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Process Integration Using a Joule Cycle Heat Pump

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This paper investigates the potential of integrating the emerging Joule Cycle Heat Pump (JCHP) to recover and upgrade process waste heat, improving process energy efficiency. Existing heat pump applications for waste heat recovery mostly adopt the two-phase vapour compression heat pump. This reliance on latent heat transfer is efficient for applications where the heat capacity flow rates of the heat sources and sinks are high, resulting in nearly flat temperature-enthalpy profiles. However, for applications with low heat capacity flowrates, applying vapour compression heat pumps results in a significant temperature lift, decreasing the Coefficient of Performance (COP). The present study simulates the JCHP using four different working fluids – Ar, CO_2, N_2, and Ne and optimises the operating parameters to obtain the maximum COP of the JCHP. The JCHP has good prospects for serving industrial processes with significant temperature changes. The developed model is applied to target the integration of the JCHP with an industrial milk spray dryer case study. The method is based on Pinch Analysis and customised to the JCHP, evaluating the process type and energy profile, for which the JCHP integration is beneficial. The COP of the integrated system using JCHP is 3.3, which is higher than COP (2.7) of the two-phase heat pump.

1. Introduction

A heat pump is an energy-saving device that recovers low-grade heat and displaces hot utility. The principle of a heat pump is to move heat from lower to higher temperatures by reversing the natural flow, at the expense of applying mechanical work. A considerable amount of heat can be saved, consuming a smaller amount of net power through the JCHP thermodynamic cycle. This has the potential to translate to a reduction of Greenhouse Gas emissions, as well as any associated Water Footprint, which will be reinforced by the decreasing emission factors of the electricity grids due to the increasing share of renewable energy in the source mix. As a result, heat pumps have received considerable attention and development, becoming an essential energy saving technology.

Pinch Analysis, pioneered by Linnhoff and Hindmarsh (1983), is a widely used tool to improve industrial energy efficiency via Heat Integration (Klemeš, 2018a). The idea of using heat pumps in Process Integration has been assessed in many recent studies. Walmsley et al. (2017) presented a hybrid compression-absorption heat pump process for convection dryers by using Pinch Methodology. Yang et al. (2016) applied Pinch Analysis to the Heat Integration of the heat pump system and the distillation process. The existing heat pump applications to waste heat recovery mostly adopt the traditional two-phase cycle heat pump process. In the traditional two-phase cycle heat pump (Zhang et al., 2019), the working fluid undergoes a phase change and uses latent heat transfer. In some applications (e.g. distillation), the latent heat transfer has the characteristics of a significant average heat transfer temperature difference, low exergy transfer efficiency, and low COP.

ECOP (ECOP Technologies GmbH) applied a heat pump process based on a Joule cycle (also known as Joule-Brayton or Reverse Brayton cycle) with the rotation heat pump implementation (Adler and Mauthner, 2017). Compared with the traditional two-phase cycle heat pump, the JCHP has the advantage of sensible heat exchange between the working fluid and source/sink fluid, more flexible temperature level, and larger temperature difference from the heat source to the sink. A JCHP can achieve a higher COP than a two-phase cycle heat pump under certain circumstances. However, there is very little research on the integration of JCHP and industrial processes.

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The aim of the present study is to improve the COP potential of JCHP and energy efficiency of industrial processes, enable energy savings and reduction of energy consumption. JCHP is simulated in Petro-SIM (KBC, 2016) using several different working fluids. The temperature and pressure operating conditions are optimised to maximise the COP. To integrate the JCHP into a process, a method based on Pinch Methodology and customised to the JCHP is developed. Through energy targeting, energy consumption can be reduced. The method is applied to the integration of JCHP with a milk spray drying process for the case study.

2. Methods

2.1 Simulation and optimisation of JCHP

The schematic illustration of the heat pump system is shown in Figure 1a. The heat pump absorbs heat Q_c from the source and releases heat Q_h into the sink. The compression work consumed is W_{com}. The COP of a heat pump is presented in Eq(1). Temperature-Entropy (T-S) diagram of a vapour compression heat pump, see Figure 1b. In the JCHP, the working fluid remains in a gaseous state when exchanging heat between it and source/sink, see Figure 1c. There is a temperature change during heat transfer. The source and sink often are not associated with a phase change. Due to sensible heat transfer, the minimum temperature difference between the working fluid and source/sink is smaller, which is beneficial to obtain a higher COP.

$$COP = \frac{Q_h}{W_{com} - W_{exp}} = \frac{Q_h}{Q_h - Q_c} \tag{1}$$

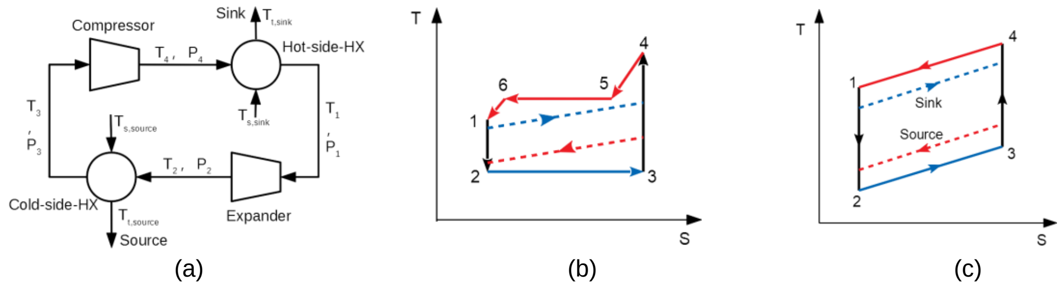


Figure 1: (a) Schematic illustration of the heat pump; (b) ideal T-S diagram of the two-phase heat pump (Khennich et al., 2017); (c) ideal T-S diagram of JCHP (Adler and Mauthner, 2017)

JCHP has been simulated by Petro-SIM (Figure 2). The pressure and temperature of the working fluid S1 are reduced through the Expander. Then S2 absorbs heat from Source in Cold-side-HX. S3 enters Compressor to increase the pressure and temperature. It (S4) heats Sink in Hot-side-HX and is cooled down. Then it returns to the Expander for circulation. Fluid packages are based on the Peng-Robinson (Lopez-Echeverry et al., 2017) in combination with the Lee-Kesler Equation of State as a standard package in Petro-SIM.

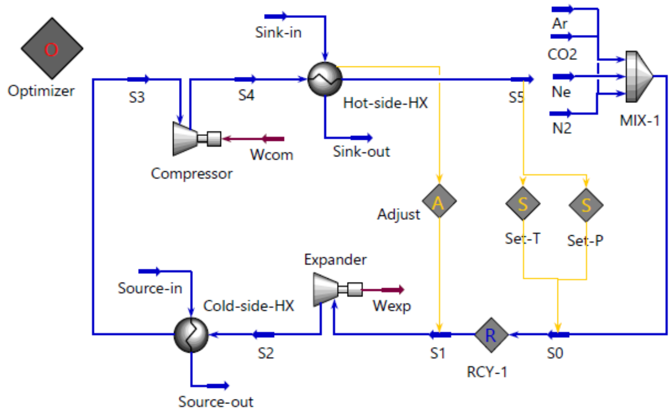


Figure 2: Simulation flowsheet of the JCHP in Petro-SIM

The parameters of the JCHP, to be specified, include: T_1, T_3, T_4 - the temperature of working fluid of JCHP (°C); P_4 - the Outlet pressure of compressor of JCHP (MPa); $T_{s,sink}$, $T_{t,sink}$, $T_{s,source}$, $T_{t,source}$ - the inlet/outlet temperature of sink/source (°C); ΔP - the pressure drop of working fluid flowing through heat exchanger (MPa); η - the

isentropic efficiency of compressor/expander (%); ΔT_{HP} - the temperature difference between working fluid and source/sink (°C). All other variables (e.g. T_2 and the other pressures) are resolved by the simulation.
It is necessary to optimise the heat pump based on the simulation to obtain the best performance of the heat pump. Petro-SIM has a multivariable Optimizer. Once a simulation converges, the Optimizer can be used to optimise selected independent variables within defined ranges, to minimise or maximise the objective function. The optimisation functionality of Petro-SIM can be used to optimise multiple process variables. It can be used for constrained optimisation expression with some flexibility, such as solving the objective function to maximise profit or minimise utility consumption. In this study, the heat pump system is optimised by adding Optimizer and Adjust units in the Petro-SIM simulation. In the Optimizer, the variables (e.g. temperature and pressure, etc.), objective (e.g. network) and constraints are defined to perform the optimisation. The iterative calculation method of the Optimizer in Petro-SIM is based on the IPOPT solver.

2.2 Process Integration

Pinch Methodology - for more details, see, e.g. Klemeš (2013) - is a method to calculate maximum-efficiency energy targets based on thermodynamic analysis. Minimum energy consumption can be obtained by optimising the heat recovery system, energy supply and process operations. The Grand Composite Curve (GCC) is a graph developed from the Composite Curves with shifted temperature to net heat flow rate as coordinate, and is a simple graphical representation of the Problem Table (Linnhoff and Hindmarsh, 1983). The Pinch Point divides the system into two thermodynamically separated subsystems.
The appropriate placement of a heat pump means that the heat must be removed below the Pinch and released above the Pinch (Klemeš, 2018b). When a heat pump is integrated with a process, the choice of a heat pump depends on the operating temperature and the heat load below/above the Pinch. Figure 3a presents the GCC with an integrated two-phase heat pump. Due to the phase change during heat transfer, the temperatures of the evaporation curve (blue line) and condensation curve (red line) are constant (i.e. horizontal lines). For a fixed condenser temperature, a COP curve (Stampfli et al., 2018) for a range of shifted evaporator temperatures is shown as the green line in Figure 3a, reflecting that the COP drops with increasing the temperature lift.

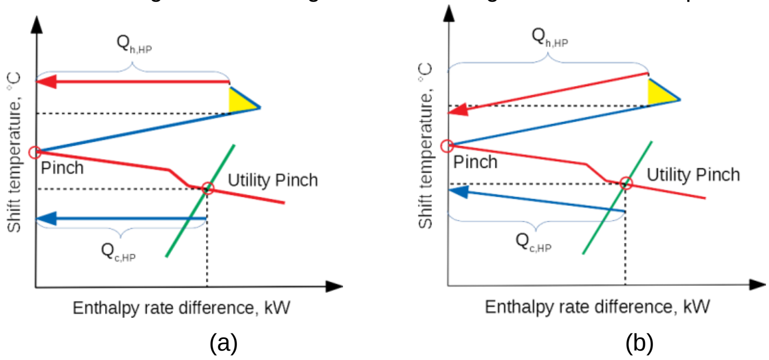


Figure 3: (a) GCC construction description of traditional two-phase vapour compression heat pump; (b) GCC construction description of JCHP. Where green lines represent the COP curve (Stampfli et al., 2018), red lines represent heat sources, and blue lines represent heat sinks

This study proposes to integrate JCHP and process by Pinch Methodology using a similar method to Stampfli et al. (2018). The conceptual diagram with the GCC is shown in Figure 3b. The COP equation of a JCHP can be expressed as a function of the temperatures and pressures, Eq(2). Specific Heat Capacity (CP) varies substantially with pressure and temperature as the working fluid of the JHCP is a non-ideal gas. When the pressure is fixed, the COP equation of the JCHP can be calculated using average CP values and expressed as a function of the temperatures, see Eq(3). In Eq(4), the ratio f varies with temperature (because $\overline{CP_h}$ and $\overline{CP_c}$ change with temperature). By simulating the JCHP in Petro-SIM, a series of COP values, which comprise the COP curve, can be obtained by changing the input temperatures and the pressure. The intersection point of the COP curve and GCC is the Utility Pinch. The energy target of JCHP integrated with the process can be obtained, as shown in Figure 3b, where $Q_{h,HP}$ and $Q_{C,HP}$ are the hot and cold utility that JCHP can provide for process.

$$COP = f_1(T_1, T_2, T_3, T_4, P_1, P_2) \quad (2)$$

$$COP_P = \frac{Q_h}{Q_{h-}Q_c} = \frac{\overline{CP_h} \cdot (T_1 - T_2)}{\overline{CP_h} \cdot (T_1 - T_2) - \overline{CP_c} \cdot (T_4 - T_3)} = \frac{\Delta T_h}{\Delta T_h - f \cdot \Delta T_c} \quad (3)$$

$$f = \frac{\overline{CP_c}}{\overline{CP_h}} = f_2(T_1, T_2, T_3, T_4) \quad (4)$$

3. Case study

3.1 Simulation of the JCHP

Case studies (Table 1) based on JCHP experimental data (Adler and Mauthner, 2017) were used for the JCHP simulation applying the model from Section 2.1. For this calculation, the working fluid of JCHP is Ar. There is a ΔT_{HP} = 3 °C gap between the heat sink/source and the working gas/refrigerant. JCHP was simulated in Petro-SIM (Figure 2). The specifications for heat source/sink and simulation results are shown in Table 1.

Table 1: The specifications and simulation results of JCHP

Case	(Adler and Mauthner, 2017) Source (°C)	Sink (°C)	COP_{actual}	Simulation results Calculated η (%) (P_4 = 5.44 MPa, ΔP = 0)	COP_{min} (η = 93.17 %)	COP_{max} (η = 98.66 %)	P_4 (η = 99 %, ΔP = 0.05 MPa)
1	60/30	60/100	5.5	96.59	4.20	7.06	7.5
2	20/2	55/70	3.7	98.66	1.47	3.70	22.2
3	60/46	60/95	4.3	93.17	4.30	7.47	3.9
4	55/30	55/75	5.8	97.30	3.27	7.53	11.7
5	42/32	55/75	4.1	95.66	3.12	6.53	6.2
6	65/45	75/95	4.9	97.06	2.85	6.76	9.9

When the isentropic efficiencies (η) of the compressor and the expander are set equal, and ΔP = 0 MPa, P_4 = 5.44 MPa, COP of JCHP can be adjusted to reach the reference value by adjusting n. The simulation results are shown in column 5 of Table 1. The isentropic efficiency of compressor and expander should be > 93 %, ranging from 93.17 % to 98.66 %. When the isentropic efficiency is the lowest η = 93.17 %, the simulation results see the COP_{min} column. When the isentropic efficiency is the highest η = 98.66 %, the simulation results see COP_{max} column. However, in actual conditions, pressure drop (ΔP) would be generated when working fluid goes through the heat exchanger. When setting ΔP = 0.05 MPa and η = 99 %, simulation results in column 8 of Table 1 are obtained. As a result, the operating conditions would be harsh if the JCHP has to meet the performance of the JCHP products developed by Adler and Mauthner (2017). The isentropic efficiency (99 %) of the compressor/expander and the outlet pressure P_4 of the compressor (e.g. P_4 = 22.2 MPa in case 2) need to reach a very high level. ECOP developed the JCHP with very high compression and expansion efficiencies of about 96 % by using a rotating heat pump system and centrifugal force (Adler and Mauthner, 2017). These efficiencies are significantly higher than a typical vapour-compression cycle, which uses conventional compression based on a high speed impeller to increase fluid velocity, which is converted to static pressure, with a compression efficiency of 65 - 70 %.
To moderate the operating conditions, in this study, the feasibility of JCHP was explored by testing four different working fluids – Ar, CO_2, N_2, and Ne. Case 1 of Table 1 was simulated with P_4 = 5.44 MPa, ΔP = 0.05 MPa, ΔT_{HP} = 3 °C, η = 96 %, F_{sink} = 1 t/h, which is also given in Table 2. Where: F_1 - the mass flow rate of working fluid (t/h), V_1 - the volume flow of working fluid under standard conditions (Nm^3/h).

Table 2: Simulation results of JCHP

Work fluids	Ar	CO_2	N_2	Ne
COP	4.00	5.26	4.24	3.78
F_1 (t/h)	7.49	3.41	3.81	4.04
V_1 (Nm^3/h)	4,202	1,738	3,046	4,491

As can be seen from Table 2, the COP of JCHP under the same conditions is in the order of CO_2 > N_2 > Ar > Ne. When the working fluid is CO_2, the mass flow rate and volume flow are minimal.

3.2 Optimisation of the JCHP

The potential for improving the COP of JCHP was explored by optimising the operating parameters to obtain the best COP. Take case 1 in Table 3 as an example of optimisation. In the Optimizer, the optimisation variables are set as T_3, T_4 and P_4. UA_h and UA_c are added as constraints, and the optimisation objective is to maximise the COP. In the "Adjust" unit, the heat transfer duty of heat exchanger Hot-side-HX is set to 700 kW by adjusting

F_1, and the efficiency of the compressor/expander is set to 96 %. The parameters of the Optimizer and the optimisation results are given in Table 3. The order of the optimal COP of the four different working fluids is the same as the simulation results (CO_2 > N_2 > Ar > Ne) and the optimal COP of CO_2 is 5.50.

Table 3: Optimised parameter settings and optimisation results

Parameters	Settings		Optimisation results			
	Lower bound	Upper bound	Ar	CO_2	N_2	Ne
T_3 (°C)	45	59	56.61	58.52	58.58	58.22
T_4 (°C)	101	115	110.2	107.9	112.3	111.5
P_4 (MPa)	1.00	7.50	7.02	7.50	7.48	7.50
UA_h (kW/°C)	50	150	100	100	100	100
UA_c (kW/°C)	50	150	93.3	144.8	138.6	149.3
F_1 (t/h)	--	--	93.00	44.31	46.48	52.76
COP (-)	--	--	4.22	5.50	4.35	3.92

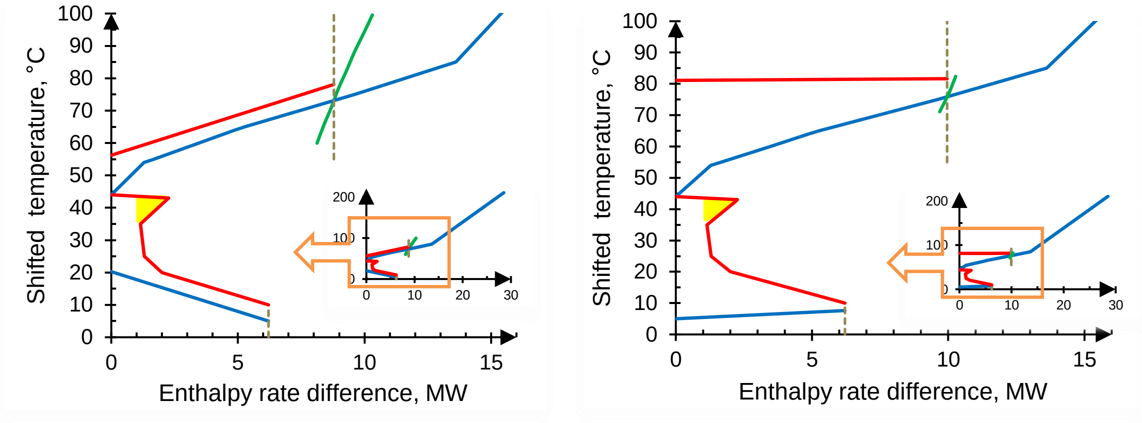
Where: UA_h, UA_c – the product of the Overall Heat Transfer Coefficient and the Total Area available for heat transfer (Hot-side-HX/Cold-side-HX) (kW/°C).

4. Process Integration

The JCHP and a process were integrated using the method proposed in section 2.2 and compared with the results of the two-phase vapour compression heat pumps to illustrate the application of JCHP in the actual industrial process. The COP curve was obtained by using JCHP data and results simulated in Petro-SIM. In this study, JCHP was used to integrate the spray drying process of a typical milk powder plant (Atkins et al., 2011). Spray drying is an energy-intensive operation, where the energy demand can be reduced through Process Integration. One can refer to (Atkins et al., 2011) for the stream data.

4.1 Evaluation and optimisation

A JCHP with CO_2 working fluid was selected to integrate with the spray drying process. The minimum temperature approach in the process ΔT_{min} = 20 °C (Atkins et al., 2011), in shifted scale this is ΔT_{pro} = 10 °C. The GCC was drawn according to the spray drying process data (Atkins et al., 2011), see Figure 4.



(a) (b)

Figure 4: (a) GCC of Process Integration using JCHP, (b) GCC of Process Integration using two-phase vapour compression heat pump

It can be concluded that: Pinch Point is 44 °C, the required cold utility duty is 6.2 MW, the required hot utility duty is 28.5 MW. The cold utility is all provided by the heat pump. The COP curve can be obtained by fixing the operating condition of the heat source (e.g. the inlet and outlet temperature), and changing the operating condition of the heat sink, see the green line in Figure 4. The intersection of COP curve and GCC indicates the minimum heat pump hot utility required by the process heat sink under the given source heat duty.
When setting P_4 = 5.44 MPa, ΔP = 0.05 MPa, η = 96 %, and ΔT_{HP} = 5 °C, the results are in Figure 4a. When the heat source energy of the process provided to JCHP is 6.2 MW, the hot utility that JCHP can provide to the process is 8.8 MW, and the COP of JCHP is 3.3. The JCHP under this condition is simulated in Petro-SIM. The

power consumption required by the compressor of the JCHP is 12.6 MW, and the compression ratio of the compressor is 2.1. The power generated by the expander of JCHP is 9.9 MW. As a result, the integration of the JCHP and the spray drying of typical milk powder plant can save 6.2 MW of cold utility and 8.8 MW of hot utility, with a power consumption of 2.7 MW and total energy saving of 12.3 MW without considering the equipment investment cost. Energy saving and emission reduction effect is obvious if powered by renewable electricity. The vapour compression heat pump with the working fluid of NH_3 was simulated to compare with the process integration of the two-phase vapour compression heat pump. When the isentropic efficiency of the compressor is set at η = 65 % (Wang et al., 2018), GCC curve see Figure 4b. The hot utility that the heat pump can provide to the process is 9.9 MW, the power consumption of compressor is 3.8 MW, the compression ratio of the compressor is 8.4, and the COP is 2.7. As a result, the COP of JCHP is higher than a two-phase heat pump.

5. Conclusions

This study extended the Pinch Methodology for integrating a new type of heat pump based on the Joule Cycle (JCHP) with a process. A milk spray drying process was undertaken as a case study. The results show that COP of Process Integration using JCHP (3.3) is higher than that of the two-phase heat pump (2.7) with NH_3 as the working fluid. If the power consumption of compressor is provided by renewable electricity, its effects on energy saving and emission reduction are significant. The method proposed in this study can provide useful guidance for the new type of JCHP and Process Integration. In this study, only energy targeting was considered without accounting for the cost. These elements will be developed in a future work, to deliver a more complete targeting and design method. The optimum process with the optimal total cost of heat pump and Process Integration is going to be explored, taking into account capital cost.

Acknowledgements

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