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A review of absorption refrigeration technologies

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Abstract

This paper provides a literature review on absorption refrigeration technology. A number of research options such as various types of absorption refrigeration systems, research on working fluids, and improvement of absorption processes are discussed. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Refrigeration; Refrigerant; Absorption; Heat pump

Contents

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1. Introduction

Most of industrial process uses a lot of thermal energy by burning fossil fuel to produce steam or heat for the purpose. After the processes, heat is rejected to the surrounding as waste. This waste heat can be converted to a useful refrigeration by using a heat operated refrigeration system, such as an absorption refrigeration cycle. Electricity purchased from utility companies for conventional vapor compression refrigerators can be reduced. The use of heat operated refrigeration systems help reduce problems related to global environmental, such as the so called greenhouse effect from CO_2 emission from the combustion of fossil fuels in utility power plants.

Another difference between absorption systems and conventional vapor compression systems is the working fluid used. Most vapor compression systems commonly use chlorofluorocarbon refrigerants (CFCs), because of their thermophysical properties. It is through the restricted use of CFCs, due to depletion of the ozone layer that will make absorption systems more prominent. However, although absorption systems seem to provide many advantages, vapor compression systems still dominate all market sectors. In order to promote the use of absorption systems, further development is required to improve their performance and reduce cost.

The early development of an absorption cycle dates back to the 1700's. It was known that ice could be produced by an evaporation of pure water from a vessel contained within an evacuated container in the presence of sulfuric acid, [1,2]. In 1810, ice could be made from water in a vessel, which was connected to another vessel containing sulfuric acid. As the acid absorbed water vapor, causing a reduction of temperature, layers of ice were formed on the water surface. The major problems of this system were corrosion and leakage of air into the vacuum vessel. In 1859, Ferdinand Carre introduced a novel machine using water/ammonia as the working fluid. This machine took out a US patent in 1860. Machines based on this patent were used to make ice and store food. It was used as a basic design in the early age of refrigeration development.

In the 1950's, a system using lithium bromide/water as the working fluid was introduced for industrial applications. A few years later, a double-effect absorption system was introduced and has been used as an industrial standard for a high performance heat-operated refrigeration cycle.

The aim of this paper is to provide basic background and review existing literatures on absorption refrigeration technologies. A number of absorption refrigeration systems and research options are provided and discussed. It is hoped that, this paper should be useful for any newcomer in this field of refrigeration technology.

2. Principle of operation

The working fluid in an absorption refrigeration system is a binary solution consisting of refrigerant and absorbent. In Fig. 1(a), two evacuated vessels are connected to each other. The left vessel contains liquid refrigerant while the right vessel contains a binary solution of absorbent/refrigerant. The solution in the right vessel will absorb refrigerant vapor from the left vessel causing pressure to reduce. While the refrigerant vapor is being absorbed, the temperature of the remaining refrigerant will reduce as a result of its vaporization. This causes a refrigeration effect to occur inside the left vessel. At the same time, solution inside the right vessel becomes more dilute because of the higher content of refrigerant absorbed. This is called the "absorption process". Normally, the absorption process is an exothermic process, therefore, it must reject heat out to the surrounding in order to maintain its absorption capability.

Whenever the solution cannot continue with the absorption process because of saturation of the refrigerant, the refrigerant must be separated out from the diluted solution. Heat is normally the key for this separation process. It is applied to the right vessel in order to dry the refrigerant from the solution as shown in Fig. 1(b). The refrigerant vapor will be condensed by transferring heat to the surroundings. With these processes, the refrigeration effect can be produced by using heat energy. However, the cooling effect cannot be produced continuously as the process cannot be done simultaneously. Therefore, an absorption refrigeration cycle is a combination

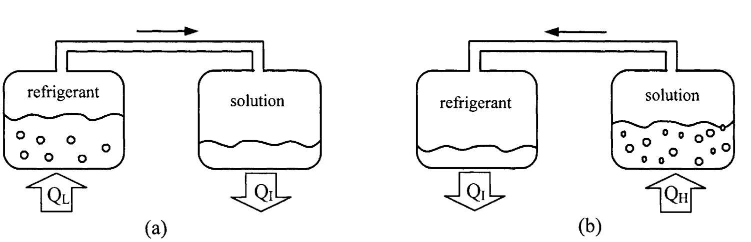

Fig. 1. (a) Absorption process occurs in right vessel causing cooling effect in the other; (b) Refrigerant separation process occurs in the right vessel as a result of additional heat from outside heat source.

of these two processes as shown in Fig. 2. As the separation process occurs at a higher pressure than the absorption process, a circulation pump is required to circulate the solution. Coefficient of Performance of an absorption refrigeration system is obtained from;

$$\mathrm{COP} = \frac{\text{cooling capacilty obtained at evaporator}}{\text{heat input for the generator} + \text{work input for the pump}}$$

The work input for the pump is negligible relative to the heat input at the generator, therefore, the pump work is often neglected for the purposes of analysis.

3. Working fluid for absorption refrigeration systems

Performance of an absorption refrigeration systems is critically dependent on the chemical and thermodynamic properties of the working fluid [3]. A fundamental requirement of absorbent/refrigerant combination is that, in liquid phase, they must have a margin of miscibility within the operating temperature range of the cycle. The mixture should also be chemically stable, non-toxic, and non-explosive. In addition to these requirements, the following are desirable [4].

- The elevation of boiling (the difference in boiling point between the pure refrigerant and the mixture at the same pressure) should be as large as possible.
- Refrigerant should have high heat of vaporization and high concentration within the absorbent in order to maintain low circulation rate between the generator and the absorber per unit of cooling capacity.

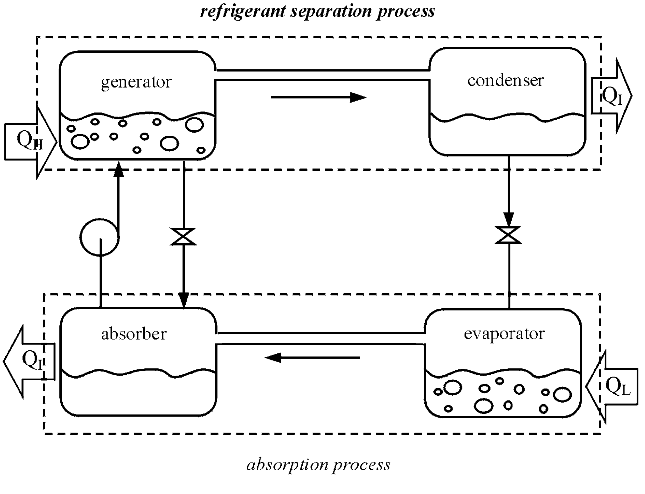

Fig. 2. A continuous absorption refrigeration cycle composes of two processes mentioned in the earlier figure.

- Transport properties that influence heat and mass transfer, e.g., viscosity, thermal conductivity, and diffusion coefficient should be favorable.
- Both refrigerant and absorbent should be non-corrosive, environmental friendly, and low-cost.

Many working fluids are suggested in literature. A survey of absorption fluids provided by Marcriss [5] suggests that, there are some 40 refrigerant compounds and 200 absorbent compounds available. However, the most common working fluids are Water/NH_3 and LiBr/water.

Since the invention of an absorption refrigeration system, water NH_3 has been widely used for both cooling and heating purposes. Both NH_3 (refrigerant) and water (absorbent) are highly stable for a wide range of operating temperature and pressure. NH_3 has a high latent heat of vaporization, which is necessary for efficient performance of the system. It can be used for low temperature applications, as the freezing point of NH_3 is -77°C. Since both NH_3 and water are volatility, the cycle requires a rectifier to strip away water that normally evaporates with NH_3. Without a rectifier, the water would accumulate in the evaporator and offset the system performance. There are other disadvantages such as its high pressure, toxicity, and corrosive action to copper and copper alloy. However, water/NH_3 is environmental friendly and low-cost. Thermodynamic properties of watre/NH_3 can be obtained from [6–10].

The use of LiBr/water for absorption refrigeration systems began around 1930 [11]. Two outstanding features of LiBr/water are non-volatility absorbent of LiBr (the need of a rectifier is eliminated) and extremely high heat of vaporization of water (refrigerant). However, using water as a refrigerant limits the low temperature application to that above 0°C. As water is the refrigerant, the system must be operated under vacuum conditions. At high concentrations, the solution is prone to crystallization. It is also corrosive to some metal and expensive. Thermodynamic properties of LiBr/water can be obtained from [12–16]. Some additive may be added to LiBr/water as an corrosion inhibitor [17–20] or to improve heat-mass transfer performance [21–25].

Although LiBr/water and water/NH_3 have been widely used for many years and their properties are well known, much extensive research has been carried out to investigate new working fluids. Fluorocarbon refrigerant-based working fluids have been studied. R22 and R21 have been widely suggested because of their favorable solubility with number of organic solvents [26]. The two solvents, which have stood out are Dimethyl Ether of Tetraethylene Glycol (DMETEG) and Dimethyl Formamide (DMF). Research on these kinds of working fluids may be obtained from the literature [27–32].

A binary mixture using inorganic salt absorbent such as LiBr/water or NaOH/water may be the most successful working for an absorption refrigeration system [33]. However, at high concentration such as at high temperature, the solution is prone to crystallization. It was found that the addition of a second salt as in a ternary mixture such as LiBr+$ZnBr_2$/water can improve the solubility of the solution. Various ternary mixtures have been tested for using with an absorption system [34–36].

4. Improving of absorption process

An absorber is the most critical component of any absorption refrigeration system [37]. Experimental study shows that the solution circulation ratio (solution circulation rate per unit of refrigerant generated) is found 2 to 5 times greater than the theoretical value. This is due to a non-equilibrium state of solution in the absorber. For given temperature and pressure in the absorber, the solution absorbs less refrigerant than that of the theoretical value. Many researches have been conducted in order to understand and to improve an absorption process between the vapor refrigerant and the solution.

The most common type of absorber used for LiBr/water system is absorption of vapor refrigerant into a falling film of solution over cooled horizontal tubes [38–45]. In this type of absorber, during the absorption process, heat is simultaneously removed from the liquid film. Hence, the absorption rate is increased. However, this design requires a high recirculation rate in order to achieve a good performance. Another notable approach devised by Rotex [46] is absorption of vapor refrigerant into liquid film on cooled rotating discs [47]. For a given surface area, absorption rate on rotating discs is much greater than that on a convention design. Thus, size of an absorber used based on this design is much smaller than a convention falling film design. Absorption process within a rotating drum was also studied [48]. For water/NH_3, literature on absorber designs are also provided [49–51].

5. Various designs of absorption refrigeration cycles

5.1. Single-effect absorption system

A single-effect absorption refrigeration system is the simplest and most commonly used design. There are two design configurations depending on the working fluids used. Fig. 3 shows a single-effect system using non-volatility absorbent such as LiBr/water.

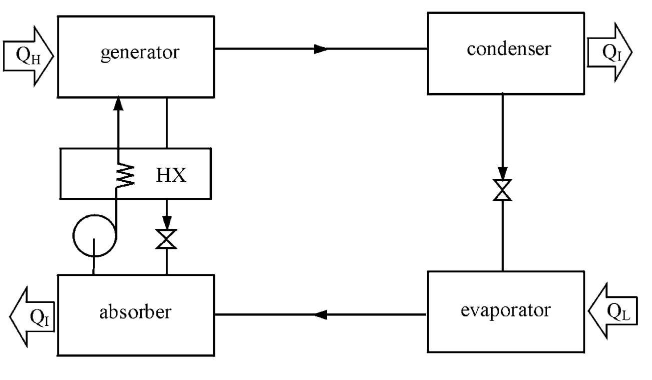

Fig. 3. A single-effect LiBr/water absorption refrigeration system with a solution heat exchanger (HX) that helps decrease heat input at the generator.

High temperature heat supplied to the generator is used to evaporate refrigerant out from the solution (rejected out to the surroundings at the condenser) and is used to heat the solution from the absorber temperature (rejected out to the surroundings at the absorber). Thus, an irreversibility is caused as high temperature heat at the generator is wasted out at the absorber and the condenser. In order to reduce this irreversibility, a solution heat exchange is introduced as show in Fig. 3. The heat exchanger allows the solution from the absorber to be preheated before entering the generator by using the heat from the hot solution leaving the generator. Therefore, the COP is improved as the heat input at the generator is reduced. Moreover, the size of the absorber can be reduced as less heat is rejected. Experimental studies shows that COP can be increased up to 60% when a solution heat exchanger is used [37].

When volatility absorbent such as water/NH_3 is used, the system requires an extra component called "a rectifier", which will purify the refrigerant before entering the condenser. As the absorbent used (water) is highly volatile, it will be evaporated together with ammonia (refrigerant). Without the rectifier, this water will be condensed and accumulate inside the evaporator, causing the performance to drop.

Even if the most common working fluids used are LiBr/water and water/NH_3, various researchers have studied performance of a single-effect absorption system using other kinds of working fluids such as $LiNO_3/NH_3$ [52], $LiBr+ZnBr_2/CH_3OH$ [53], $LiNO_3+KNO_3+NaNO_3$/water [54], LiCl/water [55], Glycerol/water [56].

5.2. Absorption heat transformer

Any absorption refrigeration cycle exchanges heat with three external reservoirs; low, intermediate, and high temperature levels. When an absorption system is operated as a refrigerator or a heat pump, the driving heat is supplied from the high temperature reservoir. Refrigeration effect is produced at a low temperature level and rejects heat out at an intermediate temperature level. The difference between them is the duty. For a refrigerator, the useful heat transfer is at a low temperature. For the heat pump, the useful heat transfer is at an intermediate temperature. Normally, the surrounding is used as a low temperature reservoir for a heat pump or as an intermediate temperature reservoir for the refrigerator.

Another type of absorption cycle is known as "an absorption heat transformer" or "a reverse absorption heat pump". This system uses heat from an intermediate temperature reservoir as the driving heat (normally from industrial waste heat). The system rejects heat out at a low temperature level (normally to the surroundings). The useful output is obtained at the highest temperature level. The use of an absorption heat transformer allows any waste heat to be upgraded to a higher temperature level without any other heat input except some work required to circulate the working fluid.

Fig. 4 shows a schematic diagram of an absorption heat transformer. This cycle has similar components as a single-effect absorption cycle. The difference is that an expansion device installed between the condenser and the evaporator is substituted by a pump. Waste heat at a relatively low temperature is supplied to the generator

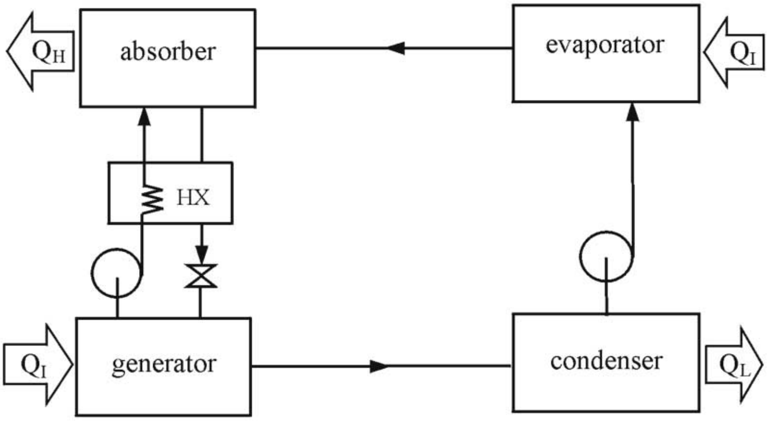

Fig. 4. Absorption heat transformer absorbs waste heat at the generator. Liquid refrigerant is pumped to the evaporator to absorb waste heat. High temperature useful heat from the absorber is heat of absorption.

for refrigerant separation in the usual manner. Liquid refrigerant from the condenser is then pumped to the evaporator with elevated pressure. In the evaporator, it is vaporized by using the same low temperature waste heat used to drive the generator (absorption heat transformers are usually operated so that the generator and evaporator temperatures are equal). The vapor refrigerant is then absorbed into solution in the absorber which reject the useful heat out at a high temperature level.

Low-grade heat can be upgraded by using a heat transformer e.g. solar energy [57], industrial waste heat [58,59]. Performance of an absorption heat transformer with various working fluids has been studied; LiBr/water [60], LiBr+$ZnBr_2$/CH_3OH [61], DMETEG/R21, DMF/R21 [62–64].

5.3. Multi-effect absorption refrigeration cycle

The main objective of a higher effect cycle is to increase system performance when high temperature heat source is available. By the term “multi-effect”, the cycle has to be configured in a way that heat rejected from a high-temperature stage is used as heat input in a low-temperature stage for generation of additional cooling effect in the low-temperature stage.

Double-effect absorption refrigeration cycle was introduced during 1956 and 1958 [65]. Fig. 5 shows a system using LiBr/water. High temperature heat from an external source supplies to the first-effect generator. The vapor refrigerant generated is condensed at high pressure in the second-effect generator. The heat rejected is used to produce addition refrigerant vapor from the solution coming from the first-effect generator. This system configuration is considered as a series-flow-double-effect absorption system.

A double-effect absorption system is considered as a combination of two single-effect absorption systems whose COP value is COP_{single}. For one unit of heat input from the external source, cooling effect produced from the refrigerant generated from

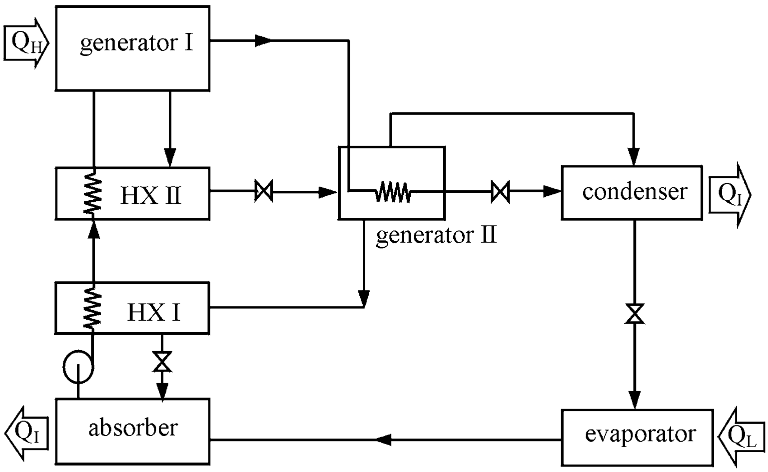

Fig. 5. A double-effect water/LiBr absorption cycle. Heat released from the condensation of refrigerant vapor is used as heat input in generator II. This cycle is operated with 3 pressure levels i.e. high, moderate and low pressure.

the first-effect generator is $1\times COP_{single}$. For any single-effect absorption system, it may be assumed that the heat rejected from the condenser is approximately equal to the cooling capacity obtained. Thus the heat supply to the second generator is $1\times COP_{single}$. The cooling effect produced from the second-effect generator is $(1\times COP_{single})\times COP_{single}$.. Therefore, the COP of this double-effect absorption system is $COP_{double}=COP_{single}+(COP_{single})^2$. According to this analysis, a double effect absorption system has a COP of 0.96 when the corresponding single-effect system has a COP of 0.6. Theoretical studies of a double-effect absorption system have been provided for various working fluids [66,67].

If LiBr/water is replaced with water/NH_3, maximum pressure in the first-effect generator will be extremely high. Fig. 6 shows a double-effect absorption system

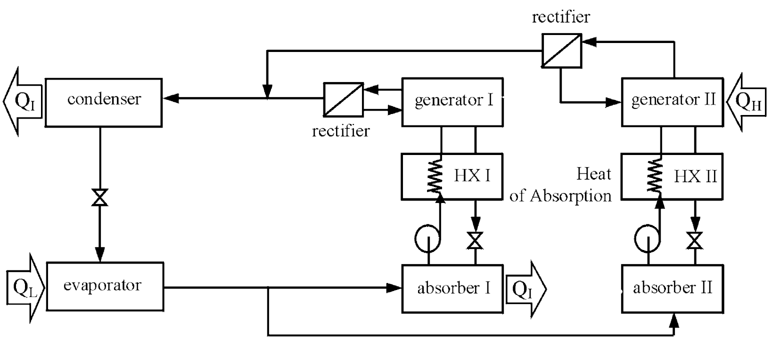

Fig. 6. A double-effect absorption cycle operates with two pressure levels. Heat of absorption from Absorber II is supplied to the Desorber I for the refrigerant separation process.

using water/NH_3. In contrast to the system for LiBr/water, this system can be considered as a combination of two separated single-effect cycles. The evaporator and the condensers of both cycles are integrated together as a single unit as shown. Thus, there are only two pressures level in this system and the maximum pressure can be limited to an acceptable level. Heat from external source supplies to generator II only. As water is an absorbent, there is no problem of crystallization in the absorber. Hence, absorber II can be operated at high temperature and rejects heat to the generator I. This system configuration is considered as a parallel-flow-double-effect absorption system.

Several types of multi-effect absorption cycle has been analyzed such as the triple-effect absorption cycle (Fig. 7) [68] and the quadruple-effect absorption cycle [69]. However, an improvement of COP is not directly linked to the increment of number of effect. It must be noted that, when the number of effects increase, COP of each effect will not be as high as that for a single-effect system. Moreover, the higher number of effect leads to more system complexity. Therefore, the double-effect cycle is the one that is available commercially [70].

5.4. *Absorption refrigeration cycle with GAX*

GAX stands for generator/absorber heat exchanger or sometimes is called DAHX which stands for desorber/absorber heat exchanger. Higher performance can be achieved with a single-effect absorption system. Referring to the parallel-flow-double-effect absorption system mentioned earlier, the system consists of two single-effect cycles working in a parallel manner. The concept of GAX is to simplify this two-stage-double-effect absorption cycle but still produce the same performance. The

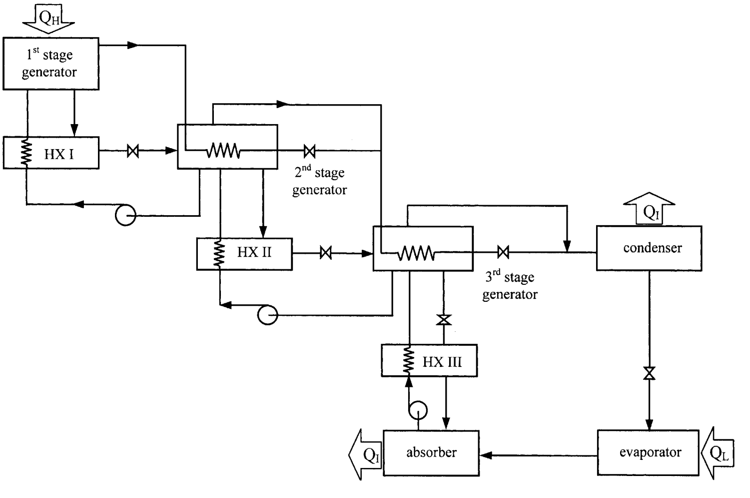

Fig. 7. A triple-effect absorption cycle operates at 4 pressure levels. Heat of condensation from the higher-pressure stage is used for refrigerant separation in the lower-pressure stage.

ideal of GAX was introduced in 1911 by Altenkirch and Tenckhoff [71,72]. The simplified configuration is shown schematically in Fig. 8.

An absorber and a generator may be considered as a counter-flow-heat exchanger as shown in Fig. 8. At the absorber, weak-refrigerant solution from the generator and vapor refrigerant from the evaporator enter at the top section. Heat produced during the absorption process must be rejected out in order to maintain ability to absorb the refrigerant vapor. At the top section, heat is rejected out at a high temperature. In the lower section, the solution further absorbs the vapor refrigerant while cooling down by rejecting heat to the surrounding. At the generator, rich-refrigerant solution from the absorber enters at the top section. In this section, the refrigerant is dried out from the solution as it is heated by using the heat rejected from the top section of the absorber. At the lower section of the generator, the solution is further dried as it is heated by the external source. Referring to Fig. 8, there is an additional secondary-fluid, which used for transferring heat between the absorber and the generator. Therefore, a single-effect absorption system can provide as high COP as that for the two-stage-double-effect absorption system by using GAX. This system has been studied [73–78].

5.5. Absorption refrigeration cycle with an absorber-heat-recovery

It is already mentioned earlier that the use of a solution heat exchanger improves the system COP. Rich-refrigerant solution from the absorber can be preheated before entering the generator by transferring heat from hot solution coming from the generator. By introducing an absorber-heat-recovery, temperature of the rich-refrigerant solution can be further increased.

Similar to the GAX system, the absorber is divided into two sections. Heat is rejected out at a different temperature. The lower temperature section rejects heat out to the surroundings as usual. However, the higher temperature section is used

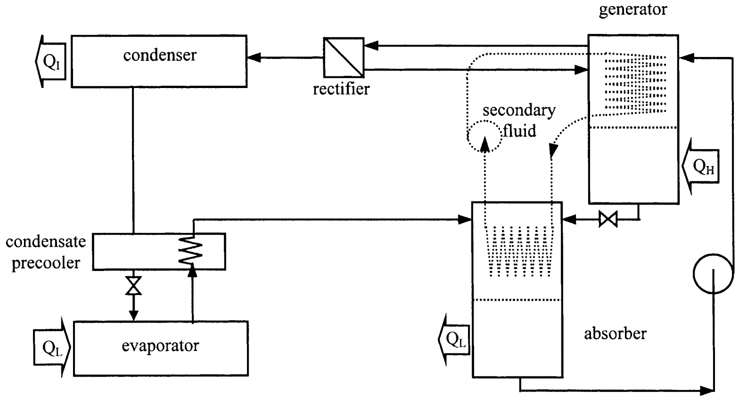

Fig. 8. The dotted loop shows secondary fluid used for transferring heat from high the temperature section in the absorber to low temperature section in the generator.

to preheat rich-refrigerant solution as shown in Fig. 9. Therefore, the heat input to the generator is reduced causing the COP to increase.

This system was studied theoretically by using various working fluids; water/NH_3 and $LiNO_3$/NH_3 [79,80]. The cycle with an absorber-heat-recovery was found to have 10% improvement in COP. However, the machine based on this absorber design has not yet been built.

5.6. Half-effect absorption refrigeration cycle

It must be noted that, any absorption refrigeration system can be operated only when the solution in the absorber is richer in refrigerant than that in the generator. When the temperature increases or the pressure reduces, the fraction of refrigerant contained in the solution is reduced, and vice versa. When the generator temperature is dropped, the solution circulation rate will be increased causing the COP to drop. If it is too low, the system can be no longer operated.

The half-effect absorption system was introduced for an application with a relatively low-temperature heat source [81]. Fig. 10 shows a schematic diagram of a half-effect absorption refrigeration cycle. The system configuration is exactly the same as the double-effect absorption system using water/NH_3 (as shown in Fig. 6) except the heat flow directions are different. Referring to Fig. 10, high temperature heat from an external source transfers to both generators. Both absorbers reject heat out to the surroundings. Absorber II and generator I are operated at an intermediate pressure level. Therefore, the circulation rate between generator I and absorber I and between generator II and absorber II can be maintained at acceptable levels. It must be noted that COP of the half-effect absorption system is relatively low as it rejects more heat than a single-effect absorption cycle around 50% [82]. However, it can be operated with the relatively low temperature heat source.

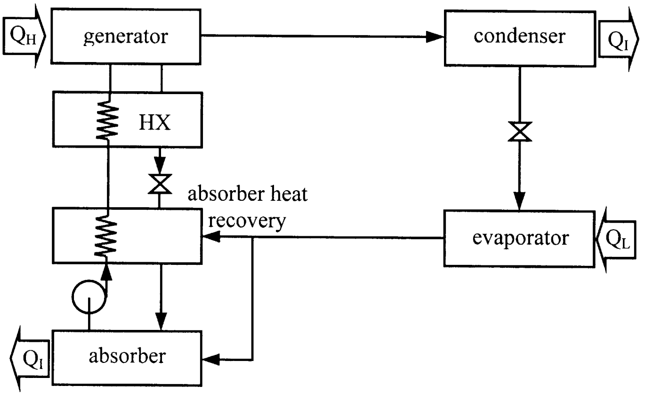

Fig. 9. The cycle with absorber heat recovery uses heat of absorption to preheat the outgoing stream from the absorber to the generator.

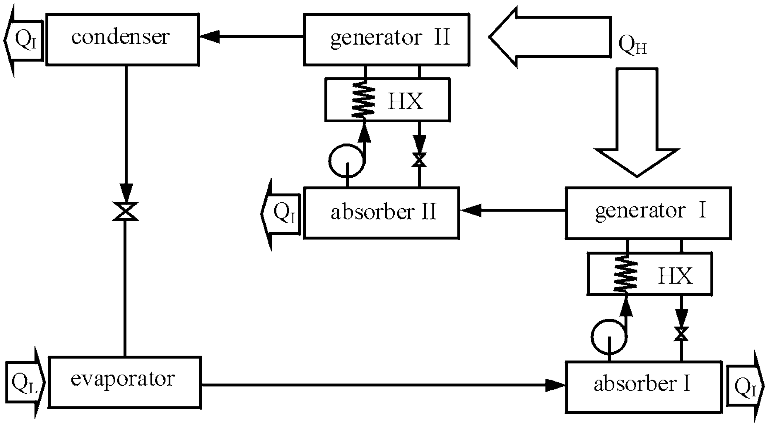

Fig. 10. A half-effect absorption cycle is a combination of two single-effect cycles but working at different pressure levels. Letting heat source temperature be lower than the minimum temperature is necessary for a single-effect cycle working at the same pressure level.

5.7. Combined vapor absorption-compression cycle

This system is usually known as an absorption-compression system. A schematic diagram of a typical absorption/compression cycle is shown in Fig. 11(a). It can be seen that, a condenser and an evaporator of a conventional vapor-compression system are replaced with a resorber (vapor absorber) and a desorber (vapor generator). For given surrounding temperature and refrigerating temperature, the pressure differential across the compressor is much lower than a conventional vapor-compression system. Thus, the COP is expected to be better than a conventional vapor-compression system. Altenkirch did the first investigation in 1950 and proposed a potential for energy-saving [82]. The cycle can be configured as a heat pump cycle. Machielsen [83] developed a heat pump cycle as shown in Fig. 11(b).

An interesting configuration is a double-effect vapor absorption/compression cycle

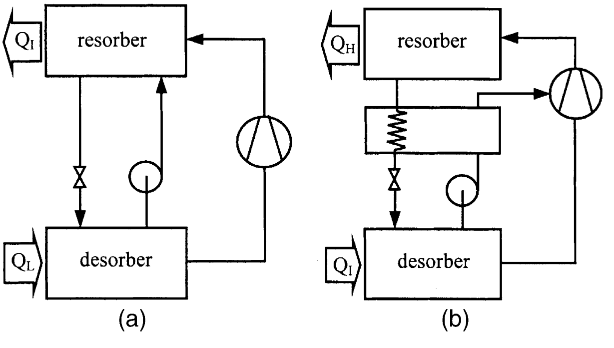

Fig. 11. Combined vapor absorption/compression heat pump.

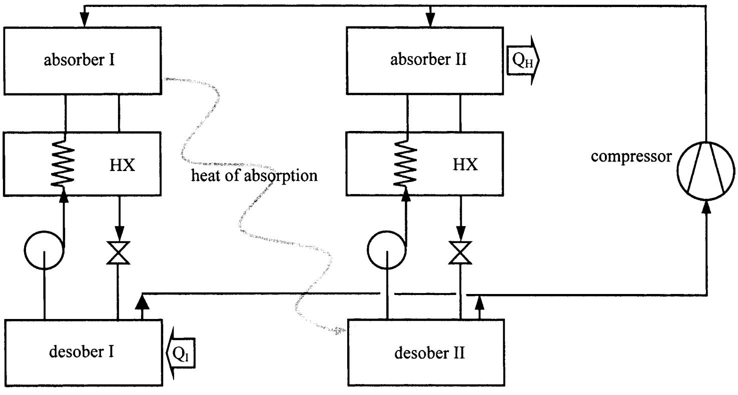

Fig. 12. A double effect absorption-compression cycle is configured as a heat pump. Heat of absorption in the first stage will be supplied to the second stage for refrigerant separation.

as shown in Fig. 12. The rejected first-stage absorber heat is supplied to the generator of the second-stage. The transfer of heat is done internally which overcomes the large temperature difference at the moderate pressure ratio. This concept has been shown successfully in several studies, [83–85].

Another configuration of the vapor absorption/compression cycle, proposed by Cacciola et al. [86] is shown schematically in Fig. 13 and employs two combinations of working fluids, water/NH_3 and KHO/water. This is a compromise of the water/NH_3 cycle and KHO/water cycle. The highest system pressure is reduced and the rectifier of water/NH_3 system is abstained. This cycle can be operated with an ambient temperature lower than 0°C without freezing or crystallization problems.

The first experimental results of an absoption/compression cycle with direct

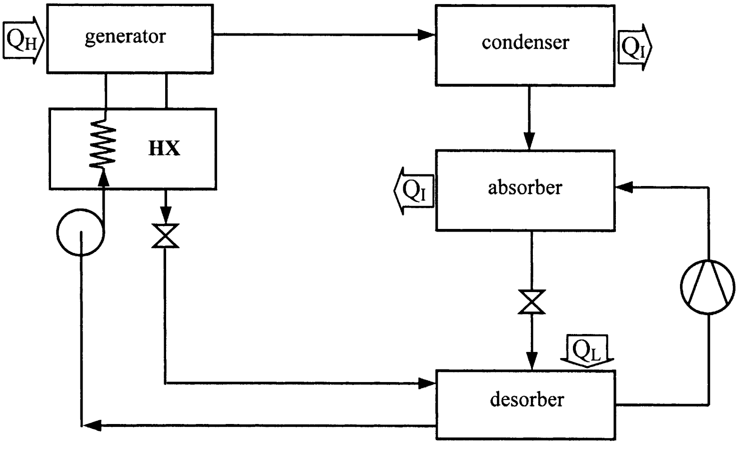

Fig. 13. A combined cycle proposed by Caccoila et al. [86], employing two combinations of working fluids i.e. NH_3/H_2O and H_2O/KHO. The rectifier is absent and also the highest pressure is decreased.

desorber/absorber heat exchanger was presented by Groll and Radermacher [87]. This is a modified plant from a two stage-solution circuit proposed by Rane and Radermacher [84] and Rane et al. [85]. This technology is the basis for the study of GAX cycle in these days.

Various designs of combined vapor absorption/compression cycle have been introduced. They can produce attractively high COP. However, they are complex and the driving energy is in the form of mechanical work. Thus, they can not be considered as a heat-operated system.

5.8. Sorption-resorption cycle

Altenkirch introduced the idea of a sorption-resorption cycle in 1913. The cycle employs two solution circuits instead of only one. The condenser and evaporator section of a conventional single-effect absorption system is replaced with a resorber and a desorber respectively as shown in Fig. 14 [87]. This provides more flexibility in the cycle design and operations. The solution loops concentrations can be varied allowing adjustment of the component temperatures and pressures to the application requirement.

5.9. Dual-cycle absorption refrigeration

The concept of a dual-cycle absorption system is similar to a parallel-double-effect absorption system. However, this system consists of two completely separated cycles using different kinds of working fluid. Hanna et al. [88] invented a dual-cycle absorption refrigeration and heat pump as shown in Fig. 15. This system consists of two single-effect absorption cycles using water/NH_3 and LiBr/water. The NH_3 system is driven by heat obtained from an external heat source. The heat reject from its absorber and condenser is used as a driving heat for the LiBr/water system. The LiBr/water system rejects heat out to the surrounding at the condenser and the absorber as usual. The cooling effect can be obtained from both evaporators.

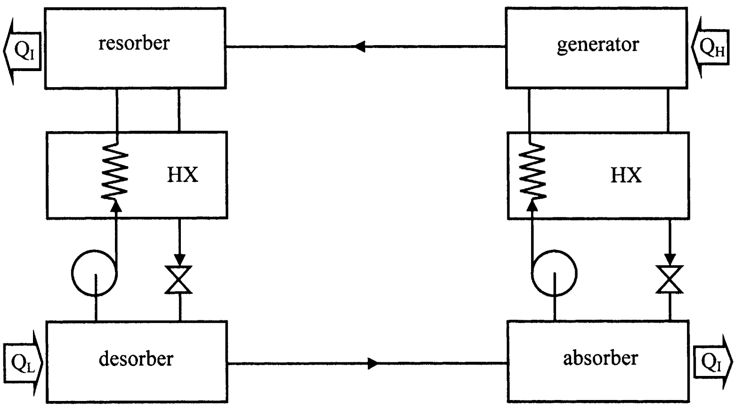

Fig. 14. A resorption cycle proposed by Altenkirch uses two solution circuits.

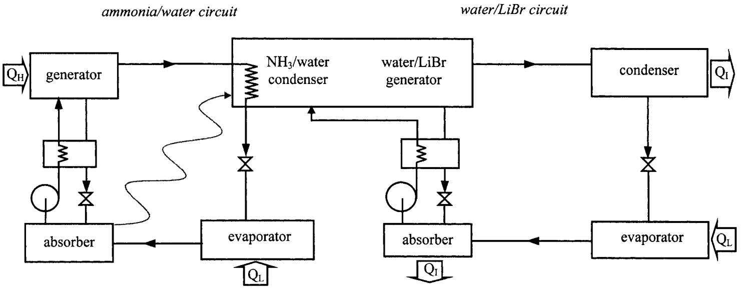

Fig. 15. Solar driven dual cycle absorption employs two different working fluids i.e. NH_3/water and water/LiBr. Heat of absorption and condensation from NH_3/water cycle are supplied to the generator of water/LiBr cycle.

5.10. Combined ejector-absorption refrigeration cycle

An ejector can be used to improve performance of an absorption refrigeration system. One notable approach devised by Kuhlenschmidt [89] is shown in Fig. 16. The aim is to develop an absorption system using working fluid based on salt absorbent, capable of operating at low evaporator temperatures and employing an air-cooled absorber. This system employs two-stage generators similar to that used in a double-effect absorption system. However, in contrast to a conventional double-effect absorption system, the low-pressure vapor refrigerant from the second-effect generator is used as a motive fluid for the ejector that entrains vapor refrigerant from the evaporator. The ejector exhaust is discharged to the absorber, causing the absorber pressure to be at a level higher than that in the evaporator. Therefore, the concentration of solution within the absorber can be kept from crystallization when the system is needed to operate with low evaporator temperature or with high absorber temperature (such as an air-cooled unit). It can be noted that there is no condenser

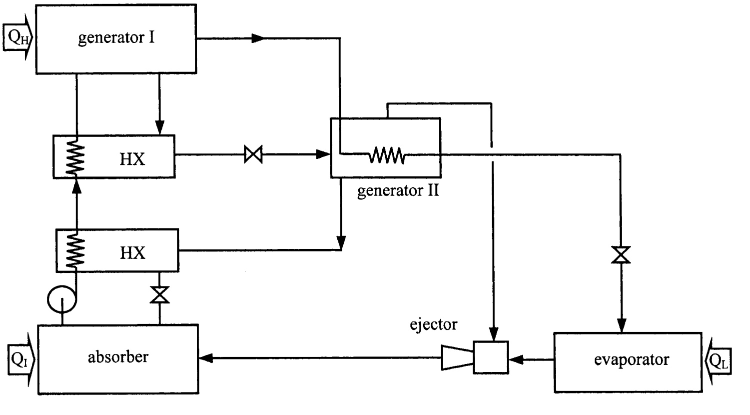

Fig. 16. A modified double-effect combined ejector-absorption refrigeration cycle where there is no condenser included.

in this system, as the high-pressure vapor refrigerant is condensed in the second-effect generator and the low-pressure vapor refrigerant is used as the motive fluid for the ejector. Neither theoretical nor experimental results of this system are available yet. However, one can expect that the COP of this system will not be higher than that of a single-effect absorption system. As some of the vapor refrigerant generated is discharged directly to the absorber (as the motive fluid) without producing any cooling effect. Moreover, the absorber used needs to have a far greater absorption capacity than any other absorption system with the same cooling capacity.

Another approach of using ejector with an absorption system was introduced by Chung et al. [90] and Chen [91], as shown in Fig. 17. Similar to Kuhlenschmidt, an ejector is used to maintain an absorber pressure at a level higher than that in the evaporator. In contrast to the previous system, the ejector's motive fluid is the high-pressure liquid solution from the generator. Therefore, high-pressure and high-density refrigerant can be used only. This is because a liquid-driven ejector is not suitable to operate with low-density vapor such water, as in the case for systems using LiBr/water. Experimental investigation showed that, by using DMETEG/R22 and DMETEG/R21 as working fluids, the pressure ratio between the absorber and the evaporator of 1.2 were found. The increase in absorber pressure results in the circulation of the solution being reduced lower than that for a conventional system operated at the same condition. Thus, an improvement in the COP can be expected.

Another approach proposed by Aphornratana and Eames [92] is shown in Fig. 18. An ejector is placed between a generator and a condenser of a single-effect absorption system. LiBr/water is used as the working fluid. The ejector uses high-pressure water vapor from the generator as the motive fluid. Thus, the generator is operated at a pressure higher than the condenser. This allows the temperature of the solution to be increased without danger of crystallization. If the temperature and pressure are simultaneously increased, the solution concentration is maintained constant and the heat input to the generator is only slightly increased. The ejector entrains vapor

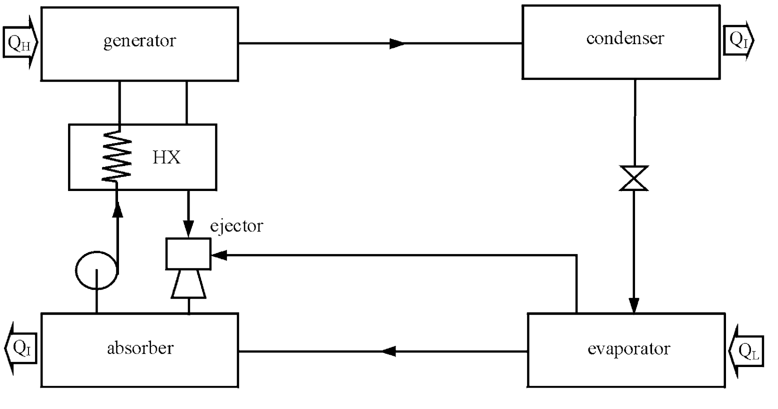

Fig. 17. A combined ejector/absorption system using DMETEG/R22 and DMETEG/R21 as working fluids. The strong solution in the returning leg from generator serves as primary fluid and refrigerant vapor from evaporator as second fluid.

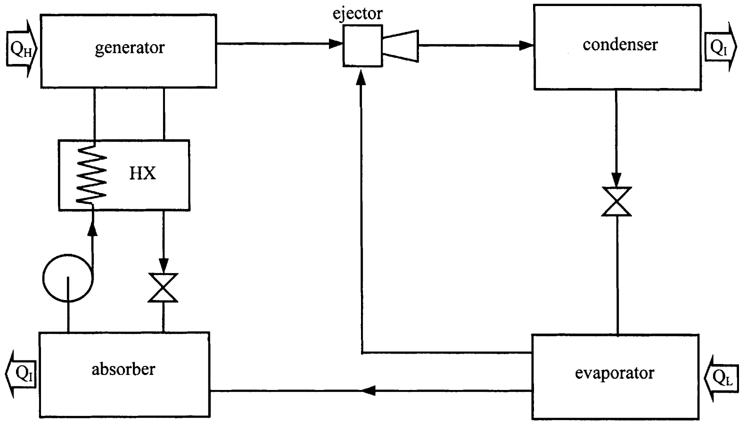

Fig. 18. A combined ejector/absorption proposed by Aphornratana and Eames [92], was invented. High pressure refrigerant vapor from the generator enters the ejector as motive fluid to carry the refrigerant vapor from the evaporator.

refrigerant from the evaporator, hence, more cooling effect is produced. COP is significantly increased over a conventional single-effect absorption system. Experimental investigation showed that COP's as high as 0.86 to 1.04 was found. However, this system must be operated with a high temperature heat source (190 to 210°C) and acceptable surrounding temperature. As the generator temperature is high, the corrosion of construction material may be problematic.

The approach proposed by Eames and Wu [93,94] is shown in Fig. 19. This cycle is a combined cycle between a steam jet heat pump and a single-effect absorption cycle. In this system, a steam jet system is used as an internal heat pump, which was used to recover rejected heat during the condensation of the refrigerant vapor from a single-effect absorption cycle. The heat pump supplies heat to the generator of an absorption system. The refrigerant vapor generated from the generator is entrained by the steam ejector and is liquefied together with the ejector's motive steam by rejecting heat to the solution in the generator. In this system the corrosion problem is eliminated as the solution maximum temperature is maintained at 80°C. The driving heat (from an external source) is supplied to the steam boiler only at temperatures around 200°C. The experimental COP of this system was found to be 1.03.

5.11. Osmotic-membrane absorption cycle

This system, as shown in Fig. 20, was proposed by Zerweck [95]. The system consists of a condenser and an evaporator as usual. Rich-refrigerant solution in the absorber and weak-refrigerant solution in the generator are separated from each other by using an osmotic membrane. The osmotic membrane allows only the refrigerant to pass. Thus, the refrigerant from the absorber can be transferred to the generator by an osmotic diffusion effect through the membrane without any mechanical pump.

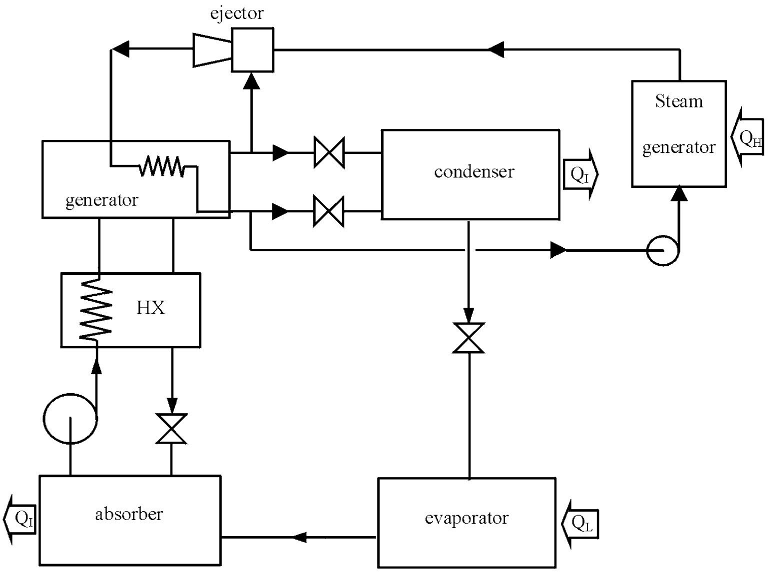

Fig. 19. A combined cycle proposed by Eames and Wu [93]. The highest solution circuit temperature is maintained at about 80°C. So the corrosion problem is alleviated.

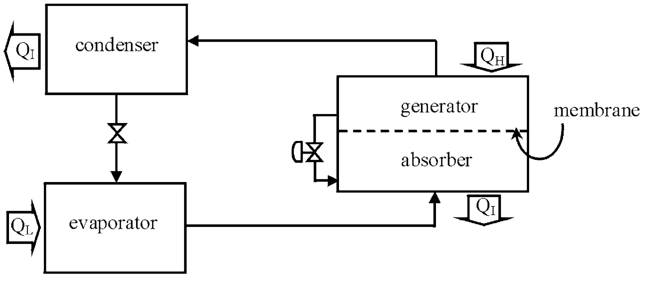

Fig. 20. An osmotic membrane absorption cycle employs heat for refrigerant separation and producing pressure difference within the system.

The pressure difference within the generator and the absorber is also dependent on the type of the membrane used. Normally, the membrane is not perfect, the absorbent from the absorber may be diffused together with the refrigerant to the generator. Thus, a bleed valve is needed to restrengthen the solution in the absorber. In practice, the membrane must be able to withstand all the operating conditions; pressure, temperature, and high aggressive working fluid. The membrane should minimize heat transfer between the generator and the absorber [96]. Moreover, a bleed valve may be needed to restrengthen the solution in the absorber if the membrane is imperfect.

5.12. Self-circulation absorption system using LiBr/water

Even if the prime energy for an absorption refrigeration system is in the form of heat, some electricity still required to drive a circulation pump. There is some absorption refrigeration systems that do not require any circulation pump. In such a system, working fluid is circulated naturally by a thermosyphon effect known as a bubble pump.

Yazaki Inc. of Japan introduced a self-circulate absorption refrigeration system based on a single-effect system using LiBr/water. Using water as a refrigerant, differential pressure between the condenser and the evaporator is very low and can be maintained by using the principle of hydrostatic-head. The solution from the absorber can be circulated to the generator by a bubble pump. The weak-refrigerant solution returns gravitationally back to absorber. A schematic diagram of this system is shown in Fig. 21. With the effect of the bubble pump, the solution is boiled and pumped at the same time. Smith and Khahra [97] carried out a study of performance of CH-900-B Yazaki absorption water chiller operated using propane gas.

Eriksson and Jernqvist [98], developed a 10 kW self-circulation absorption heat transformer using NaOH/water. Due to the high temperature and pressure differential between the condenser and the evaporator, the absorber and evaporator are located at 7 and 10 m below the condenser and generator, respectively. The lowest and highest point of this machine is 14 m. which is equivalent to a pressure difference of 1 bar inside the system.

5.13. Diffusion absorption refrigeration system (DAR)

DAR is another type of self-circulate absorption system using water/NH_3. As NH_3 is the working fluid, differential pressure between the condenser and the evaporator is too large to be overcome by a bubble-pump. The concept of DAR was proposed by Platen and Munters [99], students at the Royal Institute of Technology, Stock-

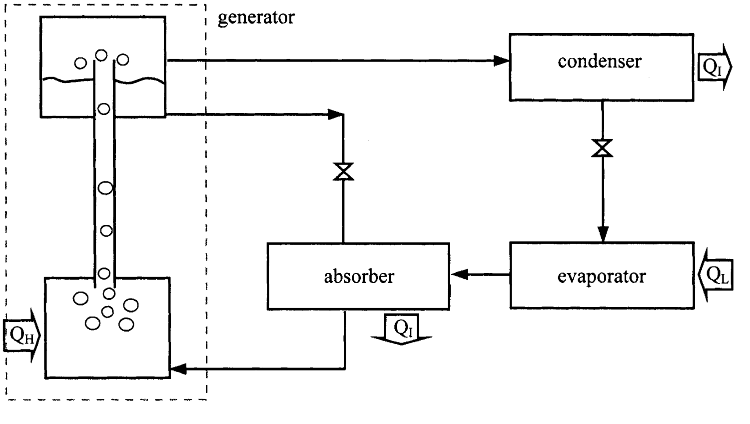

Fig. 21. The diagram shows a bubble pump in a generator module. Heat input to the generator is used for both circulation of working fluid and evaporation of refrigerant.

holm. Fig. 22 shows a schematic diagram of this system. An auxiliary gas is charged to the evaporator and the absorber. Therefore, no pressure differential in this system and the bubble-pump can be used. The cooling effect is obtained based on the principle of partial pressure. Because the auxiliary gas is charged into the evaporator and the absorber, the partial pressure of ammonia in both evaporator and absorber is kept low enough to correspond with the temperature required inside the evaporator. The auxiliary gas should be non-condensable such as hydrogen or helium.

An outstanding feature of this system is that it can be operated in places where no electricity is available. It has been used for a long time in domestic refrigerators. It contains no moving part, which means it is free of maintenance and produces less noise during the operation. However, in the traditional models, its cooling capacity is very small, less than 50 W. With this cooling capacity, it is only suitable to be used as a refrigerator in a hotel room or recreation vehicle and it is not enough for air conditioning applications [100].

Modifications of the traditional model machines have been made; for example

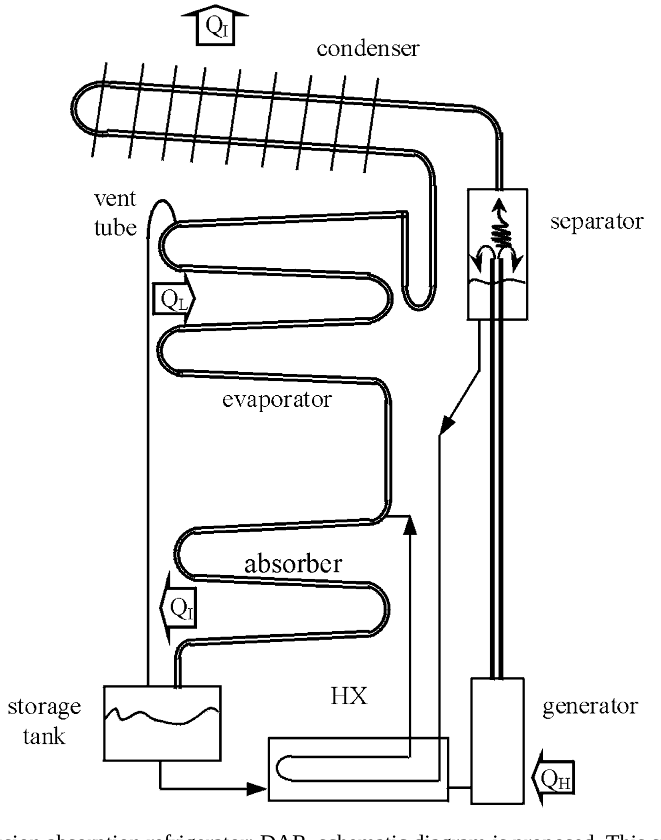

Fig. 22. A diffusion absorption refrigerator; DAR, schematic diagram is proposed. This system was once widely used as a domestic refrigerator as no electricity is required in its operation. NH_3/water/auxiliary gas is charged in the machine as the working fluid.

Table 1
Comparison of vapor absorption technology

System	Pressure level	Operating temperature (°C)		Working fluid	Cooling capacity (ton)	COP	Current status	Remark
		Heat source	Cooling					
Single effect cycle	2	80–110	5–10	LiBr/water	10–100	0.5–0.7	Large water chiller	1. Simplest and widely use 2. Using water as a refrigerant, cooling temperature is above 0°C 3. Negative system pressure 4. Water cooled absorber is required to prevent crystallization at high concentration
	2	120–150	<0	Water/NH_3	3–25	0.5	Commercial	1. Rectification of refrigerant is required 2. Working solution is environmental friendly 3. Operating pressure is high as using NH_3 4. No crystallization problem 5. Suitable for using as heat pump due to wide operating range
Double effect cycle (series flow)	3	120–150	5–10	LiBr/water	up to 1000	0.8–1.2	Large water chiller	1. high performance cycle which is available commercially 2. heat of condensation from the first effect is used as heat input for the second stage
(parallel flow)	2		<0	Water/NH_3			Experimental unit	heat release from the first stage absorber is used for the second stage generator
Triple effect cycle	4	200–230	5–10	LiBr/water	N/A	1.4–1.5	Computer model and experimental unit	1. high complexity control system 2. likely to be direct fired as the input temp is quite high 3. require more maintenance as a result of high corrosion due to high operating temperature

(continued on next page)

Table 1 (*continued*)

System	Pressure level	Operating temperature (°C)		Working fluid	Cooling capacity (ton)	COP	Current status	Remark
		Heat source	Cooling					
Half effect cycle	3	Low	<0	Water/NH_3	N/A	0.2–0.3	Computer model	1. poor efficiency and complicate 2. suitable when driving heat is cheap or free
System with absorber-heat-recovery	2	90–180	<0	Water/NH_3	N/A	0.5–0.7	Computer model	COP is claimed to be better than a single effect by 10%
Combined ejector-absorption (Kuhlenschmidt's)	3			LiBr/water			Patent	1. eliminate crystallization in the absorber by increasing pressure due to ejector operation 2. refriderent generated by the second effect generator is rather used for driving the ejector than producing cooling effect 3. COP is expected to be similar to the conventional system
Chung's and Chang's	3			DMETEG/R2 1 DMETEG/R2 2			Computer model and experimental unit	1. a liquid solution valve is substituted by a liquid driven ejector 2. solution circulation rate is reduced as a result of incremental of refrigerant containing in the solution due to higher absorber pressure caused by the ejector 3. this system is suitable for using with high density refrigerant as a result of the ejector characteristics

(continued on next page)

Table 1 (*continued*)

System	Pressure level	Operating temperature (°C)		Working fluid	Cooling capacity (ton)	COP	Current status	Remark
		Heat source	Cooling					
Aphornratana's	3	180–200	5–10	LiBr/water	2 kW	0.9–1.1	Experimental unit	1. the ejector is placed between the generator and the condenser. This lets the generator operating at high pressure and temperature while heat input is slightly increased 2. COP is increased as high as a double effect due to increasing cooling effect by ejector operation 3. corrosion rate may be increased due to high temperature operation
Eames and Wu's	3	200	5	LiBr/water	5 kW	1.03	Experimental unit	1. steam jet acts as a heat pump to recover heat from the condenser and supply back to the generator 2. the ejector helps reduce generator pressure so that the ejector exhaust can be used as heat input 3. COP is increased as a result of reduction of rejected heat i.e. via absorber only 4. low corrosion due to low temperature operation, <100°C
Yazaki Self-circulation system	2	80–110	5–10	LiBr/water	10–20 kW	0.6	Water chiller	1. water cooled absorber is required as using LiBr/water 2. no mechanical pump needed in the operation but not for chilled water and cooling water

(*continued on next page*)

Table 1 (*continued*)

System	Pressure level	Operating temperature (°C)		Working fluid	Cooling capacity (ton)	COP	Current status	Remark
		Heat source	Cooling					
Diffusion absorption cycle	1	140–200	<0	Water.NH_3/H_2 or He	50–300 W	0.05–0.2	Domestic refrigerator	1. pure heat operated refrigeration cycle 2. can be operated in areas that there is no electricity supply 3. less maintenance due to lacking of moving parts 4. working solution is environmental friendly
Osmotic membrane cycle	2						Patent	1. system possibility is limited by membrane technology 2. pure heat operated cycle as no pump, condenser and solution heat exchanger are required in the system
Absorption-compression cycle	2			Various		Up to 4.5	Computer model and experimenal units	1. system operations require some mechanical equipment for driving compressor 2. absorption circuit is used for replacing condenser and evaporator of the traditional compression cycle to reduce the compression ratio, which help reduction of compression power input

enhancement of boiler performance [101], by altering the auxiliary gas to helium [102]. The original DAR uses hydrogen as the auxiliary gas. It is known that hydrogen can cause danger if it leaks. Helium is an alternative auxiliary gas that was introduced to replace hydrogen. The comparisons of hydrogen and helium as auxiliary gas have been investigated [102–105].

6. Conclusions

This paper describes a number of research options of absorption refrigeration technology; generally three approaches have been followed. There are to develop new working fluids, improve absorber performance, and to invent new advance cycles.

Comparison of various types of absorption refrigeration systems is shown in Table 1. Many type absorption cycles have been developed, however, the system complexities were increased over a conventional single-effect absorption system. At this moment, double-effect absorption systems using lithium bromide/water seem to be the only high performance system which is available commercially. Current research and development efforts on multi-effect cycles show considerable promise for future application. A combined ejector-absorption system [92] is another possible option. This system can provide COP as high as a double-effect system with little increase in system complexity. A diffusion absorption refrigeration system is the only true heat-operated refrigeration cycle. This system has been widely used as a domestic refrigerator. However, it is only available with small cooling capacity and its COP is low (0.1 to 0.2). Many attempts have been made to improve its performance.

It is hoped that this contribution will simulate wider interest in the technology of absorption refrigeration system. It should be useful for any newcomer in this field of technology.

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