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A novel cascade absorption heat transformer process using low grade waste heat and its application to coal to synthetic natural gas

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HIGHLIGHTS

- A concept of a novel cascade absorption heat transformer (NCAHT) is proposed.
- The NCAHT can recover the low grade waste heat.
- The NCAHT overcomes the GTL limits of AHTs.
- The economic analysis of the NCAHT is conducted.

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ABSTRACT

Energy challenge is becoming more and more serious. Improving energy utilization efficiency seems to be a feasible way to tackle energy problems. A large amount of waste heat is discharged in chemical process industry. It is reported that in a coal chemical process waste heat accounts for 17–67% fuel consumption, of which 60% can be recyclable in theory. Waste heat recovery is a reliable and reasonable way for efficiency improvement. However, the low grade waste heat is difficult to be utilized. Thermodynamic cycles such as organic Rankine cycles (ORC), absorption chillers, absorption heat pumps, absorption heat transformers, and mechanical heat pumps are able to utilize wasted thermal energy for the generation of electrical power, chilling and heat at a higher temperature. In this paper, absorption heat transformer (AHT) is studied and novel cascade absorption transformer (NCAHT) is proposed to recover low grade waste heat. The NCAHT is testified in a coal to synthetic natural gas plant. Results show that the total capital investment of a 12 MW NCAHT is 924,000 USD. Financial Internal Rate of Return (*FIRR*) is used as an economic evaluation index. The *FIRR* is 62.16% and the payback time is 0.77 years. When the steam price reduced to 9 USD or the cooling water price higher than 0.96, the *FIRR* will be less than 30%.

1. Introduction

In China, coal is a dominant energy resource, with huge reserve and exploitation. Currently, 70% of total energy consumption relies on coal. According to a statistical report, there are more than one hundred large coal based plants in total. Among these, 30% are power generation plants and 70% are chemical productions plants. In addition, coal based chemical industries have 5% annual average growth rate. Coal to synthetic natural gas (SNG) is one of the most quickly developing branch [1].

Energy challenge is becoming more and more serious [2]. Improving utilization efficiency, developing clean renewable energy, and reorganizing the consumption structure are the major approaches to solving the energy problems. Improving energy utilization efficiency seems the most feasible way to tackle energy problems. A large amount of high grade energy (e.g. steam supplies of varies pressure levels) is consumed in the chemical process industry; meanwhile, a large amount of waste heat is released into the environment, which is a huge waste. Hence, the significance of waste heat recovery is prominent, which helps to improve energy efficiency. It is reported that in a coal chemical process waste heat accounts for 17–67% fuel consumption, of which 60% can be recyclable in theory [3].

In general, waste heat is categorized into three types, based on temperature levels: high temperature waste heat above 600 °C, medium temperature waste heat between 300 °C and

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Nomenclature

SNG	synthetic natural gas (–)	f	circulation ratio (–)
ORC	organic Rankine cycles (–)	$\triangle x$	concentration range (wt%)
AHT	absorption heat transformer (–)	Q_1	high temperature low-grade waste heat (MW)
NCAHT	novel cascade absorption heat transformer (–)	Q_2	low temperature low-grade waste heat (MW)
FIRR	financial internal rate of return (–)	$\triangle T$	temperature difference (°C)
ROI	return of investment (–)	T	temperature (°C)
IEA	international energy agency (–)	C_E	equipment capital cost ($)
COP	coefficient of performance (–)	Q_E	current scale (–)
ECOP	exergetic coefficient of performance (–)	Q_B	benchmark scale (–)
WGS	water gas shift (–)	M	cost exponent (–)
TCI	total capital investment ($)	C_E^r	capital actual cost ($)
FNPV	financial net present value (–)	f_M	material correction factor (–)
CEPCI	chemical economic plant cost index (–)	f_P	pressure correction factor (–)
m	mass flow rate (kg/s)	f_T	temperature correction factor (–)
x	concentration (wt%)	f_D	country correction factor (–)
Q_G	generator duty (MW)	*TCI*	total capital investment ($)
Q_A	absorber duty (MW)	*RFi*	ratio factor of other fixed investment (–)
Q_C	condenser duty (MW)	j	component index (–)
Q_V	evaporator duty (MW)	*CI*	cash in flows ($)
h	enthalpy (kJ/kg)	*CO*	cash out flows ($)
W	power rate (MW)	i	discount rate (–)

600 °C, and low temperature waste heat below 300 °C. In particular, the 90–150 °C waste heat is known as the low grade waste heat [4]. There is a large amount of the low grade temperature waste heat in the chemical process industry. The low grade waste heat is generally difficult to be utilized due to its diversified forms, environment and process restriction, and temperature limitations.

There are several categories of the waste utilization technologies: heat exchange, thermal power conversation, and heat recovery [5]. Heat driven absorption heat pump systems are heat recovery technologies, which consist of vapor compressed heat pump, absorption heat transformer (AHT), absorption heat pump (AHP), thermoelectric heat pump, chemistry heat pump, adsorption heat pump, and ejector heat pump according to their the work principle. AHT are devices for increasing the temperature of moderately heat sources to more useful level. AHTs are some of the most promising devices for upgrading industrial waste heat to higher temperature level. The typical work pairs of AHT are NH_3/H_2O and $LiBr/H_2O$. The gross temperature lift (GTL) is 30–50 °C in general [6]. The AHT can effectively recover about 50% of the waste heat and reuse it in industrial process [7]. The technology of AHT is now well developed for their future applications [8]. It will be important for energy utilization according to the International Energy Agency (IEA) [9].

Many works have been reported in the field of waste heat recovery. Olueye et al. developed a methodology to identify the potential for waste heat recovery in process sites [10], presented a novel systematic framework for optimal integration of these technologies in process [11], and proposed a novel systems-oriented criterion for conceptual screening and selection of heat pumps in process sites [12]. Sarah et al. studied an analysis of heat transformation technologies for industrial waste recovery and concluded that further research for heat transformation technologies to recover waste heat should therefore focus on system integration, design and size as well as market implementation [13]. Khosrow et al. conducted a thermo-economic analysis of absorption refrigeration for waste heat recovery [14]. Yang et al. proposed cascade refrigeration technology using low grade waste heat to producing −40 °C cold energy [15]. Al-Rabghi et al. reviewed industrial waste heat recovery system for power production and process heating purposes [16]. Mumah et al. applied NH_3/H_2O AHT to recover waste heat in a refinery plant, but the feasibility of the system was limited according to analysis based on first law of thermodynamic [17]. Bonilla et al. discussed the potential of different waste heat recovery technologies for using waste heat from the industry [4]. Zhang et al. reviewed waste heat recovery technologies for high temperature waste heat recovery [18]. Baldi et al. analyzed the AHT to recover waste heat and its application [19]. Rivera et al. applied the AHT to recover waste heat from a distillation column [20]. Van de et al. compared heat pumps and power cycles to recover low grade waste heat [21]. Kang et al. proposed a new utilization approach of the waste heat integrating heat pump [22]. Gbemi et al. developed methods for the conceptual screening and incorporation of low temperature heat upgrading technologies in process sites [12]. There is no published report about low grade waste heat utilization using novel AHTs for producing high quality energy.

The NCAHT is proposed to recover low grade waste heat using novel AHTs. The NCAHT is designed to produce 0.5 MPa steam. The NCAHT overcomes the limits of GTL, which differs from general AHTs. According to the principle of energy cascade utilization, the high temperature part is the heat source of the $LiBr/H_2O$ AHT cycle and the low temperature part is the heat source of the NH_3/H_2O AHT cycle. The NH_3 AHT cycle produces high temperature heat fed to $LiBr/H_2O$ AHT cycle; the $LiBr/H_2O$ cycle produces low temperature heat fed to the NH_3/H_2O AHT. This heat integration in NCAHT can improve the COP for efficiently low grade waste heat recovery. The NCAHT is testified in a coal to SNG plant. An economic analysis is conducted to the NCAHT application. Results show that: the total capital investment of a 12 MW NCAHT is 924,000 USD. The Financial Internal Rate of Return (*FIRR*) is 62.16%. Besides, an analysis of product price and operation cost have been conducted for potential future prices fluctuation and inflation.

This paper is organized in 4 parts. Section 2 gives a detail description of NCAHT. The model of the NCAHT is presented in Section 3. The NCAHT is designed based on the model. Section 4 introduces the NCAHT as a case study, which is applied to a coal to SNG plant. Heat source simulation, NCAHT simulation, and economic analysis are conducted. Economic analysis includes investment analysis, *FIRR*, product price analysis, and cooling water price analysis. Conclusions are given in Section 5.