is very effective. It reduces energy consumption considerably and eliminates at least one reboiler and/or condenser.

Prefractionation is also very effective. It results in stable operation, and is to be recommended where a variety of feed compositions is anticipated. It eases separation because of the volatility gap in the initial splits.

The PET configuration is the best of all configurations, with 50% reduction in separation cost not uncommon. It applies both thermal coupling and prefractionation.

The PF configuration stands second to the PET,

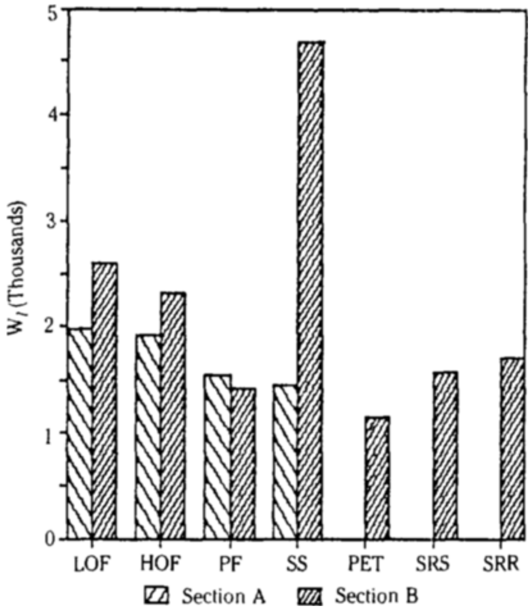


Fig. 4. Irreversibility analysis.

Table 2. Column design specifications

Case	Unit	N_t	N_f	N_s	F_o	F_s	R	P_c	P_b
2A1	1	38	14	—	0.021	—	2.9	101.3	143.3
	2	44	28	—	0.042	—	1.4	101.3	147.3
2A2	1	36	15	—	0.021	—	2.0	35.2	53.9
	2	33	21	—	0.042	—	1.1	12.0	29.6
2A3	1	29	19	—	0.042	—	1.0	130.0	165.3
	2	62	8/36	23	0.021	0.042	5.8	101.3	159.3
2A4	1	28	19	—	0.042	—	0.7	51.3	67.3
	2	57	8/34	20	0.021	0.042	4.5	35.2	60.9
2B1	1	39	17	—	0.021	—	2.6	261.3	303.9
	2	35	22	—	0.042	—	1.3	12.0	30.4
2B2	1	37	16	—	0.021	—	1.7	35.2	54.3
	2	44	29	—	0.042	—	1.5	106.0	152.0
2B3	1	31	19	—	0.042	—	1.2	323.4	360.5
	2	60	9/40	21	0.021	0.042	3.2	35.2	61.9
2B4	1	29	20	—	0.042	—	0.6	23.5	39.7
	2	82	14/54	31	0.021	0.042	2.5	216.3	287.3

with 40% reduction in separation cost. It applies prefractionation.

The SS configuration excels only at low concentrations of the most or least volatile components. It is affected most by the changes in feed composition.

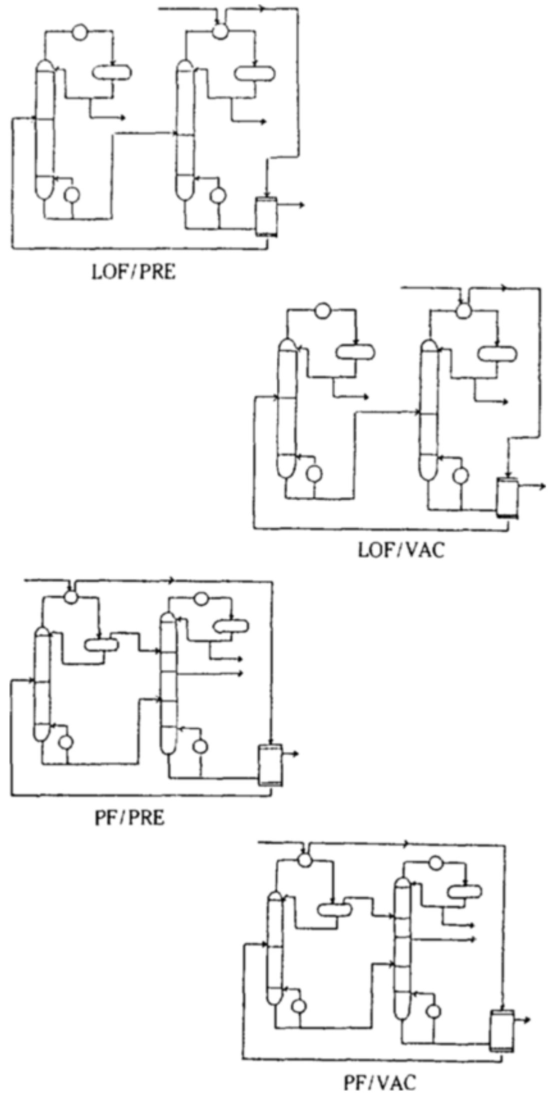


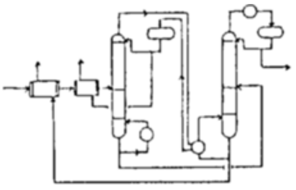
Fig. 5. Operating pressure effect.

PART TWO

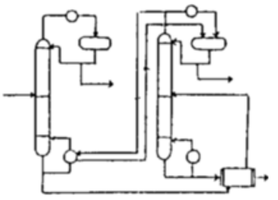
The purpose of part two is to investigate the effect of operating pressures, section A, and demonstrate the significance of heat integration in its two forms, section B.

Cases in section A are: Case 2A1. LOF/PRE, Case 2A2. LOF/VAC, Case 2A3. PF/PRE, and Case 2A4. PF/VAC.

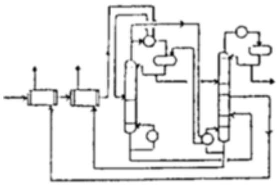
Cases in section B are: Case 2B1. LOF/F, Case 2B2. LOF/R, Case 2B3. PF/F, and Case 2B4. PF/R.



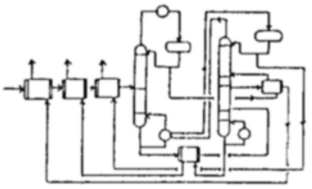
LOF/F



LOF/R



PF/F



PF/R

Table 3. Heat exchanger deisgn specifications

Case	Unit	T_{ti}	T_{to}	T_{si}	T_{so}
2A1	3	374	387	—	384
2A2	3	313	327	—	323
2A3	3	371	385	—	381
2A4	3	341	351	—	351
2B1	3	288	—	372	298
	4	—	327	388	322
2B2	3	428	405	—	389
2B3	3	288	—	360	298
	4	—	340	395	331
2B4	3	288	—	346	298
	4	—	—	374	324
	5	—	338	380	339
	6	—	—	456	374
	7	419	346	—	409

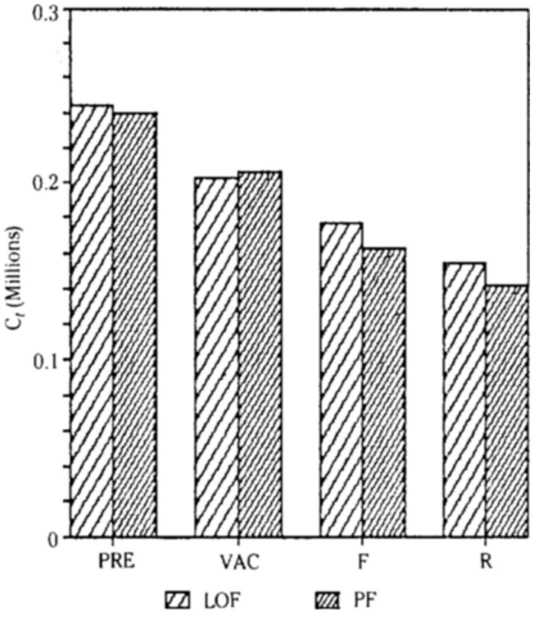


Fig. 7. Cost analysis.

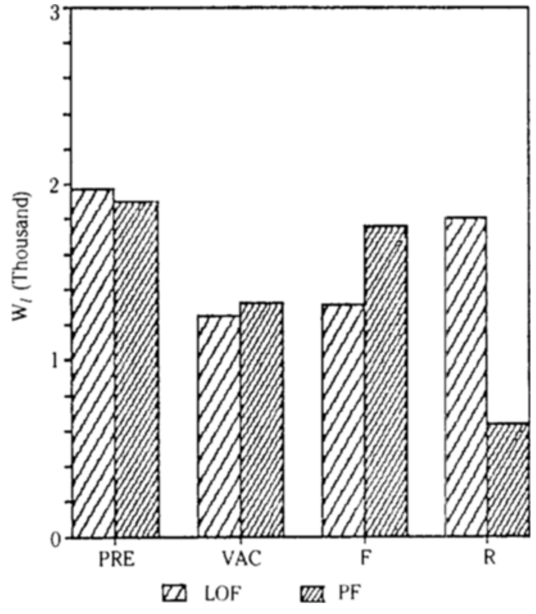


Fig. 8. Irreversibility analysis.

Special assumptions and design specifications are: (1) Minimum temperature difference at the pinch end of heat exchangers of 10K, (2) Condenser/reboiler temperature difference of 15K, (3) Pressure drop per tray: 0.3 kPa in vacuum columns, and 0.7 kPa in atmospheric or pressure columns, (4) Pressure drop across condensers: 6.7 kPa under vacuum, and 16.7 kPa under atmospheric or higher pressure, (5) Feed rate of 0.083 kgmol/s, (6) Feed temperature of 388K, (7) Feed composition of 25, 50 and 25 mol% of benzene, toluene and m-xylene, respectively, and (8) Product purity of 99, 99 and 99 mol% of benzene, toluene and m-xylene, in their respective product streams.

Conclusions

Lower operating pressures are less energy demanding than higher ones, and are to be recommended if the cost involved is reasonable. However, extreme values are not favorable. Separation cost can be reduced to the range of 15%.

Reverse heat integration is more benificial than forward heat integration, particularly in the case of complex configurations. Reduction in separation cost of 40%, can be achieved.

Heat integration reduces irreversibility considerably and results in attractive energy savings. However, it is to be noted that these savings are on the expense of flexibility, reliability and operability.

Table 4. Column design specifications

Case	BTX	N_t	N_f	N_s	F_o	F_s	R	T_f
3A1	10/45/45	40	21	14	0.007	0.038	18.2	389
3A2	20/40/40	30	11	9	0.018	0.035	20.7	383
3A3	33/33.5/33.5	46	23	22	0.028	0.028	19.3	376
3A4	45/45/10	39	19	27	0.038	0.038	2.3	369
3A5	40/40/20	40	20	22	0.033	0.033	7.6	372
3A6	33.5/33.5/33	40	20	21	0.009	0.009	17.4	376

Table 5. Compressor design specifications

Case	BTX	T_{ci}	T_{co}	F_{ci}	P_{ci}
3B1	10/45/45	343	417	0.100	26.8
3B2	20/40/40	343	417	0.296	26.8
3B3	33/33.5/33.5	343	417	0.412	26.8
3C1	10/45/45	358	417	0.008	101.3
3C2	20/40/40	358	417	0.016	101.3
3C3	33/33.5/33.5	358	417	0.027	101.3
3C4	45/45/10	358	417	0.037	101.3
3C5	40/40/20	358	417	0.033	101.3
3C6	33.5/33.5/33	358	417	0.027	101.3
3D4	45/10/10	385	417	0.037	101.3
3D5	40/40/20	385	417	0.033	101.3
3D6	33.5/33.5/33	385	417	0.027	101.3
3E1	10/45/45	343	417	0.037	10.1
3E2	20/40/40	343	417	0.033	10.1
3E3	33/33.5/33.5	343	417	0.027	10.1
3E4	45/45/10	343	417	0.008	10.1
3E5	40/40/20	343	417	0.016	10.1
3E6	33.5/33.5/33	343	417	0.027	10.1

PART THREE

The purpose of part three is to explore the validity and significance of heat pumping in five sections, A through E. Section A studies the performance of the SS configuration under different feed compositions. Sections B, C, D and E investigate the effect of introducing different types of heat pumps, on the performance and running cost of the system.

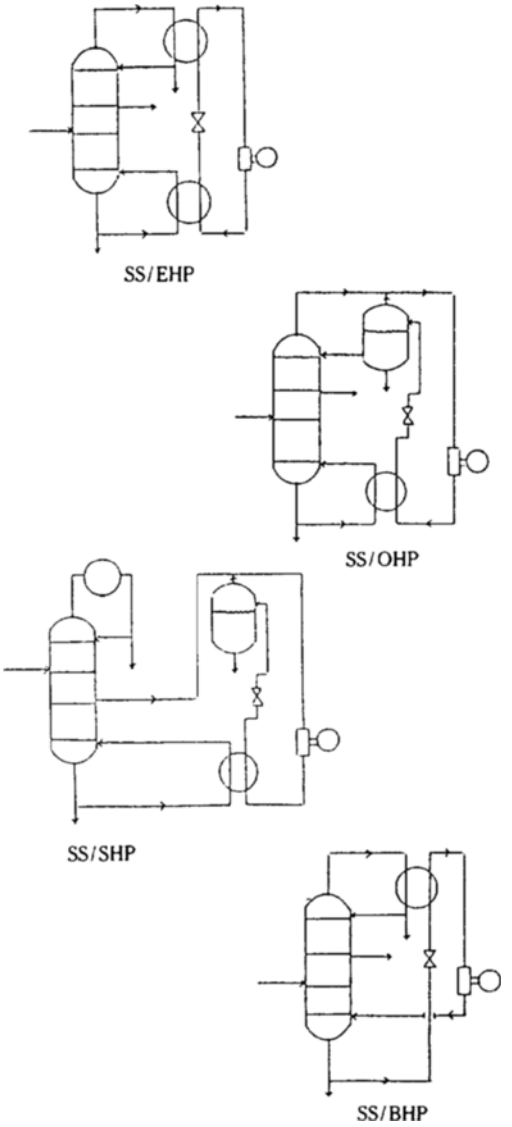


Fig. 9. Types of heat pumps.

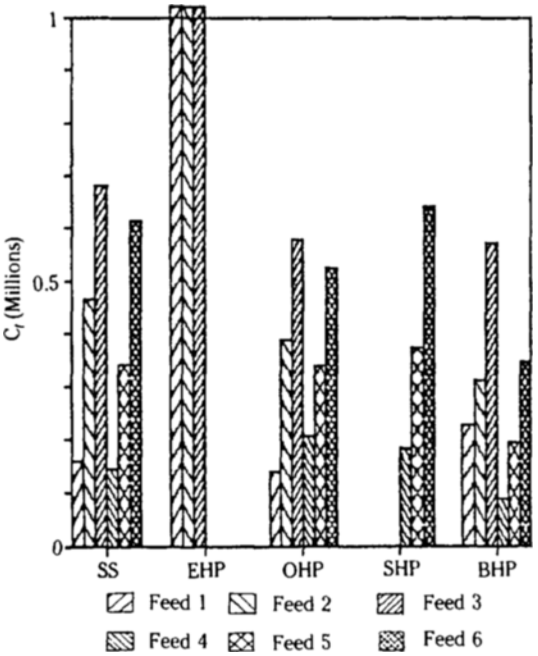


Fig. 10. Cost analysis.

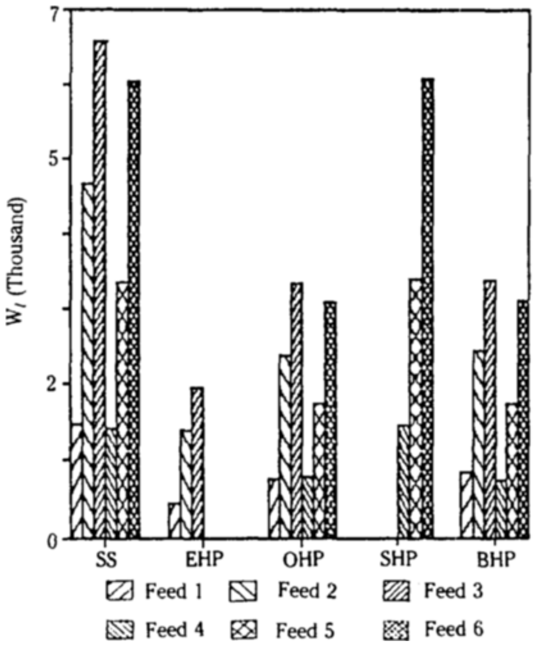


Fig. 11. Irreversibility analysis.

The heat pumps discussed are compression heat pumps implementing external medium compression (section B), overhead vapor recompression (section C), side vapor recompression (section D) and bottoms flash recompression (section E). They consequently, employ water (section B), benzene (section C), toluene (section D) and m-xylene (section E), as their compression media.

Cases in sections A through E are: Cases 3A1-3A6. SS, Cases 3B1-3B3. SS/EHP, Cases 3C1-3C6. SS/OHP, Cases 3D4-3D6. SS/SHP, and Cases 3E1-3E6. SS/BHP.

Special assumptions and design specifications are: (1) Condenser/reboiler temperature difference of 10K, (2) Operating pressure of 101.3 kPa, (3) No pressure drop across trays or condensers, (4) Compressor efficiency of 65%, (5) Feed rate of 0.083 kgmol/s, and (6) Product purity of 95, 90, and 95 mol% of benzene, toluene and m-xylene, in their respective product streams.

Conclusions

Process design innovations must be explored and implemented, if significant reductions in energy requirement are to be achieved. Heat pumping is to inforce these innovations, by further machinery-aided waste energy recovery.

Heat pumping with an external compression medium is not profitable. It becomes attractive only when a product stream could serve as the working medium. Both overhead vapor and bottoms flash recompression are attractive, while side vapor recompression is promising though less attractive. Precautions must be taken, however, to prevent the contamination of the product streams. Reductions in separation cost of 30% are not uncommon.

The applicability of heat pumping is much limited than that of thermal coupling, prefractionation or heat integration. However, where applicable it enhances flexibility and operability, and thus is to be particularly recommended in new designs.

RECOMMENDATIONS

Energy conservation and saving require a visible management commitment. A comprehensive ongoing program is essential to remain competitive in today's economy.

In the future, we see the need for even larger changes in the energy requirement of various processes, if we are to come anywhere near keeping pace with the rising demand for energy. More basic changes will be required. This kind of process step-out, provides a very important challenge for chemical engineers world wide, and should be the focus of more and more of our efforts, as we move into an energy short age.

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NOMENCLATURE

A : Heat transfer area, m^2
C : Cost, \$/year
D : Column diameter, m
F : Stream flowrate, kgmol/s
N : Number of trays from the top
P : Pressure, kPa
Q : Heat duty, kw
R : Reflux ratio
T : Absolute temperature, K
W : Work duty, kw
LOF : Light out first configuration
HOF : Heavy out first configuration
PF : Prefractionator configuration
SS : Single side stream column configuration
PET : Petlyuk configuration
SRS : Side-cut reboiled stripper configuration
SRR : Side-cut refluxed rectifier configuration
PRE : Pressure
VAC : Vacuum
F : Forward heat integration
R : Reverse heat integration
EHP : External medium heat pump
OHP : Overhead vapor heat pump
SHP : Side vapor heat pump
BHP : Bottoms flash heat pump

Subscripts

c : Condenser
r : Reboiler
t : Total
cp : Capital
op : Operating
l : Loss
f : Feed
s : Side
b : Bottom
o : Overhead
ti : Tube in
to : Tube out
si : Shell in
so : Shell out
ci : Compressor in
co : Compressor out

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