Chinese J. of Chem. Eng., 9 (2) 224 – 227 (2001)
RESEARCH NOTES

Case Studies of Heat Integration of Evaporation Systems

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Abstract In this paper, through two case studies, evaporation systems are considered in the context of overall process, and then are optimized to obtain energy-saving effect. The possible evaporation schemes are given when integrated with the background process and how to optimize the evaporator is shown. From the case studies, it can be seen that sometimes incomplete integration and heat pump evaporation are better than complete integration so should be considered as candidate retrofit schemes.
Keywords evaporation, heat integration, grand composite curve, multi-effect evaporation, vapour recompression evaporator

1 HEAT INTEGRATION OF EVAPORATORS

Evaporation is an important unit operation in process industries, which usually consumes large amount of heat. Generally, evaporation systems are not isolated from, but a part of the overall process. Therefore, integration of evaporation can play an important role in energy-saving in process industries. Integration of evaporation implies that evaporators are coupled with the process heat sink or heat source, that is, using the waste heat from the process as heat supply to evaporators, or using the evaporated steam from the evaporators as heat source to the process.

When an evaporator is integrated into the process, the grand composite curve (GCC) of the background process is used to appropriately place the evaporator. GCC curve uses the interval temperature as the ordinate and enthalpy the abscissa. GCC curve identifies the net heat source (below the pinch) and the net heat sink (above the pinch) of the process, assuming that the hot and cold streams exchange heat at an optimal minimum temperature difference $\Delta T_{\min}$. The background process is the whole process but without evaporators. In the GCC curve, an evaporator can be represented as a box, the upper horizontal line of which represents the vaporization heat duty, and the lower one the condensation duty. Because an evaporator can work under higher or lower pressure, the evaporator can be placed in the process at a suitable place in GCC curve.

There are two ways in which evaporators may be integrated: the inlet and outlet heat duties either across or not across the pinch of the background process[1], as shown in Fig. 1. If an evaporator is across the pinch [Fig. 1(a)], there is no energy-savings available from the integration; and if not across the pinch [Fig. 1(b) and 1(c)], heat integration of an evaporator are beneficial.

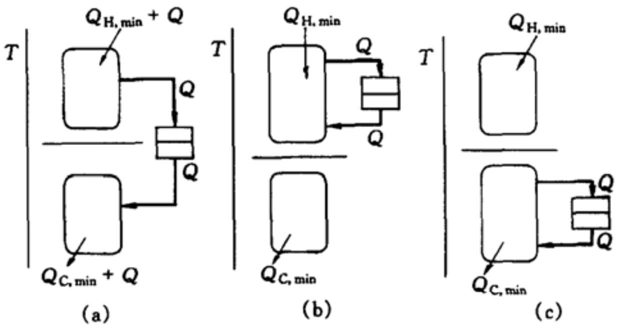

Figure 1 Complete heat integration of evaporators

Up to now, the only paper about heat integration of evaporators reported only the complete integration for single or multi-effect evaporators[1]. So there are two problems to be resolved: (1) In some cases when the evaporator duty is dominant in the overall process, complete integration is impossible. In such cases, is it possible to integrate evaporators in the process to gain energy-saving effect? And if so, how to do it? (2) There are other strategies to save energy in evaporation systems, such as heat pump evaporation[2]. In Ref. [1], there was such a conclusion that heat pump should be placed across the pinch, heat pumping should not be used with integration evaporators. The conclusion is correct for complete integration. But how about the incomplete integration? Such problems also exist in the integration of

Received 2000-01-27, accepted 2001-02-08.
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distillation[3,4]. Therefore, this paper addresses the methods of incomplete integration and the integration of heat pump evaporators using two case studies.

2 CASE STUDY 1

Table 1 presents the evaporation duty, cost and utility data for the case study[1] and Table 2 the stream data for the background process. The heat exchanger network of the background process is shown in Fig. 2. As the conventional design, the heat duties of the evaporator are supplied by the utilities, so the whole hot utility consumption including the evaporator is 4600 kW, and the whole cold utility is 4500 kW.

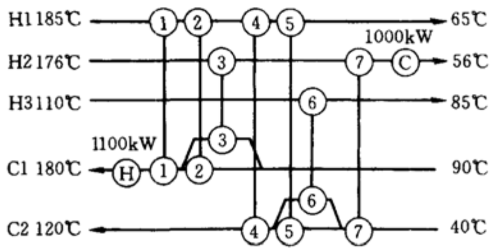

Figure 2 Heat exchanger network of the background process

Table 1 Evaporation duty, cost and utility data for the cast study 1

evaporation duty
water evaporated=1.55 $kg\cdot s^{-1}$
latent heat of vaporization=2260 $kJ\cdot kg^{-1}$
film transfer coefficient for condensation =3.0 $kW\cdot m^{-2}\cdot ℃^{-1}$
film transfer coefficient for vaporization =3.0 $kW\cdot m^{-2}\cdot ℃^{-1}$
utilities
steam (180℃)=135 $\$\cdot kW^{-1}\cdot a^{-1}$
film transfer coefficient for condensing steam =3.0 $kW\cdot m^{-2}\cdot ℃^{-1}$
cooling water (20—30℃)=12 $\$\cdot kW^{-1}\cdot a^{-1}$
film transfer coefficient for cooling water =2.0 $kW\cdot m^{-2}\cdot ℃^{-1}$
electricity=420 $\$\cdot kW^{-1}\cdot a^{-1}$
capital cost
evaporator=54000 $A^{0.57}$, \$
exchanger=6702 $A^{0.57}$, \$
compressor (mechanical)=4959 $W^{0.93}$, \$
plant lifetime=5 years

Table 2 Stream data for background process

Stream	CP kW·℃$^{-1}$	ΔH kW	T_S ℃	T_T ℃	h kW·m^{-2}·℃$^{-1}$
1 Hot	80	−9600	185	65	0.20
2 Hot	100	−12000	176	56	0.30
3 Cold	130	11700	90	180	0.22
4 Cold	150	12000	40	120	0.10
5 Hot	80	−2000	110	85	0.25

Then consider the integration of evaporator with the background process. The GCC curve for the background process of this example is shown in Fig. 3 (broken line). There are two pockets, A and B, that can be used to place the evaporator, as shown in Fig. 3. But neither of the pockets is fit for a single stage evaporator. Thus, three other schemes are proposed.

(1) Partly integration The one-stage evaporator is partly integrated in the background system (the rectangle in Fig. 3), as shown in Fig. 3. It seems that the duty of the evaporator is separated as two parts: one part is supplied by the background system, and the other is supplied by the utility.

(2) Sub-evaporators The whole evaporation duty can be apportioned to several evaporators that work at different pressures and fit the grand composite curve of the background process, as shown in Fig. 4. The two evaporators are not linked thermally (the two rectangles in Fig. 4). Each sub-evaporator is then completely integrated with the process.

(3) Multi-effect evaporator Using multi-effect evaporator (the multi-rectangle in Fig. 5) needs less heat duty to the evaporator. A two-effect evaporator can completely integrated with the process.

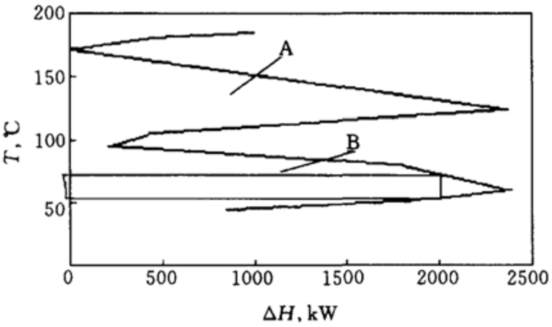

Figure 3 The partly integrated single stage optimal evaporator

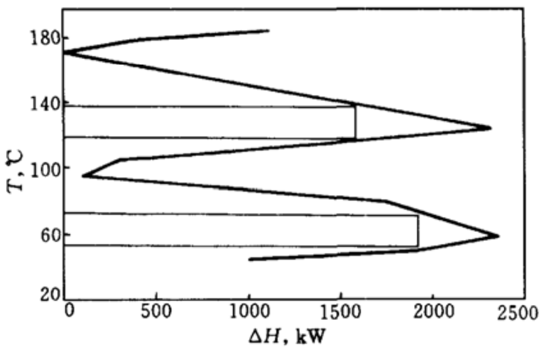

Figure 4 Two evaporators not linked thermally

The total annual cost is used as the objective for optimization, which is the annual capital cost plus the annual energy cost. First for every scheme, the minimum total annual cost is used to obtain the optimal

$\Delta T_{\min}$. Then the total annual cost of every scheme is compared. For this example, the optimal system with minimum total annual cost is a single stage incompletely integrated evaporator at $\Delta T_{\min} = 9$ ℃, as shown in Fig. 3. Fig. 6 gives the integrated network. In Fig. 6, H4 means the evaporated steam, and C3 the vaporization heat duty.

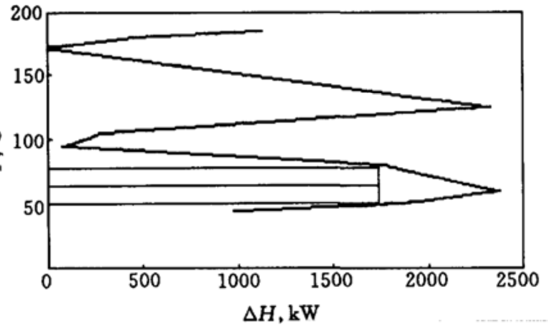

Figure 5 Two-effect evaporator completely integrated with the process

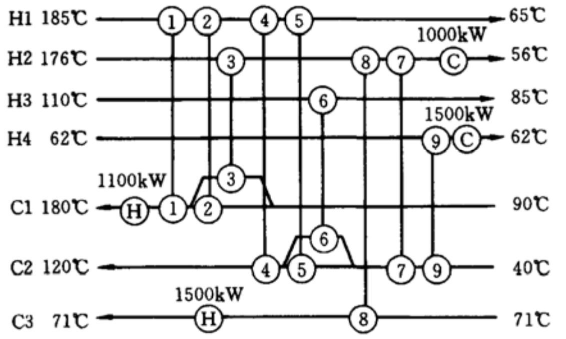

Figure 6 Evaporator integrated with the background process

From Fig. 6, it can be seen that because the heat from stream H2 supplies part of the heat demand of the evaporator, and the evaporated steam from the evaporator heats the stream C2, the utilities consumption of the whole system decreases substantially. The whole hot utility consumption is 2600 kW, and the whole cold utility is 2500 kW. More than 43% energy is saved.

From this case study, it can been seen that sometimes partial integration is economically better than complete integration, for the saved energy cost cannot compensate the increased capital cost due to more stages of evaporators should be used in complete integration.

3 CAST STUDY 2

Table 3 gives the stream data for the background process. The evaporation duty $ED = 8000$ kW, and the other data are the same as in the previous case study.

Table 3 Stream data of background process for case study 2

Stream	CP kW·℃$^{-1}$	ΔH kW	T_S ℃	T_T ℃	h kW·m^{-2}·℃$^{-1}$
1 Cold	600	3000	120	125	0.20
2 Hot	25	−1000	120	80	0.20
3 Hot	40	−2000	80	30	0.20

From the data above, it can be seen that the heat recovery in the background process is impossible, for the hot and cold utilities are both 3000 kW. Since the evaporation duty is 8000 kW, the whole heat duty of the total process is dominated by the evaporation. The total demands for both hot and cold utilities are 12000kW when not considering integration of evaporation with the background process.

Every possible scheme is considered and optimized, as shown in Table 4. Comparing these systems, it can be found that the integrated thermal vapour recompression evaporator is the best for its lowest total annual cost. Fig. 7 gives the flowsheet of the integrated thermal vapour recompression evaporator, in which an ejector is used to pump 3500 kW of the evaporated steam with 4500 kW fresh steam, and 3000 kW of the evaporated steam supplies the heat needed by the cold stream. The hot streams are cooled by the cold utility as before. So the total hot and cold utility consumptions are both 4500kW, and 62.5% enery is saved.

From this case study, it can been seen that when the evaporation duty is the dominant heat duty in the whole process, integrated heat pump scheme is feasible, and even the optimal scheme sometimes.

In conclusion, when the evaporator duty is dominant in the overall process, incomplete integration and heat pump evaporation should be considered as candidate retrofit schemes. For integrated multi-effect

Table 4 Comparison of different evaporation systems

Evaporation design	C_T, \$·a^{-1}	$\Delta T_{\min,opt}$, ℃
stand-alone, four stage	1238616	38
integrated, two stage	1074342	20
stand-alone, mechanical vapour recompression	1267892	7
integrated, mechanical vapour recompression	1076126	13
stand-alone, thermal vapour recompression	1084818	13
integrated, thermal vapour recompression	831281	24

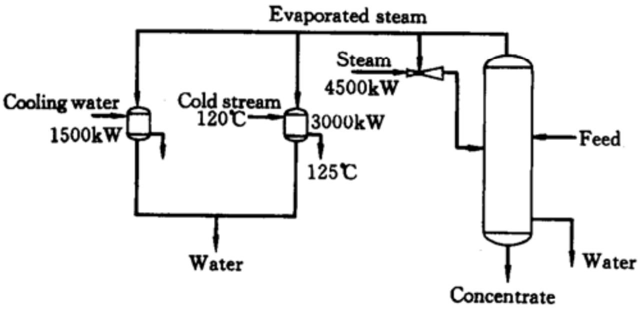

Figure 7 Integrated evaporation with thermal vapour recompression scheme

evaporation, the background process provides part or all of the evaporation duties, and normally, the total temperature difference for evaporation is reduced. Therefore, the optimal number of stages is usually less than (at most equals to) the optimal number for the corresponding stand-alone evaporator. For integrated vapour recompression evaporation, because the compressor or ejector duty decreases, the new trade-off will shift towards reducing evaporator cost, the temperature difference for evaporation will rise as compared with the corresponding stand-alone evaporator.

NOMENCLATURE

A	heat exchanger area, m^2
C_T	total cost, $\$\cdot a^{-1}$
CD	condensation duty, kW
CP	heat capacity flowrate, $kW\cdot ℃^{-1}$
ED	evaporation duty, kW
H	enthalpy, kW
h	heat transfer coefficient, $kW\cdot m^{-2}\cdot ℃^{-1}$
N	number of evaporator stages
Q	heat duty, kW
T	temperature, ℃
W	power consumption, kW

Subscripts

C	cold utility
evap	evaporation
H	hot utility
min	minimum
opt	optimum
S	supply
T	target

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