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Experimental study on an absorption refrigeration system at low temperatures ☆

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Abstract

The heat-driven auto-cascade absorption refrigeration cycle can be used at low temperatures, and a novel auto-cascade absorption refrigeration system is proposed to gain better performances with a refrigerating temperature as low as −50 °C. The new system uses a mixture of R23 + R32 + R134a/DMF as its working pair and its characteristic study is carried out under different operational conditions. It has successfully obtained a refrigerating temperature of −47.2 °C under the generating temperature of 163 °C. This refrigerating temperature is far lower than that of a traditional absorption refrigeration system with the same working pair, and it is also lower than that of an auto-cascade absorption refrigeration system using R32 + R134a/DMF as its working pair. From the experimental results, it is clearly seen that this new system shows a rapider lowering rate of refrigerating temperature than that of an auto-cascade absorption refrigeration system using R23 + R134a/DMF as its working pair. The results of experimental analyses imply that this new absorption refrigeration system can be used in the deep-freezing as low as −50 °C by utilizing low-potential thermal power. Its potential of industrial application might be greater than that of an auto-cascade absorption refrigeration system using R23 + R134a/DMF as its working pair in the future.

Keywords: Heat-driven refrigeration cycle; Absorption refrigeration cycle; Auto-cascade refrigeration cycle; Deep freezing; Experiment

1. Introduction

The absorption refrigeration system, which can be driven by low-potential thermal power, for example, solar energy, geothermal energy and wasted heat, shows potentials of saving energy. Moreover, it holds the advantages of using environmental-acceptable substances as its working pair—water/lithium bromide solution (H_2O/LiBr solution) and ammonia/water solution (NH_3/H_2O solution), for example. The researchers all over the world pay great attentions on the development of new absorption refrigeration technologies, and try to extend its applications in the industry. As we know, there are a lot of deep-freezing demands lower than −20 °C in many industrial processes, such as food industry, pharmaceutical industry and chemical engineering [1–6]; however, the traditional absorption refrigeration system is difficult to obtain a refrigerating temperature below −20 °C, for example, water/lithium bromide absorption refrigeration system as well as ammonia/water absorption refrigeration system [3,5,6]. As a result of the limitation in the temperature of water triple-point (about 0 °C), the absorption refrigeration system using water/lithium bromide solution as its working pair can be only used for air-conditioning (>0 °C) but not for cooling and/or refrigerating (<0 °C), and besides, such a system must operate under the vacuum condition. The absorption refrigeration system using ammonia/water solution as its working pair can be used for cooling and/or refrigerating (<0 °C), but it must work under the high-pressure condition and need rather high-temperature heat sources as its driving energy. It is generally required to obtain a refrigerating temperature lower than −20 °C that the ammonia/water absorption refrigeration system is driven by high-temperature heat sources and/or by a way of double- or multi-stage refriger-

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Nomenclature

ACAR	auto-cascade absorption refrigeration	
COP	coefficient of performance	
I	current	A
P	pressure	kPa
Q	heat load	W or kW
$S1$	vapor mixture separated by separator	
$S2$	liquid mixture separated by separator	
T	temperature	°C
U	voltage	V

Subscript

1, 2, ...	thermodynamic state point
a	absorbing; available load
e	evaporating
g	generating
k	condensing
l	leaking load

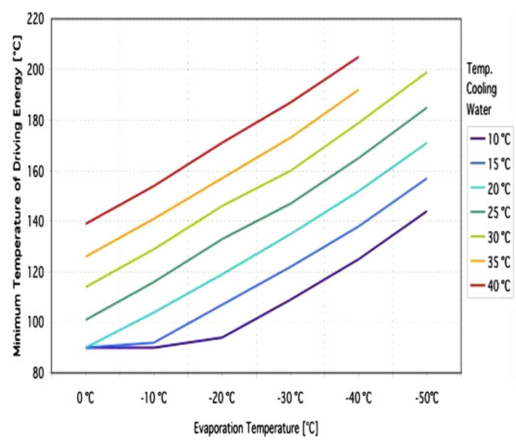

Fig. 1. Minimum temperature of driving energy for different temperatures of cooling water in the ammonia/water absorption refrigeration system [5].

ation [3,5,6]. In a case of generating temperature 160 °C and cooling water temperature 35 °C, the minimum refrigerating temperature of ammonia/water absorption refrigeration system is about −20 °C, illustrated in Fig. 1 [5]. Therefore, most applications of ammonia/water absorption refrigeration system are in cases with refrigerating temperatures higher than −20 °C. Ammonia as a refrigerant has excellent thermo-physical properties, but it is a toxic, strongly irritant, flammable substance, and is destructively corrosive to copper. With a view to overcoming these limitations of traditional absorption refrigeration system, an auto-cascade absorption refrigeration system (ACAR cycle) is proposed [7–10] and working pairs based on mixture of fluorocarbon (HFC) refrigerant and organic absorbent with good thermo-physical properties are investigated [11–16]. These working pairs are not toxic or corrosive, and they are also environmentally acceptable.

In this paper, a new absorption refrigeration system (ACAR cycle) is proposed to gain deep-freezing lower than −40 °C and shows more excellent performances. The new system uses an environmental-acceptable non-azeotropic mixture of trifluoromethane (R23), difluoromethane (R32) and 1,1,1,2-tetrafluoroethane (R134a) as its refrigerant, and N,N-dimethylformamide (DMF) as its absorbent. Experimental study of characteristics is undertaken on this new absorption refrigeration system under different operational conditions.

2. Experimental system

This new absorption refrigeration system uses R23, R32, R134a and DMF as components consisting of working pair, and their boiling point are respectively −82.1 °C, −51.6 °C, −26.5 °C and 152.8 °C under ambient atmosphere. The new system is composed of two different circulations: solution circulation and refrigeration circulation. The solution circulation is similar with that of traditional absorption refrigeration system, and its refrigeration circulation is concisely introduced here. Firstly, the mixture refrigerant vapor bubbles up from the generator, where strong DMF solution is heated (DMF as absorbent), and flows into the condenser. After the vapor is cooled by coolant at the condenser, it goes into the separator via throttling valve 2. Then, the refrigerant is separated into vapor stream and liquid stream at the separator. The main component of vapor stream is low-boiling point mixture (R23 + R32), named $S1$ and flows out from the top of separator, while the main component of liquid stream is high-boiling point mixture (R134a + R32), named $S2$ and flows out from the bottom. The stream $S2$ flows into the low-pressure side of condenser–evaporator via throttling valve 3, where $S2$ vaporizes and condenses $S1$. After the stream $S1$ is cooled at the high-pressure side of condenser–evaporator by $S2$, it passes through the regenerator, flows into the evaporator via throttling valve 4 and produces refrigeration. Finally, the stream $S1$ converges with $S2$, which comes from the condenser–evaporator, enters into the absorber and is absorbed by weak DMF solution (DMF as absorbent). In addition, when valve 4 is closed, the experimental system can operate as a traditional absorption refrigeration system. Its refrigerating temperature can be measured at the inlet and outlet of low-pressure side of condenser–evaporator—point 7 and 8, just as shown as Fig. 2.

In the absorption refrigeration experimental system, a diaphragm dosing pump of model JZM500/1.6 V with a rated flow 500 L h^{-1} and rated discharge pressure 1.6 MPa is used as the solution pump, which is made by Chongqing Pump Industry Co. Ltd., China. The valve 1 is a needle valve made of stainless steel, which can adjust the flow rate of weak solution with a good sensitivity, and valve 2 is a normal hand operated valve made of copper, which is generally used as a shut-off valve. However, valve 3 and 4 is throttle valve of model 2311F413 manufactured by Hoke, USA. In addition, a liquid level gauge is installed to indicate the level of solution at the generator and absorber, respectively. The level gauge made of carbon steel can operate between −20 °C and 250 °C and under a maximal pressure of 2.5 MPa. With regard to other components, they are self-designed and self-manufactured, for example, generator, separator and heat exchanger etc. To avoid a great fluctuation of heating power with a change of inputted voltage between two ends of the electrical heater at the generator and evaporator, a precise alternating current power supplier with a steady outputted voltage is equipped for the experimental system. It can utilize 160–260 V alternating current with a frequency of 50 ± 1 Hz and supply a maximal power 5 kW with a voltage of 220 V. The parameters of these main components are illustrated in Table 1.

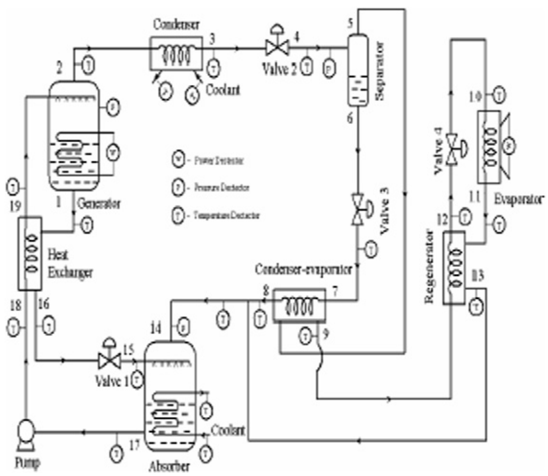

Fig. 2. Schematic diagram of auto-cascade absorption refrigeration system.

The measuring system of absorption refrigeration experimental setup, which includes the measurement of temperatures, pressures and heat loads, is shown in Fig. 2. The temperatures including generating temperature (T_g), condensing temperature (T_k, which is indirect gained by measuring the temperature of coolant, T_c), refrigerating or evaporating temperature (T_e) and absorbing temperature (T_a), are measured by 4-wire Pt100 probes + Agilent digital multi-meter, and their measurement deviation is less than or equals to 0.1 °C, which are calibrated by Zhejiang Measurement and Test Institute for Quality and Technique Supervision (Certificate No.: WD-20033446). The pressures, such as generating pressure (P_g, which is nearly equal to condensing pressure P_k) and absorbing pressure (P_a, which is nearly equal to evaporating pressure P_e), are measured by 0.4-grade precise pressure meters, which measurable range is 0–2.5 MPa. The heating load at the generator (Q_g) is supplied by a 0–250 V single-phase alternating current power and measured by a 0.5-grade digital power meter, which maximal measurable value is 2.75 kW. The refrigerating capacity of experimental system (Q_e) consists of an available refrigerating load ($Q_{e,a}$) and leaking load of refrigeration ($Q_{e,l}$) at the evap-

Table 1
Parameters of main components in the experimental system

Components	Materials	Parameters	Remarks
Generator	Carbon steel	Diameter: 207 mm Thickness of wall: 6 mm Height: 550 mm	–
Condenser	Copper	Diameter: outside-tube, 10 mm; inside-tube, 6 mm Thickness of wall: 1 mm Length: 500 mm	Double-pipe condenser
Condenser–evaporator	Copper	Diameter: outside-tube, 10 mm; inside-tube, 6 mm Thickness of wall: 1 mm Length: 400 mm	Tube-in-tube heat exchanger
Evaporator	Copper	Diameter: 10 mm Thickness of wall: 1 mm Length: 300 mm	Bare tube with a polyurethane foam thermal insulation of 50 mm
Absorber	Carbon steel	Diameter: 207 mm Thickness of wall: 6 mm Height: 250 mm	–
Solution heat exchanger	Copper	Diameter: outside-tube, 28 mm; inside-tube, 16 mm Thickness of wall: 1.5 mm Length: 1200 mm	Tube-in-tube heat exchanger
Solution pump	–	Rated flow: 500 L h^{-1} Rated discharger pressure: 1.6 MPa	Driven by three-phase alternating current motor
Level gauge	Carbon steel	Operating temperature: −20 to 250 °C Maximal operating pressure: 2.5 MPa	–
Valve 1	Stainless steel	Needle valve	–
Valve 2	Copper	Hand operated valve	–
Valve 3 and 4	Copper	Throttle valve	Manufactured by Hoke

orator, and it means $Q_e = Q_{e,a} + Q_{e,l}$. The available refrigerating load ($Q_{e,a}$) is imitated by heating a 5 Ω resistance wire, which uses a 0–30 V low-voltage direct current power supplier as its driven energy. Thus, the value of available refrigerating load is indirectly gained with $Q_{e,a} = U_{e,a} \times I_{e,a}$ by measuring the voltage ($U_{e,a}$) between input end and output end of heating resistance and its current ($I_{e,a}$) passing through the heating resistance, and can be adjusted from 0–150 W. However, the leaking load of refrigeration ($Q_{e,l}$) is rather hard to gain accurately by direct calculations because the effects resulting in heat leaking are various and very complicated at the evaporator. Thus, the leaking load of refrigeration ($Q_{e,l}$) is estimated by an experimental test of heating-balance between refrigerating temperature and ambient temperature, and the leaking load value of per °C is 0.42 W. From this experimental test, the leaking load of refrigeration ($Q_{e,l}$) can be approximately calculated in a rather simple way by measuring a refrigerating temperature and an experimental ambient temperature. The characteristics of main measured parameters in the experimental measuring system are illustrated in Table 2, i.e., measuring uncertainty of temperature. The data of experiments are automatically processed in real-time by a computer collection system.

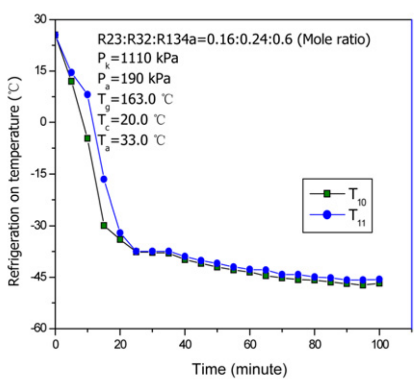

Fig. 3. Relationships between refrigerating temperature (T_e) and time in the ACAR system using R23 + R32 + R134a/DMF as its working pair.

3. Experimental results and discussion

The relationships between refrigerating temperature (T_e) and time are gained for new ACAR system using R23 + R32 + R134a/DMF as its working pair, as shown as Fig. 3. The temperatures at point 10 and 11, as shown as Fig. 2 (T_{10} and T_{11}), are inlet and outlet temperature at the evaporator, and represented as its refrigerating temperature. A refrigerating temperature as low as −47.2 °C is successfully obtained, when generating temperature (T_g), condensing temperature (T_k) and absorbing temperature (T_a) respectively equal to 163.0 °C, 20.0 °C and 33.0 °C. The used refrigerant is a mixture of R23 : R32 : R134a = 0.16 : 0.24 : 0.6 and its evaporating pressure (P_e) is 190 kPa (absolute pressure) under the experimental condition. With regard to other operational parameters, the inputted heating power (Q_g) is 2.2 kW at the generator, and refrigerating capacity (Q_e) is about 28.5 W at the lowest temperature, which is gained by the aforementioned calculating way on the refrigerating load at evaporator. Accordingly, the COP is about 0.013 for the new ACAR system with R23 + R32 + R134a/DMF working pair at the refrigerating temperature of −47.2 °C.

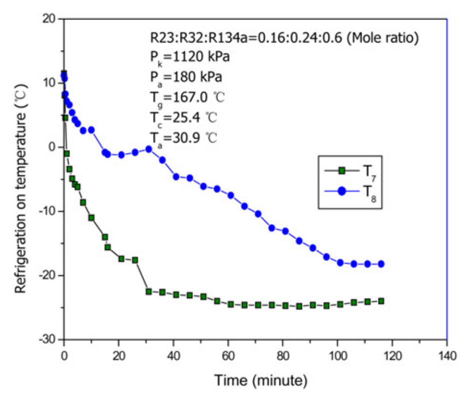

Fig. 4. Relationships between refrigerating temperature (T_e) and time in the traditional absorption refrigeration system using R23 + R32 + R134a/DMF as its working pair.

Table 2
Characteristics of measured parameters on the main instruments (component) in the measuring system

	Measurement range	Class of accuracy or uncertainty	Remarks
Temperature [°C]	–	0.1	The 4-wire Pt100 probes + Agilent digital multi-meter is calibrated and its Certificate No. is WD-20033446.
Pressure [kPa]	0–2500	0.4	–
Power at the generator [kW]	0–2.75	0.5	–
Voltage between input and output end of heater at the evaporator [V]	0–30	–	The obtained value is voltage between input and output end of a five 5 Ω resistance wire at the evaporator.
Current passing through heater at the evaporator [A]	0–5	–	The value is current passing through a 5 Ω resistance wire at the evaporator.
Leakage load at the evaporator [W^{-1} °C]	–	–	The leakage load is measured by experiment and its value of per °C is 0.42 W.

The comparisons on characteristics are carried out among new ACAR system, traditional absorption refrigeration system and ACAR system with R32 + R134a/DMF working pair etc., and their key results are illustrated in Table 3. Just as the aforesaid, the experiment on traditional absorption refrigeration system using R23 + R32 + R134a/DMF as its working pair is carried out, and its diagram between refrigerating temperature and time is shown in Fig. 4. Its composition of refrigerant with R23 + R32 + R134a mixture is as same as that of refrigerant used in new ACAR system. When its generating temperature (T_g), condensing temperature (T_k) and absorbing temperature (T_a) respectively equal to 167.0 °C, 25.4 °C and 30.9 °C, the evaporating pressure (P_e) is 180 kPa (absolute pressure) in the traditional absorption refrigeration system. Accordingly, the lowest refrigerating temperature of traditional absorption refrigeration system is as low as −24.5 °C, which is the lower of temperatures at the inlet and outlet of condenser-evaporator (T_6 and T_7), as shown as Fig. 2. Under the same operational condition, the traditional absorption refrigeration system cannot obtain a refrigerating temperature as low as that of new ACAR system, just as expatiated in the literature [9,10]. These mixtures, such as R23 + R32 + R134a, R23 + R134a and R32 + R134a etc., are generally out of a suitable area of Joule–Thomson refrigerating to obtain low temperatures, and accordingly, they can be used as a refrigerant but not to obtain low refrigerating temperatures in the traditional absorption refrigeration system. Just for the intrinsic limitations determined by the configuration of traditional absorption refrigeration system, the traditional absorption refrigeration system cannot show satisfying performances at low temperatures.

The refrigerating temperature of new ACAR system is also far lower than that of ACAR system with R32 + R134a/DMF working pair under the approximately operational condition. The lowest refrigerating temperature obtained by ACAR system using R32 + R134a/DMF as its working pair is shown in Fig. 5 [8]. From the principle of phase equilibrium, it is the reason that the boiling point of R23 is much lower than that of R32 under the same pressure. Consequently, it is essential for an ACAR system at low temperatures to use R23 as a component of refrigerant mixture. However, the difference of boiling point between R134a and R23 is great, and is about 55.0 °C. From the principles of Joule–Thomson refrigerating and heat transfer, an absorption refrigeration system at low temperatures might show better performances by lowering refrigerant temperature before throttling and reducing temperature difference of heat transfer at the condenser–evaporator. With regard to ACAR system with R23 + R134a/DMF working pair, the relationships between refrigerating temperature and time is obtained from the literature [10], and as shown as Fig. 6. The time, which is spent in lowering to the lowest temperature in new ACAR system, is shorten to about 50% comparing with that of ACAR system with R23 + R134a/DMF working pair,

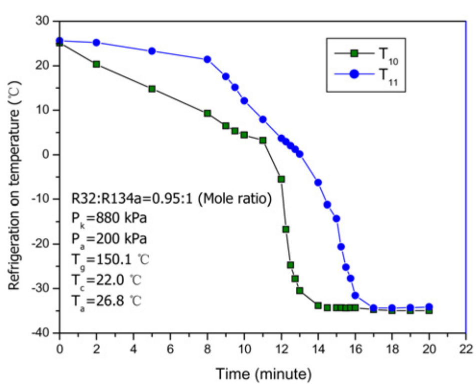

Fig. 5. Relationships between refrigerating temperature (T_e) and time in the ACAR system using R32 + R134a/DMF as its working pair.

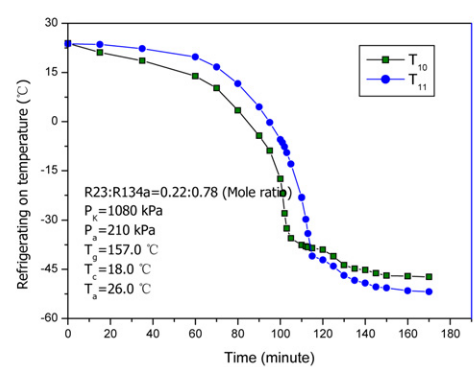

Fig. 6. Relationships between refrigerating temperature (T_e) and time in the ACAR system using R23 + R134a/DMF as its working pair.

Table 3
Comparisons on key experimental parameters of different absorption refrigeration systems

Working pair	R32 + R134a		R23 + R134a		R23 + R32 + R134a	
Cycle	Traditional	ACAR	Traditional	ACAR	Traditional	ACAR
Condensing pressure P_k (absolute pressure, kPa)	675	880	1060	1080	1120	1110
Absorption pressure P_a (absolute pressure, kPa)	190	200	170	210	180	190
Generating temperature T_g [°C]	163.4	150.1	163.1	157.0	167.0	163.0
Condensing temperature T_c [°C]	23.4	22.0	20.4	18.0	25.4	20.0
Absorption temperature T_a [°C]	17.2	26.8	32.2	28.0	30.9	33.0
Lowest refrigerating temperature T_e [°C]	20.3	−34.5	−24.3	−47.2	−24.5	−47.2
Glide of refrigerating temperature [°C]	3.8	0.3	2.3	1.6	6.4	0.2
Generating load Q_g [kW]	–	1.55	–	2.4	–	2.2
Refrigerating capacity Q_e [W]	–	27.9	–	27.4	–	28.5
COP	–	0.018	–	0.011	–	0.013

although they both obtain the same lowest refrigerating temperature under the approximately operational condition. Just because the component of R32 is added into the mixture of refrigerant for new ACAR system, the cooling temperature (T_7 and/or T_8) is lower at the condenser-evaporator. The temperature of T_7 ranges from $-21.0\,^{\circ}\mathrm{C}$ to $-25.0\,^{\circ}\mathrm{C}$ in the new ACAR system, and it does from $-16.0\,^{\circ}\mathrm{C}$ to $-20.0\,^{\circ}\mathrm{C}$ in the ACAR system with R23 + R134a/DMF working pair. Accordingly, the temperature of refrigerant at the point 12 of new ACAR system is lower than that of ACAR system with R23 + R134a/DMF working pair. For the absorbing characteristics of both working pairs are almost alike, the both systems of ACAR can operate under the similar absorbing pressure. Therefore, they can obtain the same refrigerating temperature; however, the new ACAR system can more quickly reach to the lowest point. On the other hand, the new ACAR system might show better performance with the reduction of temperature difference at the condenser–evaporator. From the experimental results of ACAR system with R23 + R134a/DMF working pair, the generating heat load (Q_g) and refrigerating capacity (Q_e) are respectively 2.4 kW and 27.4 W at the lowest refrigerating temperature, and its experimental COP is 0.011. As a result, the experimental COP of new ACAR system in value might be greater 15% than that of ACAR system with R23 + R134a/DMF working pair.

4. Conclusions

Some experiments are successfully undertaken on ACAR system and traditional absorption refrigeration system, and the characteristic comparisons are also carried out among these systems. Based on the analysis of experimental results, the following conclusions can be concluded in this paper.

(1) The experimental results also prove that the ACAR system can obtain a much lower refrigerating temperature comparing with the traditional absorption refrigeration system under the same operational condition.
(2) The new ACAR system obtains a refrigerating temperature, which is one of the lowest refrigerating temperatures obtained by absorption refrigeration system, and is suitable for deep-freezing as low as $-50\,^{\circ}\mathrm{C}$ under the driving of low-potential thermal power.
(3) A working pair has important effects on the performances of ACAR system, and R23 + R32 + R134a/DMF working pair used in ACAR system, in which a moderate boiling point substance—R32 is considered, shows better performances.
(4) For this experimental system is the first prototype of ACAR cycle, the obtained COP is not high. However, the improved performances, for example, a higher COP, might be gained in the next prototype.

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