A review of absorption refrigeration technologies engineering essay

Most of industrial processes use a lot of thermal energy by burning fossil fuels to produce steam or heat for various needs in the industry. After the processes, heat is rejected to the surrounding as waste. This waste heat can be converted to 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 and cuts down the need for expensive electricity from the central grid. The use of heat operated refrigeration systems help reduce problems related to global environmental, such as the greenhouse effect from CO2 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 thermo-physical 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. 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. However with the advent of cheaper vapor compression machines in the late 1960's and abundant and widespread availability of electricity lead to the vapor absorption machines taking a backseat. As a result we see that despite the fact that this technology has been around for almost 250 years, a viable alternative to the vapor compression machines for domestic use at a comparable cost has not been found.

The aim of this paper is to provide basic background and review existing literature 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 and generate in this area the same interest that the authors feel.

PRINCIPLE OF OPERATION

The absorption refrigeration system works with a binary solution consisting of refrigerant and absorbent. In Fig. 1(a)[1] two evacuated containers are connected to each other. The container on the left has liquid refrigerant while the right container has a binary solution of absorbent/refrigerant. The solution in the right container will absorb refrigerant vapor from the left one 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 container thus dropping its temperature. At the same time, solution inside the right container becomes weaker in concentration because of the higher content of refrigerant absorbed. This is due to the absorption process. 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.[1] Heat is usually the key for this separation process. The separation of the refrigerant is of paramount significance and most of the work recently has gone into making this as efficient as possible so as to increase the refrigeration effect. It is applied to the right container in order to dry the refrigerant from the solution as shown in Fig. 1(b).[1] 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 container causing cooling effect in the other; (b) Refrigerant

separation process occurs in the right container as a result of additional heat from outside heat source.

of these two processes as shown in Fig. 2.[1] 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

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.

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

WORKING FLUID PAIRS FOR ABSOPRTION SYSTEMS

The performance of an absorption system is heavily dependent on the properties of the working pair. We are mainly concerned with the thermal and chemical properties of the working fluids. The fundamental requirement is the absorbent/refrigerant combination, in liquid phase, must have a margin of miscibility in the operating temperature range of the cycle. The mixture should also be chemically stable, non toxic, non corrosive and should be able to maintain its fluidity in the operating range. Apart from these certain other desirable properties are:

The difference in the boiling points of the pure refrigerant and mixture at the same pressure must 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.

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 environmental friendly and low-cost, specially keeping in mind the increasing danger to the environment.

The absorption refrigeration system, which has some advantages, such as silent operation, high reliability, long service life, simpler capacity control mechanism, easier implementation, and low maintenance, is widely acknowledged as a prospective candidate for efficient and economic use of solar energy for cooling applications.

Also, the absorption refrigeration cycle is usually a preferable alternative, since it uses the thermal energy collected from the sun without the need to convert this energy into mechanical energy as required by the vapor compression cycle. In addition, the absorption cycle uses thermal energy at a lower temperature than that dictated by the vapor compression cycle.

Many working fluids are suggested in literature. A survey of absorption fluids provided by Marcriss [2] suggests that, there are some 40 refrigerant compounds and 200 absorbent compounds available. However, the most common working fluids are NH_3- H_2O and LiBr-H_2O. The binary systems of NH_3- H_2O and LiBr-H_2O are well known as working fluid pairs to be used both in absorption heat pumps and in absorption refrigerators at present.

Theoretical and experimental studies have been conducted to optimize the performance of absorption refrigeration cycles using NH3- H2O and LiBr-H2O as refrigerant- absorbent combination. The advantage for refrigerant NH3 is that it can evaporate at lower temperatures (i. e. from -10 to 0°C) compared to H2O (i. e. from 4 to 10°C), therefore, for refrigeration, the NH3-H2O cycle is used.

NH3 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 NH3 is -77°C. Since both NH3 and water are volatility, the cycle requires a rectifier to strip away water that normally evaporates with NH3. 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/NH3 is environmental friendly and low-cost.

The use of LiBr-H2O for absorption refrigeration systems began around 1930. Two outstanding features of LiBr-H2O 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.

Research has been performed for NH3-H2O systems theoretically and experimentally and these studies show that the NH3-H2O system exhibits a relatively low COP when compared to its LiBr-H20 counterpart.[1] Efforts are being made to search for better working fluid pairs that can improve system performance. It is proposed that NH3-LiNO3 and NH3-NaSCN cycles can be alternatives to NH3-H2O systems.[3]

A study on the use of NH3-LiNO3 and NH3-NaSCN cycles by Jasim M. Abdulateef [3] reveals that ammonia-lithium nitrate and ammonia-sodium thiocyanate cycles give better performance than the ammonia-water cycle, not only because of higher COP values, but also because of no requirement for analyzers and rectifiers. Therefore, they are suitable alternatives to the ammonia-water cycle. Generally speaking, the performance for the ammonia-lithium nitrate and ammonia-sodium thiocyanate cycles are similar, with the latter being slightly better than the former. However, the ammonia-sodium thiocyanate cycle cannot operate at evaporator temperatures below – 10°C for the possibility of crystallization.[3]

LITHIUM BROMIDE-WATER ABSORPTION SYSTEM

There has been renewed interest to use thermally driven cooling systems from the air conditioning and process cooling fraternities. The lithium bromide-water absorption chiller is one of the front-runners due to the following reasons [4]:

It can be thermally driven by gas, solar energy, and geothermal energy as well as waste heat, which help to substantially reduce carbon dioxide emission, this is its USP when it comes to process industries generating large amount of waste heat

Its use of water as a refrigerant, which is easily available and cheap.

It is quiet, durable and cheap to maintain, being virtually void of high speed moving parts;

Its vacuumed operation renders it amenable to scale up applications. LiBr-H2O absorption chillers enjoy cooling capacities ranging from kilowatts (kW) to megawatts (mW) which match with small residential to large scale commercial or even industrial cooling needs.

However they currently enjoy only a fraction of the extent of deployment as their vapor compression counterparts. Their major debilitating factors are a low Coefficient of Performance (COP), larger footprint and required headroom, corrosion and crystallization issues and stringent requirements of vacuum leak tightness over its design lifespan. Over the past 30 years, extensive efforts have been devoted to:

Develop advanced absorption cycles which could work at low heat source temperature or recover more heat to improve system performance.

Improve the design of major components such as generator and absorber to enhance their heat and mass transfer efficacy.

Avoid crystallization problem and,

Develop new and reliable working pairs.

Problems in domestic use of LiBr-H2O absorption systems

Even though the technology has been around for quite some time now its usage in domestic applications is hitherto seen. According to Kevin D. Rafferty [5] there is only one company (Yazaki, undated) currently manufacturing small tonnage (<20 tons) lithium bromide refrigeration equipment. This firm, located in Japan, produces equipment primarily for solar applications. Currently, units are available in 1. 3, 2, 3, 5, 7. 5, and 10 ton capacities. During our surveys to find a suitable absorption system for domestic use we came up with the following reasons which we believe may be responsible for negligible presence of LiBr-H2O absorption chillers in the domestic use market:

While calculating the mass flow rate of the refrigerant for an assumed case of 1. 5TR cooling, as is the requirement for most domestic air-conditioning applications, we obtained a very low mass flow rate in the order of a few gm/s.

Also the ensuing pressure difference to maintain such working conditions led to a very high pressure ratio, to the order of about 50, between the absorber and generator.

Upon market survey, (here in Pune, India) we discovered that pumps catering to such a low flow rate at this large a pressure differential were not readily available, some suppliers of customized pumps, however, did claim to be able to make such pumps, albeit at a very high cost.

We explored the idea of then increasing the mass flow rate to higher than what was calculated for the required tonnage, but realized that increasing mass flow rate for evaporator of same tonnage would lead to un-evaporated refrigerant thus decreasing the COP of the system.

During further study of the LiBr-H2O absorption systems we came across an interesting review on absorption chillers and their various configurations by Xiaolin Wang and Hui T. Chua [4], which provides a valuable insight. For the standard single effect system, simple structure and low cost are pursued. The single-effect double-lift absorption system are proposed and developed for the utilization of low temperature heat sources. However, multi-effect absorption systems are suggested to provide higher efficiency with a high temperature heat source. In order to increase the system performance and avoid crystallization problem, various heat and mass recovery systems, modifications to the generator and the absorber, different working pairs and additives have been developed. Furthermore hybridization of absorption chiller cycle with other cooling cycle(s) promises a higher overall performance as compared with that of each single constituent cycle.

Single-Effect Absorption Chillers

It consists of evaporator, absorber, generator, and a condenser. Its simplicity, small size, high reliability and lower maintenance cost are its advantages. While low cooling capacity, high weight and size and low COP are disadvantages

Fig. 3. A schematic of a single effect absorption cycle in a Dühring plot

Uchida from Hitachi developed a modular cascaded absorption chiller comprising of chiller units connected to one another in which chilled water flows through the chiller units in series while cooling water through parallel. [6] Water in chilled and cooling column flows in opposite direction and in absorber solution is sprayed in 1 or more stages. In this type of arrangement lower evaporator temperature can be achieved as compared to conventional arrangement. This results in lower amount of water circulation and higher efficiency due high average temperature difference, compact size, and lower capacity pumps.

Inoue from Ebara Corporation integrated the absorber, evaporator, generator, and a condenser into a compact housing so that it can be used for used in residential operations. The arrangement is as shown in Fig. 4.

A – Absorber, C – Condenser, E – Evaporator, G – Generator, X -Solution heat exchanger, SP – Solution pump, RP – Refrigerant pump

Fig. 4. A single effect absorption chiller [7]

This also resulted in reduced costs, compact size, less thermal stresses and low material usage.

Inoue from Ebara Corporation in further bid to reduce size and increase COP used plate type heat exchanger in absorber and condenser. [7] In this water flows into the absorber and condenser in parallel and is distributed according to fluid resistance in each unit. This reduces mass flow rate and distributed flow results in elimination of complicated valve system.

Problem of crystallization in chiller is avoided using popular J-tube technology. [4] Crystallization in system occurs in generator due to high concentration of LiBr resulting in blockage of flow to solution heat exchanger and will be accumulated in generator. When solution reaches certain level in generator, the hot refrigerant -weak solution will overflow via J-tube to the absorber and warms the refrigerant -strong solution immediately. This will warm the crystallized solution and dissolve them into the solution.

Single-Effect Double Lift Absorption Chillers

Fig. 5. A single-effect double lift cycle.

Since single effect cycle requires the temperature of 90oC and above for proper working, for temperature lower than this results in significant drop in efficiency of the cycle. Therefore utilize to lower temperatures single effect single lift which can work for heat source between 70oC and 90oC and single effect double lift cycle works within waste heat source temperature down to 55oC was developed. A COP in the range of 0. 35-0. 7 is obtained. [4]

Fig. 5. shows the construction of single effect double lift cycle consists of evaporator, absorber-1, generator-1, and a condenser forming single effect cycle & the evaporator, absorber-1, generator-3, absorber-2, generator-2, and condenser constitute a double lift cycle.

In this the solution from absorber1 is first is sent to generator-1 for steam generation, after this serially solution is sent generator-3 for further generation and refrigerant- weak solution is sent to absorber-1 . The steam generated in generator-3 is absorbed by the absorber-2 which then sent to the generator-2 for generation. The steam from generator-1 and generator-2 is sent in condenser to continue the cycle. The hot water in the system is supplied serially to the generator-1, generator-2, and generator-3. The cooling water flows to the condenser, absorber-1 and absorber-2 in parallel to avoid complicated control and unstable working conditions.

The advantage of this system is high COP as compared single effect cycle since energy is utilized more effectively in this cycle. But due increase in number of components this has larger size as compared to single effect cycle. This system is commercialized by INVEN absorption GmbH. [4]

Double-Effect Absorption Chillers

Fig. 6. A double effect series flow type absorption cycle.

This system is developed to increase COP of absorption chiller operating at temperature greater than 150oC since at this temperature the COP of single effect cycle is low. COP achieved in this cycle is in the range of 1. 1 to 1. 3. It was first patented by Loweth in 1970[8] and commercialized by Trane in the same year. Saito [9] from Ebara Corporation and Alefeld [10] improved and modified the double effect absorption refrigeration machine in 1980 and 1985, respectively.

As shown in the plot above, double effect cycle consists of a high temperature and a high pressure generator. Steam generated from this generator is used to generate steam from low pressure generator through a heat exchanger. This steam is further sent to the condenser and evaporator for cooling. This arrangement is known as series flow arrangement.

Therefore temperature differential utilization in double effect is more as compared to the single effect but heat rejected at the condenser and cooling temperature at the evaporator are at about the same temperature, hence COP is greater.

Above mentioned arrangement works very close to crystallization temperature of LiBr-water solution and the high temperature generator operates at high pressure in order maintain requisite solution flow rate. To avoid solution pumping, the high temperature generator has to be sufficiently elevated to enjoy gravity assisted flow, resulting in higher head room.

To avoid these problems, Hitachi developed a parallel flow double effect arrangement as shown below in Fig. 7. In this arrangement solution is separated after solution pump and is sent to high temperature generator through high temperature heat exchanger and to the low temperature generator, respectively. So, the operation condition is displaced further from crystallization point of solution. Flow rate of solution, pressure, elevation is also reduced as compared to series flow arrangement.

Nagao from Hitachi disclosed a chiller which consists of an absorption section, an evaporator section, a condenser section, a generator section all of which are divided into two stages. The first stage evaporator & second stage evaporator are arranged to be enclosed respectively by first stage absorber & second stage absorber. Similar configuration is applied to the generator and condenser. This arrangement reduces heat transfer losses.

Fig. 7. A double effect parallel flow type cycle.

Hiro [11] from Sanyo Electric Co. disclosed a double effect absorption chiller, in which the connecting pipe conveying the liquefied refrigerant in the low temperature generator to the condenser is installed with an orifice together with a control valve so as to control the refrigerant pressure. A control circuit is connected to this control valve to actively control the refrigerant pressure and therefore control the solution concentration in the high temperature generator and the absorber. This control circuit facilitates the passage of the refrigerant to the condenser without stagnation during chiller start up or in the event of a sudden increase in cooling load. It is also capable of maintaining a suitably reduced pressure in the refrigerant during steady-state operation so as to achieve a higher operating efficiency.

Recently Aoyama [12] from Ebara Refrigeration Equipment & System disclosed an internal heat recovery scheme which aims to increase intrinsic COP of the machine and heat scavenging scheme which strives to extract more energy from heat source which drives the chiller. According to this invention, the refrigerant rich solution path leading from the absorber to the high temperature generator is divided into two routes. The first route is installed with one or two drain heat exchanger to scavenge the remaining enthalpy of the heat source powering the high temperature generator. The second route is installed with one or two regenerative heat exchanger to recover the heat of the hot and refrigerant-weak solution leaving the high temperature generator.

Modeling and Simulation of LiBr-H2O absorption systems

A recent paper by V. Mittal, K. S. Kasana and N. S. Thakur on ‘ Modeling and simulation of a solar absorption cooling system for India’ [13] simulated the model of a solar-powered, single stage, absorption cooling system, using a flat plate collector and water-lithium bromide solution. A computer program was developed for the absorption system to simulate various cycle configurations with the help of various weather data for the village Bahal, District Bhiwani, Haryana, India. The effects of hot water inlet temperatures on the coefficient of performance (COP) and the surface area of the absorption cooling component were studied.

Simulation results are discussed in this section for the performance of a 10. 5 KW solar driven lithium bromide absorption cooling system. Fig. 8. depicts the effect of the hot water inlet temperatures Ts on the system COP and flow ratio FR. It can be seen that an increase in this temperature resulted in the decreases of FR. This is due to increases in the mass fraction of concentration solution (XG). While with an increase in this temperature, COP increases.

Fig. 8. The effect of the hot water inlet temperatures on the system COP and FR

(Te = 280 K, QL = 10. 5 KW, Tc = 306K)

Figure 3 depicts the effect of the hot water inlet temperature on the surface area of the system components.

It can be seen that increase in this temperature results in the decrease of the absorber and solution heat exchanger surface area. As flow ratio decreases, the thermal energy extracted from the absorber also decreases and hence the temperature of the absorber increases, which further resulted in the increase of logarithmic mean temperature difference (DTm) in the absorber and solution heat exchanger. By decreasing the heat capacity and increasing DTm, heat transfer surface area normally decreases in these components.

Fig. 9. The effect of the hot water inlet temperatures on the surface area of the system components

(Te = 280 K, QL = 10. 5 KW, Tcool, in = 291 K)

From this study the following conclusions were made:

The hot water inlet temperature is found to affect the surface area of some of the system components.

Increasing this temperature decreases the absorber and solution heat exchanger surface area, while the dimensions of the other components remain unchanged.

Although high reference temperature increases the system COP and decreases the surface area of system components, lower reference temperature gives better results for FNP than high reference temperatures do. For this study, a 353 K reference temperature is the best choice.

This paper thus provides a general idea to anyone looking to build a model of a vapor absorption system, about the generator temperature needed and its effect on the flow rate and COP.

AMMONIA-WATER ABSORPTION SYSTEM

The working of ammonia-water absorption refrigeration system is based on the simple vapor absorption refrigeration systems. In this system ammonia is used as the refrigerant and water is used as the absorbent. The ammonia-water absorption system is used in the domestic as well the commercial applications where the requirement of the temperature is below 0 degree C.

The major advantages of the ammonia-water solution are:

Water has strong affinity for ammonia and they are soluble with each other in wide operating conditions that occur in different refrigeration applications.

The ammonia-water solution is highly stable and works well with many materials.

Ammonia is a common chemical and it is easily and cheaply available.

However the system has a few disadvantages too some of which are:

Except copper and its alloys that get corroded in the presence of ammonia.

Due to its toxicity its applications are limited.

Due to the fact that some of the water in the generator also boils off with the ammonia and escapes as vapor, a rectifier is needed to remove this water vapor before it enters the condenser. This adds to the expense and complexity of the design.

The COP of the ammonia-water systems is slightly lower than their LiBr-water counterparts.

Fig. 10. Schematic of a typical ammonia-water absorption system.

Domestic use of ammonia-water absorption systems

Unlike the LiBr-H2O absorption system, the ammonia-water absorption system has found widespread use in the domestic use market. These refrigerators are very popular as car fridges used in SUV’s and RV’s. Many companies are involved in the manufacturing of such equipment. Electrolux was amongst the first companies to start manufacturing absorption refrigerators for commercial use.

One of the main issues with the early domestic absorption refrigerators was that the water would get crystallized and the whole setup would then need to be inverted for a few hours to get the system working again. Such old models of absorption models are available in scrap; however most of them are not in working condition. We came across one such model ourselves, however even on extensive research the exact composition of the water ammonia mixture or the operating pressure was not found. Most people do not recommend recharging of these old units as they are factory sealed and compositions are not known, however some people have tried recharging and obtained successful results.

Simulation of absorption diffusion Solar refrigeration systems

A study was carried out by B. Chaouachi and S. Gabsi [14] for the design and the simulation of an absorption diffusion refrigerator using solar as source of energy, for domestic use. The design holds account about the climatic conditions and the unit cost due to technical constraints imposed by the technology of the various components of the installation such as the solar generator, the condenser, the absorber and the evaporator. Mass and energy conservation equations were developed for each component of the cycle and solved numerically. The absorption diffusion refrigerating machine is designed according to the operation principle of the refrigerating machine mono pressure invented by Platern and Munter. This machine uses three operation fluids, water (absorbent), ammonia (Refrigerant) and hydrogen as an inert gas used in order to maintain the total pressure constant.

The study yielded some interesting conclusions. The operating boundaries of the system were examined by conducting simulations for various values of the generator temperature, TG, the evaporator temperature, TE, the pressure of the system, P and the generator heat input, QG. The operation ranges were found to be: 5

Fig. 11. COP vs. to generator temperature for various pressures of the system (Î¾r= 0. 45, Te= 273K)

Fig. 11. presents the COP vs. the generator temperature for different pressures of the system for a fixed rich concentration and evaporator temperature. It shows that the COP decreases as the generator temperature increases and it increases when the pressure increases too. This is may be attributed to the fact that a smaller amount of ammonia was separated from the ammonia-water solution and thus more solution had to be circulated so

as to maintain the refrigerant flow rate in the condenser. It thus recommended that pressure of the system as high as possible.

Fig. 12. OP vs. the evaporator temperature (Î¾r = 0. 4, P= 12. 5 bars)

The Fig. 12. shows that the COP decreases as the generator temperature increases. It was also found that the higher the evaporator temperature, the higher COP, i. e. that more heat was absorbed in the evaporator. There are thus opposing demands for the evaporator temperature; on the one hand, it should be high enough (depending on the desired cooling capacity) to yield a higher COP, while a lower evaporator temperature would yield better cooling.

Thermodynamic simulation of Solar absorption refrigeration systems

Another thermodynamic simulation carried out by Antonio J. Bula [15], for an ammonia water solar absorption system. The operating conditions chosen were:

Tg = 70 – 90°C

Tc = 30 °C

Ta = 25 °C

Te = 5 °C