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Simultaneous Optimization and Screening of Integrated HEN-AR System for Zeolite/NH_3 Working Pair

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ABSTRACT

Low-grade waste heat driven AR technology is considered a promising strategy to realize near-zero-carbon cooling applications. The HEN plays a critical role in the chemical process industry owing to its significant impact in the energy recovery. For abundant industrial waste heat, an integrated HEN-AR superstructure combining microscopic adsorption capacity prediction, mesoscopic AR unit and waste heat recovery system is proposed to satisfy specific refrigeration requirements. A MINLP model is formulated, and the objective function is to minimize TAC. In this paper, simultaneous optimization and screening of integrated HEN-AR system for 11 zeolite/NH_3 working pairs in a practical industrial case is investigated. 6 working pairs have the ability to achieve the cooling capacity of 1350 kW at 287 K. A new power-based coefficient of performance for cooling COP_C^P is innovatively proposed with power consumption replacing free low-grade waste heat. The optimal IRN/NH3 working pair is identified, with the highest COP_C, COP_C^P, SCP. Configuration and thermodynamic analysis for the HEN-AR system with superior IRN/NH_3 working pair are comprehensively elaborated. The integrated HEN-AR model offers bright insights for low-grade waste heat adsorption refrigeration applications.

Keywords: low-grade waste heat, integration, HEN-AR, zeolite/NH_3

NONMENCLATURE

Abbreviations	
AR	Adsorption refrigeration
AC	Activated carbon
CRF	Capital recovery factor
CT	Cost
HEN	Heat exchanger network
TAC	Total annual cost
Symbols	
CW	Cooling water
Q	Heat load

1. INTRODUCTION

Nowadays, for ever-increasing energy-intensive industry processes, large portion of the energy input is dissipated as low-grade waste heat to the environment, bringing about severe energy loss, especially lower than 363 K low-grade waste heat. As a major technology for heat utilization, HEN effectively realizes the transfer of heat from high-temperature to low-temperature streams [1].

Traditional vapor compression refrigeration systems used extensively account for about 15% of the global electricity consumption, imposing a burden on the fossil fuels [2]. Besides, the working fluids contribute to global warming and ozone depletion. AR technology driven by low-grade waste heat can be operated by 273 ~ 373 K heat sources which are available in industrial fields and so on, and is widely regarded as an alternative option.

For a basic single stage and two bed AR cycle, refrigeration performance indicators like COP_C, and SCP have been thoroughly assessed for zeolite/water [3], MOF/NH_3 [4], silica gel/water [5] and AC/CO_2 working pairs [6]. For above situation, the heat source temperature is as low as 338 K, whereas the refrigeration capacity is less than 100 kW, with the COP_C range of 0.2 ~ 0.5 and the SCP range of 50 ~ 180 W/kg.

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In this paper, we propose an integrated HEN-AR superstructure combing microscopic adsorption capacity prediction, mesoscopic AR unit and waste heat recovery system, concentrating on simultaneous optimization and screening of integrated HEN-AR system for 11 zeolite/NH_3 working pairs. A MINLP model is developed based on the superstructure to minimize the TAC of the entire system. One practical industrial example is devoted to demonstrating the performance of the proposed model. Moreover, a new COP_C^P is presented to enrich the refrigeration performance indicators.

2. HEN-AR SUPERSTRUCTURE

The integrated HEN-AR superstructure including HEN, AR, and stream transportation units is proposed and shown in Fig. 1. The combination of HEN and AR units is called a waste heat recovery system. A MINLP optimization model is formulated based on the superstructure to minimize the TAC of the entire system.

The working pair is the most critical factor deciding the refrigeration performance, and the key to determine the application of the working pair is the adsorption capacity. 11 zeolite/NH_3 working pairs with different pore size distributions are selected as candidates for AR units, including 4 zeolites frequently used for adsorption refrigeration in the literature. Microscopic adsorption phase density and adsorption capacity perspectives for 11 working pairs are presented and regressed.

For HEN unit, a set of streams originally intended to be cooled directly are regarded as hot process streams. 11 zeolites/NH_3 working pairs are selected as candidates for AR unit. Owing to the size limitations of AR unit, several AR units can be arranged in parallel. The stipulations of each AR unit in this study, including the working pair, are supposed to be the same. Pipes and

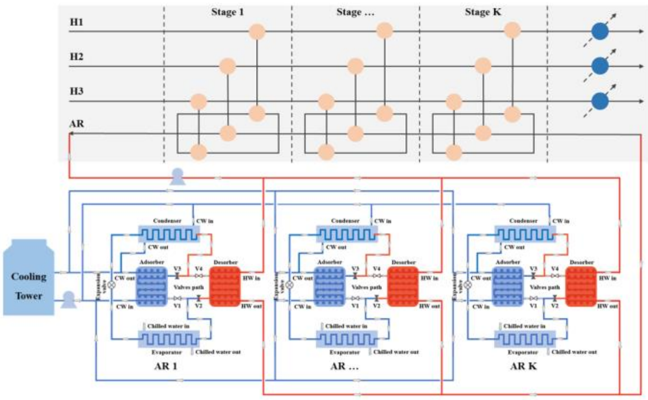

Fig. 1. HEN-AR superstructure for the integrated refrigeration system

pumps in the stream transportation unit are devoted to connecting the HEN unit, AR unit and cooling tower.

3. OBJECTIVE FUNCTION

The TAC is used as the objective for the HEN-AR system, expressed as Equation (1). It includes the cost of all heat exchangers in the HEN unit CT_{ex}, the cost of the AR unit CT_{ar}, the cost of pipes and pumps for stream transportation CT_{tr}, the cost of the cold utility consumption in HEN-AR unit CT_c.

The cost of AR unit is represented in Equation (2). The cost of pipes and pumps for stream transportation are shown in Equation (3). The cost of cold utility consumed in HEN unit is expressed in Equations (4). For the HEN unit, each stream supplying the low-grade waste heat is equipped with a cooler, and the cold utility is provided for cooling the stream to the target temperature prior to heat integration. The difference between CT_c^{int} and CT_c^{ori} is the cost of cold utility for the current system, which is negative.

$$TAC = CRF \cdot (CT_{ex} + CT_{ar} + CT_{tr}) + CT_c \tag{1}$$

$$CT_{ar} = CT_{ads} + CT_{des} + CT_{con} + CT_{ev} + CT_{zeo} + CT_{NH3} \tag{2}$$

$$CT_{tr} = CT_{par} + CT_{pcw} + CT_{mar} + CT_{mcw} + CT_{cw} \tag{3}$$

$$CT_c = CT_c^{int} - CT_c^{ori} \tag{4}$$

4. PERFORMANCE INDEX

The refrigeration capacity Q_{ev} is the heat taken up by the evaporator. The COP_C is defined as Q_{ev} divided by the heat Q_{des}. The SCP is the refrigeration capacity per unit of adsorbent. Q_{ev}, COP_C, and SCP are the indexes to evaluate the cooling performance of the AR unit. COP_C and SCP can be calculated based on Equations (5)-(6).

$$COP_C = \frac{Q_{ev}}{Q_{des}} \tag{5}$$

$$SCP = \frac{Q_{ev}}{M_{zeo}} \times 1000 \tag{6}$$

For a practical chemical plant, the low-grade waste heat source is abundant and free, and could be produced constantly, which implies that it is inaccurate to consistently regard COP_C as a measure of cooling performance. A new power-based coefficient of performance for cooling (COP_C^P) is innovatively proposed, as expressed in Equation (7), replacing free low-grade heat with power consumption compensated by two pumps for the designed HEN-AR system.

$$COP_C = \frac{Q_{ev}}{NP_{ar} + NP_{cw}} \tag{7}$$

5. RESULTS AND DISCUSSION

5.1 Case description and

Table 1 summarizes the data of lubricating oil plant with a total heat load of 11135 kW, and the stream H5 has the largest heat load among all streams, which is highly likely to participate in heat transfer. For this case, the refrigeration capacity is designated as 1350 kW and temperature is stipulated as 287 K.

Table 1 Streams data for lubricating plant

Streams	Inlet temperature TB_i^h/K	Outlet temperature TE_i^h/K	Heat load Q_i^h/kW
H1	390	343	1441.8
H2	453	318	2220.8
H3	365	340	187.2
H4	379	338	134.9
H5	493	325	5668.3
H6	440	337	431.4
H7	344	323	11.6
H8	380	312	175.6
H9	357	316	90.7
H10	499	314	145.3
H11	421	320	337.2
H12	518	312	291.8

5.2 Screening of zeolite/NH₃ working pairs

Among the 11 candidates, 6 working pairs satisfy refrigeration requirements, and the most economical one is IRN/NH_3 with TAC of 1.806×10^5 \$/year in Fig. 2. Limited by the minimum desorption temperature of 343 K, for a working pair with poor cooling performance, there is insufficient low-grade heat meeting the temperature difference, hence the refrigeration capacity of 1350 kW cannot be obtained.

For each feasible working pair, the TAC of the HEN-AR system consists CT_{ex}, CT_{tr}, CT_{ar} and CT_c, with emphasis on the negative CT_c. The cost of transportation unit CT_{tr} undoubtedly account for a considerable proportion of the TAC. From the pie chart describing the detailed composition of CT_{tr}, it can be seen that for the optimal IRN/NH_3 working pair, the cost of cooling water CT_{cw} intimately associated with the thermodynamic properties of the working pair accounts for 62% and the cost of two pipes CT_p related to the materials itself accounts for 37%. The CT_{ex} and CT_{ar}

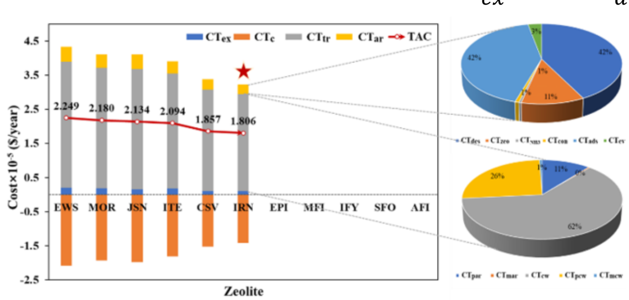

Fig. 2. Optimized TAC and cost components for 11 working pairs applied to HEN-AR system

make up a little portion of TAC, and the cost of adsorption and desorption beds accounts for 84% of CT_{ar}.

The COP_C, COP_C^P, SCP and ΔW of HEN-AR systems with 6 working pairs are determined in line with optimized working pairs, as illustrated in Fig. 3. The IRN/NH_3 working pair has the largest COP_C, COP_C^P and SCP with values of 0.274, 18.386 and 114.2 W/kg.

The working pair with excellent refrigeration performance has less zeolite mass M_{zeo} and higher SCP. Less M_{zeo} contributes to less low-grade heat load and less volume flow rates of AR stream and cooling water correspondingly, resulting in less power consumption compensated by two pumps and higher COP_C and COP_C^P for superior working pair. It is found that ΔW and SCP have exactly the same trend, implying that zeolite with excellent refrigeration performance should have outstanding working capacity ΔW, which is also compatible with the opinion of Li [7].

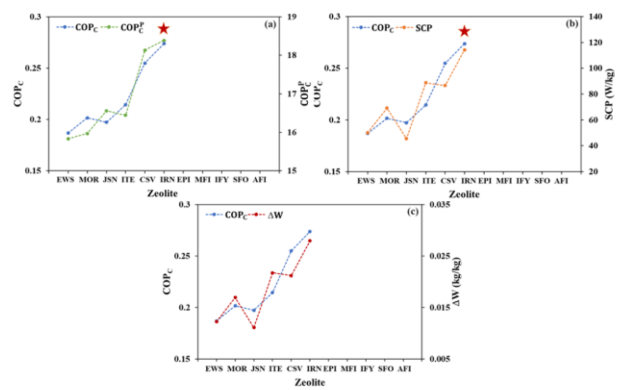

Fig. 3. COP_C, COP_C^P, SCP and ΔW for HEN-AR systems with 6 working pairs

5.3 Configuration for optimal working pair

The optimized configuration and operational specifications for HEN-AR system with exceptional IRN/NH_3 working pair are depicted in Fig. 4. Besides 4001 kW heat load provided by the stream H5 with largest heat load, the stream H2 with the second largest heat load and moderate temperature grade contributes an additional 930 kW to the AR units, and the remaining 6204 kW is straightly removed by the cold utility. It desires two AR units with 5907 kg zeolite in each bed, a T_{des} of 358 K and a mass flow rate of 3.3 kg/s of circulating NH_3 for each AR unit. The power consumption of the pump carrying the AR stream is 24.5 kW, while the power consumption of the other pump is 48.9 kW.

6. CONCLUSIONS

In this study, a novel integrated HEN-AR system containing microscopic adsorption capacity prediction,

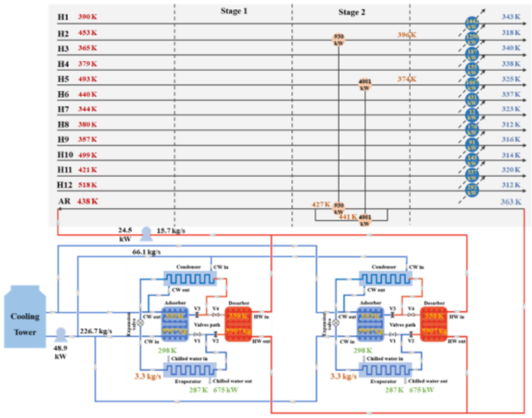

Fig. 4. Configuration obtained for HEN-AR system with IRN/NH_3 working pair

mesoscopic AR unit, and low-grade waste heat recovery system is designed for refrigeration, concurrently performing heat exchange of process streams and low-grade waste heat utilization. Based on the proposed integrated system, a MINLP model is established to simultaneously optimize and screen HEN-AR systems for 11 zeolite/NH3 working pairs in one practical industrial case. A new power-based coefficient of performance for cooling (COP_C^P) is presented to evaluate the refrigeration performance. Several conclusions are drawn as follows:

(1) 6 zeolite/NH_3 working pairs have the competence to satisfy specific refrigeration requirements of this case, verifying the feasibility of the proposed HEN-AR system.

(2) The IRN/NH_3 working pair are economically optimal with the minimum TAC of 1.806×10^5 $/year for this case, which has the largest COP_C, COP_C^P, SCP and ΔW among 6 feasible working pairs.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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