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Chemisorption cooling and electric power cogeneration system driven by low grade heat

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ABSTRACT

A novel integration of chemisorption refrigeration cycle and a scroll expander was investigated for the cogeneration of cooling and electric power. The first lab prototype machine has been built, and the two main components were tested both independently and cooperatively for comparison before and after the integration therefore leading to better knowledge of the interaction between them. Two sets of adsorption cycles utilizing the adsorbent compound of calcium chloride and activated carbon worked out-of-phase for the output continuity, and mass recovery was applied to further elevate the performance. In the cogeneration test, the cooling temperature reached 5.4 °C as minimum, while the generated electric power achieved the maximum value of 490 W. The valuable experience and the inspiration on system optimization has been reaped and discussed through this exploration.

1. Introduction

As the rapid development of technologies and the modernisation of society and human life, heating, cooling, transport and industrial processes will need to increasingly be electrified, and that implies electricity demand in UK is likely to increase by between 30% and 100% by 2050, revealed by recent Department of Energy & Climate Change analysis [1]. Meanwhile, with respect to the environmental concerns UK places high hope on meeting the indicative target of creating a decarbonized power sector which requires an emission intensity cut down to a range of from 50 to100 gCO_2/kWh from current level around 500 gCO_2/kWh, and that makes it radically essential to enhance the energy utilization efficiency by for example realizing enormous potential of recoverable but wasted heat from UK industries which is estimated to be between 10 TWh and 40 TWh per annum [2], or the penetration of renewable energy to cope with the growing energy demand and the accelerated scarcity of resources. UK's ambition has been formalised to deliver 15% of the energy demand from renewables by 2020 and to increase the amount of electricity generated by renewables from current 11% to around 30% by that time.

A combined electric power and refrigeration system based on absorption technology driven by low or medium grade heat (like waste heat, solar thermal or geothermal heat) attracts attention, due to the improved energy utilisation efficiency and CO_2 emission reduction [3–9]. The gist of the absorption cogeneration adopts the binary mixture of ammonia and water as the working fluid, and has the rich-ammonia solution from the rectifier expanding through a turbine and then exiting the turbine at a low temperature. Thus the cooling effect is extracted from the sensible heat which is unfortunately limited. In the work by Vijayaraghavan et al. [7], low grade heat source from 87 °C to 207 °C were applied to an absorption-based cogeneration system to assure low temperature exhausted vapour from the turbine and the total thermal efficiency of this theoretical analysis was from 0.05 to 0.12. Later, Liu and Zhang's work [8] employed separated cooling and power subcycles with heat source around 450 °C to improve the cogeneration capacity. Their design utilized a splitting/absorption unit to maintain the desired ammonia concentrations in different processes and a throttle valve to ensure the sub-cooling state of the working fluid before evaporation. All those additional equipment arrangements further highlighted the system complexity, though the refrigeration

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Nomenclature

Ads	adsorbent beds
Con	condenser
COP	coefficient of performance (−)
Evp	evaporator
MR	mass recovery
ΔP	pressure difference (Pa)
W	work (W)

Subscripts

ad	adsorbent beds
con	condenser
ex	expander
out	outlet
in	inlet

efficiency and the electricity output efficiency were improved up to 0.06 and to 0.21, respectively.

Adsorption is alternatively appealing refrigeration technology capable of recovering low grade thermal energy. In the desorption process of adsorption cycle, the working fluid vapour is released at high temperature and high pressure, which is capable of driving a turbine/expander to generate mechanical energy or electricity if a generator is attached; in the adsorption process, the cooling effect is produced via evaporation of the working fluid. The significant features of adsorption compared to absorption are: the less complex construction i.e. eliminating auxiliary devises such as a liquid pump, the rectifiers or separators for refrigerant, therefore leading to reinforcement of system reliability and compactness [10–12]; the potentially higher refrigeration efficiency in cogeneration scenario due to the fact that electricity generation and cooling generation are relatively separated in different half cycle [13]. Although the tempting advantages embodied in the adsorption, the concerns with respect to its distinctive characteristics would be: (1) unlike stable and continuous output from absorption, the varying evolutionary profile of chemisorption would affect the stability of electric power generation if integrated with an expansion process; (2) vice versa, the expansion process would compromise the adsorption cycle performance. To discover the mystery, an Ad-Cogen (adsorption cogeneration) prototype system has been designed, manufactured and experimentally investigated in this work for the viability demonstration and influential parameters identification. The system comprised with two adsorption units to overcome the intrinsic intermittence, which employed the compound of $CaCl_2$ and activated carbon as adsorbent with ammonia as the working fluid (termed as 'refrigerant' in the following sections), and one oil-free scroll expander, which is recognized as the preferable choice to convert low grade heat to electricity especially for small scale power generation [14–17]. The interaction between these two main components has been analysed through the comparison between the individual and incorporated performance. Potential approaches are discussed to guide the further optimization work on Ad-Cogen.

2. Cogeneration principle and theoretical analysis

The synergy operation of two adsorption units realizes continuous cogeneration. Each adsorption unit was composed of one adsorbent bed, one condenser and one evaporator as shown in Fig. 1. A boiler and a water vessel were designated to generate heat source steam and to store heat-sink water, respectively. On one side, the desorbed refrigerant entered the expander to convert thermal energy to mechanical energy while on the other side the adsorption extracted vaporized refrigerant from evaporator to yield cooling effect.

The cogeneration principle is described as follows:

(1) Electric power generation. As shown in Fig. 1(a), Ads 1 (adsorbent bed 1) is heated by hot steam that comes from the boiler through valve V1 and then return to the boiler via V3. Because of heat input the thermodynamic state of the salt complex in Ads 1 deviates from the equilibrium, and that releases high temperature and high pressure refrigerant vapour heading towards the expander through one-way valve and valve V5, resulting in work output which could generate electric power if a generator mounted. The exhausted refrigerant flows through V6 and the Con 1 (condenser 1), and ends up in the Evp 1 (evaporator 1).

(2) Cooling power generation. The internally circulated heat-sink water remains at certain temperature and dissipates heat through a plate heat exchanger that is connected with an external cooling tower. In order to simplify the water pipeline and to compact the whole system, the internal heat-sink water maintains a constant circulating route, flowing through Con 2, Con 1 and Ads 2 (or Ads 1 depending on cycles) sequentially before finally return to the water vessel. Once the Ads 2 is being cooled down, it starts to adsorb the refrigerant from the Evp 2 where the refrigerant experiences evaporation while it captures vaporization heat from surroundings. That is how the cooling effect is produced.

(3) Synchronized performance and alternate operation. As depicted in above (1) and (2), Ads 1 is undertaking decomposition while Ads 2 is simultaneously carrying out synthesis process. Afterwards, the performance of these two adsorbent beds swap, i.e. switch three-way valve V1, V2 and V3, close V5, V6, V10 and open V7, V8, V9 valves as shown in Fig. 1(b), Ads 1 would be disconnected from expander and adsorb refrigerant from Evp 1 to generate cooling while Ads 2 would be integrated with expander and undertake desorption to supply electric power generation with refrigerant.

(4) Repeat above three steps to achieve continuous cogeneration. A mass recovery process, where adsorbent uses a pressure equalization technique, is introduced at the switch interval to enhance the cyclic refrigerant quantity and boost the performance. In other words, at the end of a half cycle when Ads 1 is desorbing refrigerant vapour and becoming less saturated but its pressure is higher from the external heating, while Ads 2 is adsorbing vapour and approaching saturated state but its pressure is lower due to the external cooling, the mass recovery could be triggered by opening the valve connecting Ads 1 and Ads 2 for a short time period (45 s in this work). Therefore the pressures in two beds become equalized, and the sudden pressure swing results into that: Ads 1 experiences a further desorption and simultaneously the Ads 2 undergoes an extended adsorption, leading to the increment in the cyclic transferred amount of refrigerant. This approach has been proven effective in many works [18–20].

Fig. 2 illustrates an ideal working principle in Claperon diagram as $CaCl_2$ being the reactive adsorbent. A to B in Fig. 2 represents the heating process of the adsorbent. The temperature and pressure of the adsorbent escalate along the equilibrium line without any reaction happening until the adsorbent pressure (point B or B′) is higher than the saturated pressure of the refrigerant ammonia corresponding to the heat sink temperature (point D), then the pressure difference propels the decomposition and the refrigerant transfers. The process B to C symbolises an isentropic expansion process. For the purpose of improving output power, as B′ point displayed in