LOW-TEMPERATURE ABSORPTION REFRIGERATION INTEGRATED WITH POLYGENERATION SYSTEM

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Abstract: With increasing demand for environmentally friendly cooling, the concept of “making cooling from heat" has become increasingly interesting. In such a concept, the use of absorption refrigeration has to be integrated within a polygeneration system, like combined production of electricity, heat and cold. This requires the driving energy to be low temperature heat (below 90 ºC).
With this in mind, research of the low-temperature heat driven absorption cooling system is presented in this review. The paper consists of three parts: 1) a fundamentals part addressing findings on thermodynamic limitations of the technology; 2) an innovation part including a thorough state-of-the-art assessment of the technology; and 3) polygeneration system performance evaluation part. In the innovation part, efficiency enhancement of the low-temperature heat driven absorption cooling system is identified as one of the main problems addressed by commercial manufacturers. In this paper, a comparison of several innovative approaches to achieve increased efficiency is listed.
In summary, the low temperature absorption refrigeration comes out as a key component which will be very much in demand for the future.

Key Words: Absorption refrigeration; Low-temperature heat; Efficiency; Evaluation index

1 INTRODUCTION

With the development of society and climate change, the need for cooling continues to increase around the world. The traditional method to get cooling has been electrically driven vapor compression refrigeration. The energy consumption for home air conditioning cooling uses almost 5% of all the electricity produced at a cost to homeowners of over $15 billion per year. Also, this translates to an emission of about 140 million tons of carbon dioxide (ACEEE 2007). Following this trend, the number of installed air conditioners in the world has risen rapidly in the past ten years, from 35.2 million 1998 to over 50 million 2006 by prediction (IIR 2003).

For this reason, absorption refrigeration technology, which is a heat driven technology proposed a long time ago (Srikhirin P ,et al.2001), is experiencing a resurgence. As opposed to the vapor compression cooling (VC), absorption refrigeration (AR) can use low grade heat as driving energy, such as flue gas from cogeneration power cycles.

In the past decades, some break-through in research and development for AR technology has been developed, including:

- Cycle aspects. The basic cycle is a single effect cycle. Then it has been developed into advanced concept for improved thermal management, like multi-effect cycle, half-effect cycle, absorption cycle with ejector (Kaushik 1985; Aphornratana et al 1998; Chen 1988; M. Medrano et al 2001).
- Working pairs aspects. Water/ammonia and lithium bromide/water have been used for many years. Ternary mixtures, adding a second salt to the original mixtures, has for example been proposed to solve the crystallization phenomena (Mclinden et al 1985) (Ahlby et al 1993)(Vinay et al 2003). Also, some organic working pairs have been explored (Ando et al 1984)(He et al 2009).

- Theoretical analysis. Initially, researchers focused on using 1st law analysis, like energy balance, to analyze the absorption cycle. Nowadays, models also include 2nd law analysis, like the exergy balance, to analyze the absorption cycle (Talbi et al 2000; Sxencan et al 2005; Rabah et al 2009; Kaushik et al 2009) .

Despite such advancement, some problems still remain. In addition to several unsolved problems remaining from the past, such as crystallization and corrosion, new difficulties have appeared with latest absorption cooling (Fan 2007). These difficulties include low driving temperature, efficiency at low driving temperature, and the availability of small size chillers for domestic or district application (Felix et al 2002).

To broaden the application of AR technology, the concept of integrating heat driven cooling in a polygeneration scheme has recently gained a lot of attention stretching from the tropics to the north Europe (Louise et al 2007)(Joan 2009)(Tawatchai et al 2010). Polygeneration is processes designed for delivering multiple energy services in a combined energy system, possibly from multiple energy sources (Louise et al 2007).According to previous studies, the AR process has been proposed for integrated with polygeneration by using the low level waste heat produced by the process of power generation.

2 OBJECTIVE

The concept of polygeneration is promising to satisfy the requirement of sustainable energy system concept. Thus, there is also a significant potential of reducing CO_2 emissions in the overall energy system (Dale et al 2001). One of the outputs from it can be cooling which then has the potential for being produced in an environmentally friendly way. It can use various sources of heat as driving energy, from low grade heat at 70 ℃ to over 200℃. A recent study highlights that absorption cooling is already a commercial technology ,however, it still needs to redesign to be optimally integrated into a polygeneration system. Driving temperature for commercial absorption chillers is around 80℃, minimum (Robert 2007). From this, it can be concluded that the lower the driving temperature, the more of the available heat sources can be used. Thus, low temperature AR technology suitable for polygeneration system is an important research topic for sustainable energy conversion.

The objective of this paper is to provide a thorough assessment of the developments in low-temperature AR technologies, and to compare different innovations for efficiency increase in polygeneration system with absorption technology (PSAT). With this assessment, AR evaluation indexes proposed in the literature are used as a basis for establishing a holistic system evaluation index to evaluate PSAT properly.

3 FUNDAMENTAL ASPECTS ON ABSORPTION REFRIGERATION

3.1 Basics Of Absorption Refrigeration

Within the fundamental part, there are always two blocks of analysis carried out: the thermodynamic considerations and practical application.

The first part is generally dedicated to the analysis about various forms of absorption cycles (Herold 1996; Aphornaratana et al 1995; Omer et al 2007).Table 1 gives examples of thermodynamic studies on cycle analysis published in the past decade.

Table 1 Comparison of different thermodynamic analyses in absorption cooling technology

Type of cycle	Methods	Advantages	Limitation	Reference
Single effect	First law	1) COPs under varying operating conditions are compared. 2) Analysis are taken in various heat context, such as geothermal and	COP is the only result, which is limiting because Second law analysis had been	(Abdullah et al 2000; Andre et al 2010)

		exhausted gas.	widely used in thermodynamic analysis.	
Single effect	First law	Mass and heat transfer model of heat exchangers was included in simulation process.		(Florides et al 2003)
Single effect	First Law Second law	Comparison of exergy efficiencies working under varying operating conditions is investigated.	1) Limited in simple single effect cycle. 2) No precise model about working pairs	(Arzu et al 2005)
Single effect	First Law Second law	Heat exchanger area mass and structure model was added into first and second law analysis.	Limited in simple single effect cycle.	(Berhane et al 2010)
Single effect Multi effect	First law Second law	1) A comparison of the exergy efficiencies and the exergy destruction in different cycles 2) Simulate various type of cycle, from half effect to multi effect cycle.	1) No precise model about thermodynamics properties of working pairs 2) Type and size of heat exchanger in each component	(Berhane et al 2010; Kaushik et al 2009)
Absorption cycle with ejector	First law Second law	Ejector can make absorber pressure become higher than that of evaporator. The fact leads AR cycle to work with trip pressure level. It is a break through to analyze such cycle by use of first and second law.	Compared to traditional cycle, the main limitation is lack of experimental data to verify theoretical analysis.	(Adan et al 2003)

Studies listed in table 1 differ from conventional analysis outlined in classical text books. The main improvement is application of second law in AR cycle, thermodynamic analysis about advanced cycle and developments of heat exchanger model.

The second part is discussing AR application in commercial and industrial aspect. To satisfy practical utilization, AR needs to be applied from industrial production to domestic and district cooling supply.

3.2 Limitations of Absorption Cooling Technology

The limitations of AR might be divided into two categories: thermodynamic limitation and technical limitation. Limitations, as assessed based on published studies are indicated in Table 2.

Table 2 Limitation of absorption cycle

Category		Limitation	Effect
Thermodynamic limitation: Thermodynamic properties of working pairs		There is no precise model to calculate thermodynamic properties of working pairs.	There are two approaches to get working pair thermodynamics property model: classic theory and experimental data. There is no norm to judge which one is optimized method.
Technical Limitation	Type and size of heat exchanger	1. There are a majority of thermodynamics analysis based on horizontal or plate design, but little about vertical design (Kang et al 1998; Infante et al 1984) 2.Few absorption cycle models have heat exchanger heat and mass transfer models.	1. Vertical heat exchanger surfaces by experiments had shown that the measured heat transfer coefficient is higher than that of horizontal one. 2. The “missing” heat exchanger heat and mass model makes researchers neglect performances of different exchangers (Adnan 2001)
	Concentration and crystallization	Some absorbents are salts, and in their solid state, it has a crystalline structure. The salt begins to leave the solution and crystallize below its saturation temperature.	Concentration change could occur through crystallization procedure. This change could lead to efficiency problems (Yongqing 2004)
	Corrosion	Concentration of solution in AR	Corrosion can reduce life time of

		reaches almost 60%. This high concentration solution can lead to corrosion (Mingjun 2000)	absorption chiller. Hydrogen produced in corrosion process can cause pressure change. Iron rust could block tube and outlet (Xiaoqing 1994)
	Size of absorption chiller	Majority of AR chillers, in comparison with VC chiller, are larger. The reason is below: 1. Complicated AR structure. 2.To increase efficiency, it is inevitable to enlarge heat exchanger (Xuedong 2005).	Large size problem could restrict AR technology utilized for domestic and district cooling demand.

4 ABSORPTION REFRIGERATION INTEGRATED IN POLYGENERATION SYSTEM

4.1 Definition of polygeneration

Polygeneration is an integrated process which has three or more outputs, including energy output, produced from one or more natural resources. There are several major categories of polygeneration systems here:

- Cogeneration systems: also called combined heat and power system (CHP) converts the primary energy into heat and electricity. It is the most efficient way of converting a primary fuel to useful energy.
- Gasification systems: production of producer gas in the gasification process to be used for energy or synthesis purposes, with the residual ash to be used in construction or agriculture.
- Biogas generation: generation of biogas from organic waste to be combusted for energy purposes (heat and power), with the residuals used as fertilizer.

4.2 Role Of Absorption Refrigeration In Polygeneration Systems

To increase the efficiency of polygeneration systems and increase the full load hours of the system, the heat produced outside the heating season for example, could be converted into cooling energy. Thermal cooling systems convert thermal energy into cooling energy by an absorption process.

Heat produced by gas turbines is divided into two categories, high level heat and low level heat from Fig 1. High level heat is for district heat grid. Low level heat has two alternatives, one is discharging into environment and another is to use it as a source for drive energy for heat driven cooling.

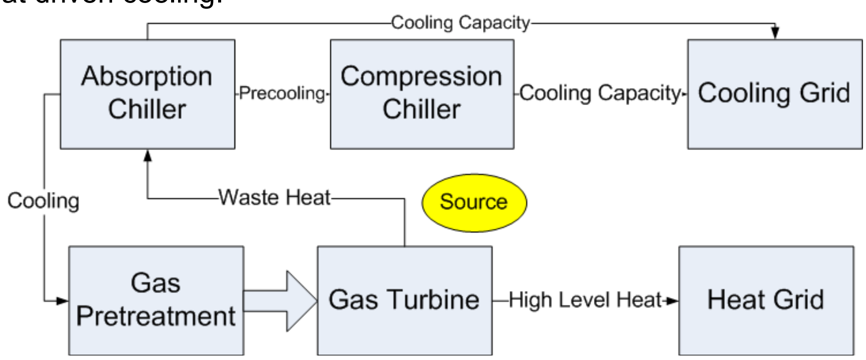

Fig 1 Absorption technology in polygeneration system

Following concept of PSAT, there had been several practical demonstrations which use this concept. Table 3 states several practical samples about AR integrated into polygeneration system.

Table 3 absorption cooling (AC) technology in polygeneration system

Case	location	Description of polygeneration	Driving Temp (℃)	Cooling Cap (kW)	Cooling application
1	Borlänge, Sweden	CHP system	75	10	Precooling for conventional chiller
2	Madrid, Spain	CHP system with 10 kW TDC	75	10	Cooling water
3	Lisbon , Portugal	Small scale CHP system for two rooms	80	7.5	1. Chilled water storage; 2. Air cooling
4	Milan, Italy	mCHCP system	200	17	Air condition
5	Diessen, Germany	CHP system	80	10	Cooling water
6	Catalonia, Spain	mCHP with biogas	90	35	1. Precooling 2.Pretreatment for biogas

From table 3 and Fig. 1, cooling capacity produced by the AR has three applications: the main usage is to satisfy the requirements of district cooling grids; the second one is pre-treatment process to condense water of biogas before its combustion in the turbine; the third one is called precooling which cool the combustion air used in the turbine.

4.3 Requirement Of Absorption Refrigeration In Polygeneration

As shown in Fig. 1, absorption refrigeration process has been proposed to integrate with polygeneration system by using the low level waste heat produced by power making process. From table 3, temperature of driving heat for AR in polygeneration system is low level heat around 80 ℃ or higher. It means that low level heat, below 80 ℃, is still treated as waste heat and dissipates into the environment. Low temperature absorption refrigeration (LTAR) technology can satisfy requirements of PSAT.

5 STATE-OF-THE-ART AND INNOVATION OF POLYGENERATION WITH LOW-TEMPERATURE ABSORPTION REFRIGERATION

5.1 Incentive of innovation

Despite many innovations about AR technology, researches about LTAR are still rare now. Most of innovations about AR require relative high driving temperature.

There are two paths to increase efficiency of system, one is AR efficiency improvement and another is optimum configuration of holistic system.

It is relatively simple to get innovations about AR technology. Through the initial theoretical analysis, the coefficient of performance (COP) can get to 0.65 at condition of 80℃ by using the single effect absorption cycle (Mohanmed 2008). There are some problems noticed by commercial manufactures and researchers when absorption cooling technology was introduced to practical industry. So, many innovations, which are consisted of cycle aspect, components aspect and others, were developed to solve the existed problems.

The efficiency of holistic system is more complicated to analysis because it should connect with various working contexts.

5.2 Cycle Aspect

Developments of absorption cycle were regarded as one of the most obvious methods to increase efficiency.

According to Table 4, half effect cycle seems to be primary choice to satisfy the requirement of lowest temperature only because it use relatively low-temperature heat source, about 55℃.

Table 4 comparison of various types of innovative cycles

Cycle	Principle	Driving T (℃)	limitation	Research focus
Half effect	Half-effect absorption cycle is a combination of two single-effect cycles but working at different pressure levels.	55-65 ℃	Relative low efficiency and poor economical value	1.Increase of efficiency 2.balance between efficiency and cost
Absorption with ejector	Adding ejector into the cycle is aiding pressure recovery from the evaporator and upgrading the mixing process and the pre-absorption by the weak solution coming from the evaporator (Kairouani et al 2009)	65-78℃	1.Ejector is complicated to analyze 2.lack of experiments	Introduce the cycle into practical application
Four –bed mass recovery*	The proposed cycle consists of two basic adsorption refrigeration cycles. The heat source rejected by one cycle is used to power the second cycle. (Alam 2004)	65℃	Many parts included in the cycle, increase of COP should face rising price.	Introduce the cycle into absorption cooling.
*It is used in adsorption cooling now.				

Through technical limitation, pressure of solution should drop down along pipes and components and working pairs need to face crystallization problem. So, the ejector combined absorption cycle is regarded as another approach to solve the low-temperature problem.

5.3 Components Aspect

Another approach to improve efficiency of absorption cooling is components improvements. Absorber is regarded as the most important component of the whole cycle. More and more researches concentrated on absorber heat exchanger surface area. Besides of absorber, other components, such as evaporator, throttling valve and cooling storage, also got some innovation showed in table 6.

Table 5 Components improvements

Component	Result and Improvement
Absorber	1. Optimum diameter and length of tube (optimum diameter can match optimum flow rate; length of tube means sufficient absorber surface area). 2.increase of the absorber pressure, solution and cooling flow rates (enhancement of absorber efficiency);
Evaporator	Focused on the controlling of liquid blowdown rate (Jose et al 2006).
Others	1. heat storage: collection of the heat reject (Helm 2009); 2. 25% opening throttling valve had the highest COP.

5.4 Configuration Aspect

AR technology can produce cooling capacity from recovered waste heat rather than from electricity like the more conventional VC technology in polygeneration system. Several studies in the literature on polygeneration systems have been based on turbines (Campanari 2004; Bruno 2005), but only a few of them have dealt with the benefits of inlet air cooling in turbine (Hwang 2004). Moreover, none of them has considered the possible additional benefit of using cooling in biogas pre-treatment to cool the biogas and reduce its moisture.

According to table 2, cooling capacity produced by absorption refrigeration was widely used for cooling grid directly. A research result showed: the greater cooling capacity required in the warm season for inlet air cooling is offset by a decrease in the heat required to keep the digesters at their set-point temperature. So, broadening new application of cooling capacity produced by PSAT is a feasible measure to increase efficiency of overall system.

6 PERFORMANCE EVALUATION OF PSAT

As a relative mature technology, there are some approaches existed to evaluate isolate AR technology, however, PSAT is still lack of its own evaluation index.

6.2 Absorption Cooling Evaluation Index

There are three main alternatives to judge an energy system: thermodynamic analysis, thermo-economics analysis and life cycle assessment.

Table 6 absorption cycle evaluation index

Evaluation approach		Evaluation Principle	Evaluation limitation
Thermodynamic	First law	To use First law as evaluation tool, COP is one and only index.	COP is just one of evaluation indexes of thermodynamic analysis.
	Second law	Compare to First law analysis, Second law use exergy efficiency as evaluation index.	It is more comprehensive than First law, but it also neglects the economical and environmental aspects.
Thermo-economical analysis (Mosttafavi 1996; Sun 1997; Dincer et al 1996; Paul et al 2009)		The objective intends to get ideal thermal efficiency with minimum economical cost. The economical value is the main index to guide the direction of absorption chiller development. It is important to determine the optimum operating temperatures and parameters in a refrigeration system design.	It focuses on price of energy and investment costs increase. So, this approach could ignore the environmental value of energy, maintenance cost of system and long term environmental affect.
Life cycle assessment (Presso 1993) (Azapagic 1999)		This concept of life cycle assessment can be explained as an objective process for evaluating the environmental loads associated with a product, process or activity. The advantage of this method is adding the environment concerns into the economical evaluation.	Life cycle assessment is a tool to calculate economical and environmental issues, but it lack of efficiency assessment.

From Table 6, COP is no longer as only index to evaluate AR system. Economy cost is also a main evaluation index (Berhane 2009) Environmental effect also needs to be assessed because the advantage of AR is environmental friendly technology.

By means of evaluation tools showed in Table 6, it is very complicated to estimate AR system with a single standard. For these reasons, it is necessary to establish a new and complete evaluation system to replace the individual indexes applied today.

6.3 Holistic System Index

To consider the whole concept, two questions need to be considered, one is configuration of PSAT and another is the objective of cooling capacity. There is little research on assessment of PSAT. As a tiny but critical step, comparison among various kinds of configurations for PSAT was necessary to do. It is difficult to identify which one is optimum choice because of the objective of cooling capacity. So, it is important to use suitable index to assess PSAT, which bind objective and configuration together.

7 CONCLUSION AND FUTURE WORK

This paper states achievements and remaining problems of low temperature AR technology in polygeneration system. The following conclusions are subject to the limitation of these studies:

- Second law analysis has applied to single AR cycle and exergy efficiency becomes to a key index to analyze an energy system. There is little research which utilizes Second law to analyze PSAT. Simulation of PSAT by Second law could become to the research focus.
- Heat exchangers should be considered as same as practical situation. Type of heat exchanger and heat exchange surface area should correspond to the specific AR cycle. Inadequate heat exchanger surface area might lead to insufficient heat exchanging. The consequence is not enough heat for driving AR cycle. So, reasonable designation about heat exchanger could be a significant project.
- Polygeneration is not only an option for large industry and district heating. Small enterprises, public authorities and owners of family houses can use the technology and reap the associated benefits. Therefore, research on small size and small scale AR chiller could catch attention from commercial AR manufacture.
- There are two orientations to increase efficiency of PSAT, one is focus on low temperature AR efficiency and another is about system configuration. Cycle innovation play an important role for the former, but balance between efficiency increase and cost cannot be neglected. To broaden the application of cooling capacity produced by AR is the later one. Exception for biogas system, there are a variety of systems belong to polygeneration concept. Similar research should be taken in all kinds of system.
- It is necessary to establish a specific and suitable evaluation index to assess PSAT. The new evaluation index needs to assess PSAT in two ways. The first one is evaluation index for overall system and the second one is a combined index of low temperature AR.

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