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A techno-economic case study using heat driven absorption refrigeration technology in UK industry

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Abstract

This paper reports a case study on a UK industry using heat driven absorption refrigeration technology. The system performance of the absorption refrigerator to recover the industry wasted heat and economic analysis using the heat driven absorption system have been conducted. Results indicates when the evaporating temperature is 5°C , the optimal COP of the absorption chiller is about 0.825 under 60°C generator temperature and the maximum COP of the system under 10°C evaporating temperature can be as high as 0.86 with 55°C generator temperature. Under the optimal operating condition to recover 200 kWh from exhaust gases, the average required heat load of absorber and condenser are 190 kWh and 175 kWh, respectively. When the generator temperature is set at 60°C , the cooling production from the absorption chiller is 172 W. The economic analysis suggests the average payback period to use the absorption system for UK industry application is about 2.5 years and the highest annual electricity cost saving can be as high as £105 per kw thermal heat input.

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1. Introduction

From 2015, the Department for Environment, Food & Rural Affairs in UK has introduced bans on the sale of fluorinated greenhouse gas filled equipment, and the report pointed out from 2020 the refrigerants with global warming potentials of more than 150 such as R134a, R245fa and R365mfc will be banned to be used in hermetically sealed system, which affects the utilization of the existing electricity driven compression refrigerators and raise the maintenance cost of the system [1]. Heat driven absorption refrigerator can therefore be promoted to be used as alternative refrigeration system in the place, where huge amount of heat is available, and can save the operational cost of using electricity driven refrigerator. Extensive research efforts have been focused on absorption cooling technology over the past few decades to compete this technology with vapour compression system through the development of energy efficient, cost effective, environmentally friendly and compact size systems [2-5]. Florides et al. [3] reports the experimental study of a 1kW absorption chiller using LiBr-H₂O and the COP of the system is about 0.7. When the absorption refrigeration technology is used in data centers, a novel system combining an on-chip two-phase cooling system and an absorption refrigeration system can potentially meet the cooling demands with 4-5 months payback period as reported by Ebrahimi et al. [4]. The optimization of a LiBr-H₂O absorption chiller using a Non-Liner Programming model has been introduced by Carlos et al. [5], which can be simply constructed to predict and optimise the annual operating cost of the system. Salmi et al. [6] conduct the study of using absorption chiller for ship wasted heat recovery. Results suggest the potential saving of 70% of electricity in accommodation, which enables between 47 and 95 tons of annual fuel saving [6]. The paper reports a case study using heat driven absorption refrigeration technologies in UK industry to explore the potential energy saving of using heat driven refrigerator. All the data presented in this paper are real and effective data, which are valuable for the both industry and academia to explore the market potential of using heat driven absorption refrigeration technologies in UK industry application.

2. 2. Description of a heat driven absorption chiller to recover STACK heat from a UK industry

The case study conducted in this paper is for the heat recovery from the exhaust STACK using heat driven absorption refrigeration technology. Due to the limitation of the exhaust temperature, which is only about 200°C in this UK industry case study, single effect LiBr-H₂O absorption chiller has been selected to recover the wasted heat. The schematic diagram of the system for the STACK heat recovery has been illustrated in Fig. 1. A hot water loop has been used to recover the heat from the exhaust STACK, store the heat in a hot water tank and provide the heat to the generator of the absorption chiller as shown in Fig. 1. The working principle of the single effect absorption chiller can be summarised as follows

- From absorber 1 $\xrightarrow{\text{pump}}$ 2 $\xrightarrow{\text{SHE}}$ 3 to Generator The weak solution has been pumps from absorber through the heat exchanger to preheat the solution before entering the generator.
- From Generator 4 $\xrightarrow{\text{SHE}}$ 5 $\xrightarrow{\text{EV}}$ 6 to Absorber The strong solution containing less refrigerant (water) flows through the heat exchanger to firstly transfer the heat to weak solution and then expands in the expansion valve.
- From Generator 7 $\xrightarrow{\text{Condenser}}$ 8 $\xrightarrow{\text{EV}}$ 9 $\xrightarrow{\text{Evaporator}}$ 10 to Absorber In this process, the refrigerant (water) flows from the generator to the condenser, where dumps the heat towards environment and cools down by the cooling tower. The condensed and high pressure refrigerant (water) is then expanded from the expansion valve. The low pressure refrigerant (State 9) enters the evaporator, where adopts heat through the refrigerant evaporating process and therefore provides the cooling effect.

The absorption heat Q_{abs} from the absorber is rejects to the environment by the cooling water from the cooling tower.

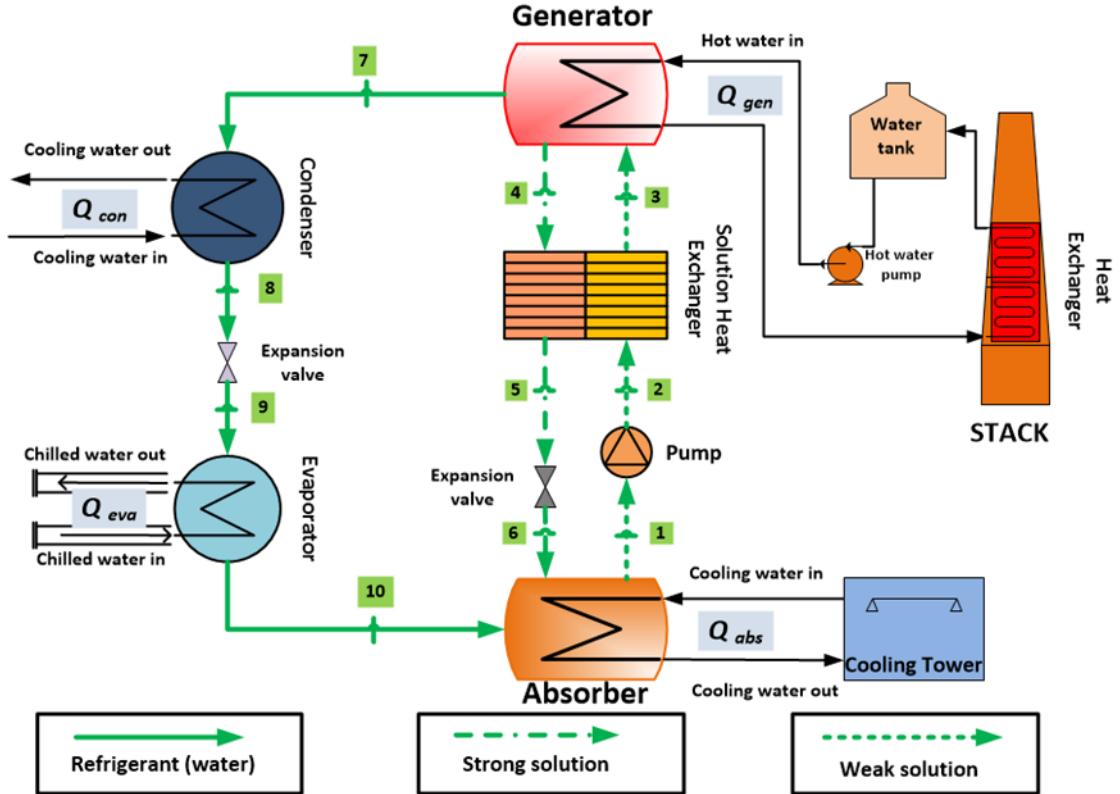


Fig. 1. Schematic diagram of the single effect absorption chiller recovering exhaust gases heat from the STACK from a UK Industry

3. Methodologies

The recoverable heat from the STACK can be calculated by the following equation, where $\dot{m}_{\text{exhaust_air}}$ is the mass flowrate and $C_p_{\text{exhaust_air}}$ is the heat capacity of the exhaust air. The parameters used in the calculation are listed in Table 1.

$$\dot{Q}_{\text{heat}} = \dot{m}_{\text{exhaust_air}} \times C_p_{\text{exhaust_air}} \times (T_{\text{STACK_bottom}} - T_{\text{STACK_top}}) \quad (1)$$

A thermodynamic simulation model has been built to evaluate the performance of the single effect LiBr-H₂O in this study. The simulation model has been coded in Engineering Equation Solver [7] using the following listed equations. The pressure condition of the condenser and evaporator are defined by the follow equation [8]

$$P = \exp \left[9.48654 + \frac{3892.7}{42.6776 - (T+273)} \right], \quad \text{when } P < 12.33 \text{ MPa} \quad (2)$$

The concentration of LiBr in the strong and weak solutions can be calculated by the following equations [9]

$$X_{\text{weak}} = X_4 = X_5 = X_6 = (49.04 + 1.125 \times T_{\text{gen}} - T_{\text{con}}) / (134.65 + 0.47 \times T_{\text{gen}}) \quad (3)$$

$$X_{\text{strong}} = X_1 = X_2 = X_3 = (49.04 + 1.125 \times T_{\text{abs}} - T_{\text{eva}}) / (134.65 + 0.47 \times T_{\text{abs}}) \quad (4)$$

The specific enthalpy of the solutions is calculated by the following equation[10], where i represents different state of the solutions.

$$h_i(T_i, X_i) = (A_0 + A_1 X_i) T_i + 0.5(B_0 + B_1 X_i) T^2 + (D_0 + D_1 X_i + D_2 X_i^2 + D_3 X_i^3)$$

$$(40 \leq X \leq 65\text{wt.\%}, \quad 20 \leq T \leq 210^\circ\text{C}) \quad (5)$$

$$A_0 = 3.462023; A_1 = -2.679895 \times 10^{-2}; B_0 = 1.3499 \times 10^{-3}; B_1 = -6.55 \times 10^{-6};$$

$$D_0 = 162.81; D_1 = -6.0418; D_2 = 4.5348 \times 10^{-3}; D_3 = 1.2053 \times 10^{-3}$$

The heat capacity of the strong and weak solutions are defined as [10]

$$C_p = (A_0 + A_1 X) + (B_0 + B_1 X) \times T \quad (6)$$

Mass flow rates of the refrigerant, strong and weak solutions are calculated by

$$\dot{m}_r = \dot{Q}_{eva} / (h_{10} - h_9) \quad (7)$$

$$\dot{m}_{strong} = \dot{m}_r X_{weak} / (X_{strong} - X_{weak})$$

$$\dot{m}_{weak} = \dot{m}_r X_{strong} / (X_{strong} - X_{weak})$$

The heat transfer relationship in the heat exchanger can be defined by the following two equations[5]. The temperature condition of strong solution after the solution heat exchanger (State 5) is calculated by equation (8) and the equation (8) is used to calculate the temperature condition of State 3.

$$T_5 = T_{gen} - \eta_{SHE} \times (T_{gen} - T_{abs}) \quad (8)$$

$$(T_3 - T_{abs}) \times X_{strong} \times C_{p_weak} = \eta_{SHE} \times X_{weak} \times C_{p_strong} \times (T_{gen} - T_{abs}) \quad (9)$$

The heat balance of the absorber, generator and condenser are defined as the following equations,

$$\dot{Q}_{abs} = \dot{m}_r \times h_{10} + \dot{m}_{strong} \times h_6 - \dot{m}_{weak} \times h_1 \quad (10)$$

$$\dot{Q}_{gen} = \dot{m}_r \times h_7 + \dot{m}_{strong} \times h_4 - \dot{m}_{weak} \times h_3 \quad (11)$$

$$\dot{Q}_{con} = \dot{m}_r \times (h_7 - h_8) \quad (12)$$

The calculation of the coefficient of performance (COP) is defined as

$$COP_{ab} = \dot{Q}_{eva} / \dot{Q}_{gen} \quad (13)$$

The annual electricity saving can therefore be calculated by Eq. (14) using the parameters listed in Table 1 and results from previously defined equations.

$$C_{electricity_per_year} = t_{hours_per_year} \times C_{electricity_per_kWh} \times \dot{Q}_{eva} / COP_{con} \quad (14)$$

In order to conduct the thermos-economic analysis, various absorption chiller manufactures in UK including Thermax, Yazaki and Carrier have been contacted to obtain the cost and specifications. The average unit cost of single effect LiBr-H₂O for 200kWh heat recovery is about £73k, which includes the cost of the chiller, an adiabatic cooler (serving as the function of cooling tower) and start-up cost. The heat exchanger required to install on the SACK will cost around £30k, which contains the cost of the exchanger and accessories. The cost of the same cooling size vapour compression chiller manufactured by Trane will cost around £50k based on the quotation provided by the UK distributor of Trane. The pay-back period of using the heat driven absorption chiller can therefore be calculated by Eq. (14), where $Cost_{abs}$ is the cost of the absorption chiller, $Cost_{con}$ is the cost of a vapour compression chiller and $Cost_{HE}$ is the cost of the heat exchanger.

$$Pay\ back\ period = (Cost_{abs} + Cost_{HE} - Cost_{con}) / C_{electricity_per_year} \quad (15)$$

Table 1. Parameters of exhaust air from the STACK[11] and the operational conditions of the industry case study

Name	Symbol	Value
Exhaust gas temperature	T_{STACK_bottom}	200°C
Exhaust gas volume flow rate	$\dot{V}_{exhaust_air}$	Averagely 9,800 m ³ /h in operational condition
Density of exhaust air at 200°C	$\rho_{exhaust_air}$	0.748 kg/m ³
Heat capacity of exhaust air	$C_p_{exhaust_air}$	1.097 kJ/(kg·K)
Condenser temperature	T_{con}	25°C
Electricity price per unit	$C_{electricity_per_kWh}$	0.083 £/Kwh
Total operational hours per year	$t_{hours_per_year}$	(256 days, 21 hours per day)=5376 hours per year
Coefficient of performance of conventional vapour compression refrigerator	COP_{con}	3.67 [12]

4. Results and discussion

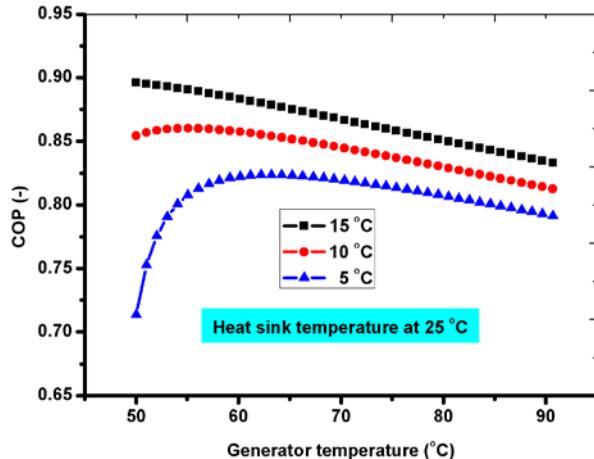


Fig. 2. COP of the single effect absorption chiller

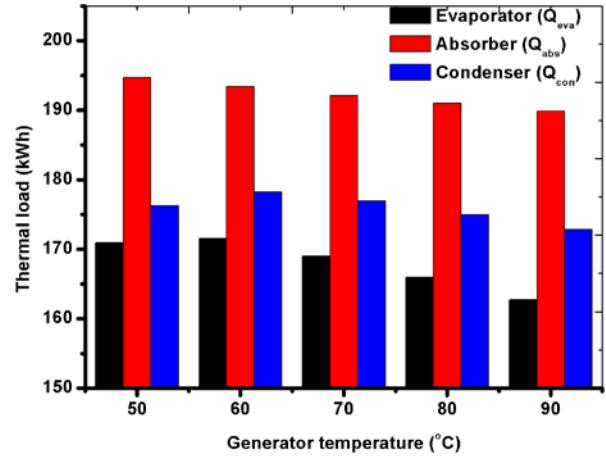


Fig. 3. Thermal loads of evaporator, absorber and condenser under different generator temperature

In order to evaluate the refrigeration performance, the COP of the single effect absorption chiller has been calculated the results of three different evaporating temperatures under the heat sink temperature at 25°C have been plotted in Fig. 2. When the evaporating temperature is 5°C, an optimal generator temperature exists, which is about 60°C and the optimal COP is about 0.825. The increase of evaporating temperature will slightly improve the cooling performance. When the generator temperature is between 60 to 90°C, every 5 degree increase of evaporating temperature can improve the COP by around 0.02 as shown in Fig 2. Under the evaporating temperature at 10°C, the peak COP of the absorption system is about 0.86 with 55°C generator temperature.

The thermal loads of the system components are analysed under the generator temperature from 50 to 90°C and the evaporating temperature is set at 10°C. The results are drawn in Fig. 3. In this case study, the dumped heat load of the absorber requires around 190 kWh and the condenser consumes about 175 kWh. The results suggested the single effect absorption chiller can be operated under the optimal condition, when the generator temperature is maintained around 60°C and the cooling production can be as high as 172 kW.

The economic analysis has been conducted on this case study to estimate the potential electricity cost saving, when the absorption chiller has been installed in the UK industry. The pay-back period and annual electricity cost saving under different designed generator temperature have been calculated. The results are plotted in Fig. 4. The highest annual electricity cost saving is about £21k, when the generator temperature is at 53°C. With the increase of designed generator temperature from 53°C, the annual electricity cost saving drops from £21k to £19.8k. The results suggested the average payback period by adopting this technology in the UK case study is about 2.5 years. The changes of designed generator temperature will slightly effect the payback period of this technology. When the generator temperature is set at 60°C, the annual electricity cost saving can be as high as £20.85k with 2.54 payback period as illustrated in Fig. 4.

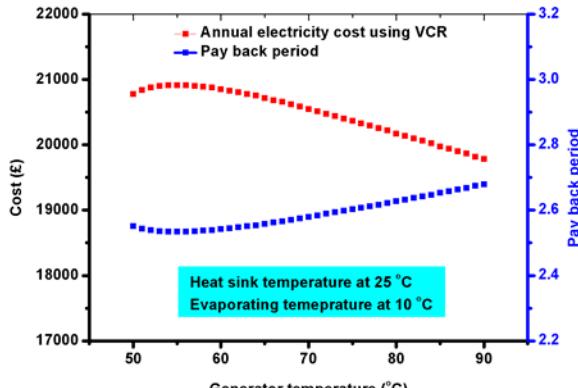


Fig. 4. Economic Analysis

5. Conclusions

This paper reports the techno-economic study of using absorption refrigeration technology in a UK industry. A thermodynamic simulation model has been developed and built to evaluate the performance of a single effect LiBr-H₂O absorption chiller under various operational conditions. The conclusions drawn from this study can be summarised as follows:

1. When the heat sink temperature is set at 25°C and the evaporating temperature of the absorption chiller is 5°C, the optimal COP of the system is about 0.825 with 60°C generator temperature. Every 5 degree increase of evaporating temperature (from 5 to 15°C) can potentially improve the COP by 0.02, when the generator temperature is from 60 to 90°C. The maximum COP of the absorption chiller under 10°C evaporating temperature is 0.86, when the generator temperature is 55°C.
2. The results of the thermal loads analysis of the system components suggested that under the evaporating temperature at 10°C, the average required heat load rejecting to the environment from the absorber and condenser are 190 kWh and 175 kWh, respectively. Under the optimal operating condition, the cooling production from the absorption chiller to recover 200 kWh from the STACK can be as high as 172 kW, when the generator temperature is set at 60°C.
3. The economic analysis indicated that the maximum annual electricity saving by using the heat driven absorption chiller can be as high as £21k under the generator temperature set at 53°C. The annual electricity cost saving drops slightly from £21 to £19.8 with the increase of designed generator temperature from 53 to 90°C. The average payback period by using this technology in UK industry is about 2.5 years

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