Korean J. Chem. Eng., **29**(3), 341-348 (2012)
DOI: 10.1007/s11814-011-0173-7

The pinch technology combined with a heat pump applied in a three-effect evaporator and energy-saving performance assessment

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(*Received 11 January 2011 • accepted 6 July 2011*)

Abstract−This research investigated optimal energy utilization with pinch technology based on an actual gelatin production factory using a three-effect evaporator (TEE). A TEE is a well-known device used extensively when concentrating process fluid with large amounts of boiler steam. Under ideal energy use conditions, the exhaust heat can be recovered with the addition of a heat pump system. The study results showed that the original energy demand and discharge of the TEE were 1,736.2 and 1,733.2 kWh, respectively. Simulating the pinch technology use, the energy demand and discharge decreased to 1,531.5 and 1,527.7 kWh, respectively. When the heat pump was used to recover the exhaust heat, 324 kL per annum of fuel oil was saved, while electricity use increased 131 kWh. The total investment cost was 86,550 US$, but the total annual operation cost could save up to 166,421 US$. The net present value was estimated to be 544,316 US$ with a 5-year equipment operation. The investment expense could be completely recovered within a seven-month remuneration period.

Key words: Vaporized Concentration, Pinch Technology, Heat Pump, Three-effect Evaporator

INTRODUCTION

Pinch technology, which has been widely applied in a plant or a complex of plants to reduce energy consumption [1], collects the thermodynamic data of each device in a process. In the 1980s, pinch technology was introduced for individual processes [2], and then designed for a heat exchanger network (HEN) [3]. Pinch technology methodologies evolved around HEN synthesis to incorporate total cost targeting and block-decomposition [4-6]. The utilization efficiency of each heat exchanger is assessed and then integrated in the HEN, modifying partial processes or energy conversion lines as needed. Then, the plant energy use is adjusted to reach an optimum goal. The concept of a HEN retrofit framework has been established at “process pinch” [7], “network pinch” [8,9], and “multiple utilities” [10] activities.

Several studies have asserted that the pinch technology is the best method for increasing energy efficiency [11,12]. However, when energy utilization is at optimum, exhaust heat is still higher than the ambient temperature. This causes energy loss and produces an environmental heating load. To resolve these problems, a heat pump application has been proposed to balance heating and cooling in thermal processes [13,14] because a heat pump is an efficient heat-energy transfer device. The heat pump refrigerant absorbs heat from a relatively low temperature source and then compresses and transports it to a relatively high temperature source, where it is released. Hence, the waste heat can be recovered and reused. A heat pump readily collects waste heat under low temperature conditions and its heating efficiency is better than that of traditional heaters [15].

In this study, we employed pinch technology combined with a heat pump and a three-effect evaporator (TEE), which is a well-known device used extensively when concentrating process fluid with large amounts of boiler steam in the first operating step. With the TEE, the emission steam from each operating effect is used as the heating source for the next, and the steam from the final effect is condensed by cooling water. The condensed steam is recovered for reuse. Large amounts of boiler steam and cooling water require large amounts of energy, which increases production cost. We simulated pinch technology with a heat pump and a TEE at an actual gelatin production factory to study energy conservation. We compared energy-saving effects in three cases: before improvement, improvement with pinch technology, and improvement with pinch technology combined with a heat pump.

SINGLE EFFECT EVAPORATOR (SEE) IMPROVEMENT

Pinch technology used for heating and cooling in thermal processes in a HEN can achieve effective internal heat circulation in a feed/effluent heat exchanger [16,17]. Figs. 1(a) and 1(b) show a simplified SEE process and its temperature-heat composite curve before improvement. Pure water is vaporized to form high temperature steam (135 °C) at the boiler by burning fuel oil to supply heat energy ($Q_{H\Delta T1}$). The steam is used to heat the liquid feed stream of the SEE and to produce hot water supplied to factory process use. The low temperature steam from the SEE exhaust is condensed by cooling water ($Q_{C\Delta T1}$). The hot stream represents the sum of all the heat sources within the heat exchanger, in terms of heat load and temperature level. The cold stream similarly represents the sum of all the heat sinks within the heat exchanger. When the curves are

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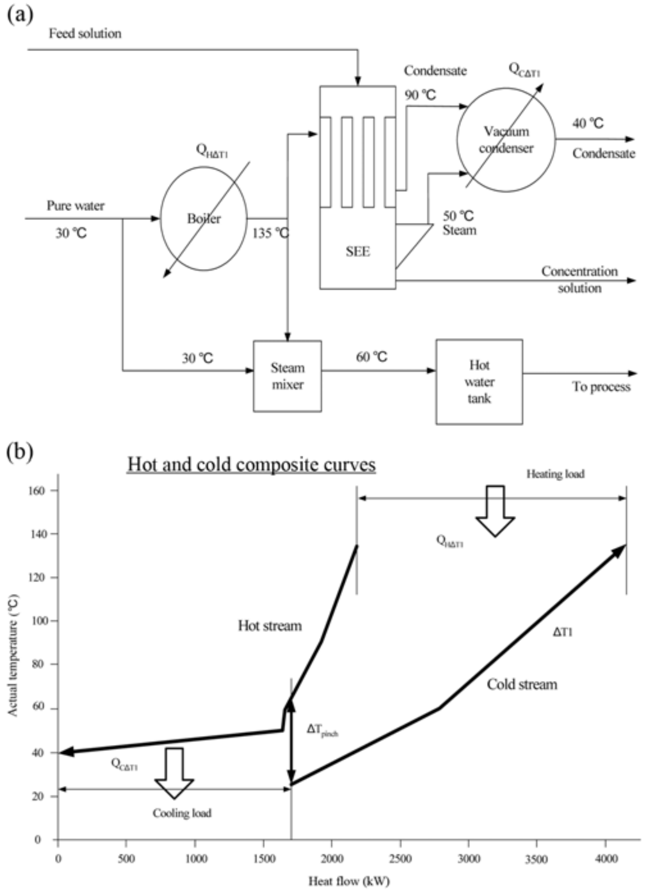

Fig. 1. System schematic and flow diagram before improvement and its composite temperature curve.

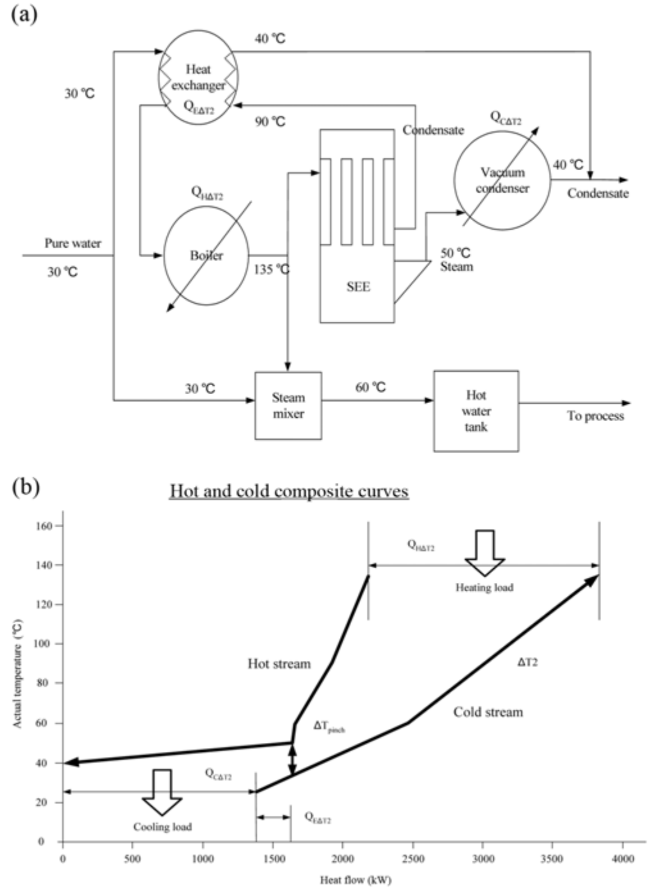

Fig. 2. System schematic and flow diagram improvement by pinch technology and its composite temperature curve.

shown together on a single temperature-heat plot (Fig. 1(b)), most processes display a pinch - a region where the hot/cold stream approaches the minimum allowable temperature, ΔT_{min}. This divides the process into two distinct regions. Above the pinch, some heat integration is possible (where the hot composite curve sits above the cold composite curve), but there is a net heat deficit and external utility heat sources ($Q_{H\Delta T1}$) are required. Below the pinch, some heat integration is possible (where the hot composite curve sits above the cold composite curve), but there is a net heat surplus and external utility heat sinks ($Q_{C\Delta T1}$) are required.

Figs. 2(a) and 2(b) show the simplified SEE process and its temperature-heat composite curve after improvement with pinch technology. The temperature of the steam condensate after heating the SEE is still high (90 ℃), and the heat energy (Q_E) can be recovered to preheat boiler feed water. Other procedures remain unchanged. The recovery energy in the composite curve figure shows the cold stream moves towards the left, until the pinch point of ΔT_1 moves to ΔT_2. This means that Q_H and Q_C are all reduced and the $Q_{E\Delta T2}$ is the horizontal distance of cold stream shift.

Recently, several studies introduced the design strategy of a heat pump with process integration under optimal matching [18-20]. The crucial point of heat pump use is to balance the energy to enhance the energy utilization efficiency. The heat pump efficiency is assessed by the coefficient of performance (COP, the ratio of output heat energy divides by input power, shown as the Eq. (1)). A higher COP value indicates better energy efficiency [21,22]. Generally, the COP values of conventional heaters (such as electricity, diesel oil, fuel oil, and natural gas) are all less than 1.0. However, the COP value of the conventional heat pump is greater than 3.0 [23].

$$COP=E/W\times 2.77778\times 10^{-4} \tag{1}$$

Figs. 3(a) and 3(b) show the simplified SEE process and its temperature-heat composite curve after improvement by pinch technology combined with a heat pump. The system with a heat pump supplies the heat required to produce hot water, instead of the boiler steam. The heat pump refrigerant absorbs the fractionated exhaust steam heat ($Q_{E,\,HPC}$) from the SEE, which is then compressed (W_{EP}). Finally, the refrigerant is transported and the heat ($Q_{E,\,HPH}$) is released to produce hot water to supply the demand of the plant. Therefore, a heat pump not only reduces the energy consumption but also decreases the required amount of circulated cooling water. In the composite curve figure, the waste energy ($Q_{E,\,HPC}$) below the pinch point is absorbed by the heat pump, is compressed with work (W_{EP}), and then the energy ($Q_{E,\,HPH}$) is released to the place above the pinch point.

CASE STUDY AND SIMULATION RESULTS OF THREE-EFFECT EVAPORATOR (TEE)

The energy requirement and thermodynamic data, for the TEE processes before and after improvement, were calculated with Mi-

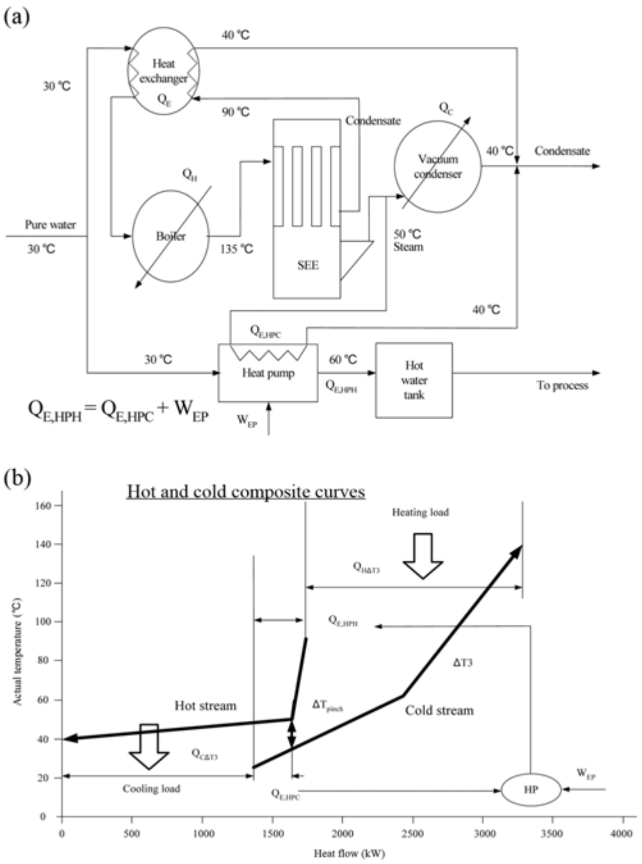

Fig. 3. System schematic and flow diagram improvement by pinch technology and heat pump and its composite temperature curve.

crosoft Office Excel 2007. Figs. 4-6 show the results of the case studies. The calculation followed the criteria of energy and mass balance and Eq. (2).

$$Q = m \times Cp \times \Delta T = CP \times \Delta T = m \times \Delta H \tag{2}$$

The 45 °C feed of the TEE process was a 7,500 kg/h gelatin solution at the first effect. The gelatin solution was concentrated from 3 to 20%. The TEE system used the boiler steam (325 kPa-saturated steam at 135 °C) as the external heat source, and the condenser used cooling water to absorb all waste heat from the TEE exhaust. All of the condensate steam was recovered and reused. Table 1 shows the minimum temperature difference (ΔT_{min}) conditions in the case studies. In the TEE process before improvement (base case), ΔT_B was 43.4 °C. Then the TEE process improvement by pinch technology simulation (case-1) was run under ΔT_P (17.5 °C) to improve heat recovery. The combined heat pump process (case-2) compared with case-1 could reduce more cooling water under the same heating load and ΔT. To confirm the thermodynamic limit in the TEE process before improvement, case-3 (ΔT=0 °C) was prepared as the ultimate condition requiring an infinitely large surface area of exchanger.

1. Before Improvement (Base Case)

Fig. 4 shows the TEE system schematic and flow diagram before improvement. The TEE process before improvement was the current operating condition in a commercial plant and was regarded as the base case. The system has three sets of heat exchangers; two sets (H_1 and H_3) are used to preheat the first-effect feed stream, and other one (H_2) is used to preheat the second-effect inlet stream. The H_1 heat exchanger heat source comes from boiler steam, and the H_2 and H_3 heat exchangers are supplied with fractional steam from

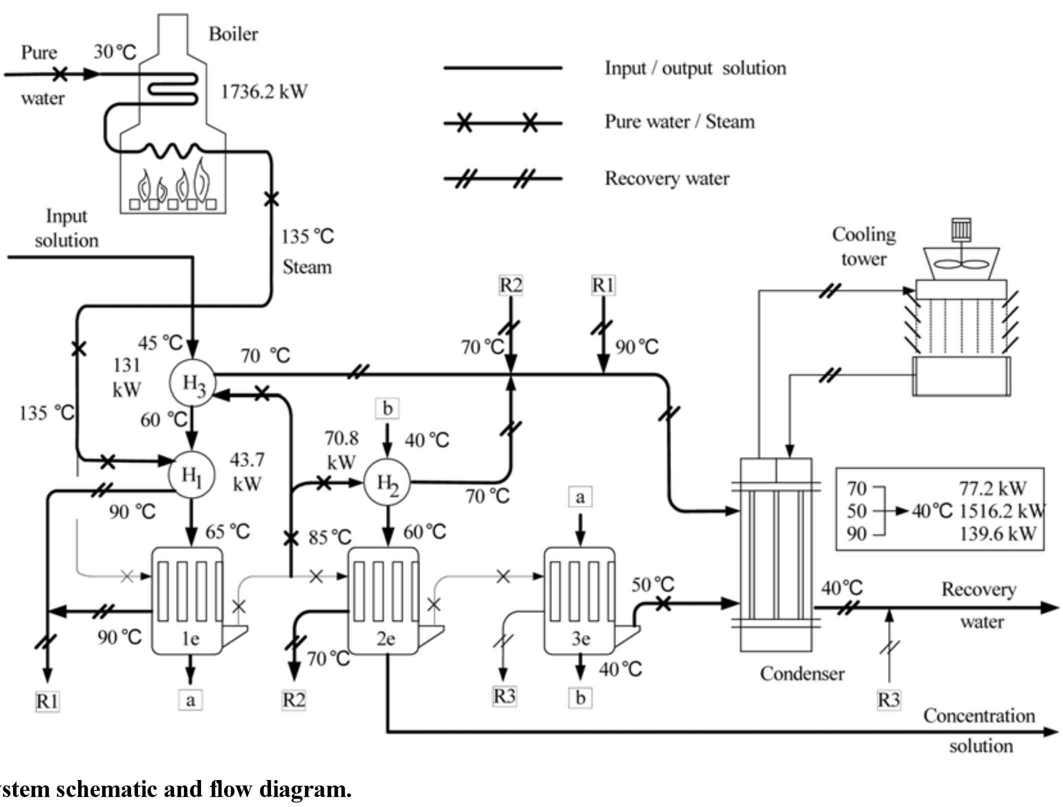

Fig. 4. TEE system schematic and flow diagram.

Table 1. The comparison of energy savings for several study cases

Study case	Improvement			Ultimate
	Before	After		
		Pinch technology	Pinch technology and heat pump	
	Base case	Case-1	Case-2	Case-3
Pinch temperature, °C	43.4 (---)	17.5 (---)	17.5 (---)	0 (---)
Heating load, kW	1736.2 (---)	1531.5 (−11.8%)	1531.5 (−11.8%)	1163.2 (−33%)
Cooling load, kW	1733.2 (---)	1527.7 (−11.8%)	1212 (−30.1%)	1160.2 (−33%)

second-effect production.

The TEE liquid feed stream is preheated to 65 °C, which is the required first effect temperature. The vaporized steam from each effect is used as the next effect's heating source. The latent heat in the phase-change and the serviceable heat are utilized. The un-recovered latent heat and serviceable heat from each effect is discarded in the condenser and the temperature is reduced to 40 °C by cooling water, then discharged to the atmosphere.

The TEE process heat supplied (1,736.2 kW) from the boiler steam was almost the same as the condenser exhaust heat (1,733.2 kW) absorbed by the cooling water, which meant that this process consumed a large amount of high-grade heat and exhausted a large amount of low-grade heat. According to the relationship between the temperature interval and the heat flow rate, the minimum temperature difference (ΔT_B) was 43.4 °C. The TEE boiler steam demand was 2,403 kg/h, the amount of cooling water was 298 m^3/h, and the temperature of the cooling water could be increased from 28 to 33 °C.

2. Improvement by Pinch Technology (Case-1)

Fig. 5 shows the TEE process improvement by pinch technology. According to the heat capacity flow rate (CP) pinch technology decision principle, the hot stream CP value above the pinch point must be less than or equal to the cold stream CP value below the pinch point ($CP_{Hot} \leq CP_{Cold}$). Therefore, the steam condensate from the first and second effects can be recovered and reused. Two new heat exchangers (N_1 and N_2) were installed in the modification. The new heat exchanger operating thermodynamic data (temperature, flow rate, etc.) were used to calculate the energy and mass balance by Eq. (2). We also found that the temperature of the feed stream at the first effect reached 65 °C when the H_1 heat exchanger was not used. The H_1 heat exchanger use was hence discontinued.

The energy of demand and emission for the TEE was reduced to 1,531.5 and 1,527.7 kWh, respectively. According to the relationship between the temperature interval and the heat flow rate, the minimum temperature difference (ΔT_P) was 17.5 °C. The TEE boiler steam demand was reduced to 2,305 kg/h, and the amount of cooling water was also reduced to 263 m^3/h. In these cases, ΔT_{min} decreased where the temperature difference was reciprocally proportional to the heat-exchange area under heat flux fixation, meaning that surface area of the heat exchanger increased compared with

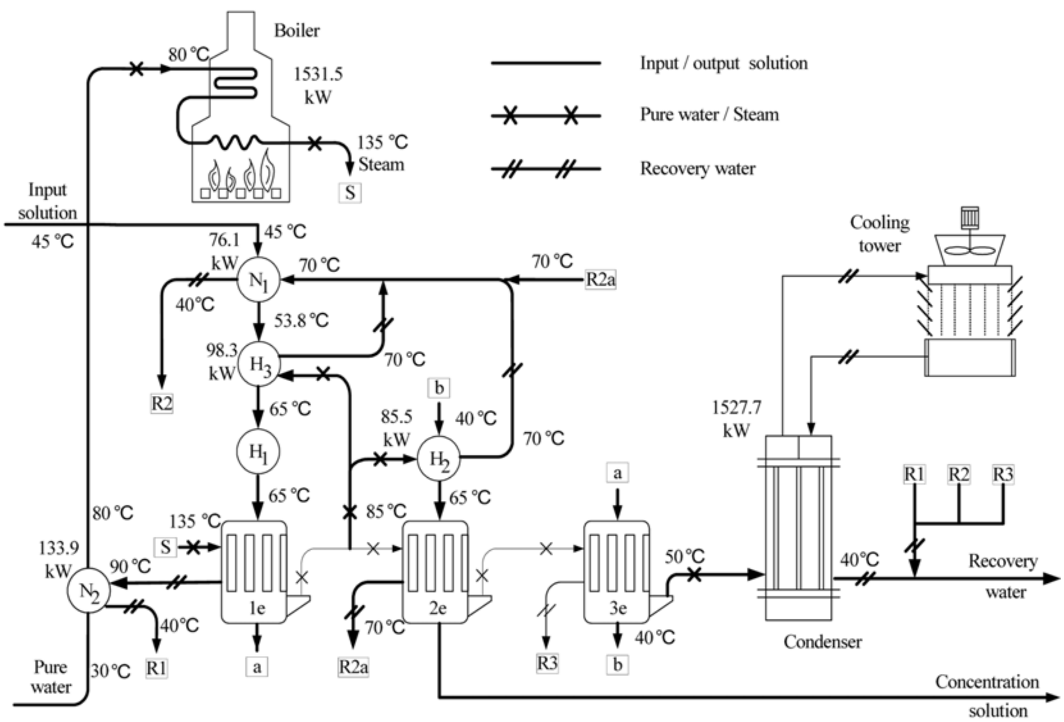

Fig. 5. Schematics of TEE system after pinch technology improvement.

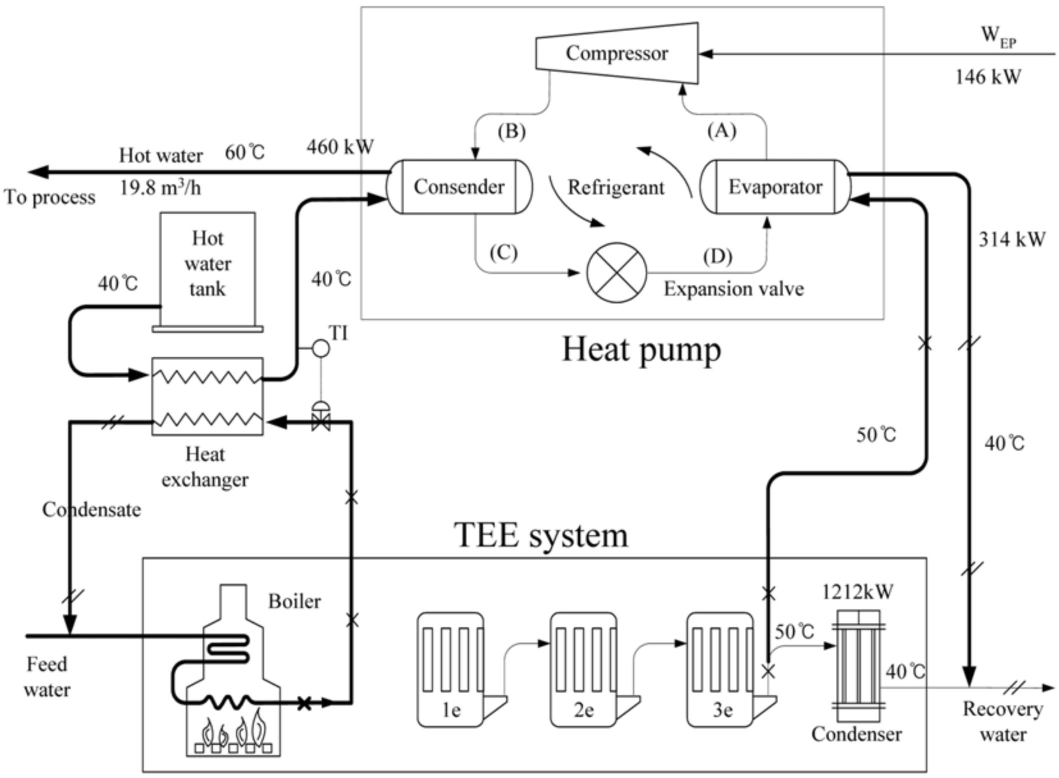

Fig. 6. Schematics of TEE after pinch technology improvement combined with heat pump.

the base case. However, the temperature of the third-effect emission steam was 50 °C, which was too low to direct recovery and reuse, but still needed to be condensed with cooling water to absorb the heat energy. Therefore, the heat had to be discharged to the atmosphere, which could have caused an environmental heating load.

3. Improvement by Pinch Technology Combined with a Heat Pump (Case-2)

Fig. 6 shows the schematic diagram of the TEE process after improvement by pinch technology combined with a heat pump. The gelatin production plant is a food factory that needs to use a large volume of 60 °C hot water. A heat pump can be used to not only reduce the heating load of the cooling water, but also to decrease the amount of boiler steam required to produce the 60 °C hot water. This further promotes the energy-saving benefit. After the heat pump refrigerant absorbs the fractional exhaust steam energy from the third effect, the refrigerant is vaporized and changed into a gaseous state (D→A), and then compressed (A→B). The compressed energy in the refrigerant is discharged to heat and produces 60 °C hot water (B→C). The energy can replace the boiler steam and the hot water can supply the demand of the factory. Finally, the refrigerant passes through an expansion valve to release pressure (C→D) and returns to its original state. The refrigerant was recycled and the process was repeated [24].

The installation of a heat pump (Fig. 6) resulted in a decrease in the waste heat at the inlet of the condenser compared with the case-1 process. The waste heat was reduced by 314 kW, which almost reduced 465 kg/h steam from the third effect emission. The 314 kW of recovered heat, after the heat pump was working, could be used to heat 19.8 m^3/h of hot water from 40 °C to 60 °C to supply other systems. The hot water made by the heat pump could reduce the use of 600 kg/h boiler steam, and save 324 kL of fuel oil per year. The cooling water amount in the condenser would be further reduced to 208 m^3/h. This could save 15 kWh of electrical power, but the electric power consumption of the heat pump was greater (146 kWh). The total power use was increased to 131 kW. As can be seen in Table 1, the TEE heat demand, comparing case-2 with the base case, was the same as case-1. Nevertheless, the 30.1% decrease for heat exhaust was better than case-1, and close to the 33% decrease in case-3.

In this study, the heat pump was a water-to-water type (WWHP-010DB, Forever-Friend, Taiwan) and the refrigerant was R134a [25]. The power demand was 146 kWh. The endothermic (314 kW) and exothermic (460 kW) COP values of the heat pump were 2.16 and 3.16, respectively, calculated by Eq. (1). This means that when we input 1 kW of electric power to the heat pump, we can absorb 2.16 kW of the waste heat from factory emissions and produce 3.16 kW of heat energy for factory reuse. The total COP value was 5.32.

DISCUSSION

In heat recovery, pinch technology has been applied to evaporation, distillation, drying [16,26] and water resource [27]. The waste heat was recovered and reused during heat exchange use. However, it did not utilize the condensation heat efficiently. In contrast, the heat pump utilized the condensation heat thoroughly by absorbing the low temperature waste heat with a refrigerant because the refrigerant had endothermic vaporization at extra low temperatures. The hot water could be completely heated by the TEE effluent waste

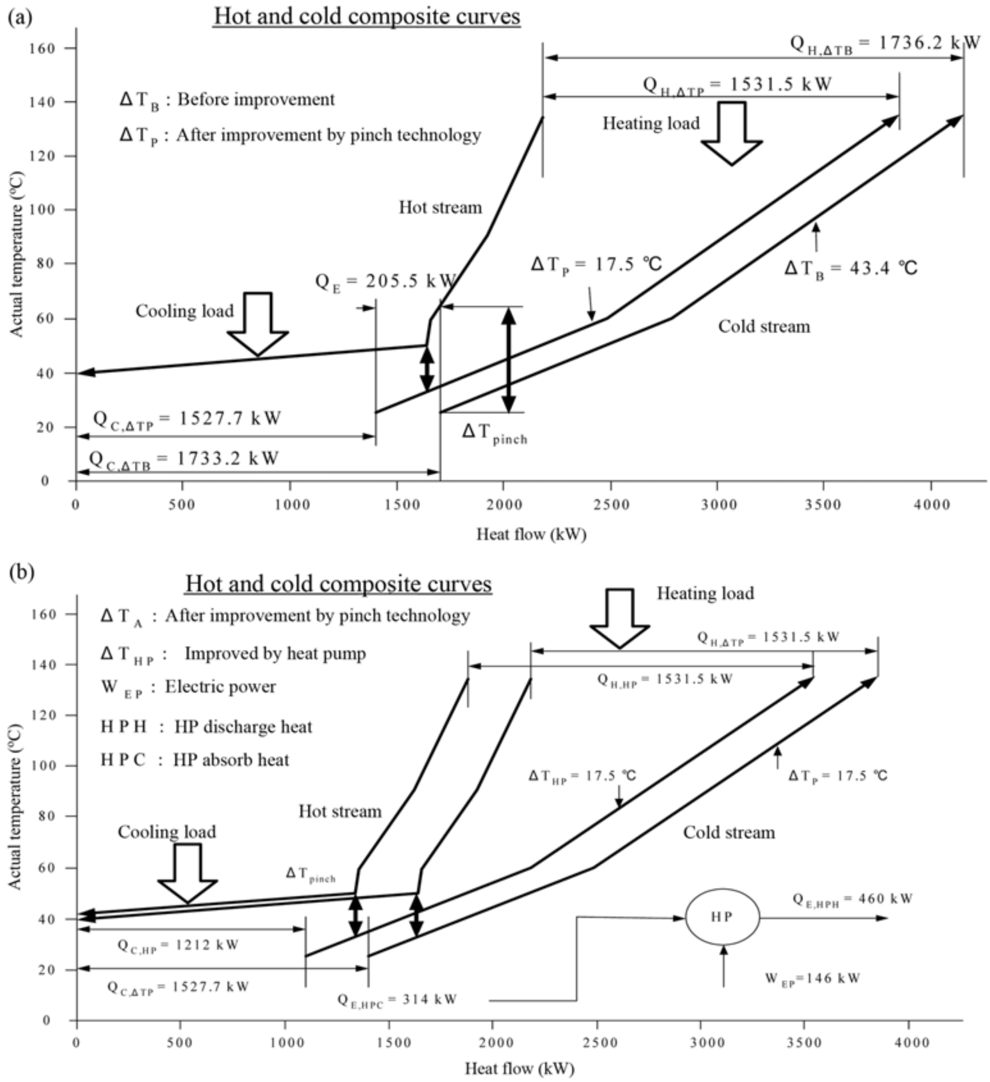

Fig. 7. Temperature-heat diagram of feed/effluent heat exchanger in pinch technology (a) and base case (b) and improvement with heat pump processes.

heat, which means that all the heat of the process streams was recirculated in the process, reducing the use of the boiler steam. Consequently, the heat pump reduced the energy loss in the boiler steam and in the cooling water condenser. It should be noted that the required heat of the input hot water in the case-2 process was obtained not by firing fuel but by electric power.

Figs. 7(a) and 7(b) show the temperature-heat diagram for the feed and effluent streams in the cases of the TEE process before improvement (base case) and after improvement by pinch technology (case-1), respectively. In Fig. 7(a), the lower two lines (ΔT_B) and (ΔT_P) represent the cold streams and the upper one represents the hot stream. The lowest line (ΔT_B), which was the current condition before improvement, has a pinch point (ΔT_B=43.4 °C) against the hot stream line in the base case. By using pinch technology, the cold stream was horizontally moved within temperature limits to the pinch point in order to increase the heat recovery. By increasing the surface area in the case-1 process, the lowest line (ΔT_B) was moved closely, horizontally, to the line (ΔT_P) until ΔT_P became 17.5 °C, resulting in an increase of 11.8% and 205.5 kW in the heat recovery as shown in Fig. 7(a). The TEE heat energy demand and exhaust were reduced to 1,531.5 and 1,527.7 kW, respectively, and yearly fuel oil demand also decreased 145.2 kL.

In Fig. 7(b), installing the TEE system with the heat pump in the case-2 process further reduced the waste heat of the exhaust stream at the condenser compared with the case-1 process. The heat pump could absorb the fractional emission waste heat ($Q_{E,HPC}$=314 kW), after compression (W_{EP}=146 kW), to supply heat ($Q_{E,HPH}$=460 kW) to produce hot water. The case-2 heat demand was the same as in case-1; therefore, the cold stream demand was not changed. Nevertheless, the heat exhaust demand of the case-2 condenser was reduced to 1,212 kW. The cold and hot streams could all be horizontally moved to the left under the same pinch point of case-1 (ΔT_P) and case-2 (ΔT_{HP}). The total power use was increased to 131 kWh, although cooling water use was greatly decreased. Power use (15 kWh) was saved because the power consumption of the heat pump increased to 146 kWh. The case-2 decreased the required boiler steam and fuel oil consumption by 600 kg per hour and 324 kL per year, respectively, which indicates that the heat pump effectively increases

Table 2. Efficiency assessment after improvement[a]

		Case-1	Case-2	total
New devices		2 sets HE[b]	Heat pump	---
Devices cost, US$		1,800	68,750	70,550
Project cost, US$		1,000	15,000	16,000
Annual maintenance cost, US$		−280	−8,375	−8,655
Electric power	amount, kWh/y	---	1,037,520	1,037,520
	fee[c], US$/y	---	-83,000	−83,000
Fuel oil	Reduction amount, kL/y	145.2	324	469.2
	Save cost[d], US$	79,878	178,200	258,078
Cost saving, US$/y		79,598	86,823	166,421
Investment money, US$		2,800	83,750	86,550
Feedback time, months		0.42	11.58	6.24

[a]Working time is 330 days per year and 24 hours per day
[b]HE is the heat exchanger
[c]Unit price of electric power is 0.08 US$/kWh
[d]Unit price of fuel oil is 550 US$/kL

energy efficiency.

In the study, the investment was assessed by the net present value (NPV) method shown in Eq. (3). NPV is a primary investment decision criterion. This method involved calculating the present value of all yearly capital costs and savings throughout the life of a project. If the NPV was positive then the project would be accepted, otherwise, it would be rejected [17]. The NPV was summed for all these present values (costs being represented as negative amounts and net savings as positive) of this project.

$$NPV = \sum_{t=1}^{t=N} CF_t/(1+r^2) - C_0 \tag{3}$$

The investment and saving cost data for the TEE efficiency improvement are shown in Table 2. After improvement by pinch technology, the yearly operating cost could save 79,598 US$. The project investment cost was 2,800 US$, which included new purchase heat exchanger devices, piping connections, and insulation. When combined with a heat pump, the yearly operating cost could save 86,823 US$ more, with a project investment cost of 83,750 US$. This included new heat pump devices, piping connections, and insulation purchases. In the case study, the total project investment cost was 86,550 US$, and after improvement, the yearly operating cost could save 166,421 US$. When the net cash flow was based on a 10% discount rate of investment and five years operation of the equipment, the NPV was 544,316 US$. The investment expense could be completely recovered within seven months. Because the NPV is positive in the first year and the break-even time is very short, this project should be quickly accepted by any decision-maker to lower the production cost.

CONCLUSION

Saving energy is a major environmental goal worldwide. Therefore, effective energy use, and recovery and reuse of waste heat are essential and urgent. Pinch technology integrating a HEN combined with a heat pump to collect waste heat for reuse could help reach that goal. Our results show that after improvement, the demand for heat energy and reduction of exhaust heat were all greatly reduced. Many pieces of factory equipment need to absorb and discharge energy. Therefore, the scope of this study could be expanded to include all factory equipment. The pinch technology/heat pump application would decrease the production cost and promote energy efficiency as well as reduce environment pollution by recovering waste heat. Furthermore, it can promote energy-saving achievements.

ACKNOWLEDGEMENTS

Gail Bowers-Irons is appreciated for her editorial assistance.

NOMENCLATURE

E : output heat energy [kJ]
W : input power [kWh]
COP : coefficient of performance [kW/kW]
Q : heat-transfer rate [kW]
m : mass flow rate [kg/h]
Cp : specific heat [kJ/kg K]
ΔH : the difference in enthalpy [kJ/kg]
CP : the heat capacity flow rate (kJ/K h)=Cp (kJ/kg K)×m (kg/h)
t : the number of periods
NPV : net prevent value
N : the expected number of the whole period
ΔT : the difference in temperature [K]
C_o : initial costs of investment
r : the discount rate
CF_t : the net cash flow in a time period

REFERENCES

1. A. E. Niesnfeld, *Industrial evaporators*, Instrument Society of America (1985).
2. B. Linnhoff, D. W. Townsend, D. Boland, G. F. Hewitt, B. E. A. Thomas, A. R. Guy and R. H. Marsland, *User guide on process integra-*

tion for the efficient use of energy, 1st Ed., Institution of Chem. Eng., Rugby, UK (1982).
3. B. Linnhoff and E. Hindmarsh, *Chem. Eng. Sci.*, **38**, 745 (1983).
4. B. Linnhoff and S. Ahmad, *Comp. Chem. Eng.*, **147**, 729 (1990).
5. S. Ahmad, B. Linnhoff and R. Smith, *Comp. Chem. Eng.*, **14**, 751 (1990).
6. H. P. Lee, I. Y. Lee and K. O. Yoo, *Korean J. Chem. Eng.*, **12**, 589 (1995).
7. T. N. Tjoe and B. Linnhoff, *Chem. Eng.*, **28**, 47 (1986).
8. N. D. K. Asante and X. Y. Zhu, *Comp. Chem. Eng.*, **20**, S7 (1996).
9. M. A. Phipps and A. F. A. Hoadley, *Korean J. Chem. Eng.*, **20**, 642 (2003).
10. A. I. A. Salama, *Appl. Therm. Eng.*, **29**, 2633 (2009).
11. T. Gundersen and L. Naess, *Heat Recovery Systems & CHP*, **10**, 301 (1990).
12. F. Staine and D. Favrat, *Appl. Therm. Eng.*, **16**, 497 (1996).
13. R. M. Lazzarin, *Heat Recovery System & CHP*, **14**, 581 (1994).
14. R. M. Lazzarin, *Heat Recovery System & CHP*, **15**, 305 (1995).
15. Langley and C. Billy, *Heat pump technology,* 1st Ed., Prentice Hall, New Jersey, USA (2001).
16. I. C. Kemp, *Pinch analysis and process integration*, 2nd Ed., Elsevier Ltd, UK (2007).
17. T. D. Eastop and D. R. Croft, *Energy efficiency*, 1st Ed., Longman Group Ltd., Malaysia, KPP (1995).
18. Z. Fonyo and N. Benko, *Comp. Chem. Eng.*, **20**, S85 (1996).
19. C. Wu, L. Chen and F. Sun, *Energy Convers. Manage.*, **39**, 445 (1998).
20. J. M. Smith, H. C. Van Ness and M. M. Abbott, *Introduction to chemical engineering thermodynamics*, 7th Ed., McGraw-Hill, New York (2005).
21. A. Nguyen, Y. Kim and Y. Shin, *Int. J. Refriger.*, **28**, 242 (2005).
22. K. J. Park, Y. Lee and D. Jung, *J. Mechanical Sci. Technol.*, **24**, 879 (2010).
23. IEA, Heat Pump Centre, *Heat pump performance*, International Energy Agency (IEA) Heat Pump Centre, retrieved November 22, 2010 from: <http://www.heatpumpcentre.org>.
24. W. F. Stoecker and J. W. Jones, *Refrigeration and air conditioning*, 2nd Ed., McGraw-Hill, Taipei, Taiwan (1982).
25. C. M. Tan, *Metal extraction in refrigerant R134a*, Master's Thesis, National Chiao Tung University, Hsinchu, Taiwan (2002).
26. M. Y. Lee, D. W. Choi and Y. H. Kim, *Korean J. Chem. Eng.*, **26**, 631 (2009).
27. C. K. Yoo, T. Y. Lee, J. Kim, I. Moon, J. H. Jung, C. Han, J. M. Oh and I. B. Lee, *Korean J. Chem. Eng.*, **24**, 567 (2007).