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## Review

A review of low-temperature heat recovery technologies for industry processes<sup>☆</sup>Li Xia<sup>1,\*</sup>, Renmin Liu<sup>1</sup>, Yiting Zeng<sup>1</sup>, Peng Zhou<sup>1</sup>, Jingjing Liu<sup>1</sup>, Xiaorong Cao<sup>2</sup>, Shuguang Xiang<sup>1,2,\*</sup><sup>1</sup> College of Chemical Engineering, Qingdao University of Science and Technology, Qingdao 266042, China<sup>2</sup> Chemistry and Chemistry Engineering Faculty, Qilu Normal University, Jinan 250013, China

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## ABSTRACT

The amount of low-temperature heat generated in industrial processes is high, but recycling is limited due to low grade and low recycling efficiency, which is one of the reasons for low energy efficiency. It implies that there is a great potential for low-temperature heat recovery and utilization. This article provided a detailed review of recent advances in the development of low-temperature thermal upgrades, power generation, refrigeration, and thermal energy storage. The detailed description will be given from the aspects of system structure improvement, work medium improvement, and thermodynamic and economic performance evaluation. It also pointed out the development bottlenecks and future development trends of various technologies. The low-temperature heat combined utilization technology can recover waste heat in an all-round and effective manner, and has great development prospects.

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## 1. Introduction

After the industrial revolution, the global energy consumption and carbon dioxide emissions increase, which makes the global resource and environment problem more and more serious [1]. The energy consumed in various industrial fields accounts for about 53% of the total energy consumption, due to the limitation of technical level, about 72% of the primary energy sources are wasted in the process of combustion and conversion [2]. Low grade heat accounts for about 60% of waste heat [3]. Even though the amount of waste heat is enormous, it is difficult to use due to its low grade and low energy efficiency in the process of utilization [4]. At present, there is no clear indication of the temperature range of low temperature heat. Ji *et al.* [5] refers to a heat source less than 230 °C as low-temperature heat, 230 to 650 °C as medium-temperature heat, and higher than 650 °C as high-temperature heat. The issues of environmental and resource have aroused interest in the recovery and use of low-grade heat sources. Low-grade heat sources include geothermal energy, biomass energy, solar heat, and industrial waste heat [6,7]. The effective recovery and utilization of low-temperature heat in industrial processes has become

an important way to increase energy efficiency, achieve energy conservation and reduce emission.

Low-temperature heat utilization technology covers many aspects such as heat pump, power generation, refrigeration, heat pipe, heat storage, process optimization, *etc.* Donnellan *et al.* [8] introduced the development of heat exchangers for low-temperature heat in the past 20 years. Garcia *et al.* [4] focused on the thermodynamic cycle of recovery of low-grade heat ORC (Organic Rankine Cycle) and TC (Trilateral Cycles) from a thermodynamic point of view. Ni *et al.* [9] reviewed the progress in the application of heat pumps in HVAC (Heating, Ventilating and Air Conditioning) systems at home and abroad. The abovementioned documents are only summarized in one aspect of low-temperature heat utilization. This article mainly summarizes the five aspects of low-temperature heat recovery, such as low-temperature heat upgrade utilization, power generation, refrigeration, thermal energy storage, and combined utilization. Both the system evaluation and the important issues of development are summarized in detail for each low-temperature heat utilization system. A low-temperature heat utilization technology framework was described. Moreover a more combined understanding of the present situation and future development trend of low-temperature heat technology is put forward.

## 2. Low-temperature Heat Upgrade Utilization

Low temperature heat is difficult to be used directly because of its low grade. The upgrading and utilization of low grade heat is an important way to recover industrial waste heat. In 1824, Carnot put forward the concept that refrigerators can also be used effectively for heating.

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The earliest heat pump can be traced back to this point. The performance of heat pump system is mainly characterized by COP (ratio of heating capacity to input power) [10]. Heat pump can be classified into absorption heat pump, compression heat pump, chemical heat pump, etc. The heat pump includes single-stage, two-stage, multi-stage, cascade and other types. Compared with single stage heat pump, multistage heat pump has higher performance and can operate effectively under cold conditions, which is a hot spot of research at present.

### 2.1. Absorption heat pump

AHP (absorption heat pump) is used to upgrade the temperature of heat source through the absorption-desorption of the working fluid [11], which includes generator, condenser, evaporator, absorber, heat exchanger, etc. Absorber is the most important device in AHP [12]. Due to the high exergy loss, it is usually necessary to increase the surface area to overcome this problem, resulting in a larger absorber volume [13,14]. Improving the efficiency of mass and heat transfer plays an important role in the performance of absorber, which has attracted the attention of many researchers [15,16]. The second law of thermodynamics can evaluate the performance of AHP very well. There are many references to analyze the energy and exergy of AHP. AHP can be divided into Type-I AHP and Type-II AHP. Type-I AHP is driven by fuel, gas, steam and low-temperature hot water, which plays a leading role in the recovery and utilization of oil field waste heat [11]. Type-II AHP can be driven by the medium-temperature of 60–150 °C in the petrochemical industry to produce high-temperature heat source [17].

The improvement of the working fluid has always been the focus of research on the AHP. Among the common working fluids, there are some problems. For example, ammonia has leakage problem. LiBr has problems of corrosion and crystallization. Some working pairs modified, LiBr–LiNO<sub>2</sub>–H<sub>2</sub>O, LiBr–ZnCl<sub>2</sub>–H<sub>2</sub>O can reduce corrosion by adding buffers [18]. In order to solve the crystallization of lithium bromide in the AHP, an overconcentration control system was developed by Martini *et al.* [19] Liao *et al.* [20] proposed a new method to improve the temperature of cooling water to reduce exhaust temperature, or set the entrance to prevent crystallization phenomenon. Wang and Chua *et al.* proposed that J tube technology is another way to prevent the crystallization of LiBr solution in a solution heat exchanger, which has been widely used [21].

On the other hand, single-effect AHP do not work effectively at low ambient temperatures and limit temperature rising [22]. Double-effect system has become an effective solution to solve this kind of problem. The double-effect AHP has a higher COP than a single-effect AHP. However, the double-effect AHP requires a higher heat source temperature requirement. Zhao *et al.* [23] studied the AHP with TFE/E181 as the working fluid. When the temperature of the high pressure generator is above 100 °C and the gross temperature rise is 30 °C, the COP of the double-effect absorption system was higher than that of the single-stage absorption system. A new type of open AHP (OAHP) that can operate in both modes is proposed by Ye *et al.* [24]. When the heat source temperature is 160–175 °C, it operates with a high COP in single-stage mode. When the heat source temperature is between 130 and 160 °C, it operates with a high COP in dual-stage mode operates. Wu *et al.* [25] studied a multi-effect air source AHP, which overcomes the disadvantages of the single-effect air source absorption heat pump that cannot work normally when the outside temperature is low. In extremely cold conditions, the energy saving rate reaches 7.73%. Farshi *et al.* [22] proposed a cascade system with ammonia and water as its working pair with the AHP. The thermodynamic analysis and comparison between CCAHP (cascad compression absorption heat pump) and CHP, AHP, CAHP (compression–absorption heat pump) were carried out. The compression of CCAHP is relatively small, and the maximum pressure and outlet temperature of the compressor are lower than other cycles. The range of temperature increasing is wider than other systems,

and the effective energy loss is distributed approximately among the various components. The performance of each improved system is shown in Table 1.

**Table 1**  
Comparison of different system performance

	Type	COP <sub>h</sub>	ζ	Temperature/°C
B. Ye [24]	Multi-effect AHP	1.52–1.97	15.1%–54.8%	135–175
W. Wu [25]	OAHP	1.27	7.73%	
L. G. Farshi [22]	Cascade AHP	5.18	80%	50–200
Y. Li [17]	IAHP	1.67–2.30	22.1%	40–80
F. Li [26]	Heat and Power Cogeneration		38.3%	≥90

Some researchers have successfully applied AHP systems in industrial processes. Li *et al.* [17] proposed a new type of distillation system using the residual heat from condenser of tower of the type-I AHP. The new system overcomes the limitation of applying scope of absorption heat pump in ordinary distillation. The average exergy efficiency is improved obviously. After optimization, the total steam consumption is reduced by 22.1%. Wang *et al.* [11] used a direct-fired AHP to recover waste heat from oily wastewater. The energy efficiency (ζ) was as high as 63%, and the annual gas consumption was about 1.8 million cubic meters. The gas heat recovery technology of gas cogeneration realized energy cascade utilization and solved the problem of recovery heat from flue gas (above 90 °C) [26]. In order to achieve cascade utilization, AHP and steam-water heat exchanger were heated step by step to design temperature. The improved heating efficiency of the system was increased by more than 38.3%, and the operating cost was reduced by 54.7 million yuans per year.

### 2.2. Compression heat pump

CHP (compression heat pump) composed of compressor, condenser, evaporator and throttle valve is a common low-temperature heat utilization technology. CHP is widely used because of its simple structure and low cost. In the evaporator, the refrigerant enters the compressor by endothermic evaporation. After adiabatic compression, the refrigerant gas at high temperature and low pressure changes into the gas at high temperature and high pressure. The refrigerant releases heat to the heat source in the condenser. After throttling, it turns into a low temperature and low pressure refrigerant. The heating capacity of compression heat pump is poor. When the outlet temperature is raised, the compression efficiency, heating capacity and COP could reduce [27]. At present, two-stage and multi-stage compression systems have emerged.

According to the number of refrigerant compressed, the compression heat pump is divided into single-stage and double-stage systems. The compression systems based on the number of compressors and the separation cycle [28]. As the two-stage compression system is operated in a cold area, the compression ratio at each stage is maintained at an appropriate value, so that the compression efficiency and the system performance are improved. The quasi-two-stage compression system has a compressor and a separate circuit. The refrigerant is compressed twice in the compressor, by reducing the compression ratio of each stage, and increasing the flow of refrigerant. The two-stage compression system, shown in Fig. 1(a), has two compressors in series and one independent circuit. Fig. 1(b) shows a cascade compression system with two compressors and two independent circuits. Refrigerant of cascade compression system can be selected according to operating conditions [29].

Using steam injection, variable speed compressors and steam injection technology improves the poor heating performance of single-stage compression systems in cold regions [29–31]. Yan *et al.* [32] designed a new type of dual-rotation frequency conversion compressor that can achieve single-stage compression and quasi-two-stage compression, which can adapt to changes in operating conditions. The cooling

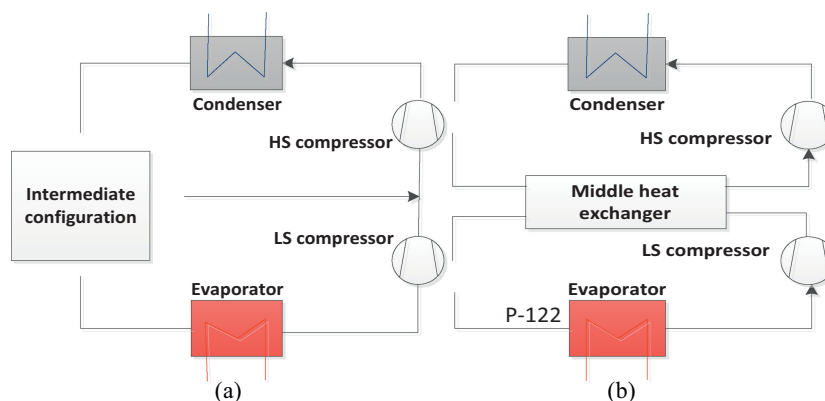


Fig. 1. Schematics of (a) two-stage compression system, (b) cascade compression system [29].

steam can be directly injected into the cylinder through two symmetrical injection holes on the middle plate, the heating capacity of the system is increased by 5.6% to 14.4%, and the COP is increased by 3.5%.

Two-stage compression systems and cascaded loops are good choices to improve system performance [33,34]. The cycle configuration of a two-stage compression heat pump system is focused on the FTC (flash tank cycle) in recent years [35]. In order to make effective use of the FTC, it is necessary to clarify the relationship between the configuration parameters and the main performance parameters. Li *et al.* [36] analyzed a two-stage compressed air source heat pump system based on FTC. Optimizing the thermal conductivity of the two heat exchangers maximizes COP of the heat pump system, which provides guidance for optimizing the air source heat pump system based on the FTC. In some two-stage compression systems, the mode can be switched between single-stage and dual-stage based on changing heat source temperature. Jiang *et al.* [37] studied a two-stage compression air source heat pump configured with inter-coolers, which operates in single or two-stage mode. The compressor frequency is variable. The average COP values for the entire heating season at different design temperatures were compared and analyzed to determine the optimum design temperature and the corresponding compressor cylinder volume ratio. Compared to conventional vapor compression heat pumps, CAHP systems can operate at much lower pressures and produce higher temperatures. Therefore, the CAHP system is suitable for applications with wide temperature variations and high temperature operating conditions [38]. In the comparative study of CAHP performance, many researchers have taken into account economic factors. Hultén *et al.* [39] took economic factors into account when comparing the COP of  $\text{NH}_3\text{-H}_2\text{O}$  CAHP and isobutylene compression heat pumps. From the comparison results, the performance of CAHP is high, but its cost is also high. Most of the current research on CAHP focuses on modeling and optimization methods [40], however CAHP has less research on specific industrial applications. CAHP theoretically has lower COP than CHP, but CAHP provides higher heat source temperature [10]. The  $\text{NH}_3\text{-H}_2\text{O}$ CAHP proposed by Wu *et al.* effectively operated at extremely low evaporator inlet temperatures [41, 42]. The gas separator is installed at the inlet of the compressor, and a set of filters is arranged at the outlet of the compressor to ensure the reliable operation of the compressor. At generator inlet temperature of 130 °C, CAHP increases heating capacity by 96.4% compared to AHP.

### 2.3. Chemical heat pump

The chemical heat pump with high thermodynamic efficiency does not require electric power, using reversible chemical reaction to change the thermal energy stored in the chemical. It will not cause the loss of heat by temperature difference. Chemical heat pump can recover low-temperature heat about 333 K–353 K [43]. It can also be used to recover ultra-low temperature heat of 30–100 °C [44]. Recently, solid–gas and liquid–gas heat pump has continuously developed, and systems with multiple components have emerged [45]. The forward and reverse

reactions in chemical heat pump reactor react at different temperatures, thus increasing the heat from low temperature to higher temperature. Chemical heat pump applications have a variety of working pairs, including water systems, ammonia systems, sulfur dioxide systems, and hydrogen systems. Chemical heat pump involves gas–liquid absorption process or solid–gas adsorption process [46,47]. COP and exergy efficiency are commonly used to evaluate the thermodynamic properties of a system. The new concept of thermal efficiency has proved to be a reasonable criterion for performance evaluation [48].

Isopropanol–acetone–hydrogen (IAH) chemical heat pump is a type of gas–liquid chemical heat pump. Isopropanol completes the dehydrogenation reaction with low-temperature heat driven in an endothermic reactor. Acetone and isopropanol separated which was then compressed by the compressor. Acetone was heated to the reaction temperature in the regenerator. Acetone and hydrogen were completed reaction in the exothermic reactor and high-temperature heat was released [48]. The principle is shown in Fig. 2. The design of catalyst, performance evaluation and reactor design in IAH–chemical heat pump system are the key points of the research [49–53]. Gandia *et al.* [51] first studied the main factors affecting the reactor and distillation column in the IAH–chemical heat pump system, and then performed a two-hour operation test to analyze the thermal and economic performance of the system. Xu *et al.* [54] proposed the IAH–chemical heat pump exothermic reactor cascade device, which overcomes the problem that the higher reaction temperature will reduce the equilibrium conversion of acetone and the heat release of the system. When the maximum exothermic temperature was 493 K, compared with the IAH–chemical heat pump system of a single exothermic reactor, the COP and exergy efficiency increase by 7.6% and 10.3%, respectively. In addition to advanced structure, some researchers have evaluated and

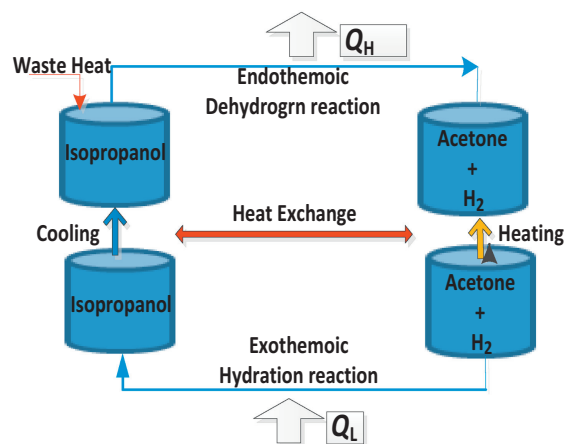


Fig. 2. Schematics of IAH–chemical heat pump system [61].

optimized their thermodynamic properties [55]. Kim *et al.* [56] established a mathematical model of the IAH-chemical heat pump system and evaluated its thermodynamic properties. The results show that the optimal COP and exergy efficiency are 0.18 and 0.268, the input temperature is 80 °C, and the output temperature is 200 °C. However, most of the studies are based on numerical simulation and few experimental models. Xu *et al.* [48] constructed an IAH-chemical heat pump experimental prototype and evaluated its economic analysis of the technology. The waste heat temperature increased from 95 °C to 136 °C. COP and the thermal efficiencies were 0.38 and 0.27, respectively.

Thermal economic analysis results show that the total investment cost of the 100 kW IAH-chemical heat pump system is approximately 59674 USD. On the best condition, the payback period is 5.6 years.

For the solid–gas, the single-stage metal hydride heat pump has disadvantages such as low COP and limitation of temperature range, which can be overcome by multiple stages. Multi-stage systems have been developed in recent years in terms of thermodynamic analysis and experiments [57–59]. Satheesh *et al.* [60] studied a multi-stage and multi effect CHP using  $\text{LaNi}_{4.1}\text{Al}_{0.51}\text{Mn}_{0.38}$ ,  $\text{LaNi}_{4.91}\text{Sn}_{0.15}$  and  $\text{Ti}_{0.99}\text{Zr}_{0.01}\text{V}_{0.48}\text{Fe}_{0.09}\text{Cr}_{0.05}\text{Mn}_{1.5}$  as the working pairs, and introduced the half-cycle time, the hydride mass ratio (air bed quality/hydride mass), the effect of sensible heat exchange coefficient and operating temperature on the performance of the DSDE-MHHP system.

Saha *et al.* [62] conducted a detailed study of an advanced dual-mode adsorption chiller, which can be operated not only small regenerative temperature rise (10 K), but also medium regenerative temperature rise (50 K). Fixed beds require adsorbents to repeatedly switch between adsorption and desorption modes, which result in loss of irreversible heat. Adsorption chemical heat pump usually uses zeolite and silica gel as adsorbent. The traditional adsorbent has some shortcomings, which lead to the degradation of system performance. Some researchers pay attention to the modification of adsorbent. Mastronardo *et al.* [63] used the newly developed mixed material of magnesium hydroxide and carbon nano tubes as the heat storage medium for the  $\text{MgO}/\text{H}_2\text{O}/\text{Mg}(\text{OH})_2$  chemical heat pump and studied its thermo chemical properties. Calabrese *et al.* [64] proposed a novel method based on the use of composite SAPO-34 filled silicone foam for innovative adsorbent, which can improve the adsorption surface area without changing the dynamic performance of the adsorption pump. Van der Pal *et al.* [65] refers to two kinds of MOFs, CPO-27(Ni) and aluminum fumarate, both of which have high water absorption, thermal stability and high surface area, so they can be used in chemical heat pump. Herzog *et al.* [66] studied how to replace adsorbent to improve the operating range of the zeolite-driven heat pump or thermo chemical storage system. Zeolite ion exchange could improve the adsorption of energy density. Organic molecules instead water that does not improve the adsorption performance. It also affects the performance parameters of the adsorption heat pump due to the low cumulative adsorption capacity and higher desorption temperatures.

### 3. Low-temperature Heat Power Generation

#### 3.1. Organic rankine cycle

ORC (Organic Rankine Cycle) takes organics with low boiling point as working fluid. In the process of circulation, low boiling organics is endothermic vaporizing, expanding work done to drive generator. The working principle of ORC is shown in Fig. 3. It is often used to recover industrial waste heat and renewable heat source (biomass, solar, geothermal, or oceanic energy) [67]. Evaporator is an important part of the ORC system which main function is to transfer low-temperature heat to the working fluid to cause phase change. Some researchers perform multi-objective optimizations to improve the performance of the system. Turbine is widely used in ORC because of simple structure, light weight and high efficiency. Some researchers have summarized turbine

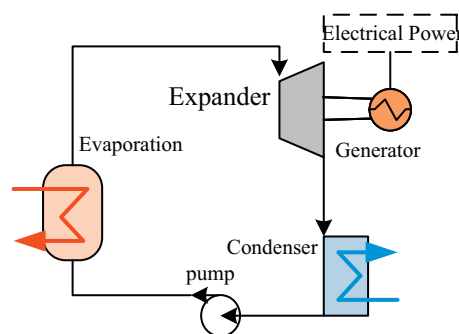


Fig. 3. Schematic diagram of ORC.

optimization from different aspects [68]. Tables 2, 3 summarize the performance evaluation of ORC system. In addition to the thermodynamic analysis of the entire system during the performance evaluation of the ORC, the exergy efficiency analysis of single important component could also be performed.

**Table 2**  
Optimization method of evaporator in ORC

Reference	Type	Optimization Method
[69]	Plate	Using the NSGA-II method to optimize the geometry of the plate evaporator with the objective function of minimum pressure drop and cost
[70]	Shell and tube	Exergoeconomic analysis of the system using SECM, also analyzing the effect of imported water on system performance
[71]		ORC system performance with new brazed nickel foam plate heat exchangers
[72]	Fine and tube	Application of Particle Swarm Optimization (PSO) Algorithm in Multi-objective Finned Tube Evaporator
[73]	Plate/Shell and tube	Outlet superheat of ORC systems for different types of evaporators is analyzed

The key element of ORC design is the selection of working fluid and turbine. The improvement of turbine has been summarized above, and the computer aided molecular design method has been considered for the selection of working pairs [82,83], but it needs powerful optimization algorithm and database [84].

Thermal efficiency is an important parameter to evaluate the performance of working fluids. It is generally obtained by the calculation of enthalpy equilibrium equation, performance diagram or state equation. It can also be calculated by experimental performance diagram. Liu *et al.* [85] deduced the analytical expression of the ORC thermal efficiency for the approximate isentropic fluid through the entropy relationship and the Watson equation, but it is not accurate. Li *et al.* [86] established the theoretical expression of the thermal efficiency of ORC through the second law of thermodynamics, which provides the basis for the simulation, optimization design, and working fluid selection of ORC, and took  $cT_3/r$  ( $T_3$  is the evaporating temperature,  $r$  is the heat of evaporation at the evaporating temperature, and  $c$  is the average heat capacity of the saturated liquid) as key parameters of the working fluid. The ORC operating in the trans-critical region has better performance than in the subcritical region, but the heat transfer area and cost increase [87]. Non-azeotropic mixture improves the temperature slip in the evaporator and condenser, resulting in improved system performance [88–90]. Satanphol *et al.* [91] studied the application potential of non-azeotropic mixtures in low-temperature heat recovery and found that non-azeotrope working fluids R-218/227ea/C318/245fa have better performance. The addition of the third component to the binary fluid provides a significant improvement in power output and cycle efficiency compared to the original binary fluid.

In addition to working fluids and hardware components, the main considerations for optimizing ORC include heat source type, control



**Table 3**  
Optimization method of turbine in ORC

Reference	Working fluid	Simulation	Centry
[74]	R143a	3D	Radial-inflow
[75]	R143a/R1234yf/R245fa/cyclohexane/N-pentane	0D	Radial Turbo-expander
[76]	Air/R123		Radial-inflow
[77]	R134a/R245fa/R123/R236ea/N-pentane/Isobutene	Mean-linemode (G.A)	Radial-inflow
[78]	R365mfc/R236fa/R123/R245fa/N-pentane/Isobutene	Mean-line mode DIRECT	Small-scale Radical turbine
[79]		Mean-line mode 3D	Radial-inflow
[80]	R123/R600/ R236fa/ R245fa/ R245ca	1D	Radial inflow
[81]	R1416/R245fa/N-pentane	Mean-line mode 3D CFD	Small-scale Two-stage axial Turbine

strategy, and component layout and size [92]. From the perspective of the whole ORC structure, several alternatives to single-level ORC have been proposed. Among them, the two-stage ORC is optimized by some scholars for thermodynamics [93,94]. It is also a research direction to make the ORC structure more compact and effective. Pump-free ORC (PORC) and micro-ORC have been proposed [95]. Bao *et al.* [96] analyzed PORC from a thermodynamic point of view and compared it with a re-absorption power generation cycle. It was found that PORC has a higher working output thermal efficiency in most cases. Many experimental prototypes about micro ORC have appeared, but its market application is limited [97,98]. Thermodynamic research mainly involves the characterization of ORC expanders [99]. Yu *et al.* [100,101] proposed a new transcritical cascade organic ORC cycle C-ORC system composed of HT-Loop and LT-Loop to recover multistage waste heat of heavy duty diesel engine. It also assesses technology, costs, and benefits in terms of energy and exergy.

### 3.2. Kalina cycle

In the 1980s, Kalina proposed a thermodynamic power cycle with high thermoelectric efficiency using ammonia-water as the working medium. It is suitable for using in low and medium-temperature heat sources and small-power demand [102]. The ammonia gas is volatilized of the mixed working fluid during the heating. The reduction of residual liquid concentration increases the saturated vapor pressure, and the system is more flexible than zeotropic evaporation. The schematic diagram is shown in Fig. 4. In different KC system, KCS-11 is an efficient use of geothermal energy, which has been studied by many researchers [104–106]. Zare *et al.* [107] proposed an improved Kalina cycle design for low-temperature geothermal power generation. TEG uses part of the waste heat from KCS-11 to convert it into electricity. The net output power, energy and exergy efficiency can be increased by 7.3%. For low-temperature heat sources, Kalina proposed the KCS-34 power cycle, and

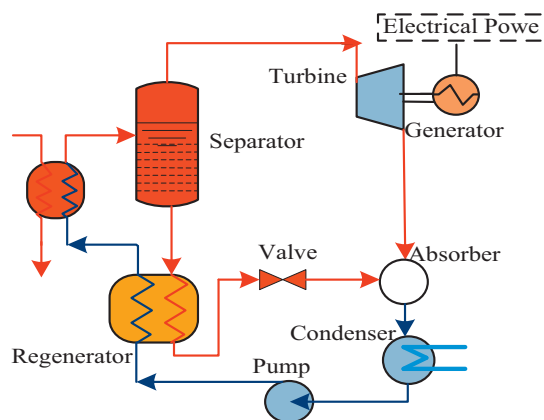


Fig. 4. Schematic diagram of KC [103].

the researchers improved its performance improved them from different perspectives [108,109]. The turbine expansion of KCS-34 cycle is relatively high, which requires multi-stage turbine. Lengert *et al.* proposed a new power cycle KSG-1 by change the position of heat exchanger in KCS-34. The instability of industrial waste heat causes KC to operate under non-design conditions, resulting in system performance deviating from the design value. Adjusting the mass fraction of ammonia in the KC can increase the average thermal efficiency [110]. In addition to the sliding condensation pressure method, the condensation pressure is controlled to match the cycle with the changing ambient temperature [111,112]. The expansion pressure ratio and net power output of the turbine can be significantly increased. The exergy loss in the condenser can be significantly reduced when the ambient temperature decreases. In the case of sliding condensation pressure, adjusting the ammonia mass fraction has little effect on the system efficiency [113]. Wang *et al.* [114] proposed a compositionally adjustable KC that has higher annual average thermal efficiency than a conventional cycle with a fixed mixture composition, but the investment cost increased. Guo *et al.* [115] adopts double pressure vaporization KC to further improve the cycle efficiency and reduce the exhaust temperature of heat source. The optimum technological parameters obtained under the design conditions are that the corresponding power recovery efficiency of double pressure vaporization KC reaches 27%.

The condensation pressure of ammonia water mixture is high at ambient temperature. Cao *et al.* [103] inserts the flash tank into DCSS modified KC, which makes the system reduce the condensation pressure of ammonia mixture and make full use of the ammonia poor solution at high temperature and high pressure. Under the optimum conditions, KFC (Kalina Flash Cycle) can achieve higher exergy efficiency than KC, and is superior to KC in thermodynamics and economic performance. Eller *et al.* [116] used a new non-azeotrope mixture of alcohol/water and alcohol/alcohol as the working medium of KC, and compared it with the sub-critical and supercritical ORC based on the second law efficiency. The mixture of alcohol and alcohol can improve the secondary efficiency of KC. Especially using heat source above 250 °C, the efficiency is improved by 16%–75%. Khankari *et al.* [117] used the alcohol/alcohol mixture as the working pairs to improve the efficiency of the second law of KC, and conducted a detailed evaluation of the operating parameters of the KC whose working medium was a novel ethanol/hexanol mixture.

## 4. Low-temperature Heat Refrigerate

### 4.1. Absorption refrigeration

Absorption refrigeration driven by low-temperature thermal energy achieves the purpose of cooling and heating double layers without atmospheric pollutants. Some researchers have established double-effect and three-effect systems. Although the efficiency of heat sources for double-effect recycling is high, investment costs increase [118].

#### 4.1.1. LiBr absorption refrigeration

LiBr refrigeration can use a large amount of waste heat to recycle secondary energy, including generators, absorbers, condensers, evaporators and other components.

As with AHP, absorbers play a key role in the performance of the system. The performance of the absorber is usually increased by adjusting the vapor–liquid phase area of the absorber, such as an absorber using steam through a liquid solution and an absorber using a fine solution droplet spray [119,120]. In order to reduce the size of the absorbent body, Zacarías *et al.* [121] considered the use of full-cone nozzles for droplets of LiBr/water solution. Palacios *et al.* [122] considered using flat blades using nozzles. Osta-Omar *et al.* [123] configured adiabatic absorbers in LiBr based micro-adsorption/absorption refrigeration systems to optimize the vapor–liquid interface area and improve system efficiency. The addition of new configurations in the LiBr cycle can improve the performance of the system. The COP of the absorption-injection refrigeration system is higher than that of a single absorption refrigeration system, and the temperature rise is also high [124,125]. This is also a research focused on refrigeration systems. Majidi *et al.* [126] combined a single-effect absorption refrigeration system with an ejector to use the potential kinetic energy of the original gas flow to achieve the goal of reducing energy consumption and improving system performance. The COP was increased by up to 60%. However, the ejector manufacturing cost is inefficient. Xu *et al.* [127] proposed a new type of LiBr cycle, which includes the absorption cycle of absorption generator heat exchanger, which can use 80–150 °C heat, and can also operate in single-effect and double-effect modes, with COP in single-effect mode ranging from 0.75 to 1.08.

In the refrigeration system with LiBr–H<sub>2</sub>O working pairs, LiBr–H<sub>2</sub>O requires a high recycle ratio. Some scholars are dedicated to finding alternatives to LiBr. In the same working conditions, LiCl–H<sub>2</sub>O has a circular greater vapor pressure and low ratio than LiBr–H<sub>2</sub>O [128], which decreases the energy consumption of high pressure circulating. She *et al.* [129] proposed a new low-grade heat-driven absorption refrigeration system. LiCl–H<sub>2</sub>O with higher vapor pressure was used as the working pairs in the high pressure cycle, and LiBr–H<sub>2</sub>O used in the low pressure cycle. Li *et al.* [130] proposed a new single-stage solar absorption refrigeration cycle with CaCl<sub>2</sub>–LiBr–LiNO<sub>3</sub>/H<sub>2</sub>O as the working fluid. Under the same cooling conditions, COP (0.805) is higher than LiBr/H<sub>2</sub>O and the corrosion rate is small. The research of ORC mainly focused on the selection of working fluid and optimization of internal operating parameters. The research on the economic performance of LiBr absorption refrigeration system was limited to calculation and optimization of the area of heat exchangers. Wu *et al.* [131] compared with ORC and LiBr absorption refrigeration cycle performance. Adsorption refrigeration cycles and ORCs using non-azeotrope working fluids have better thermal economic performance than ORC systems using pure working fluids.

#### 4.1.2. Ammonia absorption refrigeration

The ammonia absorption refrigeration cycle consists of two cycles of circulation of refrigerant ammonia and circulation of absorbent water. The NH<sub>3</sub>–H<sub>2</sub>O has excellent heat and mass transfer characteristics, but it needs to remove water vapor from the ammonia refrigerant as much as possible, which will lead to a decrease in the performance of the system. Some researchers tried to join the working medium pairs. Salt overcomes this shortcoming [132,133]. The addition of LiBr allows the ammonia molecules to be more easily separated from the aqueous solution in the generator, allowing the system to have higher performance but hindering the absorption of NH<sub>3</sub> molecules by dilute solutions. Liang *et al.* [134] proposed a new NH<sub>3</sub>–H<sub>2</sub>O–LiBr absorption cycle, using an electro dialysis device to separate LiBr from the solution entering the absorber, leaving LiBr as much as possible in the generator. When the LiBr mass fraction is high, the separation of LiBr can reduce the operating temperature and significantly improve the performance of the ternary absorption cycle. Cai *et al.* [135] analyzed the thermal performance of a single-effect absorption refrigeration cycle using NH<sub>3</sub>–

LiNO<sub>3</sub> and NH<sub>4</sub>SCN–NaSCN as the working pairs. The actual COP value of the NH<sub>3</sub>–NaSCN system is between 0.20 and 0.35, which is slightly higher than the NH<sub>3</sub>–LiNO<sub>3</sub> system (actually measured COP range is from 0.15 to 0.29). This study demonstrated the feasibility and capability of an ammonia/salt absorption refrigeration cycle for refrigeration under air-cooled conditions.

Due to the relatively high irreversibility of the ammonia absorption system [136], the system COP is lower. System performance can be improved by the use of a solution heat exchanger (SHE) or a refrigerant heat exchanger (RHE) to recovery internal heat [137]. There is a temperature overlap between the absorber and the generator in ammonia water absorption cycle [138], such that the GAX cycle has higher superiority [139]. If the gas (generator absorber heat exchange) effect is not available, Chen *et al.* [137] proposed combining the solution recirculation with the heat integration of the rectifier when operating the chiller at high temperature or low heat source temperatures. Compared with the traditional single-effect cycle, COP increased by 24%. A single-stage ammonia absorption refrigeration system does not operate when the temperature of the heat source is low. At present, there are two types of two-stage absorption refrigeration cycles: thermal coupling and mass coupling [140,141]. Du *et al.* [142] analyzed the maximum internal heat recovery of a mass-coupled two-stage ammonia absorption refrigeration system using a fitting technique. The minimum system heat input and related thermal matching are determined by the problem table method and the grid method. The COP is increased by 34.1% compared to the conventional system. The use of carbon dioxide as a working fluid in the refrigeration cycle is increasingly gaining attention as potential. However, due to the high pressure difference between the evaporator and the condenser, the use of carbon dioxide as a working fluid in a single-stage refrigeration cycle is generally uneconomical [143]. CO<sub>2</sub>/NH<sub>3</sub> cascade refrigeration system has emerged [144–146]. Mosaffa *et al.* [143] conducted an economic and environmental analysis of two CO<sub>2</sub>/NH<sub>3</sub> cascade refrigeration systems equipped with two flash tanks. A flash tank intercooler equipped with a flash tank and another indirect equipped with a cooler. It achieved the best balance between the exergy losses and the capital costs.

#### 4.2. Adsorption refrigeration

Adsorption refrigeration uses a wide range of heat source temperatures, compared with absorption refrigeration. There is no crystallization problem [147]. In recent years, low heat and mass transfer performance has become the technical bottleneck of adsorption refrigeration [148]. Adsorption cycle includes four types: heat recovery, mass recovery, heat, mass recovery and cascade recovery. The principle is shown in Fig. 5. (See Fig. 6.)

The heat recovery is generally in a two-bed or multi-bed system. After switching between adsorption and desorption, the cooling/heating medium is immediately circulated between the hot and cold adsorbers. A part of the heat of the adsorber is recovered and the COP is increased by about 25%. The mass recovery uses the pressure difference between the desorption of the adsorption bed and the completion of the adsorption. The two beds are connected to promote further desorption of the high-pressure strong adsorption bed. The desorption refrigerant is adsorbed by the low-pressure strong adsorption bed, which increases the cooling capacity of the system.

The heat of the high-temperature bed transfers to the cryogenic bed. It recovers some of the sensible heat of the system. The mass and heat recovery combines heat recovery with the mass recovery. The time of the heat recovery and the mass recovery is appropriate. The COP and SOP of the system will increase. The mass and heat recovery cycle is one of the most commonly cycles used. The cascade system utilizes different operating temperature ranges for different working fluids. It allowed the high temperature heat source and the low temperature heat source to drive different working fluid pairs, respectively. The COP and SCP are improved [151]. Qu *et al.* [152] has developed an

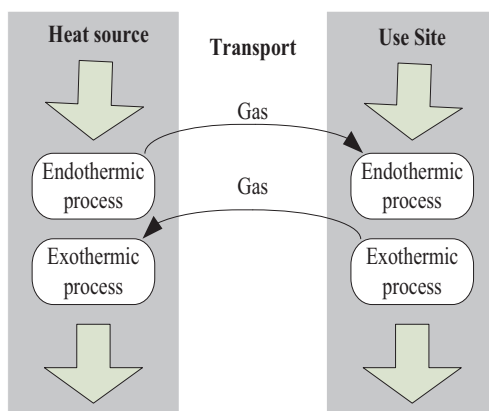


Fig. 5. Schematic diagram of adsorption cycle [149].

adsorptive air conditioning system with activated carbon/methanol as adsorption pair using heat recovery. The heat capacity ratio of bed metal and hot fluid to activated carbon is  $R_m = 1.35$  and  $R_f = 1.4998$  respectively. When oil is used as heat transfer fluid,  $R_f$  becomes 0.5. The performance of the system will be improved by adding heating and cooling processes to the regenerative cycle. Akahira *et al.* [153] added heating and cooling processes to the mass recovery cycle to speed up the desorption and adsorption processes and increase the cooling capacity of the system. Compared with the conventional recycling cycle, the cycle has a long COP, but the energy efficiency is improved. Wang *et al.* [154] studied a double adsorption air conditioning system using a mass recovery cycle. The COP can reach 0.5 when the heat source temperature is 100 °C in the test cycle. Alam *et al.* [155] proposed and analyzed a new method for four-bed adsorption refrigeration. Use the different pressures maintained by the heat exchanger to achieve a high cooling effect. The COP is higher than the traditional twin-bed system, and the cooling effect is better than the double-stage chiller. The adsorption and desorption process of  $\text{CaCl}_2$ -activated carbon adsorbed system with or without return cycle was studied by Wang *et al.* [156]. He compared it with the equilibrium adsorption. In the case of the mass recovery cycle, SOP and COP are greatly improved, and the adsorption and desorption ratio and adsorption capacity are also

improved. Lu *et al.* [157] optimized the performance of the absorption cogeneration system with the stabilization unit and the regenerative heat recovery cycle. The  $\text{SrCl}_2\text{-MnCl}_2$  working medium performed better in the optimized cycle. After the heat recovery cycle is increased, the cooling capacity of the system is improved. The combined heat and power system has the advantages of low heating, simple operation, and high COP. Dakkama *et al.* [158] simulated a cascade system with five different refrigerant pairs. The use of industrial low-temperature heat to produce colder cold has greater potential for ice making. The cascade system proposed by Liu *et al.* [159] consists of two high-temperature zeolite adsorption beds and one low-temperature silica adsorption bed. Water is a refrigerant. The two zeolite beds can regenerate heat, and the zeolite bed and silica gel bed can also transfer heat. The COP of 1.3 is more than twice that of the intermittent cycle. The return to the heat is higher than 0.8, but the SCP value is low.

## 5. Low-temperature Thermal Energy Storage

To a certain extent, TES (Thermal energy storage) technology solves the problem of different time between heat source and heat demanding users. It can be stored for a long period of time or can be stored for a short period of time. TES mainly includes sensible heat storage, latent heat storage, and thermo chemical heat storage. The thermo chemical heat storage can store higher quality heat, but the system is complex. The sensible heat storage system is simple and widely used. The transfer process of latent heat storage heat is stable and the heat storage density is high [160].

On the other hand, the successful implementation of TES depends on the long-term thermal stability and corrosion characteristics of phase change materials (PCM). G. Alva *et al.* [161] has a detailed summary of the problems in the TES application process including poor heat transfer, leakage control, etc. G. R. Dheep *et al.* [162] studied the thermal reliability and corrosion characteristics of glutaric acid after two thousand accelerated thermal cycling tests. M. Walczak *et al.* [163] described the possibility of affecting the generalized and local corrosion of the TES system, providing a comprehensive summary of the uniform corrosion rate determined by common and uncommon alloys used in TES.

PCMs (phase change materials) include organic materials such as fatty acids, sugar alcohols, inorganic materials such as salts, salt hydrates, and metals. PCMs should ensure that the phase transition temperature is

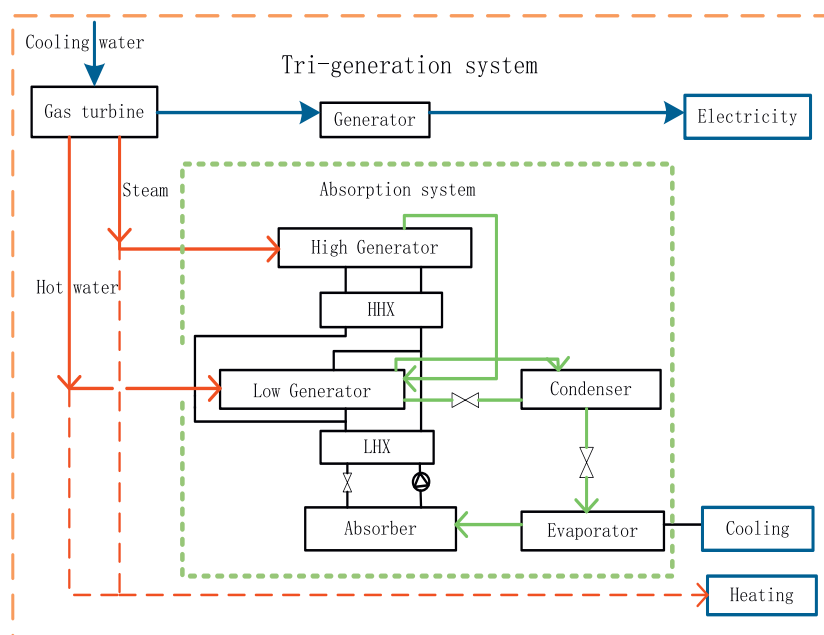


Fig. 6. Schematic diagram of Tri-generation [150].

within the operating temperature range of the system and has a high storage density and thermal conductivity [164]. The thermal expansion coefficient should be specified at design to avoid leakage [165]. PCMs have low thermal conductivity, they are not stable over a long period of time, and are incompatible with container materials [166]. Methods for selecting high performance PCMs can be found in references [167]. In order to solve the compatibility of PCMs with metals, Krishna *et al.* [166] used the immersion corrosion test to predict the corrosion rate, and gave detailed step-by-step methods and preventive measures for evaluating metal corrosion rates with PCMs. In order to solve the clogging problem caused by solidification deposition of PCMs, Wang *et al.* [168] proposed that the QC (quick channel) formed by using an electric heater in direct contact with the M-TES container can be used to solve the jamming problem. By using QC, the heat transfer fluid easily flows through the PCMs, enhancing convective heat transfer. Although the formation of QC consumes a small part of heat storage heat, overall, QC is a suitable choice for solving the blocking problem. Some researchers continue to research new PCMs to improve the performance of thermal storage systems. The references [169] proposed the halide salt PCMs and measured ammonia adsorption/desorption thermodynamic properties. Thermal energy available in a wide temperature range of 100–210°C is stored as ammonia desorption enthalpies of aminated salts ( $\text{MnCl}_2$ ,  $\text{FeCl}_2$ ,  $\text{CaCl}_2$  and  $\text{SrCl}_2$ ). Karthik *et al.* [170] produced a P-wax/G-foam composite by impregnation using an impregnation method (impregnation ratio of 78%). Jiang *et al.* [171] developed a new and stable  $\text{LiNO}_3$ - $\text{NaNO}_3$ - $\text{KNO}_3$ - $\text{Ca}(\text{NO}_3)_2$ /calcium silicate composite using cold-press sintering technology. Both materials have low melting point, high thermal conductivity and excellent stability.

TES can solve the problem of mismatch between heat demand and heat source in distance and time. Deckert *et al.* [172] proposed a mobile latent heat storage system that uses salt water as an energy storage material. Each cycle of transport volume is  $1500 \text{ kW} \cdot \text{h}^{-1}$ , and 200 cycles can be run each year. The distance between the heat source and the hot trap in the pilot operation is 5.6 km, and the profit is 2.4 carats per kW.

## 6. Low-temperature Heat Combined Utilization System

The single-function low-temperature heat utilization system will be limited by the change of the heat source temperature or the user's demand in the actual production. The current direction development is the combined utilization. For example, the heat pump can be integrated into the combined heat and power system to form a power generation-refrigeration-heating, or tri-generation systems. Heat pump systems and thermal energy storage systems all play an important role in energy saving. A new idea is to combine the cascade heat pump system with the heat storage technology to develop a high pressure specific heat pump circulation system that can operate at low ambient temperatures. Zhang [173] combined the cascade heat pump system with the heat storage technology, developed a high-pressure specific heat pump cycle using PCM, and used a particulate compound of 75 wt% paraffin and 25 wt% expanded graphite as PCM. When the ambient temperature is high, the cascade type air source heat pump system runs single stage (COP 1.5–3.05) heating mode. When the ambient temperature is reduced to a certain degree, the system switches to the cascade heating mode (COP is 1.74–2.55).

The ORC system and the inverse Carnot cycle based heat pump have similar main components. Its working fluid makes it possible to integrate the expansion and compression functions into one machine while simultaneously generating and heating. The system can increase the temperature range of available heat sources and reduce the investment cost compared to two separate devices. Therefore, the composite system is particularly suitable for applications where it is difficult for a single function to cover a variable heat source temperature range and meet a variety of user needs. A composite system was designed that

can realize the dual function of power production, and evaluated the two models of power generation and heat pump [174].

The tri-generation system can generate electricity at the same time, cooling/heating. In addition, it also recovers heat generated by power generation. Therefore, it is highly energy-efficient. Compared with traditional systems, it can save more energy and emit fewer greenhouse gases, which can solve the imbalance of power demand in summer. M. Yang *et al.* [150] studied a tri-generation system that uses high-temperature steam and hot water as multiple heat sources to generate electricity for cooling and heating. The authors innovatively analyzed the effect of heat source ratio on COP and the ability of multiple heat source double effect absorption cycles in the tri-generation system. Rashidi *et al.* [175] combined the KC and a single-effect lithium bromide-water absorption chiller with the KLACC (Kalina lithium bromide absorption chiller cycle). The total annual cost of the KLACC system has increased, but the refrigeration efficiency of the KLACC has increased and can be applied to cooling power generation without considering economic factors.

## 7. Conclusions

This article reviews the recent development of low-temperature heat utilization in the industrial field in terms of low-temperature heat upgrade utilization, power generation, refrigeration, thermal energy storage, and combined utilization. It is worth noting that the selection and modification of the working pairs through the various technologies mentioned above play a key role.

The heat pump upgrades the low-grade heat to make recycling easier. Various types of heat pumps are developing to multiple stages and cascades. This article also summarizes the efficiency improvement of other heat pump systems. The most widely used thermodynamic cycles for converting low-grade thermal energy into electricity are the ORC and KC. The two cycles have their own advantages and disadvantages, and the most suitable ones are different. Each part of the thermodynamic cycle system has a crucial influence on the exergy efficiency of the system. Therefore, the improvement of the system structure becomes an important direction to increase its thermodynamic performance. Refrigeration technology is also used for low-temperature heat recovery. The refrigeration system has a similar structure to the heat pump system. In addition to the improvement of the working medium, GAX absorption cycle cooling system has also attracted the attention of some scholars. Thermal energy storage compensates for the mismatch between the heat source and the heat sink, and is also one of the key technologies for low-temperature heat utilization. In addition, the combined utilization of technology has also become a hot issue. The literature has introduced the combined heat and power system, heat pump and heat storage technology combined system and three-function system.

In the current, the apple of system performance is mainly based on thermodynamic exergy efficiency and energy efficiency. Only one article in the range known by the author has used pyrolysis efficiency to evaluate the performance of low-temperature heat recovery systems. On the other hand, although low-temperature heat utilization technologies are diverse, there are no literatures that provide detailed and combined comparisons of the optimal application scenarios and conditions for each technology. This will likely become a hot area in the future.

## References

- [1] V. Minea, Power generation with orc machines using low-grade waste heat or renewable energy, *Appl. Therm. Eng.* 69 (1–2) (2014) 143–154.
- [2] C. Forman, I.K. Muritala, R. Pardemann, *et al.*, Estimating the global waste heat potential, *Renew. Sust. Energ. Rev.* 57 (2016) 1568–1579.
- [3] T.X. Li, R.Z. Wang, T. Yan, *et al.*, Integrated energy storage and energy upgrade, combined cooling and heating supply, and waste heat recovery with solid-gas thermochemical sorption heat transformer, *Int. J. Heat Mass Transf.* 76 (2014) 237–246.



- [4] S. Iglesias Garcia, R. Ferreiro Garcia, J. Carbia Carril, *et al.*, A review of thermodynamic cycles used in low temperature recovery systems over the last two years, *Renew. Sust. Energ. Rev.* 81 (Part 1) (2018) 760–767.
- [5] C. Ji, Z. Qin, S. Dubey, *et al.*, Three-dimensional transient numerical study on latent heat thermal storage for waste heat recovery from a low temperature gas flow, *Appl. Energy* 205 (2017) 1–12.
- [6] R.A. Victor, J.-K. Kim, R. Smith, Composition optimisation of working fluids for organic rankine cycles and kalina cycles, *Energy* 55 (2013) 114–126.
- [7] J. Sarkar, Review and future trends of supercritical CO<sub>2</sub> rankine cycle for low-grade heat conversion, *Renew. Sust. Energ. Rev.* 48 (2015) 434–451.
- [8] P. Donnellan, K. Cronin, E. Byrne, Recycling waste heat energy using vapour absorption heat transformers: A review, *Renew. Sust. Energ. Rev.* 42 (2015) 1290–1304.
- [9] L. Ni, J. Dong, Y. Yao, *et al.*, A review of heat pump systems for heating and cooling of buildings in China in the last decade, *Renew. Energy* 84 (2015) 30–45.
- [10] J. Zhang, H.-H. Zhang, Y.-L. He, *et al.*, A comprehensive review on advances and applications of industrial heat pumps based on the practices in China, *Appl. Energy* 178 (2016) 800–825.
- [11] Q. Wang, X. Liu, X. Guo, Application of waste heat recovery technology in union station and analysis of energy efficiency, *Procedia Eng.* 205 (2017) 3860–3866.
- [12] J. Ibarra-Bahena, R. Romero, Performance of different experimental absorber designs in absorption heat pump cycle technologies: A review, *Energies* 7 (2) (2014) 751–766.
- [13] S. Aphornratana, I.W. Eames, Thermodynamic analysis of absorption refrigeration cycles using the second law of thermodynamics method, *Int. J. Refrig.* 18 (4) (1995) 244–252.
- [14] M. Kilic, O. Kaynakli, Second law-based thermodynamic analysis of water-lithium bromide absorption refrigeration system, *Energy* 32 (8) (2007) 1505–1512.
- [15] K.C. Ng, K. Tu, H.T. Chua, *et al.*, Thermodynamic analysis of absorption chillers: Internal dissipation and process average temperature, *Appl. Therm. Eng.* 18 (8) (1998) 671–682.
- [16] J.-K. Kim, C.W. Park, Y.T. Kang, The effect of micro-scale surface treatment on heat and mass transfer performance for a falling film h<sub>2</sub>O/liBr absorber, *Int. J. Refrig.* 26 (5) (2003) 575–585.
- [17] Y. Li, L. Wang, M. Zhu, *et al.*, Optimization study of distillation column based on type i absorption heat pump, *Appl. Therm. Eng.* 116 (2017) 33–42.
- [18] Y. Ru, The Application Research of Absorption Heatpump Technology in the Recycle of Industrialexhaust Heat, PhD Thesis, Taiyuan University of Technology, China (in Chinese), 2012.
- [19] D.M. Martini, S.W. Harold, S.P. Christopher, *et al.*, Absorption over-concentration control, 1996, EP0836060. EU Pat.
- [20] X. Wang, H.T. Chua, Absorption cooling: A review of lithium bromide–water chiller technologies, *Recent Pat. Mech. Eng.* 2 (3) (2009) 193–213.
- [21] K. Wang, O. Abdelaziz, P. Kisari, *et al.*, State-of-the-art review on crystallization control technologies for water/liBr absorption heat pumps, *Int. J. Refrig.* 34 (6) (2011) 1325–1337.
- [22] L.G. Farshi, S. Khalili, A.H. Mosaffa, Thermodynamic analysis of a cascaded compression – absorption heat pump and comparison with three classes of conventional heat pumps for the waste heat recovery, *Appl. Therm. Eng.* 128 (2018) 282–296.
- [23] Z. Zhao, X. Zhang, X. Ma, Thermodynamic performance of a double-effect absorption heat-transformer using tfe/e181 as the working fluid, *Appl. Energy* 82 (2) (2005) 107–116.
- [24] B. Ye, J. Liu, X. Xu, *et al.*, A new open absorption heat pump for latent heat recovery from moist gas, *Energy Convers. Manag.* 94 (2015) 438–446.
- [25] W. Wu, W. Shi, B. Wang, *et al.*, A new heating system based on coupled air source absorption heat pump for cold regions: Energy saving analysis, *Energy Convers. Manag.* 76 (2013) 811–817.
- [26] F. Li, L. Duanmu, L. Fu, *et al.*, Research and application of flue gas waste heat recovery in co-generation based on absorption heat-exchange, *Procedia Eng.* 146 (2016) 594–603.
- [27] X.-Q. Cao, W.-W. Yang, F. Zhou, *et al.*, Performance analysis of different high-temperature heat pump systems for low-grade waste heat recovery, *Appl. Therm. Eng.* 71 (1) (2014) 291–300.
- [28] Q. Wang, W. He, Y. Liu, *et al.*, Vapor compression multifunctional heat pumps in China: A review of configurations and operational modes, *Renew. Sust. Energ. Rev.* 16 (9) (2012) 6522–6538.
- [29] L. Zhang, Y. Jiang, J. Dong, *et al.*, Advances in vapor compression air source heat pump system in cold regions: A review, *Renew. Sust. Energ. Rev.* 81 (2018) 353–365.
- [30] R.S. Adhikari, N. Aste, M. Manfren, *et al.*, Energy savings through variable speed compressor heat pump systems, *Energy Procedia* 14 (2012) 1337–1342.
- [31] Y. Ko, S. Park, S. Jin, *et al.*, The selection of volume ratio of two-stage rotary compressor and its effects on air-to-water heat pump with flash tank cycle, *Appl. Energy* 104 (2013) 187–196.
- [32] G. Yan, Q. Jia, T. Bai, Experimental investigation on vapor injection heat pump with a newly designed twin rotary variable speed compressor for cold regions, *Int. J. Refrig.* 62 (2016) 232–241.
- [33] X. Lv, G. Yan, J. Yu, Solar-assisted auto-cascade heat pump cycle with zeotropic mixture r32/r290 for small water heaters, *Renew. Energy* 76 (2015) 167–172.
- [34] C. Baek, J. Heo, J. Jung, *et al.*, Performance characteristics of a two-stage CO<sub>2</sub> heat pump water heater adopting a sub-cooler vapor injection cycle at various operating conditions, *Energy* 77 (2014) 570–578.
- [35] A. Redón, E. Navarro-Peris, M. Pitarch, *et al.*, Analysis and optimization of subcritical two-stage vapor injection heat pump systems, *Appl. Energy* 124 (2014) 231–240.
- [36] Y. Li, J. Yu, Theoretical analysis on optimal configurations of heat exchanger and compressor in a two-stage compression air source heat pump system, *Appl. Therm. Eng.* 96 (2016) 682–689.
- [37] S. Jiang, S. Wang, X. Jin, *et al.*, Optimum compressor cylinder volume ratio for two-stage compression air source heat pump systems, *Int. J. Refrig.* 67 (2016) 77–89.
- [38] Q. Zhou, R. Radermacher, Development of a vapor compression cycle with a solution circuit and desorber/absorber heat exchange, *Int. J. Refrig.* 20 (2) (1997) 85–95.
- [39] M. Hultén, T. Berntsson, The compression/absorption cycle – influence of some major parameters on cop and a comparison with the compression cycle, *Int. J. Refrig.* 22 (2) (1999) 91–106.
- [40] M. Hultén, T. Berntsson, The compression/absorption heat pump cycle—conceptual design improvements and comparisons with the compression cycle, *Int. J. Refrig.* 25 (4) (2002) 487–497.
- [41] W. Wu, W. Shi, J. Wang, *et al.*, Experimental investigation on nh<sub>3</sub>–h<sub>2</sub>O compression-assisted absorption heat pump (cahp) for low temperature heating under lower driving sources, *Appl. Energy* 176 (2016) 258–271.
- [42] W. Wu, B. Wang, S. Shang, *et al.*, Experimental investigation on nh<sub>3</sub>–h<sub>2</sub>O compression-assisted absorption heat pump (cahp) for low temperature heating in colder conditions, *Int. J. Refrig.* 67 (2016) 109–124.
- [43] G.L.M. M. M. Effect of the design variables on the energy performance and size parameters of a heat transformer based on the system acetone/h<sub>2</sub>O–propanol, *Int. J. Energy Res.* 16 (9) (1992) 851–864.
- [44] H. Bao, Z. Ma, A.P. Roskilly, Integrated chemisorption cycles for ultra-low grade heat recovery and thermo-electric energy storage and exploitation, *Appl. Energy* 164 (2016) 228–236.
- [45] Y. Chung, B.-J. Kim, Y.-K. Yeo, *et al.*, Optimal design of a chemical heat pump using the 2-propanol/acetone/hydrogen system, *Energy* 22 (5) (1997) 525–536.
- [46] M.I. Fadhel, K. Sopian, W.R.W. Daud, *et al.*, Review on advanced of solar assisted chemical heat pump dryer for agriculture produce, *Renew. Sust. Energ. Rev.* 15 (2) (2011) 1152–1168.
- [47] W. Wongsuwan, S. Kumar, P. Neveu, *et al.*, A review of chemical heat pump technology and applications, *Appl. Therm. Eng.* 21 (15) (2001) 1489–1519.
- [48] M. Xu, J. Cai, J. Guo, *et al.*, Technical and economic feasibility of the isopropanol–acetone–hydrogen chemical heat pump based on a lab-scale prototype, *Energy* 139 (2017) 1030–1039.
- [49] L.M. Gandia, A. Diaz, M. Montes, Selectivity in the high-temperature hydrogenation of acetone with silica-supported nickel and cobalt catalysts, *J. Catal.* 157 (2) (1995) 461–471.
- [50] W. Mooksuwan, S. Kumar, Study on 2-propanol/acetone/hydrogen chemical heat pump: Endothermic dehydrogenation of 2-propanol, *Int. J. Energy Res.* 24 (12) (2000) 1109–1122.
- [51] I. Klinsoda, P. Piumsomboon, Isopropanol–acetone–hydrogen chemical heat pump: A demonstration unit, *Energy Convers. Manag.* 48 (4) (2007) 1200–1207.
- [52] M. Xu, F. Xin, X. Li, *et al.*, Equilibrium model and performances of an isopropanol–acetone–hydrogen chemical heat pump with a reactive distillation column, *Ind. Eng. Chem. Res.* 52 (11) (2013) 4040–4048.
- [53] X. Zhou, Y. Duan, X. Huai, *et al.*, 3d cfd modeling of acetone hydrogenation in fixed bed reactor with spherical particles, *Particuology* 11 (6) (2013) 715–722.
- [54] M. Xu, Y. Duan, F. Xin, *et al.*, Design of an isopropanol–acetone–hydrogen chemical heat pump with exothermic reactors in series, *Appl. Therm. Eng.* 71 (1) (2014) 445–449.
- [55] L.M. Gandia, M. Montes, Effect of the design variables on the energy performance and size parameters of a heat transformer based on the system acetone/h<sub>2</sub>O–propanol, *Int. J. Energy Res.* 16 (9) (1992) 851–864.
- [56] T.G. Kim, Y.K. Yeo, H.K. Song, Chemical heat pump based on dehydrogenation and hydrogenation of i-propanol and acetone, *Int. J. Energy Res.* 16 (9) (1992) 897–916.
- [57] D.W. Sun, Thermodynamic analysis of the operation of two-stage metal-hydride heat pumps, *Appl. Energy* 54 (1) (1996) 29–47.
- [58] A. Satheesh, P. Muthukumar, Simulation of double-stage double-effect metal hydride heat pump, *Int. J. Hydrog. Energy* 35 (3) (2010) 1474–1484.
- [59] H.P. Klein, M. Groll, Development of a two-stage metal hydride system as topping cycle in cascading sorption systems for cold generation, *Appl. Therm. Eng.* 22 (6) (2002) 631–639.
- [60] A. Satheesh, P. Muthukumar, Performance investigation of double-stage metal hydride based heat pump, *Appl. Therm. Eng.* 30 (17–18) (2010) 2698–2707.
- [61] E. Mastronardo, L. Bonaccorsi, Y. Kato, *et al.*, Efficiency improvement of heat storage materials for mgo/h<sub>2</sub>O/mg(oh)<sub>2</sub> chemical heat pumps, *Appl. Energy* 162 (2016) 31–39.
- [62] B.B. Saha, S. Koyama, K. Choon Ng, *et al.*, Study on a dual-mode, multi-bed regenerative adsorption chiller, *Renew. Energy* 31 (13) (2006) 2076–2090.
- [63] E. Mastronardo, L. Bonaccorsi, Y. Kato, *et al.*, Thermochemical performance of carbon nanotubes based hybrid materials for mgo/h<sub>2</sub>O/mg(oh)<sub>2</sub> chemical heat pumps, *Appl. Energy* 181 (2016) 232–243.
- [64] L. Calabrese, L. Bonaccorsi, A. Freni, *et al.*, Synthesis of sapo-34 zeolite filled macroporous foams for adsorption heat pump applications: A preliminary study, *Appl. Therm. Eng.* 124 (2017) 1312–1318.
- [65] E. Elsayed, R. Al-Dadah, S. Mahmoud, *et al.*, Aluminium fumarate and cpo-27(ni) mofs: Characterization and thermodynamic analysis for adsorption heat pump applications, *Appl. Therm. Eng.* 99 (2016) 802–812.
- [66] T.H. Herzog, J. Jänchen, Adsorption properties of modified zeolites for operating range enhancement of adsorption heat pumps through the use of organic adsorptive agents, *Energy Procedia* 91 (2016) 155–160.
- [67] M. Bianchi, L. Branchini, A. De Pascale, *et al.*, Experimental performance of a micro-organic energy system for low grade heat recovery, *Energy Procedia* 129 (2017) 899–906.
- [68] S.-Y. Cho, C.-H. Cho, K.-Y. Ahn, *et al.*, A study of the optimal operating conditions in the organic rankine cycle using a turbo-expander for fluctuations of the available thermal energy, *Energy* 64 (2014) 900–911.

- [69] M. Imran, M. Usman, B.-S. Park, et al., Multi-objective optimization of evaporator of organic rankine cycle (orc) for low temperature geothermal heat source, *Appl. Therm. Eng.* 80 (2015) 1–9.
- [70] N.F. Tumen Ozdil, M.R. Segmen, Investigation of the effect of the water phase in the evaporator inlet on economic performance for an organic rankine cycle (orc) based on industrial data, *Appl. Therm. Eng.* 100 (2016) 1042–1051.
- [71] D.Y. Kim, Thermal performance of brazed metalfoam-plate heat exchanger as an evaporator for organic Rankine cycle, *Energy Procedia* 129 (2017) 451–458.
- [72] H. Liu, H. Zhang, F. Yang, et al., Multi-objective optimization of fin-and-tube evaporator for a diesel engine-organic rankine cycle (orc) combined system using particle swarm optimization algorithm, *Energy Convers. Manag.* 151 (2017) 147–157.
- [73] K. Hu, J. Zhu, W. Zhang, et al., Effects of evaporator superheat on system operation stability of an organic rankine cycle, *Appl. Therm. Eng.* 111 (2017) 793–801.
- [74] E. Sauret, Y. Gu, Three-dimensional off-design numerical analysis of an organic rankine cycle radial-inflow turbine, *Appl. Energy* 135 (2014) 202–211.
- [75] D. Fiaschi, G. Manfrida, F. Maraschiello, Design and performance prediction of radial orc turboexpanders, *Appl. Energy* 138 (2015) 517–532.
- [76] B. Ssebabi, R.T. Dobson, A.B. Sebitosi, Characterising a turbine for application in an organic rankine cycle, *Energy* 93 (2015) 1617–1632.
- [77] K. Rahbar, S. Mahmoud, R.K. Al-Dadah, et al., Parametric analysis and optimization of a small-scale radial turbine for organic rankine cycle, *Energy* 83 (2015) 696–711.
- [78] K. Rahbar, S. Mahmoud, R.K. Al-Dadah, et al., Modelling and optimization of organic rankine cycle based on a small-scale radial inflow turbine, *Energy Convers. Manag.* 91 (2015) 186–198.
- [79] A. Al Jubori, A. Daabo, R.K. Al-Dadah, et al., Development of micro-scale axial and radial turbines for low-temperature heat source driven organic rankine cycle, *Energy Convers. Manag.* 130 (2016) 141–155.
- [80] J. Song, C.-W. Gu, X. Ren, Influence of the radial-inflow turbine efficiency prediction on the design and analysis of the organic rankine cycle (orc) system, *Energy Convers. Manag.* 123 (2016) 308–316.
- [81] A.M. Al Jubori, R. Al-Dadah, S. Mahmoud, An innovative small-scale two-stage axial turbine for low-temperature organic rankine cycle, *Energy Convers. Manag.* 144 (2017) 18–33.
- [82] C.S. From, E. Sauret, S. Armfield, et al., Turbulent dense gas flow characteristics in swirling conical diffuser, *Comput. Fluids* 149 (3) (2017) 100–118.
- [83] A.I. Papadopoulos, M. Stijepovic, P. Linke, et al., Multi-level design and selection of optimum working fluids and orc systems for power and heat cogeneration from low enthalpy renewable sources, in: I.D.L. Bogle, M. Fairweather (Eds.), *Computer Aided Chemical Engineering*, vol. 30, Elsevier 2012, pp. 66–70.
- [84] P. Linke, A. Papadopoulos, P. Seferlis, Systematic methods for working fluid selection and the design, integration and control of organic rankine cycles—a review, *Energies* 8 (6) (2015) 4755.
- [85] B.-T. Liu, K.-H. Chien, C.-C. Wang, Effect of working fluids on organic rankine cycle for waste heat recovery, *Energy* 29 (8) (2004) 1207–1217.
- [86] M. Li, B. Zhao, Analytical thermal efficiency of medium-low temperature organic rankine cycles derived from entropy-generation analysis, *Energy* 106 (2016) 121–130.
- [87] R. Rademacher, Thermodynamic and heat transfer implications of working fluid mixtures in rankine cycles, *Int. J. Heat Fluid Flow* 10 (2) (1989) 90–102.
- [88] J.G. Andreasen, U. Larsen, T. Knudsen, et al., Selection and optimization of pure and mixed working fluids for low grade heat utilization using organic rankine cycles, *Energy* 73 (2014) 204–213.
- [89] K. Braimakis, M. Preißinger, D. Brüggemann, et al., Low grade waste heat recovery with subcritical and supercritical organic rankine cycle based on natural refrigerants and their binary mixtures, *Energy* 88 (2015) 80–92.
- [90] S. Lecompte, B. Ameer, D. Ziviani, et al., Exergy analysis of zeotropic mixtures as working fluids in organic rankine cycles, *Energy Convers. Manag.* 85 (2014) 727–739.
- [91] K. Satanphol, W. Pridasawas, B. Suphanit, A study on optimal composition of zeotropic working fluid in an organic rankine cycle (orc) for low grade heat recovery, *Energy* 123 (2017) 326–339.
- [92] S. Lecompte, H. Huisseune, M. Van Den Broek, et al., Review of organic rankine cycle (orc) architectures for waste heat recovery, *Renew. Sust. Energ. Rev.* 47 (2015) 448–461.
- [93] Z. Gnutek, A. Bryszewska-Mazurek, The thermodynamic analysis of multicycle orc engine, *Energy* 26 (12) (2001) 1075–1082.
- [94] H.G. Zhang, E.H. Wang, B.Y. Fan, A performance analysis of a novel system of a dual loop bottoming organic rankine cycle (orc) with a light-duty diesel engine, *Appl. Energy* 102 (2013) 1504–1513.
- [95] N. Yamada, M. Watanabe, A. Hoshi, Experiment on pumpless rankine-type cycle with scroll expander, *Energy* 49 (2013) 137–145.
- [96] H. Bao, Z. Ma, A.P. Roskilly, Chemisorption power generation driven by low grade heat – theoretical analysis and comparison with pumpless orc, *Appl. Energy* 186 (Part 3) (2017) 282–290.
- [97] M. Li, J. Wang, W. He, et al., Construction and preliminary test of a low-temperature regenerative organic rankine cycle (orc) using r123, *Renew. Energy* 57 (2013) 216–222.
- [98] S. Declaye, S. Quoilin, L. Guillaume, et al., Experimental study on an open-drive scroll expander integrated into an orc (organic rankine cycle) system with r245fa as working fluid, *Energy* 55 (2013) 173–183.
- [99] M. Imran, M. Usman, B.-S. Park, et al., Volumetric expanders for low grade heat and waste heat recovery applications, *Renew. Sust. Energ. Rev.* 57 (2016) 1090–1109.
- [100] G. Shu, G. Yu, H. Tian, et al., Multi-approach evaluations of a cascade-organic rankine cycle (c-orc) system driven by diesel engine waste heat: Part a – Thermodynamic evaluations, *Energy Convers. Manag.* 108 (2016) 579–595.
- [101] G. Yu, G. Shu, H. Tian, et al., Multi-approach evaluations of a cascade-organic rankine cycle (c-orc) system driven by diesel engine waste heat: Part b-techno-economic evaluations, *Energy Convers. Manag.* 108 (2016) 596–608.
- [102] X. Zhang, M. He, Y. Zhang, A review of research on the kalina cycle, *Renew. Sust. Energ. Rev.* 16 (7) (2012) 5309–5318.
- [103] L. Cao, J. Wang, L. Chen, et al., Comprehensive analysis and optimization of kalina flash cycles for low-grade heat source, *Appl. Therm. Eng.* 131 (2018) 540–552.
- [104] M. Fallah, S.M.S. Mahmoudi, M. Yari, et al., Advanced exergy analysis of the kalina cycle applied for low temperature enhanced geothermal system, *Energy Convers. Manag.* 108 (2016) 190–201.
- [105] F. Sun, W. Zhou, Y. Ikegami, et al., Energy–exergy analysis and optimization of the solar-boosted kalina cycle system 11 (kcs-11), *Renew. Energy* 66 (2014) 268–279.
- [106] J. He, C. Liu, X. Xu, et al., Performance research on modified kcs (kalina cycle system) 11 without throttle valve, *Energy* 64 (2014) 389–397.
- [107] V. Zare, V. Palideh, Employing thermoelectric generator for power generation enhancement in a kalina cycle driven by low-grade geothermal energy, *Appl. Therm. Eng.* 130 (2018) 418–428.
- [108] Nasruddin, R. Usvika, M. Rifaldi, et al., Energy and exergy analysis of kalina cycle system (kcs) 34 with mass fraction ammonia-water mixture variation, *J. Mech. Sci. Technol.* 23 (7) (2009) 1871–1876.
- [109] O. Arslan, Power generation from medium temperature geothermal resources: Ann-based optimization of kalina cycle system-34, *Energy* 36 (5) (2011) 2528–2534.
- [110] P.K. Nag, A.V.S.S.K.S. Gupta, Exergy analysis of the kalina cycle, *Appl. Therm. Eng.* 18 (6) (1998) 427–439.
- [111] J.Y. Wang, J.F. Wang, Y.P. Dai, et al., Assessment of off-design performance of a kalina cycle driven by low-grade heat source, *Energy* 138 (2017) 459–472.
- [112] K. Jonshagen, M. Genrup, Improved load control for a steam cycle combined heat and power plant, *Energy* 35 (4) (2010) 1694–1700.
- [113] E. Wang, Z. Yu, F. Zhang, Investigation on efficiency improvement of a kalina cycle by sliding condensation pressure method, *Energy Convers. Manag.* 151 (2017) 123–135.
- [114] E. Wang, Z. Yu, A numerical analysis of a composition-adjustable kalina cycle power plant for power generation from low-temperature geothermal sources, *Appl. Energy* 180 (2016) 834–848.
- [115] Z. Guo, Z. Zhang, Y. Chen, et al., Dual-pressure vaporization kalina cycle for cascade reclaiming heat resource for power generation, *Energy Convers. Manag.* 106 (2015) 557–565.
- [116] T. Eller, F. Heberle, D. Brüggemann, Second law analysis of novel working fluid pairs for waste heat recovery by the kalina cycle, *Energy* 119 (2017) 188–198.
- [117] G. Khankari, J. Munda, S. Karmakar, Power generation from condenser waste heat in coal-fired thermal power plant using kalina cycle, *Energy Procedia* 90 (2016) 613–624.
- [118] R. Maryam, A.A. Dehghan, An exergy based comparative study between libr/water absorption refrigeration systems from half effect to triple effect, *Appl. Therm. Eng.* 124 (2017) 103–123.
- [119] Y. Tae Kang, A. Akisawa, T. Kashiwagi, Analytical investigation of two different absorption modes: Falling film and bubble types, *Int. J. Refrig.* 23 (6) (2000) 430–443.
- [120] F. Su, H.B. Ma, H. Gao, Characteristic analysis of adiabatic spray absorption process in aqueous lithium bromide solution, *Int. Commun. Heat Mass Transfer* 38 (4) (2011) 425–428.
- [121] A. Zacarias, M. Venegas, A. Lecuona, et al., Experimental assessment of vapour adiabatic absorption into solution droplets using a full cone nozzle, *Exp. Thermal Fluid Sci.* 68 (2015) 228–238.
- [122] E. Palacios, M. Izquierdo, J.D. Marcos, et al., Evaluation of mass absorption in libr flat-fan sheets, *Appl. Energy* 86 (12) (2009) 2574–2582.
- [123] S.M. Osta-Omar, C. Micallef, Effect of the vapour-solution interface area on a miniature lithium-bromide/water absorption refrigeration system equipped with an adiabatic absorber, *Energy Procedia* 118 (2017) 243–247.
- [124] D.-W. Sun, I.W. Eames, S. Aphornratana, Evaluation of a novel combined ejector-absorption refrigeration cycle – I: Computer simulation, *Int. J. Refrig.* 19 (3) (1996) 172–180.
- [125] P. Srihirin, S. Aphornratana, S. Chungpaibulpatana, A review of absorption refrigeration technologies, *Renew. Sust. Energ. Rev.* 5 (4) (2001) 343–372.
- [126] H.S. Majidi, Performance evaluation of combined ejector libr/h<sub>2</sub>o absorption refrigeration cycle, *Case Stud. Therm. Eng.* 7 (2016) 25–35.
- [127] Z.Y. Xu, R.Z. Wang, Z.Z. Xia, A novel variable effect libr–water absorption refrigeration cycle, *Energy* 60 (2013) 457–463.
- [128] R. Saravanan, M.P. Maiya, Thermodynamic comparison of water-based working fluid combinations for a vapour absorption refrigeration system, *Appl. Therm. Eng.* 18 (7) (1998) 553–568.
- [129] X. She, Y. Yin, M. Xu, et al., A novel low-grade heat-driven absorption refrigeration system with licl–h<sub>2</sub>o and libr–h<sub>2</sub>o working pairs, *Int. J. Refrig.* 58 (2015) 219–234.
- [130] N. Li, C. Luo, Q. Su, A working pair of cacl<sub>2</sub>–libr–lino<sub>3</sub>/h<sub>2</sub>o and its application in a single-stage solar-driven absorption refrigeration cycle, *Int. J. Refrig.* 86 (2018) 1–13.
- [131] S.-Y. Wu, H. Yang, L. Xiao, et al., Comparative investigation on thermo-economic performance between orc and libr absorption refrigerating cycle in waste heat recovery, *Energy Procedia* 105 (2017) 1446–1453.
- [132] D.-W. Sun, Comparison of the performances of nh<sub>3</sub>-h<sub>2</sub>o, nh<sub>3</sub>-lino<sub>3</sub> and nh<sub>3</sub>-nascn absorption refrigeration systems, *Energy Convers. Manag.* 39 (5–6) (1998) 357–368.
- [133] F. Táboas, M. Bourouis, M. Vallès, Boiling heat transfer and pressure drop of nh<sub>3</sub>/lino<sub>3</sub> and nh<sub>3</sub>/(lino<sub>3</sub> + h<sub>2</sub>o) in a plate heat exchanger, *Int. J. Therm. Sci.* 105 (2016) 182–194.
- [134] Y. Liang, S. Li, X. Yue, et al., Analysis of nh<sub>3</sub>-h<sub>2</sub>o-libr absorption refrigeration integrated with an electrodialysis device, *Appl. Therm. Eng.* 115 (2017) 134–140.
- [135] D. Cai, J. Jiang, G. He, et al., Experimental evaluation on thermal performance of an air-cooled absorption refrigeration cycle with nh<sub>3</sub>-lino<sub>3</sub> and nh<sub>3</sub>-nascn refrigerant solutions, *Energy Convers. Manag.* 120 (2016) 32–43.

- [136] A. Myat, K. Thu, Y.-D. Kim, *et al.*, A second law analysis and entropy generation minimization of an absorption chiller, *Appl. Therm. Eng.* 31 (14) (2011) 2405–2413.
- [137] X. Chen, R.Z. Wang, S. Du, An improved cycle for large temperature lifts application in water-ammonia absorption system, *Energy* 118 (2017) 1361–1369.
- [138] C.P. Jawahar, R. Saravanan, Generator absorber heat exchange based absorption cycle—a review, *Renew. Sust. Energ. Rev.* 14 (8) (2010) 2372–2382.
- [139] Q.W. Liu, Performance Studies on  $\text{nh}_3\text{-h}_2\text{O}$  Absorption Refrigerationhgax Cycles Using Low Temperature Exhaust Heat, PhD Thesis, DalianUniversity of Technology, China, 2012 (in Chinese).
- [140] P. Lin, R.Z. Wang, Z.Z. Xia, Numerical investigation of a two-stage air-cooled absorption refrigeration system for solar cooling: Cycle analysis and absorption cooling performances, *Renew. Energy* 36 (5) (2011) 1401–1412.
- [141] W. Wu, X. Zhang, X. Li, *et al.*, Comparisons of different working pairs and cycles on the performance of absorption heat pump for heating and domestic hot water in cold regions, *Appl. Therm. Eng.* 48 (2012) 349–358.
- [142] S. Du, R.Z. Wang, X. Chen, Analysis on maximum internal heat recovery of a mass-coupled two stage ammonia water absorption refrigeration system, *Energy* 133 (2017) 822–831.
- [143] A.H. Mosaffa, L.G. Farshi, C.A. Infante Ferreira, *et al.*, Exergoeconomic and environmental analyses of  $\text{co}_2/\text{nh}_3$  cascade refrigeration systems equipped with different types of flash tank intercoolers, *Energy Convers. Manag.* 117 (2016) 442–453.
- [144] T.-S. Lee, C.-H. Liu, T.-W. Chen, Thermodynamic analysis of optimal condensing temperature of cascade-condenser in  $\text{co}_2/\text{nh}_3$  cascade refrigeration systems, *Int. J. Refrig.* 29 (7) (2006) 1100–1108.
- [145] H.M. Getu, P.K. Bansal, Thermodynamic analysis of an  $\text{r744-r717}$  cascade refrigeration system, *Int. J. Refrig.* 31 (1) (2008) 45–54.
- [146] M. Ma, J. Yu, X. Wang, Performance evaluation and optimal configuration analysis of a  $\text{co}_2/\text{nh}_3$  cascade refrigeration system with falling film evaporator–condenser, *Energy Convers. Manag.* 79 (2014) 224–231.
- [147] K. Wang, A. Vineyard Edward, Adsorption refrigeration: New opportunities for solar, *ASHRAE Journal* 9 (2011) 14–24.
- [148] D.C. Wang, Y.H. Li, D. Li, *et al.*, A review on adsorption refrigeration technology and adsorption deterioration in physical adsorption systems, *Renew. Sust. Energ. Rev.* 14 (1) (2009) 344–353.
- [149] Q. Ma, L. Luo, R.Z. Wang, *et al.*, A review on transportation of heat energy over long distance: Exploratory development, *Renew. Sust. Energ. Rev.* 13 (6) (2009) 1532–1540.
- [150] M. Yang, S.Y. Lee, J.T. Chung, *et al.*, High efficiency  $\text{H}_2\text{O}/\text{liBr}$  double effect absorption cycles with multi-heat sources for tri-generation application, *Appl. Energy* 187 (2017) 243–254.
- [151] S.Z. Xu, L.W. Wang, R.Z. Wang, Thermodynamic analysis of mass and heat recovery adsorption refrigeration cycles and scheme selection, *J. Chem. Ind.* 67 (6) (2016) 2202–2210.
- [152] T.F. Qu, R.Z. Wang, W. Wang, Study on heat and mass recovery in adsorption refrigeration cycles, *Appl. Therm. Eng.* 21 (4) (2001) 439–452.
- [153] A. Akahira, K.C.A. Alam, Y. Hamamoto, *et al.*, Experimental investigation of mass recovery adsorption refrigeration cycle, *Int. J. Refrig.* 28 (4) (2005) 565–572.
- [154] R.Z. Wang, Performance improvement of adsorption cooling by heat and mass recovery operation, *Int. J. Refrig.* 24 (7) (2001) 602–611.
- [155] K.C.A. Alam, A. Akahira, Y. Hamamoto, *et al.*, A four-bed mass recovery adsorption refrigeration cycle driven by low temperature waste/renewable heat source, *Renew. Energy* 29 (9) (2004) 1461–1475.
- [156] L.W. Wang, R.Z. Wang, Z.S. Lu, *et al.*, Comparison of the adsorption performance of compound adsorbent in a refrigeration cycle with and without mass recovery, *Chem. Eng. Sci.* 61 (11) (2006) 3761–3770.
- [157] Y. Lu, H. Bao, Y. Yuan, *et al.*, Optimisation of a novel resorption cogeneration using mass and heat recovery, *Energy Procedia* 61 (2014) 1103–1106.
- [158] H.J. Dakkama, A. Elsayed, R.K. Al-Dadah, *et al.*, Integrated evaporator–condenser cascaded adsorption system for low temperature cooling using different working pairs, *Appl. Energy* 185 (Part 2) (2017) 2117–2126.
- [159] Y. Liu, K.C. Leong, Numerical study of a novel cascading adsorption cycle, *Int. J. Refrig.* 29 (2) (2006) 250–259.
- [160] L. Lu, Research on Industrial Waste Heat Applied to Mobile energyStorage for Heating Supply, PhD Thesis, DalianUniversity of Technology, China, 2016 (in Chinese).
- [161] G. Alva, Y. Lin, G. Fang, An overview of thermal energy storage systems, *Energy* 144 (2018) 341–378.
- [162] G.R. Dheep, A. Sreekumar, Investigation on thermal reliability and corrosion characteristics of glutaric acid as an organic phase change material for solar thermal energy storage applications, *Appl. Therm. Eng.* 129 (2018) 1189–1196.
- [163] M. Walczak, F. Pineda, G. Fernández, *et al.*, Materials corrosion for thermal energy storage systems in concentrated solar power plants, *Renew. Sust. Energ. Rev.* 86 (2018) 22–44.
- [164] R.K. Sharma, P. Ganesan, V.V. Tyagi, *et al.*, Developments in organic solid–liquid phase change materials and their applications in thermal energy storage, *Energy Convers. Manag.* 95 (2015) 193–228.
- [165] J. Gasia, L. Miró, L.F. Cabeza, Review on system and materials requirements for high temperature thermal energy storage. Part 1: General requirements, *Renew. Sust. Energ. Rev.* 75 (2017) 1320–1338.
- [166] D. Jaya Krishna, A. Shinde, Step by step methodology for the assessment of metal corrosion rate with pcms suitable for low temperature heat storage applications, *Mater Today Proc.* 4 (9) (2017) 10039–10042.
- [167] A.I. Fernandez, M. Martínez, M. Segarra, *et al.*, Selection of materials with potential in sensible thermal energy storage, *Sol. Energy Mater. Sol. Cells* 94 (10) (2010) 1723–1729.
- [168] W. Wang, S. Guo, H. Li, *et al.*, Experimental study on the direct/indirect contact energy storage container in mobilized thermal energy system (m-tes), *Appl. Energy* 119 (2014) 181–189.
- [169] R. Sharma, E. Anil Kumar, Study of ammoniated salts based thermochemical energy storage system with heat up-gradation: A thermodynamic approach, *Energy* 141 (2017) 1705–1716.
- [170] M. Karthik, A. Faik, B. D’Aguanno, Graphite foam as interpenetrating matrices for phase change paraffin wax: A candidate composite for low temperature thermal energy storage, *Sol. Energy Mater. Sol. Cells* 172 (2017) 324–334.
- [171] Z. Jiang, G. Leng, F. Ye, *et al.*, Form-stable  $\text{lino } 3\text{-nano } 3\text{-kno } 3\text{-ca}(\text{no } 3)\text{ } 2/\text{calcium silicate composite phase change material (pcm)}$  for mid-low temperature thermal energy storage, *Energy Convers. Manag.* 106 (2015) 165–172.
- [172] M. Deckert, R. Scholz, S. Binder, *et al.*, Economic efficiency of mobile latent heat storages, *Energy Procedia* 46 (2014) 171–177.
- [173] J. Wu, Z. Yang, Q. Wu, *et al.*, Transient behavior and dynamic performance of cascade heat pump water heater with thermal storage system, *Appl. Energy* 91 (1) (2012) 187–196.
- [174] Z. He, Y. Zhang, Z. Wu, *et al.*, Experimental study on a bifunctional heat utilization system of heat pump and power generation using low-grade heat source, *Appl. Therm. Eng.* 124 (2017) 71–82.
- [175] J. Rashidi, P. Ifaei, I.J. Esfahani, *et al.*, Thermodynamic and economic studies of two new high efficient power-cooling cogeneration systems based on kalina and absorption refrigeration cycles, *Energy Convers. Manag.* 127 (2016) 170–186.