CHEMICAL ENGINEERING TRANSACTIONS
VOL. 76, 2019
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Petar S. Varbanov, Timothy G. Walmsley, Jiří J. Klemeš, Panos Seferlis

ISBN 978-88-95608-73-0; **ISSN** 2283-9216
DOI: 10.3303/CET1976058

Integration of Low-grade Waste Heat System Based on Lithium Bromide Refrigeration in a Polysilicon Industry

Youlei Wang[a], Yufei Wang[a,*], Xiao Feng[b]

[a]State Key Laboratory of Heavy Oil Processing, China University of Petroleum, Beijing 102249, China
[b]School of Chemical Engineering, Xi'an Jiaotong University, Xi'an, Shanxi, 710049, China
wangyufei@cup.edu.cn

Heat Integration is a crucial method for making reasonable and effective utilization of waste heat in industrial enterprises. In a polysilicon production enterprise, some hot streams are cooled to a specified temperature by circulating cooling water followed by the ethylene glycol compression refrigeration. But the temperature of streams is still high after cooling by water, which results in high energy consumption of compression refrigeration. There is low-grade waste heat in the enterprise, so that lithium bromide absorption refrigeration driven by waste heat can be considered to replace some duty of compression refrigeration. In this work, hot water is used as intermediate fluid to recycle waste heat, which drives the lithium bromide absorption refrigeration. Then cascade cooling of the hot streams by circulating water, absorption refrigeration and compression refrigeration can be achieved. In this work, the consumption and temperature of hot water used in waste heat recovery, the temperature of the absorption refrigeration, and the load distribution of water cooling, absorption refrigeration and compression refrigeration are solved through simulation and modelling. The cost of the two cooling processes is calculated and compared. Finally, a case study is given to illustrate the feasibility and economy of the method.

1. Introduction

In the face of the world energy crisis, the development of new energy is a very important solution, but improving the efficiency of energy utilization and saving energy are also essential. Compression refrigeration consumes large amounts of electricity, which results in a lot of primary energy consumption. In China, waste heat resources of industries account for 17 % - 67 % of the total fuel consumption, and recyclable waste heat accounts for 60 % of the total waste heat. However, the recovery rate of waste heat is only about 30 % (He, 2016). It can be considered to recycle waste heat by the absorption refrigeration and replace partial load of the compression refrigeration, so as to further improve economic benefits, save energy and reduce CO_2 emissions.

There are many ways to recycle waste heat in the industry. Besides direct heat transfer, power generation and heating, driving absorption refrigeration is also the research hotspot. Zhang et al. (2016) proposed a large scale network for recovering low-grade waste heat, and a MINLP model considering mass and energy network, pipeline, refrigeration station, absorption refrigeration machine was established and solved. Liew et al. (2015) introduced that low-grade waste heat in the industry can be used in refrigeration system of building trades with high demand on zone or central cooling system in tropical regions. Refrigeration technology for recycling low-grade waste heat can be used not only in industrial park, but also in recycling waste heat from Marine ship engine (Cao et al., 2015) and data centres' servers (Ebrahimi et al., 2015).

Cascade cooling can reduce the energy consumption of compressive refrigeration. Yang et al. (2018) combined $LiBr/H_2O$ absorption refrigeration cycle with NH_3/H_2O absorption refrigeration cycle, and proposed a novel cascade absorption refrigeration (NCSR), which can produce high-grade (-40 °C) cold energy through using low-grade waste heat. Xu et al. (2015) presented a novel absorption-compression cascade refrigeration system, which can reach an evaporating temperature of -170 °C. In this system, refrigerant of compression refrigeration was subcooled by the refrigerant of absorption refrigeration driven by low-grade waste heat. Leong et al. (2017) studied on the combined system of vapor compression refrigeration system (VCRS) and absorption refrigeration

Paper Received: 04/04/2019; Revised: 15/06/2019; Accepted: 17/06/2019
Please cite this article as: Wang Y., Wang Y., Feng X., 2019, Integration of Low-grade Waste Heat System Based on Lithium Bromide Refrigeration in a Polysilicon Industry, Chemical Engineering Transactions, 76, 343-348 DOI:10.3303/CET1976058

system (ABS). The new system was integrated with the chilled and cooling water network (CCWN) by using different waste heat in an eco-industry park. Patel et al. (2017) introduced a new concept of two stage vapor compression-absorption cascade refrigeration system (TSVCACRS), in which two stage vapor compression refrigeration system (TSVCRS) and single stage vapor absorption refrigeration system were coupled. The cascade condenser heat exchanger worked as the evaporator for VARS and the condenser for TSVCRS.
The previous researches study more on absorption-compression cascade refrigeration system. In this work, a new cascade cooling system consisting of water cooling, absorption refrigeration and compression refrigeration is proposed. Since the hot streams of a polysilicon enterprise possess relatively high temperature after cooling by circulating water, it will consume large amounts of energy if the streams are then cooled by ethylene glycol compression refrigeration directly. By using the cascade cooling of water cooling, absorption refrigeration driven by waste heat and compression refrigeration, low-grade waste heat recovery and energy saving can be realized. This work will achieve the optimal load distribution of water cooling, absorption refrigeration and compression refrigeration after simulation and optimization.

2. Simulation modelling

The cooling process of the hot streams in a polysilicon enterprise is simulated and calculated by the process simulation software Aspen Plus (v8.6).

2.1 The original cooling process of hot streams

The hot streams of the polysilicon enterprise are the intermediate product of the hydrochlorination plant. The streams are cooled to specific temperature sequentially by the material preheating exchanger (E-1A), air cooler (E-2A), water cooler (COOLER-1A) and compression refrigeration exchanger (COOLER-2A). In the process of simulation, SRK physical method is selected. The flow diagram for device A is shown in Figure 1. In which, A1-A6 stand for hot streams, STC represents the silicon tetrachloride, CW stands for cooling water, and EG represents the ethylene glycol solution.

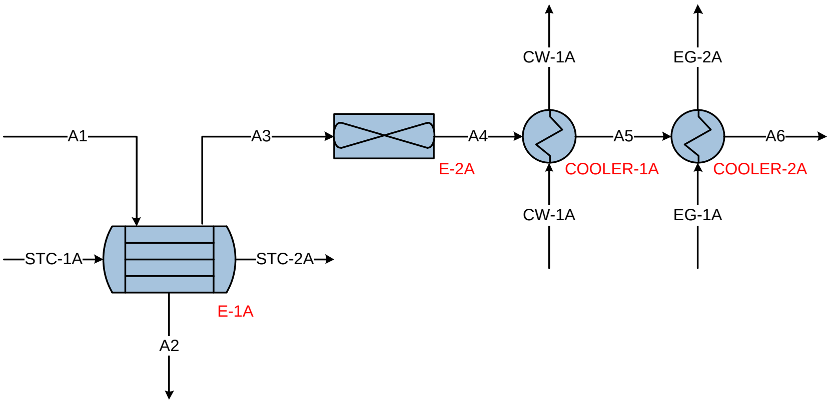

Figure 1: Schematic diagram of the original cooling process of hot stream for device A

The pressure of streams A1-A6 is 1.88 MPa, and their temperatures are 144 °C, 132.19 °C, 132.19 °C, 60 °C, 31.6 °C and 7 °C. The mass flow of A1 is 142,417.9 kg/h, and it is composed by HCl (hydrogen chloride), DCS (silicon dichloride), TCS (silicon trichloride), STC, and H_2 (hydrogen), and the mass flow of these ingredients are 44.7 kg/h, 806.8 kg/h, 26,828.6 kg/h, 113,050.5 kg/h, 1,687.7 kg/h. The parameters of other streams are shown in Table 1.

Table 1: The parameters of the streams

Stream	Mass flow (kg/s)	Pressure (MPa)	Inlet temperature (°C)	Outlet temperature (°C)
STC	18.71	3	45	115
CW	13.43	0.10325	25	45
EG	246.2 (m^3/h)	0.24	-13	-8.5

There are 6 hydrochlorination devices in the enterprise. Through simulation and calculation, the heat load of each heat exchanger and the compressor power are shown in Table 2. Q_1 and Q_2 stand for the load of water cooling and compression refrigeration. P stands for the power of compressor.

Table 2: Heat load of each heat exchanger and compressor power in original process (unit: kW)

Device	E-1	E-2	COOLER-1 (Q_1)	COOLER-2 (Q_2)	COMP (P)
A	1,081.31	6,605.55	1,292.75	978.72	287.86
B	1,085.45	6,501.02	1,297.68	1,025.09	301.50
C	1,081.07	6,474.83	1,284.01	993.00	292.06
D	1,090.06	6,748.70	1,261.75	983.86	289.37
E	1,092.34	6,718.49	1,272.91	984.04	289.42
F	599.77	3,688.94	718.03	599.53	176.33
SUM		36,737.53	7,127.13	5,564.24	1,636.54

The coefficient of performance (COP) of the ethylene glycol compression refrigeration cycle used in this process is set as 3.4. The power of compressor can be calculated by Eq(1).

$$COP = \frac{Coolingcapacity}{Power} = \frac{Q_2}{P} \tag{1}$$

It can be seen from Table 2 that the hot streams release a large amount of low-grade waste heat when cooling by air coolers. The compressor power consumed by compression refrigeration cycle is 1,636.54 kW in total. If the compressor efficiency is 0.7, the electricity charge is 1.2 ¥/(kW·h), and the annual operating time is 8,000 hours, then the electric charge consumed by the compression refrigeration cycle is 22,443,428 ¥/y.

2.2 The new cascade cooling process of hot streams

From the analysis above, large amounts of low-grade waste heat will be released by air coolers. In this work, hot water is used to recycle waste heat, drive LiBr/H_2O absorption refrigeration, and produce refrigerant water for the cascade cooling of hot streams. The new cooling process containing waste heat recovery (COOLER-3A) and absorption refrigeration (COOLER-4A) is simulated. The diagram of the new process is shown in Figure 2. In which, HW stands for hot water and RW stands for refrigerant water. The parameters of hot water are determined in section 3. The inlet and outlet temperature of refrigerant water are 7 °C and 12 °C, and the pressure is 0.10325 MPa. The minimum temperature approach of each heat exchanger (COOLER-1/2/3/4A) is set as 5 °C. The outlet temperature of hot water is set to be 10 °C lower than the inlet temperature of the hot streams. When hot water of 6 devices is collected together, its temperature will be 122.23 °C.

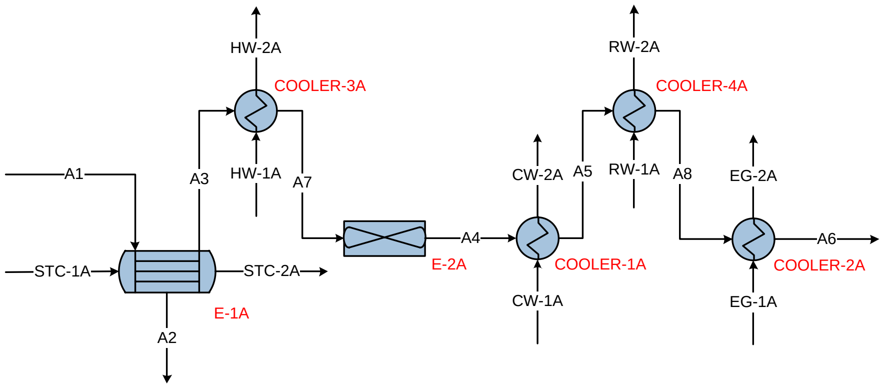

Figure 2: Schematic diagram of the new cascade cooling process of hot stream for device A

In order to determine the optimal load distribution of the new cascade cooling system, sensitivity analysis of the flow rate of cooling water (F_1) and refrigerant water (F_2) is carried out in each device. The temperature T_1 of hot streams after water cooling and the temperature T_2 of hot streams after absorption refrigeration are calculated. The heat load $Q_1/Q_4/Q_2$ for water cooling, absorption refrigeration and compression refrigeration are reached. The data series with the smallest compression refrigeration load (i.e. Q_2) are selected from the calculation results, so as to save more electric energy consumed by compression refrigeration. Then the group of data with the least total consumption of cooling water and refrigerant water is selected, so as to reduce the pumping cost. The smallest operating cost is 688,621 ¥/y for 12 cooling water pumps and 992,270 ¥/y for 12 refrigerant water pumps. The optimal load distribution of the new cascade cooling system is shown in Table 3.

Table 3: The optimal load distribution of the cascade cooling system

Device	F_1 (kg/s)	F_2 (kg/s)	T_1 (°C)	T_2 (°C)	Q_1 (kW)	Q_4 (kW)	Q_2 (kW)
A	14.3	29.6	30.20	12.01	1,376.47	715.38	185.88
B	14.2	29.1	30.13	12.06	1,366.84	703.30	258.00
C	14.1	29.2	30.23	12.03	1,357.22	705.72	219.88
D	14.5	29.9	30.16	12.05	1,395.72	722.63	134.19
E	14.5	29.8	30.12	12.02	1,395.72	720.22	147.78
F	7.9	16.6	30.37	12.03	760.43	401.19	158.66
SUM	79.5	164.2			7,652.40	3,968.44	1,104.40

2.3 Lithium bromide absorption refrigeration cycle

Absorption refrigeration used in this work is a single-effect LiBr/H_2O absorption refrigeration cycle. The cycle is simulated in Aspen Plus, and the ELECNRTL Equation of State is selected for the electrolyte system (Reid, 1988). The electrolyte guide in the software is used to generate a series of ionic reactions for key components of lithium bromide and water automatically. The flow diagram is shown in Figure 3 (Wang et al., 2018).

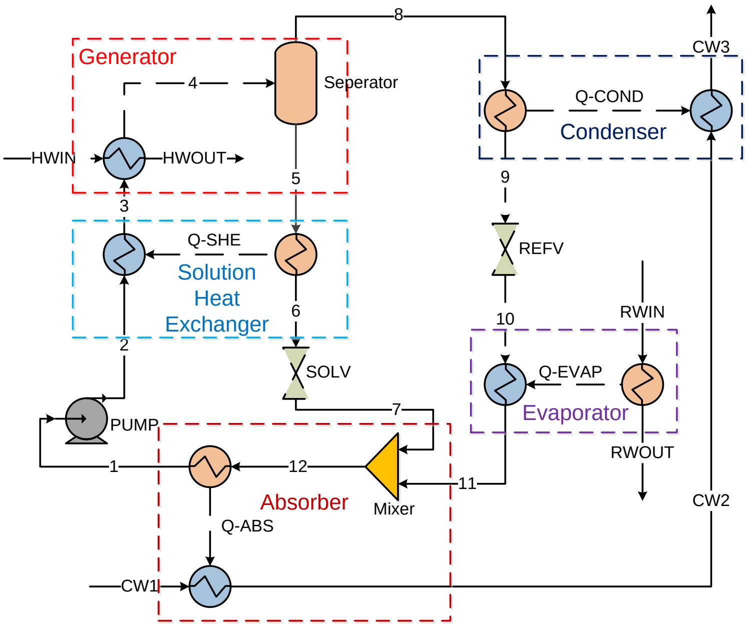

Figure 3: Schematic diagram of single-effect LiBr/H_2O absorption refrigeration cycle

The working fluid is the lithium bromide aqueous solution, whose original state is 36.62 °C, 800 Pa and the concentration is 0.58 (mass fraction). The efficiency of the solution heat exchanger is set as 0.64. Refrigerant water used in evaporator has the inlet temperature of 12 °C and outlet temperature of 7 °C, and its flow rate is 164.2 kg/s according to section 2.2. The cooling capacity of evaporator is 3,968.44 kW by calculating. Heat source of generator is the hot water used for waste heat recovery, whose inlet temperature is 122.23 °C and pressure is 0.28 MPa. While its outlet temperature is decided by the flow rate of hot water, the optimal flow rate of hot water will be discussed in section 3.

3. Optimization of hot water flow for waste heat recovery

For hot water, the inlet temperature in waste heat recovery is the same as the outlet temperature in generator in the LiBr/H_2O absorption refrigeration cycle, which is decided by the flow rate. It is noted that the flow rate not only affects the temperature of hot water, but also affects the COP, the flow rate of working fluid in the absorption refrigeration cycle and the amount of waste heat recovery. On the premise of meeting the fixed refrigeration demand (3,968.44 kW), this part takes various values of hot water flow rate, and the outlet temperature of hot water in generator, the flow rate of working fluid, the COP of the cycle and the total amount of waste heat recovery are calculated together. Through simulation and calculation, it is found that the absorption refrigeration cycle will be wrong when hot water flow rate is lower than 45.5 kg/s, so the flow rate of hot water is chosen to vary from 45.6 kg/s to 90 kg/s. Taking the hot water flow rate as the abscissa, plotting with the outlet temperature of hot water, the flow rate of working fluid, COP, and the total amount of waste heat recovery, the effects of changes in hot water flow rate is shown as Figure 4.

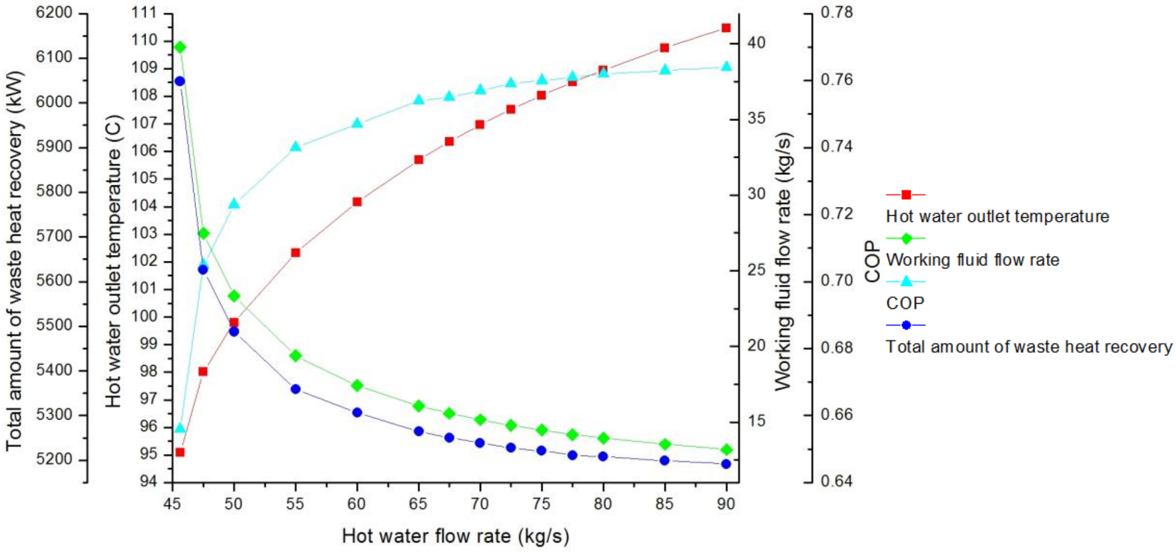

Figure 4: Effects of changes in hot water flow rate

As can be seen from Figure 4, with the increase of hot water flow rate, the outlet temperature of hot water in generator increases, and the value of COP for absorption refrigeration cycle increases rapidly first and then trends to be stable. The flow rate of working fluid required and the total amount of waste heat recovery decrease rapidly first and then trend to be stable. Since at least two pumps for hot water transport are required in each device, huge pump cost will be produced, indicating that using less hot water is advantageous in saving pump cost. But in order to ensure higher COP and less flow rate of working fluid, the better flow rate of hot water is selected as 47.5 kg/s. The capital cost of 12 hot water pumps is 1,692,026 ¥.

4. Results

Through the discussion in section 3, the hot water flow rate is 47.5 kg/s, and the temperature of hot water after waste heat recovery is 122.23 °C. The temperature drops to 98.01 °C after driving absorption refrigeration, and hot water provides 5,626.08 kW of heat. The absorption refrigeration cycle consumes 27.48 kg/s of working fluid and produces 3,968.44 kW of refrigerating capacity. The COP of the cycle is calculated as 0.705. The amount of waste heat recovery in each device is calculated as Q_3. Table 4 shows the total heat load of the two cooling processes.

Table 4: The total heat load of the two cooling processes (unit：kW)

Process	E-2	COOLER-3 (Q_3)	COOLER-1 (Q_1)	COOLER-4 (Q_4)	COOLER-2 (Q_2)	COMP (P)
Original	36,737.53	-	7,127.13	-	5,564.24	1,636.54
New	31,111.45	5,626.08	7,652.40	3,968.44	1,104.40	324.82

The waste heat recovered is 5,626.08 kW, which accounts for 15.31 % of the total waste heat. Waste heat recovered by hot water is used to drive absorption refrigeration, providing 3,968.44 kW of cold. The effective output ratio of waste heat is 70.54 %.

It can be seen from Table 4 that the cooling load of water cooling increases by 525.27 kW, and the cooling load of compression refrigeration decreases by 4,459.84 kW. As a result, the power of compressor decreases from 1,636.54 kW to 324.82 kW. The electric charge consumed by the compression refrigeration cycle in the new cooling process is calculated as 4,454,674 ¥/y. Compared with the electric energy cost of the original cooling process, the new process will save the electric charge by 17,988,754 ¥/y.

The new cascade cooling process needs to invest a set of LiBr/H_2O absorption refrigeration equipment. 6 waste heat recovery heat exchangers and 6 absorption refrigeration heat exchangers are required, and 6 compression refrigeration heat exchangers may also need to be replaced due to the reduction of load. 12 hot water pumps and 12 refrigerant water pumps are also required. The capital cost of new equipment and operating cost of pumps for the new process are calculated and shown in Table 5.

Table 5: The capital cost and operating cost for the new process

Items	Equipment	Number	Cost data
Capital cost (CC)	LiBr/H_2O absorption refrigeration equipment	1	3,911,477 ¥
	Heat exchanger	18	3,260,233 ¥
	Pump	24	3,482,939 ¥
Operating cost (OC)	Pump	24	1,491,431 ¥/y
	Compressor in compression refrigeration	6	4,454,674 ¥/y
Total annual cost (TAC)	TAC = Af × (CC) + OC (Af: annual factor)	Af = 0.264	8,758,932 ¥/y

The new process has a total annual cost of 8,758,932 ¥/y, while it saves electric charge by 17,988,754 ¥/y, so the final economic benefits obtained by the new cascade cooling process is 9,229,822 ¥/y.

5. Conclusions

In this paper, the cooling process of hot streams in the hydrochlorination plant in a polysilicon enterprise is simulated and calculated, and the new cascade cooling system is proposed. 5,626.08 kW of waste heat is recycled and 3,968.44 kW of cooling capacity is produced in absorption refrigeration through the optimization. The optimal load distribution of cascade cooling system is obtained, in which the load of water cooling has a slight increase and that of compression refrigeration decreases to a large extent. There is 4,459.84 kW of cooling load in compression refrigeration decreased, so as to reduce 1,311.72 kW of compressor power, and 17,988,754 ¥/y of electric charge is saved. Finally, taking the 8,758,932 ¥/y of capital cost and operating cost into account, the new process can obtain 9,229,822 ¥/y of economic benefits. It can be seen from the results that the new cascade cooling system has considerable energy saving ability and economic benefits. However, in the current work, the optimization of total cost and the segmentation point for the new process have not been taken into account. These considerations will be carried out in the future work.

References

Cao T., Lee H., Hwang Y., Radermacher R., Chun H.H., 2015, Performance investigation of engine waste heat powered absorption cycle cooling system for shipboard applications, Applied Thermal Engineering, 90, 820-830.

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

He Y., 2016, Study on the common basic problems of high efficiency comprehensive utilization of industrial waste heat, Science China Bulletin, 61, 1856-1857.

Leong Y.T., Chan W.M., Ho Y.K., Isma A.I.M.I.A., Chew I.M.L., 2017, Discovering the potential of absorption refrigeration system through industrial symbiotic waste heat recovery network, Chemical Engineering Transactions, 61, 1633-1638.

Liew P.Y., Alwi S.R.W., Manan Z.A., Kleme J.J., Varbanov P.S., 2015, Incorporating district cooling system in total site heat integration, Chemical Engineering Transactions, 45, 19-24.

Patel B., Kachhwaha S.S., Modi B., 2017, Thermodynamic Modelling and Parametric Study of a Two Stage Compression-Absorption Refrigeration System for Ice Cream Hardening Plant, Energy Procedia, 109, 190-202.

Reid R., Prausnitz J., Poling B., 1988, The Properties of Gases & Liquids, 4th ed, McGraw-Hill.

Wang M., Wang Y., Feng X., Deng C., Lan X., 2018, Energy Performance Comparison between Power and Absorption Refrigeration Cycles for Low Grade Waste Heat Recovery, ACS Sustainable Chemistry & Engineering, 6, 4614-4624.

Xu Y., Chen F., Wang Q., Han X., Li D., Chen G., 2015, A novel low-temperature absorption compression cascade refrigeration system, Applied Thermal Engineering, 75, 504-512.

Yang S., Wang Y., Gao J., Zhang Z., Liu Z., Olabi A.G., 2018, Performance Analysis of a Novel Cascade Absorption Refrigeration for Low-Grade Waste Heat Recovery, ACS Sustainable Chemistry & Engineering, 6, 8350-8363.

Zhang B.J., Zhang Z.L., Liu K., Chen Q.L., 2016, Network Modeling and Design for Low Grade Heat Recovery, Refrigeration, and Utilization in Industrial Parks, Industrial & Engineering Chemistry Research, 55, 9725-9737.