Chinese J. of Chem. Eng., **7** (2) 126–131 (1999)

Heat Integration for Different Separation Processes*

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Abstract The distribution of heat duties among individual separation subsystems and other aspects of heat integration in such systems are reviewed. Heat integration for different separation processes is investigated, using the pinch point method. Such a study will provide theoretical guide lines for the proper choice of a desirable separation process.

Keywords separation, heat duty, pinch analysis, heat integration

1 INTRODUCTION

In many cases, several different types of separators are being involved in a chemical process, for instance, the combination of evaporation and drying. The unit energy consumption of each process may be very different, owing to the distribution of heat duties. Much work has been done on heat conservation in separation processes during the past years[1−12]. Most of the work done, however, were concerned with heat integration within various subsystems and/or in an individual separator of a separation system. Integration of several different separation processes is more difficult than integration in one and the same separation process. Therefore, the different separation systems must be carefully handled.

A case study, on the heat integration for different separation processes is investigated, employing the method of pinch analysis.

2 DISTRIBUTION OF HEAT DUTIES AMONG DIFFERENT SEPARATION PROCESSES

Fig. 1 shows a chemical separation system involving evaporation, mechanical separation, and drying. Any changes in the operation conditions of the proceeding process would bring about not only changes in its energy consumption, but also that in the subsequent processes. This means that these separation subsystems influence one another. Therefore, the separation system should be taken as an entity for the optimization of energy consumption.

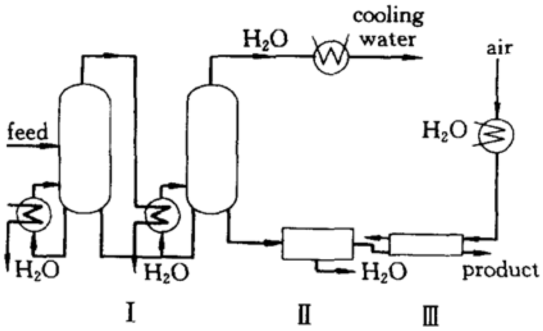

Figure 1 Chemical separation system
I—double effect evaporation;
Ⅱ—centrifugal seperation;
Ⅲ—rotative drying

Received 1998-02-25, accepted 1998-10-23.

* Supported by the Research Promotion Foundation for Returned Scholar of the China Education Commission.

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In the system under study, dewatering energy consumption of centrifugal separation is small, and can be neglected, when compared with the other two subsystem. So only the energy consumptions in the evaporation and drying subsystems will be discussed.

In a multiple-effect evaporation subsystem, if the effect of boiling temperature rise on energy consumption is ignored, the following correlations will be valid.[13]

$$\sum_1^n V_i = V_0 \Delta H_0 \left(\frac{\eta}{\Delta H_1} + \frac{\eta^2}{\Delta H_2} + \cdots\cdots + \frac{\eta^n}{\Delta H_n} \right) = F_0 (1 - W_0 / W_n) \tag{1}$$

$$Q_e = V_0 \Delta H_0 \tag{2}$$

$$q_e = Q_e / \sum V_i \tag{3}$$

Whereas for the drying subsystem, we have[13]

$$Q_d = F H_v (\omega_f - \omega^*) \frac{T_i - Ta}{T_i - T_o^*} \tag{4}$$

$$q_d = \frac{Q_d}{F(\omega_f - \omega^*)} \tag{5}$$

$$V_d = Q_d / \Delta H_0 \tag{6}$$

Different distribution of heat duties in the evaporator and the drier may turn out to be a major factor affecting the capital investment, as shown in the following[14]

$$\frac{Cost2}{Cost1} = \left(\frac{Q_2}{Q_1} \right)^f \tag{7}$$

where f represents the size exponent of the process equipment, $f = 0.7$ for the evaporator, while for the drier, $f = 0.8$.

In the case study, it is assumed that the temperature of steam employed is 120 ℃, the temperature difference of each effect is 20 ℃, $\eta = 97\%$, $F_0 = 3.60\,\mathrm{kg \cdot s^{-1}}$, $W_0 = 20\%$, $T_i = 90$℃, $T_w = 40$℃, $T_{oc} = 45$℃, $T_a = 25$℃, $\omega_c = 0.10$, $\omega^* = 0.02$. The water extracted by centrifugal separation is supposed to be equal to 40% of the inlet water content (In this study, for convenience, the inlet and outlet water contents are assumed to be linearly related). If the concentration of evaporation effluent W_n is known, the energy consumption and capital investment of the entire system can be calculated through Eqs. (1)—(7). The results are shown in Fig. 2.

Fig. 2 shows the changes in the energy consumption and investment index of evaporation and drying processes with W_n. It can be seen that as W_n increases, unit energy consumption and capital investment of evaporation process will increase only slightly, while those of the drying process will decrease to a comparatively great extent. This can also be seen from Table 1, that the dewatering energy consumption of the drying process is much higher than that in the evaporation process. Thus it is beneficial in both energy consumption and capital investment when decreasing the water content of the substance entering the dryer.

When the number of effects in the evaporation subsystem is increased, energy consumption of the system will be reduced, while the capital investment will be increased, as shown in Fig. 3.

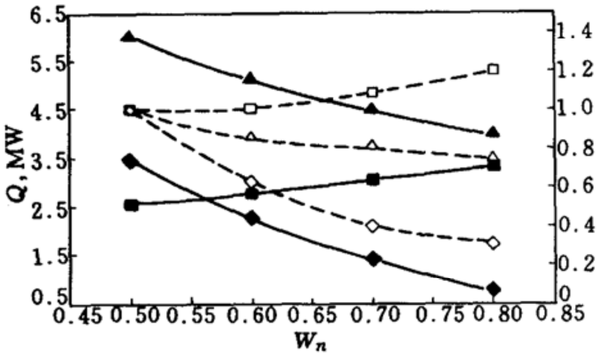

Figure 2 **Energy consumption and capital cost ratio *vs.* W_n**
—— energy consumption; - - - - capital cost ratio;
□, ■ evaporation process;
◇, ◆ drying process; △, ▲ system process

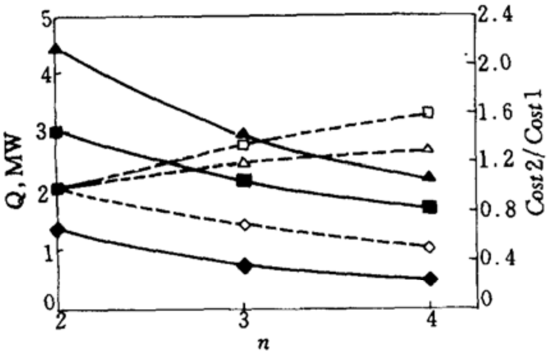

Figure 3 **Energy consumption and capital cost ratio *vs.* number of effects**
—— energy consumption; - - - - capital cost ratio;
□, ■ evaporation process;
◇, ◆ drying process; △, ▲ system process

Table 1 **Relationship between unit dewatering energy consumption and the number of effects (n) of evaporation**

n	q_e, kJ·kg^{-1}	q_d, kJ·kg^{-1}
1	1191	8501
2	816	8501
3	628	8501

3 SCHEMES OF HEAT INTEGRATION FOR DIFFERENT SEPARATION PROCESSES

In the above discussion, heat integration in the separation subsystems has not been considered. The secondary steam from the last effect evaporator is condensed by cooling water, while the air entering the drier is preheated by process utility. If the secondary steam is used to preheat the air for the drier, remarkable energy savings may be achieved.

Fig. 4 shows the changes in the energy consumption of the drying process and the evaporation duty with W_n. It can be seen that when W_n increases, energy consumption of the drying process decreases, whereas evaporation duty will be slightly increased. The concentration of the substance corresponding to the intersection point $W_{\rm cr}$ is known as the critical concentration, and here it equals to 57%. At the critical concentration, the evaporation duty can exactly satisfy the energy requirement of the drying process. If $W_n > W_{\rm cr}$, the energy consumption of the drying process can be totally provided by the secondary steam, and the drying process utility is zero; if $W_n < W_{\rm cr}$, this can be only done partially with the secondary steam, the other to be supplemented with process utility.

Fig. 5 gives the relationship between utility consumption and W_n. It can be seen that as W_n increases, the process utility needed for drying decreases rapidly, and when W_n reaches $W_{\rm cr}$, it becomes zero, meaning that the secondary steam is acting as the sole heat source of the drying. The process utility for evaporation increases with W_n. Consequently, the overall utility consumption (represented by dash line in Fig. 5) will reach minimum when $W_n = W_{\rm cr}$, meaning that the optimal economy of the system is achieved.

It should be noted that when W_n increases in a system without heat integration, the overall energy needed from the process utility will decrease. But when heat integration is involved, the situation will be quite different. It is interesting to notice that a minimum utility can be obtained at W_{cr}.

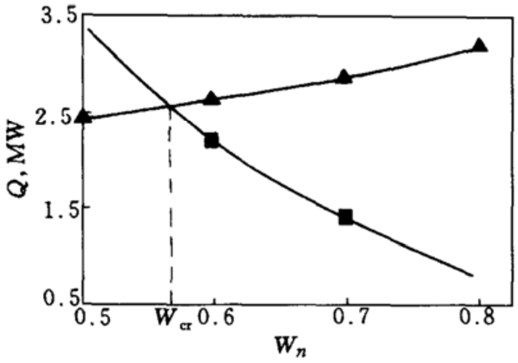

Figure 4 Energy consumption of drying and evaporation duty *vs.* W_n
■ energy consumption of drying;
▲ the evaporation duty

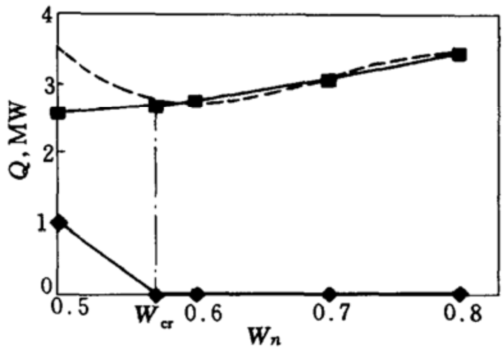

Figure 5 Hot utility *vs.* W_n after heat integration
■ the evaporation process utility;
◆ the drying process utility;
---- the overall utility consumption

For the system in Fig. 1, if the double effect evaporators are replaced by a mechanical vapor recompression(MVR) evaporator, much more energy savings can be expected. Fig. 6 shows the composite curves for each unit. The heat duties of the evaporator and its associated condenser straddle the pinch and hence the MVR operation can be used to save energy. Figs. 7 and 8 are illustrations of potential MVR schemes.

Fig. 7 is a 'conventional' MVR operation in which all of the secondary steam from the evaporator are introduced into a heat pump driven by a steam turbine. The exhaust steam from the turbine can then be used for the air preheater of the drier. In this scheme, steam of 3.4×10^6 Pa is provided to the turbine, but more capital investment will be needed. Even when the heat pump is properly placed in the flowsheet, heat transfer across the pinch exists because exhaust steam from the turbine is used in the air preheater. Thus energy consumption of the system does not reach the minimum and the scheme is not the best.

Fig. 8 is an optimized MVR scheme in which the secondary steam from the evaporator is only partially used for the air preheator, supplemented by exhaust steam from the turbine. In this manner, energy needed from the process utility may be reduced and the increased capital cost can be paid back within two years. Judged by pinch analysis, the heat pump is properly located, and there in no heat transfer across the pinch.

A comparison of the energy needed from the process utility at $W_n = 0.7$ is given in Table 2 for non-integrated and heat integrated systems. Considering the different energy content in the different steams sources, process utility costs at different pressures are used for the comparison in Table 3. The price of low-pressure steam is assumed to be 30 Yuan$\cdot$t^{-1}, 60 Yuan$\cdot$t^{-1} for medium-pressure steam, whereas the price of electrical energy is 0.5 Yuan$\cdot$kW$^{-1}\cdot$h^{-1}, and the working hours of the system are 8000 per year. Under such assumptions, it is found that energy cost savings of 20% will be attained with heat integration, and 36% energy cost savings are achieved for the scheme in Fig. 8.

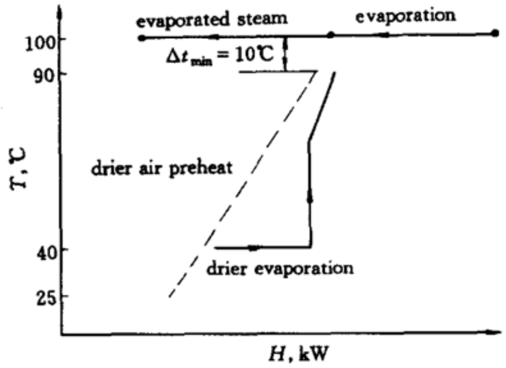

Figure 6 Composite curve

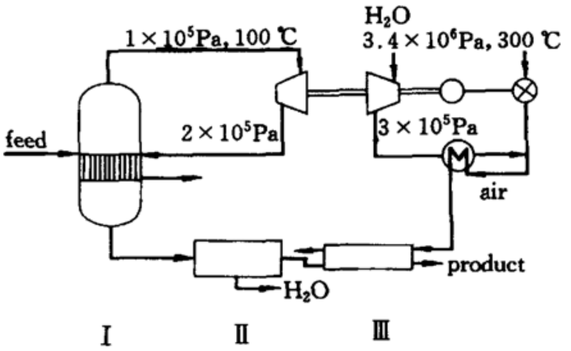

Figure 7 Potential MVR Scheme 1
I—MVR; Ⅱ—centrifugal separation;
Ⅲ—rotary drying

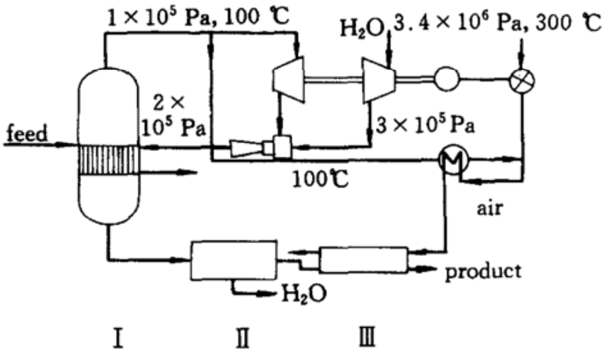

Figure 8 Potential MVR Scheme 2
I—MVR; Ⅱ—centrifugal separation;
Ⅲ—rotary drying

Table 2 Comparison of energy needed from process utility in different schemes

Energy	Fig. 1(non-integrated)	Fig. 1(integrated)	Fig. 7	Fig. 8
electricity, kW	247	247		
steam, $kg{\cdot}s^{-1}$				
3.4MPa			1.25	1.01
0.2MPa	2.03	1.39		

Table 3 Comparisons of energy costs in different schemes

Energy	Fig. 1(non-integrated)	Fig. 1(integrated)	Fig. 7	Fig. 8
	Cost $\times10^{-6}$, Yuan·a^{-1}	*Cost* $\times10^{-6}$, Yuan·a^{-1}	*Cost* $\times10^{-6}$, Yuan·a^{-1}	*Cost* $\times10^{-6}$, Yuan·a^{-1}
electricity	0.99	0.99		
steam				
3.4 MPa			2.16	1.74
0.2MPa	1.75	1.20		
total	2.74	2.19	2.16	1.74

4 CONCLUSIONS

(1) In a separation system employing several different separation equipment, the heat duties should be properly shared to minimize the overall energy consumption. The higher the unit dewatering energy consumption is, the less the heat duty should be allocated.

(2) Heat integration in such a system is highly recommended. That is to say it is always advisable to use exhaust heat from one process in the subsequent process.

(3) If separation processes close to and cross the pinch, the employment of heat pump may be favorable.

NOMENCLATURE

$Cost1$	capital cost of process equipment for heat duty1
$Cost2$	capital cost of process equipment for heat duty2
F	feed flow rate of dryer, kg·s^{-1}
F_0	feed flow rate of evaporator
H_v	latent heat of water in drying process
ΔH_i	latent heat of the ith effect steam, kJ·kg^{-1}
ΔH_0	condensing latent heat of steam, kJ·kg^{-1}
Q_d	energy consumption of drying process, kW
Q_e	energy consumption of evaporation process, kW
q_d	unit dewatering energy consumption of drying process, kJ·kg
q_e	unit dewatering energy consumption of evaporation process, kJ·kg
T_a	ambient temperature, ℃
T_i	dry bulb temperature of inlet air, ℃
T_{oc}	dry bulb temperature of inlet air at constant-speed drying stage, ℃
T_w	wet bulb temperature of air, ℃
T_o^*	dry bulb temperature of outlet air at ω^*, ℃
V_d	steam consumed in drying process, kg·s^{-1}
V_i	flow rate of secondary steam from the ith effect evaporator, kg·s^{-1}
V_0	steam flow rate supplied to the first effect evaporator, kg·s^{-1}
W_n	outlet concentration of product in evaporation, %
W_0	initial concentration of solution, %
ω_c	critical water content, %
ω_f	inlet water content, %
ω^*	final water content, %
η	efficiency of each effect in evaporation

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