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Heat Pump Integration for Total Site Waste Heat Recovery

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Total Site Heat Integration (TSHI) promotes energy recovery between processes to enhance overall energy efficiency of an industrial complex. Various industrial waste heat utilisation technologies have been studied to improve the energy efficiency of energy system. Vapour compression as an open loop heat pump system has good potential to be used to upgrade the waste heat to useful heat in Total Site systems. Vapour compression systems upgrade low grade waste heat by supplying a low quantity of high pressure steam (thermo-compressor) or mechanical work (mechanical-compressor) to generate higher pressure steam, as is common with evaporation systems. The vapour compression system recovers the latent heat content of the industrial waste heat, which reduces cooling demand, decreasing the demand for high quality steam and reducing boiler load. This paper introduces an effective Total Site targeting methodology to integrate open cycle heat pump systems, i.e. vapour compression technologies, into an integrated industrial energy system for enhancing overall site energy efficiency. Industrial waste heat and high quality steam demand are able to be reduced simultaneously though this integration. The energy reduction and cost-benefit of thermo-compressor and mechanical-compressor installations are compared through a literature case study. The case study showed a deficit of heat at the MPS and a surplus of heat the LPS, which was identified as a candidate for compression according to the appropriate placement principle for heat pumps. For the case study, a four-stage mechanical vapour compression system and two-stage thermal vapour compression system resulted in an energy cost reductions of 343,859 USD/y and 168,829 USD/y.

1. Introduction

Pinch Analysis was introduced as a tool for reducing industrial energy consumption since the oil crisis in late 1970s. Many years later this tool continues to be developed to enhance industrial energy efficiency for improving profitability margin of a company. Total Site Heat Integration - TSHI (Dhole and Linnhoff, 1993) extended the individual process Pinch Analysis heat targeting methodology for inter-process energy recovery through utility systems (e.g. steam, hot oil, hot water and chilled water). Through TSHI, industrial waste heat from an individual process is able to be recovered by supplying it across the process boundary to neighbouring processes using utility systems.

Typically, there is still remaining waste energy from the integrated TS system, even after extensive optimisation for steam pressure selection and cogeneration (Sun et al., 2013). Utilisation of this waste heat has been actively discussed, especially for low grade waste heat. Oluleye et al. (2015) explored the potential for low grade waste heat recovery through Organic Rankine Cycle, absorption chiller and absorption heat pump using mathematical modelling methodology. District heating has been widely discussed as one of the possible waste heat utilisation (Kapil et al., 2011). In addition, Liew et al. (2015) proposed the integration of district cooling system for utilising industrial low grade waste heat through absorption chillers.

Bagajewicz and Barbaro (2003) developed targeting methodologies for single and two heat pumps usage in a Total Site processing systems, which mechanical heat pump or vapour compression cycle is assumed in the work. The work also explored the potentials of heat pump usage in Total Site involving assisted heat transfer in heat recovery pocket. Walmsley et al. (2016) considered Mechanical and Thermal Vapour Recompression

systems as heat pumps for steam upgrading in milk evaporators given the Total Site energy context of a dairy factory.
In this work, the usage of different types of vapour compression heat pump systems in TSHI for direct integration with the utility system is discussed, i.e. mechanical and thermo-compressor. The motivation of this system is to utilise the remaining energy contents in industrial low grade waste heat, and upgrading it to become useful energy for the system. A TSHI targeting methodology is introduced for incorporating and selecting the appropriate type of heat pumps to be used in a Total Site system. The cost-benefit of the heat pumps application are demonstrated in the case study.

2. Compressor Heat Pump

This work studies the possible application of open cycle mechanical vapour compression and thermo-compressor as heat pump system for upgrading the low grade waste heat for an industrial cluster, as illustrated in Figure 1.

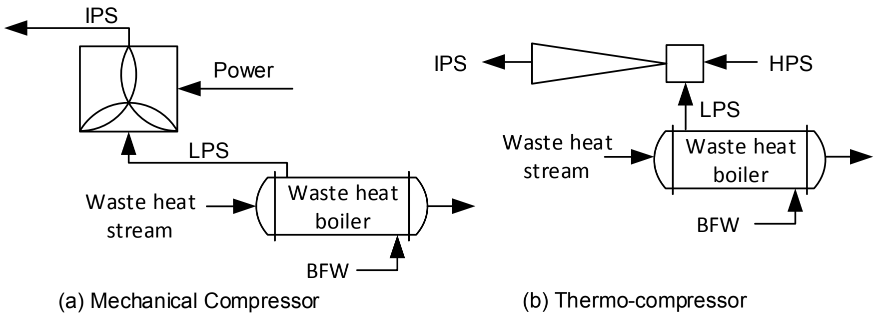

Figure 1: The concepts of mechanical and thermo-compression for waste heat regeneration.

2.1 Multi-stage Mechanical Vapour Recompression (MVR) fans

MVR fans perform a pressurisation process through mechanical work, which compresses lower pressure inlet steam to a higher pressure and saturation temperature. The concept of MVR is similar to a mechanical compressor. However, MVR fans is generally bigger in physical size and more energy efficiency. A single MVR stage is able to raise saturation temperature in the range of 7 to 12 °C. MVR fans may be used in series for higher saturation temperature rises. The typical configuration for waste steam regeneration is using up to four units of MVR fans in series, which achieves about 40 °C of saturation temperature rise.
In TSHI context, the steam excess (below TS Pinch region) could be mechanically compressed to increase the saturation temperature of the steam, to satisfy the heat deficit above TS Pinch region.
The power consumption (brake power, $\dot{W}_{brake}$) of a mechanical compressor for a single stage can be estimated through its isentropic efficiency, η_s, as shown in Eq(1). Typical MVR manufacturer values for η_s are 76 – 82 %.

$$\eta_s = \frac{\dot{W}_{isentropic}}{\dot{W}_{brake}} = \frac{h_{2,is} - h_1}{h_2 - h_1} \quad (1)$$

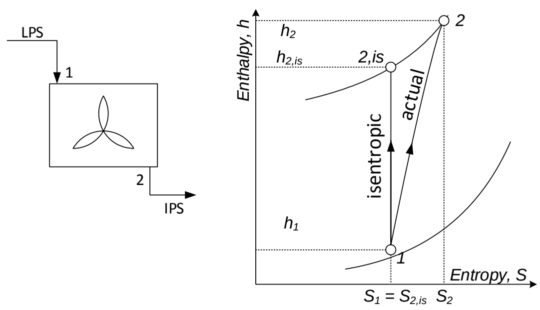

Figure 2: Isentropic and actual compression process for a MVR fan system.

2.2 Thermal Vapour Recompression (TVR) or thermo-compressor

Thermo-compressors are also known as steam jet ejectors. This a technology known for energy conservation in refrigeration and evaporation systems. Low pressure steam (suction steam) is compressed to a usable higher pressure level through high pressure fluid jet ejection (motive steam). The ratio between the motive steam's pressure and the suction steam's pressure is known as the expansion ratio (Eq(2)), which is typically less than 1.8 for a typical TVR system (Kadant Johnson Inc, 2011). The ratio between the discharge pressure and the suction steam's pressure is known as the compression ratio (Eq(3)), which is always kept above 1.4 for ensuring the system works well (Kadant Johnson Inc, 2011). The expansion and compression ratios contribute to an entrainment ratio (Eq(4)), which is obtained from performance and sizing curves.

In TSHI context, the waste heat generated low grade steam serves as the suction steam of the TVR system, while HPS (or VHPS) generated from boiler is supplied as the motive steam. The system produces MPS, which is in deficit and located above the TS Pinch region. This integration reduces the waste heat below the TS Pinch region, while trading-off the MPS and HPS demand of the system. Therefore, this type of system retrofit may not be suitable for steam system with dedicated steam boiler for each steam header.

$$Expansion\ Ratio = \frac{P_{motive}}{P_{suction}} \tag{2}$$

$$Compression\ Ratio = \frac{P_{discharge}}{P_{suction}} \tag{3}$$

$$Entrainment\ Ratio = \frac{\dot{m}_{suction}}{\dot{m}_{motive}} \tag{4}$$

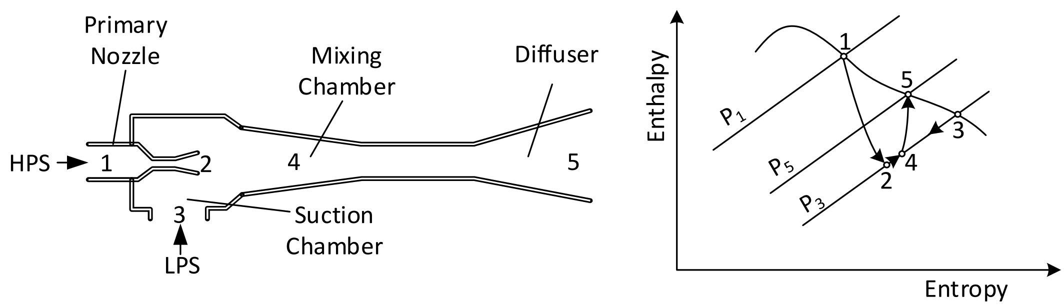

Figure 3: Schematic diagram and thermodynamic properties diagram for TVR system (Chen et al., 2014).

3. Methodology

This work proposes a new TSHI targeting methodology incorporating MVR and TVR, which is used to assess the feasibility of these systems. The methodology is graphically summarised in Figure 4 using following steps:

1. Data Collection. Collect stream data on the inlet and outlet temperature, as well as heat capacity flow, for streams requires heating or cooling.
2. Energy Requirement Targeting. Perform individual process Pinch Analysis targeting and Total Site energy targeting, to obtain the minimum energy requirement of the integrated processes. This step determines the amount of waste heat available in the TS system.
3. Heat Pump Integration. Calculate the electricity (MVR) or steam (TVR) consumption for the heat pump installation, based on waste heat availability and useful heat demands.
4. Technology Selection. Compare the feasibility of the MVR and TVR systems based on utility cost in the TS system.

4. Case Study

The new concept is demonstrated through an illustrative case study from Liew et al. (2013). The TS system consists of three industrial sites, as tabulated in Table 1. There are three steam headers available on site connecting all the processes, which includes High Pressure Steam at 55 bar, Medium Pressure Steam at 8 bar and Low Pressure Steam at 3 bar. Cooling towers are supplying cooling water (CW) at 25 °C. The minimum temperature difference between the process streams and the utility ($\Delta T_{min,up}$) and the minimum temperature difference between the process streams ($\Delta T_{min,pp}$) are assumed to be 10 °C and 20 °C.

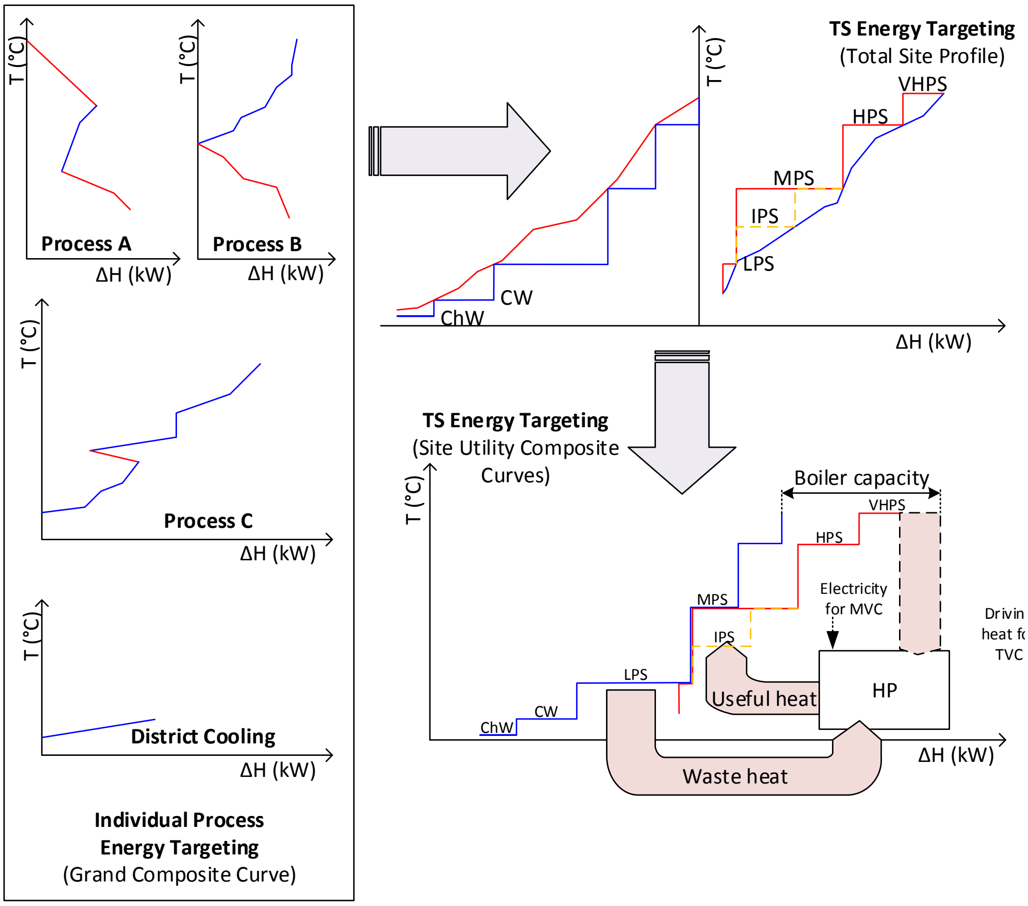

Figure 4: Methodology for feasibility study of open loop heat pump integration into the TS utility system.

Table 1: Stream data for the case study.

Stream	T_S (°C)	T_T (°C)	ΔH (kW)	CP (kW/°C)	T_S' (°C)	T_T' (°C)
Process A						
A1 Hot	200	100	20,000	200	190	90
A2 Hot	150	60	36,000	400	140	50
A3 Cold	50	220	-25,500	150	60	230
A4 Hot	170	150	10,000	500	160	140
Process B						
B1 Hot	200	50	4,500	30	190	40
B2 Hot	200	119	18,630	230	190	109
B3 Cold	30	200	-6,800	40	40	210
B4 Cold	130	150	-3,000	150	140	160
Process C						
C1 Hot	240	100	2,100	15	230	90
C2 Cold	50	250	-4,000	20	60	260
C3 Cold	40	190	-15,000	100	50	200
C4 Cold	109	140	-1,860	60	119	150

4.1 Energy requirement targeting results

Algebraic cascade analysis (Liew et al., 2012) is performed for determining the energy requirements at different temperature levels as shown in Table 2. There is 13.4 MW of low grade waste heat available at LPS level. Instead of utilizing this energy to produce chilled water as described in Liew et al. (2015), the waste heat available is considered to be upgraded to MPS level. MVR and TVR are both considered to be integrated in this system for steam upgrading. The heat available is used to heat and vaporize boiler feed water to LP level at 133.5 °C. From waste process heat, 5.15 kg/s of LPS could be generated. By utilizing this heat, the heating and cooling demands could be reduced, which contributes to reductions in boiler fuel use and electricity consumption for the cooling towers.

Table 2: Total Site Problem Table Algorithm for the case study.

Utility	Heat Source (kW)	Heat Sink (kW)	Heat Requirement (kW)	Initial Cascade (kW)	Final Cascade (kW)	MU Cascade (kW)	Utility Requirement (kW)
				0	14,423	0	
HPS	0	-11,200	-11,200				11,200
				-11,200	3,223	0	
MPS	2,200	-5,423	-3,223				3,223
				-14,423	0	0	(TS Pinch)
LPS	21,905	-8,538	13,368				-13,368
				-1,055	13,368	0	
CW	34,500	0	34,500				-34,500
				33,445	47,868	0	

4.2 Heat Pump Integration

4.2.1 Mechanical Vapor Recompression fans

The LPS generated is considered to be compressed to MPS at 8 bar and 170 °C. The saturated temperature lift is 36.5 °C. Four MVR fans in series is used to satisfy this saturation temperature rise requirement. Assuming each MVR stage has an isentropic efficiency of 79 %, the electricity consumption of the MVR fans to upgrade all the LPS is 1.68 MW. With this system configuration, the MVR system produces an additional 14.27 MW of MPS for satisfying the MPS requirement at above TS Pinch region.

However, the MPS produced by fully consuming the LPS available is much higher than the deficit as shown in Table 2. Therefore, the MVR size should be reduced for handling 4.07 MW or 1.57 kg/s of LPS, which produces 3.22 MW of MPS and consumes 376.36 kW of electricity only.

4.2.2 Thermal Vapor Recompression (TVR)

The waste heat generated LPS could alternatively be compressed through two unit of TVRs in series, which the Intermediate Pressure Steam (IPS) is set at 5 bar for maintaining the compression ratio below 1.8. The first TVR system has lower suction pressure at 3 bar to be compressed to 5 bar, while the second TVR sucks the IPS at 5 bar to compress to the required pressure of 8 bar. HPS is considered as the motive steam for both TVR systems, which leads to an increased HPS demand.

At the first TVR, the compression ratio is 1.67 and the expansion ratio is 18.33, which contribute to entrainment ratio at 1.15 kg of LPS per kg of HPS (Kadant Johnson Inc, 2011). The second TVR has compression ratio at 1.6 and expansion ratio at 11, which results in an entrainment ratio to 1.10 kg of IPS per kg of HPS (Kadant Johnson Inc, 2011). For producing 3.22 MW (1.16 kg/s) of MPS, the first TVR stage needs 0.89 MW (0.32 kg/s) of LPS and 0.79 MW (0.28 kg/s) of HPS, while the second TVR stage requires 1.55 MW (0.55 kg/s) of HPS and 1.68 MW (0.61 kg/s) of IPS.

Overall the TVR system to compress LPS for producing 3.22 MW of MPS requires 0.89 MW of LPS and 2.34 MW (0.79 MW + 1.55 MW) of HPS. The performance ratio of the TVR system is 0.39 kg/kg.

4.3 Technology selection

For this feasibility study, the utility cost changes from the MVR or TVR heat pump integration are analysed. The assumed utility price in this case study is USD 701.92 /kW·y for electricity from grid, USD 162.00 /kW·y for natural gas consumption of steam boilers and USD 28.45 /kW·y for electricity consumption of cooling towers (Liew et al., 2014). The utility consumption changes and the respective cost savings are analysed in Table 3.

It can be concluded that the boiler and cooling tower loads for the system with MVR has higher energy saving potential by consuming electricity. Due to the high compression ratio between LPS and MPS and its resulting poor overall performance ratio, this system is more appropriate to be integrated with MVR heat pump compared TVR. TVR has lower entrainment ratio when the compression ratio is high, which causes waste heat available in the system is under-utilised in the case study.

Future work will look at the impact of MVR and TVR integration on TS cogeneration as well as a detailed capital cost and total cost optimisation for an installation. It will also investigate the opportunity to utilise some of the IPS from the first TVR stage as an added steam main.

Table 3: Energy and cost saving from heat pump integration.

Utility		Existing	MVR	TVR
HPS	kW	11,200	11,200	13,537
MPS	kW	3,223	0	0
LPS	kW	-13,368	-9,294	-12,479
CW	kW	-34,500	-34,643	-34,500
Boiler Load	kW	14,423	11,200	13,537
Boiler Load Changes	kW	-	-3,223	-886
	USD/y	-	-522,143	-143,537
Cooling Tower Load	kW	47,868	43,936	46,979
Cooling Tower Load Changes	kW	-	-3,932	-889
	USD/y	-	-85,891	-25,292
Electricity Load Changes	kW	-	376	0
	USD/y	-	264,175	0
Total Utility Cost Changes	USD/y	-	-343,859	-168,829

5. Conclusion

A new methodology for incorporating two types of open cycle heat pumps is introduced in this study. The case study proves that heat pump is able to bring utility and cost savings to an industry. MVR fan type of heat pump shows higher saving potential for system that requires high compression ratio, while TVR suits system that needs lower compression ratio. The capital cost implications of the two systems will be a key element in future work. Future work will look at the impact of MVR and TVR integration on TS cogeneration as well as a detailed capital cost and total cost optimisation for an installation. It will also investigate the opportunity to utilise some of the IPS from the first TVR stage as an added steam main.

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