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Integration of LiBr/H_2O Absorption Heat Pump and Absorption Heat Transformer in Total Site Heat Integration

Kai Jun Hoong[a], Peng Yen Liew[a,*], Timothy Gordon Walmsley[b], Nor Ruwaida Jamian[a], Jeng Shiun Lim[c]

[a]Department of Chemical and Environmental Engineering, Malaysia – Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Jalan Sultan Yahya Petra, 54100 Kuala Lumpur, Malaysia.
[b]Sustainable Energy, Water and Resilient Systems Group, School of Engineering, The University of Waikato, Hamilton 3216, New Zealand
[c]School of Chemical and Energy Engineering, Faculty of Engineering, Universiti Teknologi Malaysia, 83100 UTM Johor Bahru, Johor, Malaysia.
pyliew@utm.my

Energy efficiency is one of the main solutions to reduce CO_2 emissions in the energy sector and improve primary energy intensity. Energy savings are at the centre of the numerous advantages of energy efficiency and connect to many other economic, social and environmental advantages. Total Site Heat Integration (TSHI) was introduced to maximise the heat recovery from various processes through a centralized utility system. Heat pump using absorption cycle has been identified as one of the waste heat recovery techniques. The challenges of heat pumps applications include limited temperature applications and long payback periods. However, these problems can be tackled by proper design and suitable types of heat pumps considerations. This paper integrates two different kinds of absorption cycle heat pump which are absorption heat pump (AHP) and absorption heat transformer (AHT) into the context of TSHI. This integration is able to reduce the industrial waste heat and generate quality steam. The heat generation of AHP and AHT are estimated based on the enthalpy of working fluid pair of water-lithium bromide. A case study is done to compare and verify the proposed methodology. Economic analysis is performed to compare the different integration approaches of AHP and AHT. Results showed that the integration of hybrid AHP and AHT contribute to the highest annual saving (21,351 USD/y) of utility cost compared to 12,356 USD/y for AHP system and 9,119 USD/y for AHT system.

1. Introduction

The increasing world energy consumption and energy-related CO_2 emissions have contributed to the serious global challenge of climate change. Energy efficiency is one of the main solutions for decreasing CO_2 emissions in the energy sector and decreasing primary energy intensity. Improving energy efficiency and increasing the use of renewable energy are two useful approaches to reduce greenhouse gas emissions in the perspective of the global energy transition. It is estimated that energy efficiency enhancements since 2000 prohibited 12 % more energy use in 2017 globally (IEA, 2018). Energy savings connect to many other economic, social and environmental advantages.

To conserve energy, one of the effective approaches is by maximising heat recovery via heat integration (Klemeš et al., 2018). By developing heat integration concept, Total Site Heat Integration (TSHI) has received increasing attention since its beginning in the 90s (Dhole and Linnhoff, 1993). TSHI integrates individual processes for inter-process heat recovery through a centralized utlitiy system (Liew et al., 2017). TSHI has been practised not only in various chemical industrial sites (Matsuda et al., 2009) but also in heterogeneous Total Sites, e.g., consisting of industrial, municipal and commercial energy consumers (Lee et al., 2020).

Heat pumps have been identified as one of the energy recovery techniques. Xu and Wang (2017) reviewed different types of absorption heat pumps and absorption heat transformers available and its respective applications for waste heat recovery. Some of the application problems that heat pumps face include limited

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temperature applications and long payback periods (IEA, 2014). However, these challenges can be solved by proper design and suitable types of heat pumps considerations.
Horuz and Kurt (2010) presented an industrial application of absorption heat transformers to increase the temperature of waste heat. Liew and Walmsley (2016) proposed a novel methodology for integrating two forms of open cycle heat pumps to recover waste heat in Total Sites. A hybrid heat pump concept is introduced for energy recovery in a spray dryer system by Walmsley et al. (2017). Li et al. (2019) proposed the integration of an absorption heat pump in solar thermal power plants for cogeneration. Schlosser et al. (2019) reviewed and evaluated the concept of heat pump integration for industrial uses based on Pinch Analysis. Gai et al. (2020) explored the possibility for integrating conventional heat pump and Joule Cycle in Process Integration methodologies for waste heat utilisation in process plants.
Latest study has developed methods for the applications of AHP-alone-system, AHT-alone-system and other various types of heat pumps. In this study, the use of two different kinds of absorption heat pump systems for direct incorporation with the utility system in TSHI is presented. This study explores the effective utilisation of Absorption Heat Pumps (AHP) and Absorption Heat Transformers (AHT) in TSHI methodology based on the enthalpy of working fluid pair of water-lithium bromide. The combined impact of both AHP and AHT systems are also studied in this work. The study compares the options based on the reduction of utility consumption and simple payback period based on the existing system without AHP and AHT.

2. Heat recovery via absorption cycle

The absorption heat pump has diverse configurations for different objectives. Commonly, the term Absorption Heat Pump (AHP) not only denotes to the common idea of absorption heat pump but also refers exactly to the absorption heat pump for heat amplification while the term Absorption Heat Transformer (AHT) refers to the absorption heat pump for temperature upgrading. AHP is also being labelled as type-I AHP while AHT is referred to as type-II AHP. AHP is used for heat amplification while AHT is used for temperature upgrading. The AHT operates in a reverse cycle to that of AHP. Four heat exchangers: an evaporator, condenser, generator, and absorber are found in both AHP and AHT systems as shown in Figure 1. The heat pump cycle consists of a refrigerant cycle and an absorbent cycle. Lithium bromide solution and water is the typical working medium pair being used. This study will focus on the application of water-LiBr solution in both AHP and AHT systems with water as the refrigerant.
The flow ratio, R, is a vital design parameter in the absorption cycle. It is defined as the ratio of the mass flow rate of the strong solution, $\dot{m}_s$, to the mass flow rate of refrigerant, $\dot{m}_r$ in Eq(1).

$$R = \dot{m}_s/\dot{m}_r \qquad (1)$$

The water vapour produced in the generator and evaporator of both AHP and AHT systems is in superheated conditions. The enthalpy of superheated water vapour, $h_{w,sup}$ at different temperatures can be estimated by Eq(2), where the reference temperature is at 0 °C.

$$h_{w,sup} = 2501 + 1.88(T - T_{ref}) \qquad (2)$$

Stream 2 that leaves the condenser is in a liquid state. The enthalpy of pure liquid water, $h_{w,liquid}$, at any temperature, T, can be estimated from Eq(3), where the reference temperature, Tref, is at 0 °C.

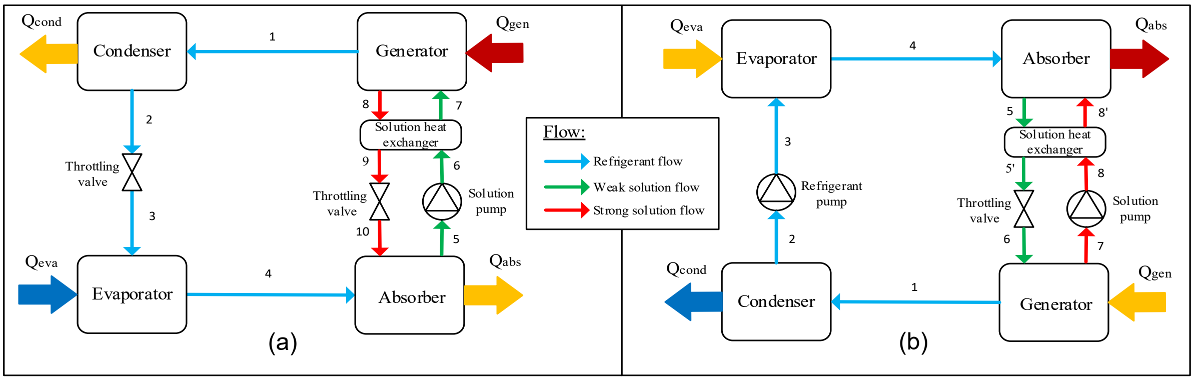

Figure 1: System configurations of a) absorption heat pump b) absorption heat transformer (Xu and Wang, 2017)

$$h_{w,liquid} = 4.19(T - T_{ref}) \quad (3)$$

The strong and weak water-lithium bromide solution deviates from ideal solution behaviour. The specific enthalpy of the solution can be obtained from the thermophysical properties table of water-lithium bromide solution pair by ASHRAE (2009).

2.1 Absorption heat pump (Type-I AHP)

The heat flows, Q, in the major components in the AHP can be calculated using Eq(4-7) below:

$$Q_{gen} = \dot{m}_r(h_1 - h_7) + \dot{m}_r R(h_8 - h_7) \quad (4)$$

$$Q_{abs} = \dot{m}_r[(h_4 - h_5) + R(h_{10} - h_5)] \quad (5)$$

$$Q_{eva} = \dot{m}_r(h_4 - h_3) \quad (6)$$

$$Q_{cond} = \dot{m}_r(h_1 - h_2) \quad (7)$$

The first term in Eq(4) signifies the heat required to produce water vapour at state 1 (refer to Figure 2) from weak solution at state 7 and the second term in Eq(4) denotes the sensible heat required to increase the temperature of the solution from state 7 to state 8. The first term in Eq(5) signifies the enthalpy change of water as it condenses from vapour at state 4 to liquid at state 5. The second term in Eq(5) denotes the sensible heat transferred as the solution at state 10 is cooled to state 5.

2.2 Absorption Heat Transformer (Type-II AHP)

The heat of the input of evaporator and heat output of condenser can be calculated using Eq(6) and Eq(7). The heat flows in the other two major components in the AHT can be calculated via Eqs(8) to (9) as shown:

$$Q_{gen} = \dot{m}_r[(h_1 - h_6) + R(h_7 - h_6)] \quad (8)$$

$$Q_{abs} = \dot{m}_r[(h_4 - h_5) + R(h_{8'} - h_5)] \quad (9)$$

The first term in Eq(8) signifies energy required to produce water vapour from solution at state 6 to state 1 and the second term in Eq(8) denotes the sensible heat necessary to heat the solution from state 6 to state 7. The first term in Eq(9) signifies the enthalpy change of water changes from vapour at state 4 to liquid at state 5. The second term in Eq(9) denotes the sensible heat transferred as the solution at state 8' is cooled to state 5.

3. Methodology

This study suggests a new TSHI targeting methodology integrating AHP and AHT, which is used to determine the feasibility of the absorption cycle techniques in TS.

3.1 Data extraction

Processes stream data has to be analysed to determine the heating and cooling requirements. The data extraction involves temperature, enthalpy and heat capacity of the stream flowing in each process.

3.2 Individual process Pinch Analysis

From the process stream data obtained previously, the minimum energy required for hot and cold utilities is targeted based on the process using Pinch Analysis. The numerical approach of the Problem Table Algorithm (PTA) will be used to identify the Pinch temperature in each process. The amount of heat source and heat sink will be identified. With the use of Multiple Utility Problem Table Algorithm (MU-PTA), the exact amount of utilities required within the given temperature ranges of utilities can be targeted (Liew et al., 2012).

3.3 Total Site Heat Integration (TSHI)

The utility production and consumption possibilities are determined via the Total Site Problem Table Algorithm (TS-PTA) (Liew et al., 2012). The quantity of heat targeted at above the TS Pinch denotes the heat demand while the quantity of heat available below TS Pinch denotes the waste heat obtainable in the TS level.

3.4 Heat generation estimation

By setting the temperatures of the major equipment in the absorption cycle, the enthalpies at all of the state points are obtained using Eq(2-3) and through ASHRAE (2009). The heat generation estimation can be calculated using Eqs(1) to (9). The following assumptions have been made to estimate the heat generation in both AHP and AHT systems:

a. The refrigerant, weak and strong solution are in steady-state and thermodynamic equilibrium conditions.
b. The solution exiting the generator and absorber, the refrigerant exiting the condenser and the evaporator are all saturated.
c. The mechanical work required by the pump is considered negligible, the temperature and enthalpy of the fluid entering and exiting the pump remained constant.
d. Throttling valve does not change the enthalpy of the working fluid.
e. The gross temperature lift of AHT is taken as 50 °C (Horuz and Kurt, 2009).
f. The temperatures of evaporator and generator in AHT are the same, while the temperature of condenser and absorber in AHP are also the same.
g. The flow ratio of the absorption cycle is 12.0 (Horuz and Kurt, 2009).
h. The concentrations of strong and weak solutions are 0.65 and 0.60 (Horuz and Kurt, 2009).

3.5 Economic analysis

The economic analysis is done by comparing the total utility cost saving in the possible system configurations. The natural gas consumption of the boiler and heater as well as electricity consumption of the cooling tower are used to estimate the operating cost reduction (Liew and Walmsley, 2016). The reduction of utility loads is estimated to compare the effectiveness of each configuration. The equipment cost is estimated and the payback period is analysed.

4. Case study

A modified case study is shown to demonstrate the methodology suggested. The case study involves four different processes which consist of industrial plants, hotel and residential area (Liew et al., 2014). 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 both assumed to be 12 °C. The utilities obtainable in Total Site are Intermediate Pressure Steam (IPS) at 180 °C, Low Pressure Steam (LPS) at 130 °C, a hot water system (HW) at 50 °C and the cooling utility of cooling water (CW) at 30 °C.

After performing Total Site energy targeting, the TS Pinch is located between IPS and LPS. This means that the excess LPS below the Pinch can be used in AHP or AHT to fulfil the IPS demand above Pinch. From TS-PTA, the HW is in deficit although it is located below the TS Pinch. This potential heat demand could be satisfied by the integration of AHP. In all the 3 cases, the net heat requirements before heat cascade will be used for the integration of AHP and AHT. The case study is done under 3 cases: Absorption heat transformer (AHT) (Case 1), Absorption heat pump (AHP) (Case 2), and Hybrid AHP and AHT (Case 3).

In Case 1, all of the excess LPS is fed into the AHT system. By using Eq(6-9), the heat generated from the AHT system can be calculated. The integration of AHT has successfully achieved temperature upgrading from LPS to IPS. From Eq(6-9), the required refrigerant mass flow rate, $\dot{m}_r$, is obtained as 0.0248 kg/s. The net heat requirement after AHT integration is summarized in Table 1. The integration of AHT has successfully achieved the IPS heat demand, however, the HW demand is not satisfied. Unlike AHP, the function of AHT serves to provide heat demand above TS Pinch by increasing the temperature of the excess available heat.

In Case 2, the HW output requirement is set and the heat input requirements to the AHP system are calculated using Eq(4) and Eq(6). The integration of AHP system has successfully achieved heat amplification from 24.80 kW of LPS to 44.48 kW of HW generation. From Eq(4-7), the required refrigerant mass flow rate, $\dot{m}_r$, is obtained as 0.0084 kg/s. The net heat requirement after AHP integration is summarized in Table 1. The integration of AHP has successfully achieved the HW demand, however, the IPS demand is not satisfied.

Case 3 is the extension of Case 2 by considering both AHP and AHT system. Once the IPS heat output is set, the heat input requirements can be calculated using Eq(6) and Eq(8). The CW generation is calculated using Eq(7). From Eq(4-9), the required refrigerant mass flow rate, $\dot{m}_r$, is obtained as 0.0084 kg/s in AHP system and 0.0117 kg/s in AHT system. The net heat requirement after hybrid AHP and AHT integration is summarized in Table 1. The integration of two absorption systems has successfully achieved both IPS and HW demand. The integration of AHT satisfied the heat demand of IPS above TS Pinch; integration of AHP satisfied the heat demand of HW below TS Pinch; whereas the integration of both systems satisfied both IPS and HW demands above and below TS Pinch.

The utility cost consumption estimation is 302.21 USD/kW·y for natural gas of steam boilers and 28.45 USD/kW·y for power of cooling towers (Liew and Walmsley, 2016). Assuming the gas fired heater has efficiency of 88.0 %, the assumed utility price is 249.32 USD/kW·y for natural gas consumption of heaters (Raluy and Dias, 2020). The cost changes for boiler, heater and cooling tower, as well as total utility cost-saving from different absorption systems, are analysed and summarised in Table 2. It can be said that the integration of a hybrid AHP and AHT system provides the biggest saving of utility cost compared to AHP and AHT alone system. The heat amplification AHP system is not very effective because it does not upgrade the heat across the Pinch. The use of temperature upgrading AHT system is more effective due to the heat transfer across the Pinch. However, the integration of both AHP and AHT systems is found to be the most effective solution when there is both IPS and HW demand by using excess LPS in Total Site. The equipment cost of AHP and AHT is estimated as 275 USD/kW of heat output and 270 USD/kW of heat output (Zhang et al., 2016). Considering the equipment cost and total utility cost-savings, the payback periods for AHT is 3.6 y; 1.0 y for AHP; and 1.3 y for hybrid AHP and AHT systems. Based on the overall results of economic analysis, a relatively short payback period (1.3 y) for hybrid AHP and AHT systems which offers the highest annual saving of utility cost signify that hybrid system is the best integration choice.

Table 1: Summary of the net heat requirements after integration of AHP and AHT

Utility	Utility temperature (°C)	Net heat requirement - before (kW)	System utility input (kW)	System utility generation (kW)	Net heat requirement - after (kW)
Integration of AHT (Case 1)					
IPS	180	26.9	-	56.8	-29.9
LPS	130	-130.0	130.0	-	0.0
HW	50	44.5	-	-	44.5
CW	15	-76.4	-	65.0	-141.4
Integration of AHP (Case 2)					
IPS	180	26.9	-	-	26.9
LPS	130	-130.0	24.8	-	-105.2
HW	50	44.5	-	44.5	0.0
CW	15	-76.4	19.7	-	-56.7
Integration of hybrid AHP and AHT (Case 3)					
IPS	180	26.9	-	26.9	0.00
LPS	130	-105.2	61.5	-	-43.7
HW	50	0.0	-	-	0.0
CW	15	-56.7	-	30.8	-87.5

Table 2: Energy and cost saving from AHP and AHT integration

Utility	Unit	Existing	AHT (Case 1)	AHP (Case 2)	AHP+AHT (Case 3)
IPS	kW	26.9	-29.9	26.9	0.0
LPS	kW	-130.0	0.0	-105.2	-43.7
HW	kW	44.5	44.5	0.0	0.0
CW	kW	-76.4	-141.4	-56.7	-87.5
Boiler Load	kW	26.9	0.0	26.9	0.0
Boiler Load Changes	kW	-	-26.9	0.0	-26.9
Boiler Cost Changes	USD/y	-	-8,121	0.0	-8,121
Heater Load	kW	44.5	44.5	0.0	0.0
Heater Load Changes	kW	-	0.0	-44.5	-44.5
Heater Cost Changes	USD/y	-	0.0	-11,090	-11,090
Cooling Tower Load	kW	206.4	171.3	161.9	131.2
Cooling Tower Load Changes	kW	-	-35.1	-44.5	-75.2
Cooling Tower Cost Changes	USD/y	-	-998	-1,265	-2,140
Total Utility Cost Saving	USD/y	-	9,119	12,356	21,351
Capital Cost	USD	-	32,885	12,232	27,791
Payback Period	y	-	3.6	1.0	1.3

5. Conclusions

A new methodology for integrating water-lithium bromide absorption heat pump and absorption heat transformer is presented in this work. The case study demonstrates that the use of absorption cycle can help reduce utility demand and achieve cost saving in Total Site. The integration of hybrid AHP and AHT (Case 3) provides the highest annual saving of utility cost of USD 21,351 compared to USD 9,119 for AHT-alone-system (Case 2) and USD 12,356 for AHP-alone-system (Case 1). The combination of both AHP and AHT systems has a relatively short payback period of only 1.3 y. This study provides a different approach by taking two different absorption cycles into the consideration of increasing energy efficiency. A detailed capital cost and operating cost for the absorption cycles should be considered in future study. The consideration of different time slices in Total Site will be the opportunitiy for enhancing heat recovery in a Locally Integrated Energy System.

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