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Heat Exchanger Network Synthesis with Absorption Refrigeration Cycle Integrated Considering the Optimization of Operating Condition

Xiaojing Sun, Linlin Liu, Yao Sheng, Lei Zhang, Jian Du*

Institute of Chemical Process System Engineering, School of Chemical Engineering, Dalian University of Technology, Dalian, 116024, Liaoning, China
dujian@dlut.edu.cn

Absorption refrigeration cycle (ARC) is a high-efficiency energy cycle for heat recovery from middle- and low-temperature heat sources in term of generating cold utility. ARC is utilised to the best advantage especially in heat exchanger networks (HENs) which have waste heat and refrigeration demand. In this work, a synthesis method is proposed to make the most effective heat management design of HEN with ARCs incorporated. A stage-wise superstructure is presented to integrate the generation and evaporation processes of ARCs within HEN where hot process streams provide heat to drive generators, and then are refrigerated to target temperatures by the evaporators of ARCs. Potential matches between ARCs and process streams are given in the superstructure to present the topological structure of coupling. Furthermore, the operating condition of ARC which refers to heat source temperature and evaporation temperature in this work is optimized simultaneously according to their cooperating influence on the coefficient of performance (COP). The optimal design purpose is realized via a mixed integer non-linear programming (MINLP) model formulated towards the objective of minimum total annualized cost (TAC). Finally, a case study is illustrated to demonstrate the application of the proposed method, the mutual relations among characteristics of process streams, COP, the structure of HEN with ARC incorporated and TAC are analysed, and the results show superiority in rational utilisation of energy and reduction of economic cost.

1. Introduction

In past four decades, plenty of methods for heat exchanger network synthesis have been systematically developed but the exploration never slow down as the research content has always been extending. Traditional HEN synthesis efforts contribute to solve the problem by posing heat exchange matches between hot and cold process streams, meanwhile employing hot and cold utilities to complement the heat exchange load of process streams. On base of which, incorporating thermodynamic cycles into HEN has been seen as a promising route for the further intensification of energy utilisation and increasing attention has been paid on this issue.

Among the thermodynamic cycles, absorption refrigeration cycle (ARC) is an effective technology aiming at refrigerating with low- and middle- grade heat sources, and some research has been launched on the simulation and optimization or system design of single ARC for performance improvement and efficiency enhancement. Chen et al. (2017) investigated the heat integration of ammonia-water absorption refrigeration system through heat-exchanger network analysis. The maximum heat saving capacity and higher COP can be obtained at the assistance of energy transfer diagram. A single absorption refrigeration cycle (LiBr/H_2O cycle) was modelled and simulated by Wang et al. (2017), the COP and exergy efficiency were used as indicators to determine the optimal matches between refrigeration levels and heat source temperatures. Takeshita et al. (2018) presented the optimal design/operating conditions by considering cost-effectiveness and operability of a single-stage ammonia/water absorption refrigerator via exergy analysis.

Studies have been also launched to integrate the ARC-based refrigeration system with industry processes for waste heat recovery. Ebrahimi et al. (2015) presented the utilisation of ARC in a data centre. The heat dissipated by servers is used to drive an absorption system, which in turn produces cooling for other servers. Yang et al.

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(2016) combined the LiBr and NH_3 absorption refrigeration in sequence for waste heat recovery from methanation unit, with the cold energy meanwhile produced to satisfy the refrigeration demand of Rectisol unit in coal-to-SNG.

For greater energy-saving potential, some studies focused on the investigation of ARC incorporated with HEN. Lira et al. (2013) presented a superstructure having heat exchange system combined with solar absorption refrigeration system, for the sake of reaching the optimal configuration of the whole system, but the placement of generation process of ARC and the selection of evaporation temperature were not well investigated. This work was later extended by taking Organic Rankine Cycle into consideration for process heat recovery in 2014, but the ARC was still supposed working at certain conditions rather than its optimal interior behavior accompanying with the system synthesis.

As mentioned, previous research focused either on the thermodynamic optimization of ARC, or the incorporation of ARC with HEN for heat recovery. However, the operating parameters of ARC were not optimized in relevant studies that considered the combination of HEN and ARC, in which the COP of ARC was also assumed to be constant. In this paper, ARC and HEN are considered as a whole system to recover heat for refrigeration, where the operating parameters of ARC and the structure of HEN are optimized simultaneously. There's a trade-off between heat recovery amount and operating performance of ARC, which is influenced by selection of generation temperature and evaporation temperature. The operating temperature intervals are recognized through disjunctive model in mathematical formulation. With this method, the optimal integrated system can be obtained with high operating performance and energy efficiency, large amount of process heat was also recovered to minimize the economic cost.

2. Superstructure and model formulation

The cooperation of HEN and ARC can be performed in two parts: (*i*) hot process streams provide heat to drive the generators of ARC, (*ii)* low-temperature cold energy produced in evaporators of ARC cool hot process streams to sub-ambient temperatures. The synthesis problem to be addressed in this paper can be stated as follows.

A set of hot process streams (some are below room temperature), and a set of cold process streams are given with their perspective heat capacity flow rates, supply and target temperatures. Utility parameters, such as inlet temperatures, outlet temperatures and unit costs are also given. Other given include the cost coefficients of heat transfer units and the minimum approach temperatures. The generation and evaporation processes of ARCs are implemented cooperatively with the heat exchange of mentioned process streams, wherein each hot process stream can be cooled down by cold process stream, cooling water and/or the generation and evaporation processes of ARC, and each cold process stream can be heated by hot process stream, low-pressure steam (LPS) and/or high-pressure steam (HPS).

2.1 Superstructure presentation

A stage-wise superstructure is proposed to present the configuration of HEN incorporated with generation and evaporation processes of ARC in Figure 1.

As shown in Figure 1, for ARC part, the generator and evaporator get heat from hot process streams, and the absorber and condenser are cooled down with cooling water; for HEN part, in addition to heat exchange between hot and cold streams, generation process within stages (ARGEn) and evaporation process (AREVs) at hot stream ends are presented in HEN. Each hot process stream is allowed to be cooled down by multiple parallel evaporation processes belonging to different grades (AREVs1, AREVs2 and so on) after the using of cooling water. Also, the non-isothermal mixing of stream split branches between adjacent stages is taken into account, and the utilisation of low-grade utilities (cooling water and LPS) within stages and at stream ends and high-grade utilities (the evaporation process of ARC and HPS) at stream ends are all included in the superstructure.

2.2 Model formulation

A MINLP model consisting of HEN and ARC parts is formulated according to the superstructure proposed in this paper. The following sets are defined before presenting the model formulation: *I, J*, *ST* represent the sets for hot process streams, cold process streams, stage numbers of heat exchange in the superstructure, *N* and *S* are the sets for temperature grades of heat sources and evaporation processes for ARC.

2.2.1 Model for heat exchanger network synthesis

The model formulation for heat exchanger network synthesis includes: total energy balances for process streams, energy balance for each superstructure stage, energy balance for each match, energy balances for utilities at the stream end of the superstructure, energy balances for non-isothermal mixing, constraints for the existence of heat exchanger units and the temperature differences in heat transfer units, heat exchanger area calculation and so on. All these equations and constraints can refer to the model established in the work by Lira et al. (2013).

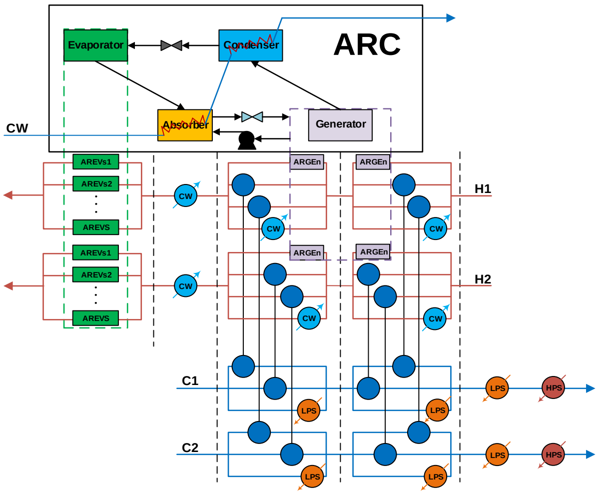


Figure 1: Schematic representation and superstructure of the integrated system.

2.2.2 Model for ARC

In the ARC, the condensation and absorption temperatures are constants since the absorber and condenser are cooled down with cooling water which is used as cold utility in HEN with given inlet and outlet temperatures. Therefore, the COP is related to heat source temperature and evaporation temperature. These two critical temperatures are graded by dividing heat source temperature into several intervals and discretizing evaporation temperature into several values. Once the grades of heat source and evaporation temperatures are determined, the matrix of COP can be established.

- Grading of heat resource temperature

$$T1_n^{ARGEin} \times \sum_S Z_{i,k,n,s}^{AR1} \le tk_{i,k,n}^{ARGEin} \times \sum_S Z_{i,k,n,s}^{AR1} \le T2_n^{ARGEin} \times \sum_S Z_{i,k,n,s}^{AR1} \quad \forall i \in I, \forall k \in ST, \forall n \in N \tag{1}$$

$Z_{i,k,n,s}^{AR1}$ is the binary variable denoting the existence of generator of ARC in stage ‘k’ with the heat source temperature belongs to grade ‘n’ and the temperature of cold energy produced in the evaporator belongs to grade ‘s’. $T1_n^{ARGEin}$ and $T2_n^{ARGEin}$ are the lower bound and upper bound of heat source temperature in grade ‘n’. The constraints on binary variable of ARC are given by Eq(2) and Eq(3), which indicate that for the generation and evaporation processes of ARC, one grade of heat source temperature corresponds to one evaporation temperature, and for each hot process stream, the same grade of heat source temperature is not allowed to appear more than once.

- Existence of ARC

$$\sum_N \sum_S Z_{i,k,n,s}^{AR1} \le 1 \quad \forall i \in I, \forall k \in ST \tag{2}$$

$$\sum_K \sum_S Z_{i,k,n,s}^{AR1} \le 1 \quad \forall i \in I, \forall n \in N \tag{3}$$

- The determination of matrix $COPar$

$$COPar = \begin{pmatrix} cop_{n1,s1}^{ar} & \cdots & cop_{n1,S}^{ar} \\ \vdots & cop_{n,s}^{ar} & \vdots \\ cop_{N,s1}^{ar} & \cdots & cop_{N,S}^{ar} \end{pmatrix} \tag{4}$$

In Eq(4), $cop_{n,s}^{ar}$ is the element of matrix $COPar$ which is determined by the inlet temperature of generator (heat source temperature) $t_{i,k,n}^{ARGEin}$ which belongs to grade ‘*n*’ and evaporation temperature T^{EVARC} for ARC in grade ‘*s*’.

- Energy balances for ARC

COP is the ratio of cooling load produced in evaporator to heat load imported to generator of ARC by hot process stream.

$$\sum_{I}\sum_{K} q_{i,k,n}^{ARGEn} Z_{i,k,n,s}^{ARGEn} \times cop_{n,s}^{ar} = \sum_{I}\sum_{S} (Z_{i,s}^{AREVS} qk_{i,s}^{AREVs}) \quad \forall n \in N, \forall s \in S \tag{5}$$

2.2.3 Objective function

Objective of the optimization is to minimize the total annualized cost, considering both the expenditures for HEN and ARC. The corresponding cost representations are given in Eqs(6)-(8).

$$\mathrm{minTAC} = TAC_{HEN} + TAC_{ARC} \tag{6}$$

$$\begin{aligned} TAC_{HEN} = K_F \times \Bigg[& coeff_{EXC} \times \sum_{I}\sum_{J}\sum_{K} A_{i,j,k}^{aexp} + coeff_{CU} \times \Big(\sum_{I}\sum_{K} A_{i,k}^{CW\,aexp} + \sum_{I} A_{i}^{CW'aexp} \Big) + \\ & coeff_{LPS} \times \Big(\sum_{J}\sum_{K} A_{j,k}^{LPSHEN\,aexp} + \sum_{J} A_{j}^{LPSHEN'aexp} \Big) + coeff_{HU} \times \sum_{J} A_{j}^{HUaexp} + \\ & unitic \times \Big(\sum_{I}\sum_{J}\sum_{K} Z_{i,j,k} + \sum_{I}\sum_{K} Z_{i,k}^{CW} + \sum_{I} Z_{i}^{CW'} + \sum_{J}\sum_{K} Z_{j,k}^{LPSHEN} + \sum_{J} Z_{j}^{LPSHEN'} \Big) \Bigg] \\ + \Bigg[& \Big(\sum_{J} \mathrm{q}_{j}^{LPSHEN'} + \sum_{J}\sum_{K} \mathrm{q}_{j,k}^{LPSHEN} \Big) \times \mathrm{lpscost} + \sum_{J} \mathrm{q}_{j}^{HU} \times \mathrm{hucost} + \Big(\sum_{I} \mathrm{q}_{i}^{CW'} + \sum_{I}\sum_{K} \mathrm{q}_{i,k}^{CW} \Big) \times \mathrm{cwcost} \Bigg] \end{aligned} \tag{7}$$

$$\begin{aligned} TAC_{ARC} = & \Big(\sum_{I}\sum_{N}\sum_{S} q_{i,k,n}^{ARGEn} + \sum_{I}\sum_{S} qk_{s,i}^{AREVs} \Big) \times \mathrm{cwcost} + \\ & 268.45 \times \Bigg[\Big(\sum_{I}\sum_{K}\sum_{N}\sum_{S} Z_{i,k,n,s}^{ARGEn} + \sum_{I}\sum_{N}\sum_{S} Z_{i,n,s}^{AREVs} + Z^{ARCO} + Z^{ARAB} \Big) \Bigg] + \\ & 516.2 \times \Bigg[\Big(\sum_{I}\sum_{K}\sum_{N}\sum_{S} A_{i,k,n,s}^{ARGEn} + \sum_{I}\sum_{N}\sum_{S} A_{i,n,s}^{AREVs} + \sum_{I}\sum_{K}\sum_{N}\sum_{S} A_{i,k,n,s}^{ARCO} + \sum_{I}\sum_{N}\sum_{S} A_{i,n,s}^{ARAB} \Big) \Bigg] \end{aligned} \tag{8}$$

HEN cost is the summation of capital cost for heat exchangers and operating cost for utility consumption. ARC cost is deduced from the investment of generator, evaporator, absorber and condenser, as well as the using of cooling water in the absorber and condenser. Here it should be noted that, the sum of $t_{i,k,n}^{ARGEin}$ and $qk_{s,i}^{AREVs}$ in Eq(8) equals to the heat taking away by cooling water in absorber and condenser of ARC.

3. Case study

In this section, the proposed model is demonstrated through a case study. The data of the involved three hot process streams and two cold streams are shown in Table 1. The minimum approach temperature for process stream matching and ARC matching are stipulated to be ΔT_{min1}=10 ℃ , ΔT_{min2}=5 ℃ . The inlet and outlet temperatures of cooling water are 30 °C and 40 °C, temperatures of LPS and HPS are 158 °C and 255 °C respectively.

Table 1: Stream data for case study

Streams	Inlet temperature T_{in} (°C)	Outlet temperature T_{out} (°C)	*FCp* (kW/°C)
H1	165	15	38.75
H2	145	25	48.75
H3	120	20	43.75
C1	35	240	20
C2	60	120	36.25

In ARC, LiBr/H_2O is used as the working fluid. And for single LiBr/H_2O absorption refrigeration, the temperature of heat source is not allowed to be lower than 80 °C or higher than 180 °C. In this paper, the COP lower than 0.5 is not considered, so the designated range of heat source temperature is 105 °C to 175 °C. To make comparison, a base case is set to cool down process streams by employing electrical compression refrigeration (ECR), which produces cold energy by consuming electricity rather than process heat. Similarly, the condenser

of ECR is also cooled down by cooling water, and accordingly, the COP of ECR can be determined by the selectable evaporation temperatures T^{EVECR} (denoted by *s'*) which are identical to ARC.
In order to optimize the operating condition of ARC, heat source temperature of ARC is divided into four grades as listed in Table 2, meanwhile four evaporation temperatures for ARC and ECR are also given. Corresponding $cop_{n,s}^{ar}$ in matrix *COPar* are given in Eq(9) according to the general presentation of Eq(5). And cop_{s}^{ec} in matrix *COPec* are given in Eq(10). The formulated MINLP mathematical models for mentioned HEN-ARC and HEN-ECR designs are coded and solved in GAMS.

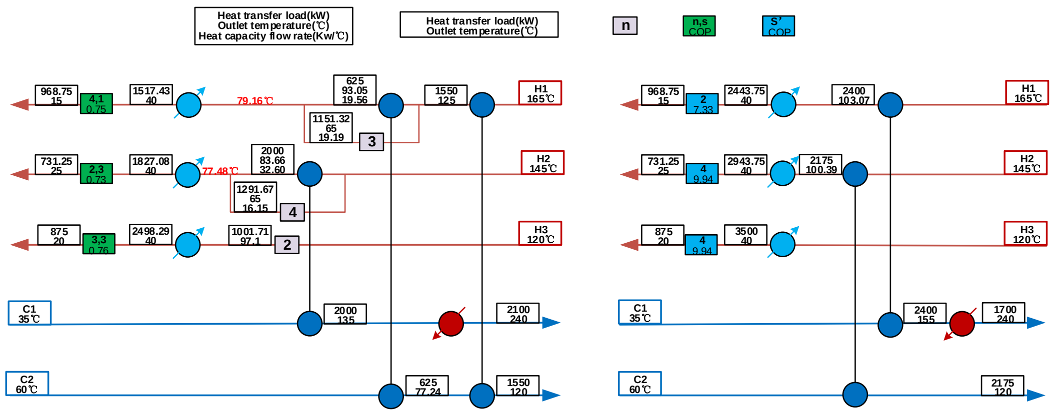
Table 2: Grading about operating temperatures

n	$t_{i,k,n}^{ARGEin}$ (°C)	*s/s'*	T^{EVARC} / T^{EVECR} (°C)
n1	$105 \le t_{i,k,n}^{ARGEin} \le 115$	s1/s1'	5
n2	$115 \le t_{i,k,n}^{ARGEin} \le 125$	s2/s2'	8
n3	$125 \le t_{i,k,n}^{ARGEin} \le 135$	s3/s3'	11
n4	$135 \le t_{i,k,n}^{ARGEin} \le 175$	s4/s4'	15

$$COPar = \begin{pmatrix} 0.59 & 0.61 & 0.66 & 0.73 \\ 0.67 & 0.70 & 0.73 & 0.78 \\ 0.72 & 0.74 & 0.76 & 0.79 \\ 0.75 & 0.77 & 0.78 & 0.80 \end{pmatrix} \quad (9)$$

$$COPec = \begin{pmatrix} 6.55 & 7.33 & 8.30 & 9.94 \end{pmatrix} \quad (10)$$

Optimal structures of the integrated HENs with ARC and ECR is presented in Figure 2(a) and (b), respectively. In HEN-ARC result, (*n, s*) denotes an integrated ARC having generator motivated by the hot process stream belonging to temperature grade '*n*' meanwhile producing cold energy at evaporation temperature of grade '*s*', while for HEN-ECR result, just the evaporation temperature grade of '*s*'' needs to be determined.



(a) (b)

Figure 2: (a) Structure of the integrated HEN with ARC. (b) Structure of the integrated HEN with ECR.

As shown in Figure 2(a), three ARCs are implemented to absorb heat from process streams for refrigeration purpose. In addition to exchanging heat with cold process stream and cooling water, H1 heats the generator of ARC (*n* = 3), and the cold energy, 11 °C produced in evaporator, is used to refrigerate H3 (3, 3); H2 and H3 motivate the ARCs (*n* = 4) and (*n* = 2), with the cold energy produced at 5 °C and 11 °C cooling down H1 (4, 1) and H2 (2, 3) to their target temperatures. In HEN-ECR result, as shown, the mentioned refrigeration demands are all satisfied by ECRs.
In the two network solutions, COPs of ARC (4, 1), (2, 3) and (3, 3) are 0.75, 0.73 and 0.76, ECR (2), (4), (4) are 7.33, 9.44 and 9.44. Apparently, the COP of ECR is much higher than ARC on account of that heat is low-level energy compared with electricity. In Figure 2(b), the evaporation temperature grades of ECR is higher than ARC, in order to decrease the consumption of electricity with higher COP. And for ARC in Figure 2(a), the lower the

target temperature is, the higher the hot source temperature (inlet temperature of generator) will be needed for higher COP.

ARC and ECR both prefer higher COP, which means producing specific amount of refrigeration, the system consumes less heat or less electricity. But when they are integrated into HEN with the limit of cost target and characteristics of process streams (inlet temperature, outlet temperature and heat load), it can’t be reached all the time.

In HEN-ARC scenario, the evaporation temperatures selected are related to the target temperatures of hot process streams. On one hand, higher evaporation temperature contributes to higher COP which will lessen the heating load in generator, so hot process streams can offer much heat to cold process stream and the consumption of hot utility will decrease, leading to lower operating cost. On the other hand, higher evaporation temperature will decrease the temperature difference of heat exchanger, resulting in the increase of heat exchanger area and higher capital cost. The effect of evaporation temperature on operating cost and capital cost of HEN-ECR is in accordance with HEN-ARC. So COP is a key parameter for trade-off between operating cost and capital cost. Also, for HEN-ARC, higher heat source temperature is beneficial to higher COP, but it is restricted by inlet temperature of hot process streams and affected by heat exchange between cold and hot process streams. So, the COP is a relatively high value when ARC or ECR is integrated with HEN.

The optimal integrated HEN-ECR system is achieved at the TAC of 998,965 $/y, and the TAC of optimal integrated HEN-ARC is 751,157 $/y, which is 24.8 % lower than HEN-ECR. The analysis is as follows: in the HEN with ARC integrated, apart from heat exchanging between cold and hot process streams, some process heat is allocated to drive the generators of ARC, which increases energy efficiency. Even though the hot utility consumption is increased, the cooling water utilisation is less, and the integrated system can satisfy its refrigeration demand with the cold energy produced in the evaporators of ARC, with no need for producing cold energy through purchasing electricity. So, compared with HEN-ECR, HEN-ARC shows superiority in rational utilisation of energy and reduction of economic cost when low-temperature waste heat is existent in HEN.

4. Conclusions

This paper has presented a mathematical programming model to consider the integration of HEN with ARC. The operating condition of ARC is optimized simultaneously within the design by dividing generation temperature into several intervals and discretizing evaporation temperature values in this model. With this approach, the optimal integrated system can be obtained with relatively high COP and minimum cost. Compared with the results of base case where only electrical compression refrigeration used for refrigeration purpose, it can be found that the integrated HEN-ARC system is capable to utilise energy reasonably and reduce the total annualized cost by 24.8 % since it could recover waste heat from hot process stream to produce the cold energy required by the system. On base of this study, future work will be concentrated on the optimal design of the cooling and cold water system which are relevant to both HEN and ARC.

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References

Chen X., Wang R. Z., Du S., 2017, Heat integration of ammonia-water absorption refrigeration system through heat-exchanger network analysis, Energy, 141, 1585–1599.

Ebrahimi K., Jones G. F., Fleischer A. S. 2015, Thermo-economic analysis of steady state waste heat recovery in data centers using absorption refrigeration. Applied Energy, 139, 384–397.

Lira-Barragán L.F., Ponce-Ortega J.M., Serna-González M., El-Halwagi M.M., 2013, Synthesis of integrated absorption refrigeration systems involving economic and environmental objectives and quantifying social benefits, Applied Thermal Engineering, 52(2), 402-419.

Lira-Barragán L. F., Ponce-Ortega J. M., Serna-González M., El-Halwagi M. M., 2014. Sustainable Integration of Trigeneration Systems with Heat Exchanger Networks, Industrial and Engineering Chemistry Research, 53(7), 2732–2750.

Takeshita K., Amano Y., 2018, Optimal operating conditions and cost-effectiveness of a single-stage ammonia/water absorption refrigerator based on exergy analysis, Energy, 155, 1066–1076.

Wang Y., Wang C., Feng X., 2017, Optimal match between heat source and absorption refrigeration, Computer Chemical Engineering, 102, 268-277.

Yang S., Liang J., Yang S., Qian Y., 2016, A novel cascade refrigeration process using waste heat and its application to coal-to-SNG, Energy, 115, 486-497.