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Industrial Heat Pump Study Using Pinch Technology for a Large Scale Petrochemical Site

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The heat pump has for long years been studied as an important tool and a means of energy saving in a site. However it has lately become possible for an industrial heat pump to produce a higher temperature heat from waste heat in an industrial site, which leads to it having a wider scope in its application. Pinch technology was used to identify an appropriate heat source and sink, and the installation of an industrial heat pump was studied for energy saving on a large petrochemical site. The study confirmed that there could be a significant reduction in the consumption of energy in the utility system by introducing an industrial heat pump, and clarified the requirements and specifications for the development of an industrial heat pump.

1. Introduction

An industrial heat pump collects and utilizes a lower level waste heat in a site and generates a higher level heat which is then supplied to the users of steam in a utility system. A typical utility system in a large petrochemical plant, shown in Figure 1, has boilers, turbines and three levels of steam header, which supply the steam to the users. When an industrial heat pump is installed, lower level heat collected from the condensate can be used to produce

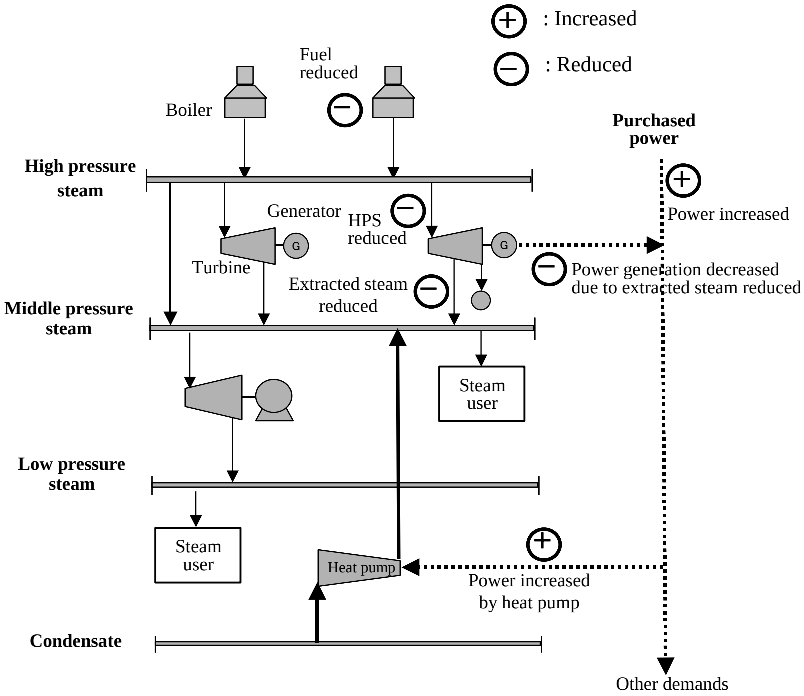

Figure 1: Typical utility system in a large petrochemical plant

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Table 1: Collected heat exchangers

	Number of sets	Heat duty MW
Cooler	149	405
Heater	106	290

Table 2: Utility header conditions in a large petrochemical plant

Steam header	Operating temperature, ºC	Operating pressure, MPag
VHPS (Very high pressure steam)	317	10.7
HPS (High pressure steam)	254	4.15
MPS (Middle pressure steam)	191	1.18
LPS (Low pressure steam)	145	0.31
LLPS (Low low pressure steam)	115	0.07

middle pressure steam, which results in a reduction in the fuel consumption of the boiler. An industrial heat pump was used conventionally within one process system based on the study results of pinch technology, but recently the concept of a total site approach was developed for an energy saving study using pinch technology for the whole of a utility system. The new industrial heat pump, with a released temperature of 165 °C (Chuden, 2011), was developed in Japan. This development has made it possible to consider introducing an industrial heat pump to higher temperature heat users than ever before and, by applying the total site approach, providing cover for the whole of the utility system. The utility system must be considered and optimized in the context of the total site approach, whereby many process plants are integrated for optimization and energy saving. In pinch technology (Kenney, 1984) a graphical method, so called site profiles, was first introduced by Dhole and Linnhoff (1992) and later extended by Raissi (1994). Klemes et al (1997) considerably extended this methodology to site-wide applications. Data for individual process heat recovery is first converted to grand composite curves (GCCs). GCCs are combined to form a site heat source profile and a site sink profile. These two profiles form total site profiles (TSP) analogous to the composite curves for individual processes. Perry et al. (2008) extended the site utility grand composite curves (UGCC) and Bandyopadhyay et al (2010) developed a methodology to estimate the cogeneration potential of an overall site through UGCC. A total site approach was applied in this study by using the UGCC of pinch technology, which analyzed the heat profile based on the data obtained from utility heaters and coolers in a large petrochemical site and identified the potential energy saving with the introduction of the industrial heat pump.

2. Study basis and cases

2.1 Energy saving by heat pump

(1) Concept of calculation for energy saving

As can be seen in Figure 1, it is often found that the utility system in a large petrochemical plant has an integrated power generation facility. The boilers produce the high-pressure steam (HPS) which generates power by the use of turbines. Middle-pressure steam (MPS) is provided from such turbines. If a heat pump were installed to generate some amount of MPS, the exhausted or extracted MPS from turbines would be surplus to requirements and would need to be reduced. This condition results in reducing the HPS generation in boilers and, consequently, the fuel consumption of such boilers would be reduced. However it also leads to reduction of power generation in turbines due to there being less steam throughput. The installed heat pump simultaneously consumes electricity and therefore additional electricity purchased from a power company will be required. The energy saving study has to take into account not only the fuel reduction in boilers but also the increase in purchased electricity.

(2) Coefficient of performance

Coefficient of performance (COP) can be used and understood as a measure of the energy efficiency of heat pump. The theoretical COP (COP_{th}) is the delivered heat (output; $Q + W$) divided by the heat equivalent of the electric energy consumption (input; W). In this study COP_{th} is defined in Eq. 1.

$$(COP_{th}) = (Q + W) / W = T2 / (T2 - T1) \quad (1)$$

Q: Heat intake to heat pump
W: Heat equivalent of the electric consumption of heat pump
$T1$: Inlet temperature of heat pump, K
$T2$: Outlet temperature of heat pump, K

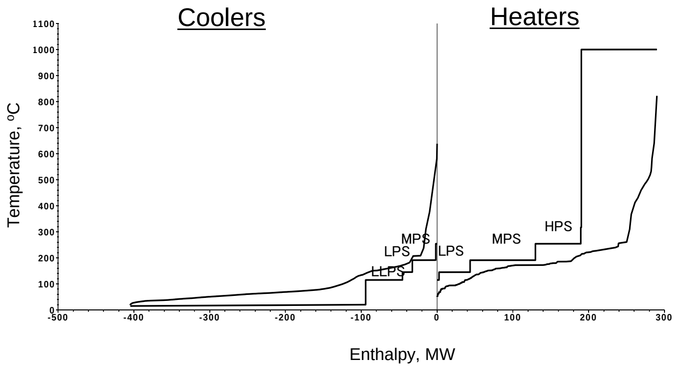

Figure 2: Total site profile in a large petrochemical plant

The performance required of the heat pump can be calculated based on Eq. 1 once the conditions of heat source and heat sink are specified. However the theoretical COP is calculated under ideal conditions and it is necessary to take into account some of the losses in actual operation, such as a heat loss in the heat exchange that takes place between the working fluid of the heat pump and utility, the mechanical loss in rotating equipment and so on. The practical COP (COP_{pr}) in this study is used to approximate the actual operating conditions by using the parameter 0.8 as shown in Eq. 2. This parameter takes all the losses into account.

$$(COP_{pr}) = 0.8\ (COP_{th}) \qquad (2)$$

2.2 A large petrochemical plant

A large petrochemical plant, producing as much as 450,000 t/y of ethylene, was used in this study. The data of the utility coolers (149 sets) and heaters (106 sets) was collected as shown in Table 1 and the steam header conditions of the plant are shown in Table 2; the total site profile (TSP) was prepared from this data. Figure 2 shows the current operating conditions by TSP and it is apparent that 1) in the heater side, HPS, MPS and low-pressure steam (LPS) approach the cold composite curve very well, which consists of many cold process streams under 200 °C and 2) in the cooler side, the hot composite curve, which consists of many process hot streams, was cooled down by producing MPS, LPS and low low-pressure steam (LLPS). LPS and LLPS were considered as a possible heat source for the heat pump, but such heat sources had already been designated for other purposes and could not be used for this purpose. When looking at the region of less than 200 °C in the hot composite curve, it was found that there was a potential to produce a new utility. It meant that four lower level waste heats (un-utilized heat, 140 °C, 100 °C, 80 °C, and 60 °C) were therefore adopted as a heat sources for the heat pump. The new conditions of such four low level heats (140 °C, 100 °C, 80 °C, and 60 °C) were added to the cooler side in Figure 2 to prepare the enlarged view of the composite curves of Figure 3. The broken line in Figure 3 shows the current operating condition (current case) and the solid line shows the target operating condition (target case). The line in the target case approached the hot composite curve and showed the potential for energy saving. It should be noted that the heat duty of LLPS generated in the target case was maintained, as it was in the current case.

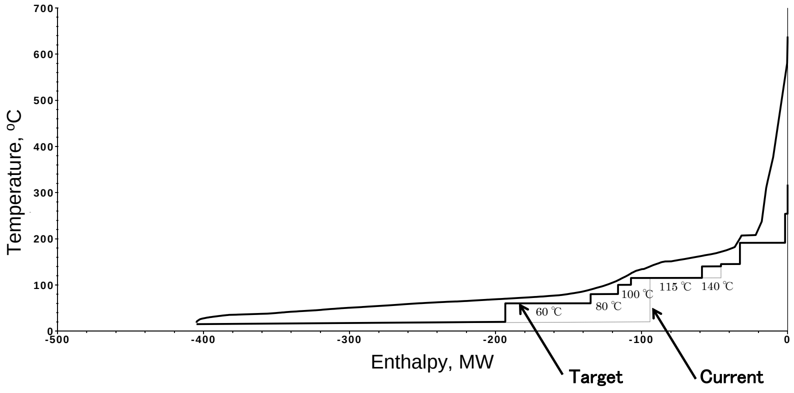

Figure 3: Additional heat recovery in cooler side

2.3 Study cases

A heat pump absorbs the low level heat and releases the higher level heat by heat pumping. The industrial heat pump collects the waste heat and the low level un-utilized heat. In this study four low level heats (140 °C, 100 °C, 80 °C, and 60 °C) were to be absorbed. On the other hand, the heat released from the industrial heat pump were LPS and MPS conditions, as releasing such steam would result in reduction in fuel consumption by the boiler. Six cases were defined for the industrial heat pump study by a combination of four low heat levels for the absorbing side of the heat pump and two steam levels (LPS and MPS) released from the heat pump.

Table 3: Study cases

Case	(1)	(2)	(3)	(4)	(5)	(6)
1. Parameters for heat pump						
Absorbed temperature, °C	140	100	80	80	60	60
Released temperature, °C	145	145	145	191	191	254
Absorbed heat (A), MW	13.0	8.9	3.6	15.2	21.7	31.4
Electric consumption (B), MW	0.2	1.4	0.9	6.5	11.8	26.8
Released heat (C=A+B), MW	13.2	10.3	4.5	21.7	33.5	58.2
Theoretical COP COP*th*, -	83.6	9.3	6.4	4.2	3.5	2.7
Practical COP COP*pr*, -	66.9	7.4	5.1	3.3	2.8	2.2
2. Increasing and decreasing by implementing heat pump						
Private power generation (D), MW	-3.2	-2.5	-1.1	-3.8	-5.9	-5.8
Purchased power (E=B-D), MW	3.4	3.9	2.0	10.3	17.7	32.6
Boiler fuel (F) *1, MW	-17.8	-13.9	-6.1	-27.7	-42.8	-69.5
Total (E/39.6% *2 +F), MW	-9.3	-4.1	-1.1	-1.7	1.8	12.7

Note) *1: Boiler efficiency = 92%、, *2: Power generation efficiency = 39.6%,
*3: Mechanical efficiency of heat pump = 80%

3. Results

The application of the heat pump was studied by using utility grand composite curves (UGCC) for the six cases in Figure 4, based on the data from Figure 3. The narrow section to the left in Figure 4 is the pinch point. The above pinch point is the heat sink and the below pinch point is the heat source. It is important to remember that the appropriate placement for heat pump is across the pinch point. This means that a heat pump should absorb heat from the heat source and release the increased heat to the heat sink. The parameters for the heat pump in case studies are summarized in Table 3. In combination with the absorbed heat and released heat around a heat pump, three kinds of absorbed heat, 140 °C, 100 °C and 80 °C, were used to meet the released heat conditions of 145 °C (Cases-1,2 and 3). Two kinds of absorbed heat, 80 °C and 60 °C, were used to meet the released heat conditions of 191 °C (Cases-4 & 5). Finally absorbed heat of 60 °C was used to meet the released heat conditions of 254 °C (Case-6). It appears in Table 3 and Figure 4 that there is no temperature difference between the absorbed heat and the heat source, as well as between the released heat and the heat sink, but there is assuredly some temperature loss in a heat exchanger under practical operation. Such practical heat exchanging loss was taken into account and was included in the parameter (0.8) for the practical COP. It was considered that the

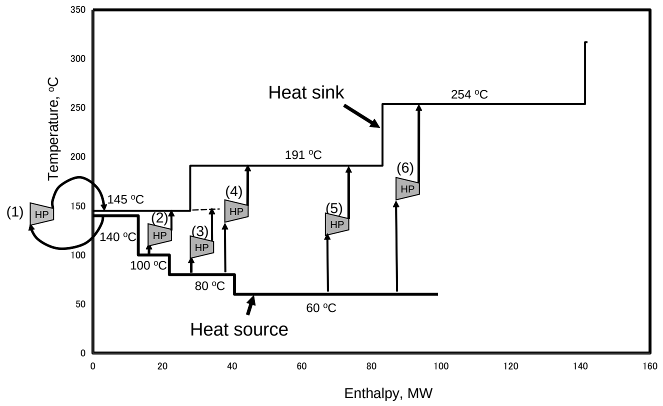

Figure 4: Six cases of heat pump application in Utility Grand composite Curves (UGCC)

combination of the smaller temperature difference between the absorbed and the released heat around heat pump should be adopted because a smaller temperature difference would lead to a higher efficiency heat pump with a higher COP. The absorbed heat in case-1 was 140 °C and the released heat was 145 °C. The practical COP was expected to be 66.9 which meant that the heat pump for the combination of absorbed and released heat conditions resulted in very high efficient performance. The consumption of electricity of the heat pump was 0.2 MW. Applying the heat pump in case-1 led to the situation whereby purchased power increased by 3.4 MW but the boiler fuel consumption was decreased by 17.8 MW. By taking into account a power generation efficiency of 39.6 %, energy consumption was decreased by 9.3 MW, as the reduction in the boiler fuel consumption was larger than the increase in the amount of purchased power. As the case study went on, the increase in purchased power became larger than the reduction in the amount of boiler fuel consumption. In the end, energy saving could not be achieved in case-5 and energy consumption was increased by 1.8 MW. In cases later than case-5, there were further increases in energy consumption and no further energy saving was expected.

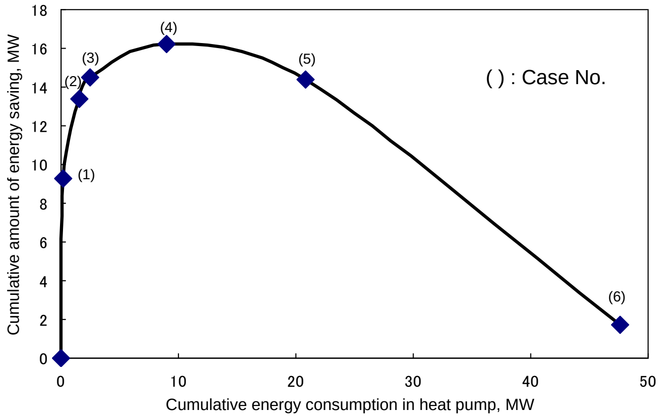

Figure 5: The effect of heat pump introduction

4. Discussion

Wallin and Berntsson (1994) considered that the composite curves of pinch technology and COP were important factors for the appropriate design of a heat pump and Helen Becker et al. (2011) later developed the integration of industrial heat pumps. The utility grand composite curves (UGCC) would suggest what would be a good combination of heat source and sink for use in an industrial heat pump. Six cases were studied on the basis of the combination of absorbed heat and released heat from the result of UGCC as shown in Figure 4, and the results are summarized in Table 3. It is understood that smaller temperature difference between absorbed heat and released heat leads to high COP condition and a significant reduction in energy consumption. Figure 5 was prepared by utilizing the data from Table 3, which shows the analysis of the effect of installing the heat pumps. The cumulative data of the energy consumption of the heat pump and the cumulative amount of energy saving were plotted in Figure 5 from the result of the six cases. This figure shows that the turning point was case-4. Table 3 shows that case-4 needs a very large temperature difference of 111 °C between the absorbing lower heat and the releasing higher heat, and that the practical COP of 3.3 slightly exceeds the minimum requirement value of 3.0 for heat pump in general. The new heat pump, with a released temperature of 165 °C (Chuden website, 2011), will be able to be applied for case-1 to case-3, which will lead to a reduction in energy consumption. It was realized that in cases later than case-3 the higher temperature heat pump was required for further energy saving and this has clarified the requirements and specifications for the development of such industrial heat pump.

5. Conclusion

The concept of total site approach from pinch technology for the whole of a utility system was applied to an industrial heat pump study for energy saving. It was considered that applying the utility grand composite curves (UGCC) of the pinch technology would lead to the identification of the appropriate combination of heat source and sink for the introduction of an industrial heat pump in a large petrochemical site and would result in a situation whereby a significant energy savings could be expected. Furthermore the requirements and specifications became apparent for the development of an industrial heat pump applied in higher temperature heat conditions.

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