Journal of Postharvest Technology
2022, **10**(2): 16-27
www.jpht.in

REVIEW ARTICLE

Food refrigeration system using low grade energy input from renewable and sustainable sources of energy: an overview

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Received: 28.01.2022 Accepted: 10.03.2022

ABSTRACT

In the present era, when the rate of depletion of existing fossil fuels is increasing rapidly, it is seen that there is a global transmission towards alternate energy sources. One such example is switching towards vapor absorption refrigeration system (VARSs) since it has many advantages than the conventional compression refrigeration systems (VCRSs). This is because absorption refrigeration facilitates reduction of cost as it provides a very good opportunity for using waste heat which could be from either stream or nonconventional solar, biogas, waste heat from industries, waste heat from vehicles, geothermal energy etc. The technology does not affect the environment in any harmful way which is otherwise ill-treated by VCRSs by depleting the protective ozone layer and the emissions of harmful greenhouse gases caused by chlorofluorocarbons used in. Also as the input fuel is available at free or very low cost, it helps saving money. However, low COP is a point to be considered which, could be enhanced by the use of double and triple effect VARS. In this review paper an overview of different renewable energy sources as a heat input to VARS is done.

Keywords: Refrigeration systems, food preservation, refrigerants, renewable energy source, cold storage

Citation: Gupta, A. and Sharma, D. 2022. Food refrigeration system using low grade energy input from renewable and sustainable sources of energy: an overview. *Journal of Postharvest Technology*, **10**(2): 16-27.

INTRODUCTION

Climate change is the greatest challenges the mankind is experiencing these days. The scientific community provides a strong scientific proof on the fact that climate is changing. According to Chigullapalli et al. (2019) "the GHG emissions have reached to huge amounts of 49 Gigatons of carbon dioxide equivalents. Fossil fuel combustion leads to emissions which are around 70% of the total GHG emissions and 80% of the total CO_2 emissions". An average annual increment of 2.07 ppm in atmospheric CO_2 concentration is observed during 2004–2013 (AR-5, WG-II, IPCC 2014). If the data continue to increase at the same rate, then the sea level will rise and the global surface temperature will also increase to some degrees. We can protect our environment from the harmful GHG concentrations if decarbonization of the energy supply is done. Renewable energy sources are the traditional and multifaceted energy source of energy which could be counted on since it has zero

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ISSN: 2348-4330

carbon emission. Refrigeration has always been an inevitable need for individuals since long back and till now. “The refrigeration system could be run on many types of heat energy sources such as hot air; hot water and steam are capable of running a refrigeration system” as concluded by Kaynakli (2007). Absorption refrigeration technology is not a new technology since it has been in existence for cooling purposes from the past hundred years. It was first unfolded in the 1700s. It is advantageous where a large quantity of low-grade thermal energy is available freely at required temperature. The performance of an absorption cycle is affected by the working fluid’s thermodynamic properties.

CLASSIFICATION OF VARS

Based on single/multi effect

Depending upon how the solution regenerates and on thermodynamic cycle of operation the absorption systems is categorized as: single-effect and double-effect absorption cycles.

Single effect absorption cycle

When in a single step the refrigerant and the absorbent are regenerated using a lower grade of heat source, we term it as a single stage or single effect absorption machine. Kaushik and Arora (2009) analysed the energy and exergy of single effect refrigeration system and concluded that “lowering the value of the absorber temperature helped in bringing down the optimum generator temperature and increased the COP and exergetic efficiency. The increase in evaporator temperature increases the COP but reduces exergetic efficiency”. Similarly, Aphornratana and Sriveerakul (2007) suggested that the “absorber should have a larger surface area such that the rates of transfer of heat could be maximum, so that the input to generator reduces and hence COP improves”. Pongtornkulpanich et al. (2008) while performing a case study on single-effect absorption cooling system in Thailand suggested that “the optimum range of temperatures of hot water for operating the system should be between 75-90° C”. Another case study was conducted on the performance analysis of solar powered lithium bromide absorption system (single-effect) in which the authors Ali and Pollerberg (2002) explained that “the backup heater gets activated when hot water from the tank drops below 78° C”. Marc et al. (2015) concluded that “the temperature of fluid should not be more than 90 °C for the generator and should not be below 28 °C for the absorber and the evaporator should work up to 12 °C”. Single effect machines fail to compete economically and thermally with the other available refrigerating systems because if it’s low COP.

Double effect absorption cycle

A double effect system consists of two heat exchangers and two generators (high and low pressure). It is an absorption system with improved efficiency which employs a second generator which uses water vapor from first generator to provide its heat supply. The double effect system has higher COP and exergetic efficiency compared with the single effect system. With the increase in evaporator temperature, the thermal loads of absorber and generator decrease with constant cooling load (Qe) and hence COP increase. Higher values of the evaporator temperature provide maximum COP whereas lower values provide maximum exergetic efficiency. It is shown in the figure 1 that the increase in solution heat exchanger effectiveness increases the COP and the exergetic efficiency for both single and double-effect absorption systems.

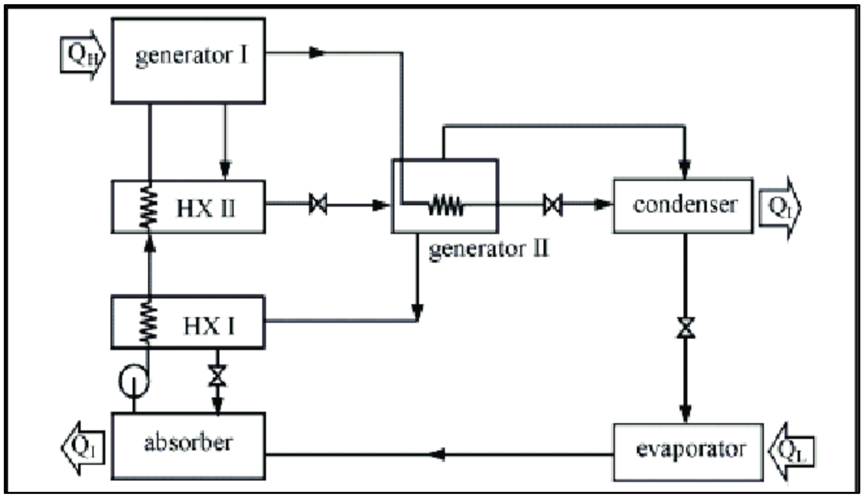

Figure 1: Double effect VARS

With the help of above schematic diagram it can be understood that the COP decreases with an increase in the condenser temperature due to a larger heat rejection to the generator G1 (Sahata et al, (2012), (Khaliq et al, (2005) Also, the COP and ECOP of the system increase while total exergy destruction decreases with increase in temperature of the generator1. However, another author Rabah, (2015) increased low-pressure generator (LPG) temperature and decreased it with increasing high-pressure generator (HPG) and found that the best COP and exergy were obtained for LPG temperature varying between 78 °C and 81 °C and HPG temperature varying between 125 °C and 135 °C. Arun et al, (2001) found that exergetic efficiency is more in parallel flow configuration as compared to the series flow configuration for the same parameters. The external heat input at the low pressure has greater impact on parallel flow than on series and therefore the COP of parallel system is more than that of series system. Table 1 shows the effect on COP by various design considerations.

Table1: Design considerations and effect on COP on VARS

Type of absorption system	COP	Design considerations	Reference
Single-stage and two-stage ammonia–water absorption refrigeration systems	0.734 of double stage system at evaporator temp. of -10°C 0.598 of single stage at same evaporator temp.	Two-stage system has a higher $\dot{S}_{tot}$ and COP, while the single-stage system has a lower $\dot{S}_{tot}$ and COP.	Adewusi and Zubair (2004)
Heat integration of existing single-effect ammonia-water absorption system	22% increase in COP	T_H =150 °C, T_{EVAP} = 30°C and T_{COND} = 30 °C	Chen et al. (2016)
Introduction of Macroscopic magnetic field force for improving absorptivity of ammonia	4.73% increase in COP	Magnetic induction of 3 Tesla increases absorbability by 5.9%	Xiaofeng et al, (2007)

Energy and exergy analysis of single effect and series flow double effect water–lithium bromide absorption system	COP of the single effect system lies in range of 0.6–0.75 and COP for the series flow double effect system lies in the range of 1–1.28.	Irreversibility is highest in the absorber in both systems when compared to other system components.	Kaushik and Arora (2009)
A novel reformed LBAC based on the absorption principle of the lithium–bromide/water solution	COP increses by 1.5 times.	The COP of the chiller increase respectively by 2 times and 1.5 times when absorbed vapor pressure increases within 1.2 kPa - 2.2 kPa	Xie et al, (2012)
Energy and exergy investigation of absorption refrigeration system (ARS) in LiBr - H_2O solution	COP = 0.74	COP increases with an increment in generator temperature from 75˚C to 110˚C.	Modi et al. (2017)
Analysis for optimizing solar absorption system in hot region.	COP of absorption unit exceeded by 0.8.	The source hot water temperature must be between 80-90°C to improve the COP	Saleh and Mosa (2014)
Solar powered NH_3–H_2O absorption refrigerator.	COP = 0.69	GEN/COND/EVAP temperatures of 114/23/−2 °C respectively.	Said et al. (2012)

REFRIGERANTS FOR VARS

Generally, the refrigerant being used in VARS uses a solution consisting of refrigerant and absorbent, among which the two common ones are Ammonia – Water Absorption Refrigeration System where Ammonia is used as the refrigerant and the water is used as the absorbent and second one is the Water – Lithium Bromide Absorption Refrigeration System Wherein Lithium bromide is used as the absorbent while water is used as the refrigerant.

Ammonia- water

Presently, ammonia as a refrigerant is gaining huge attention and is attracting a number of manufacturers since it has a higher auto-ignition temperature, a lower vaporization pressure, a greater heat of vaporization and is more soluble in water when compared with other refrigerants. Shukla et al. explained that "COP of the system is greatly influenced by the parameters like condenser, generator, absorber and evaporator temperature". Seara et al, (2013) worked upon control of OGT and concluded that "it could be achieved by reducing the solution heat exchanger efficiency and by increasing the pressure drop between evaporator and absorber". A major problem working with ammonia as the refrigerant is the need of rectification column which helps in removing all the amount of water vapor (moisture) present which prevents it from entering the evaporator and prevents from freezing and chocking the system. For this purpose, rectifiers and super heaters are used. Table 2 shows the various drawbacks and the required remedies for the different types of refrigerants in a VARS. Padila et al, (2010) reported that "Superheating enhances the power output and in order to maximize the refrigeration output rectifier column is vital".

Ammonia water as a refrigerant can be readily used in large-tonnage industrial applications requiring low temperatures for process work with a benefit of cost savings as the cost of heat source is zero.

Table 2: Various drawbacks and relative remedies for VARS

Type	Problem associated	Conclusion	Reference
Single-effect absorption using aqueous lithium–bromide	Crystallisation	The concentration of solution in the generator can not be greater than 70%, beyond this limit, crystallization occurs	Aphornratana and Sriveerakul (2007)
Heat and mass transfer enhancement of binary nanofluids for H_2O/LiBr falling film absorption process	Sedimentation, cohesion and corrosion	Fe nanoparticles and CNT can resolve sedimentation	Kang et al. (2008)
Ammonia–water absorption refrigeration unit	Ammonia leakage	Hermetic vessel located at an intermediate elevation between the absorber and generator helps preventing leakage	Sohel and Dawoud (2006)
LiBr-H_2O absorption system	The formation of slush in the piping network forms a solid, blocking the flow quickly	The concentrated solution temperature should be raised above its saturation point so that the salt crystals gets dissolve within a reasonable time, freeing the machine.	Liao et al. (2017)
Double effect series flow LiBr-H_2O absorption system	Crystallisation	The possibility of crystallization increases with increasing T_{HPG}, T_{eva} and effectiveness of the LTHE and decreasing T_{abs} . Also the double effect parallel and reverse parallel are less prone to crystallization.	Farshi et al. (2011)
LiBr + water solutions.	Lower mass transfer rate	LiBr + CHO_2Na (sodium formate) + water solution increases the absorbent concentration from 30 to 45 mass % thereby improving the thermophysical properties	Lucas et al. (2017)
LiBr + water solutions.	Crystallization	A novel CHP system developed where increased chilled water temperature and reduced exhaust temperature was set.	Liao and Radermacher (2017)
Ammonia+ water	High operation pressure, toxicity and a corrosive action over copper or copper alloys.	Materials such as carbon steel could be used	Rodríguez-Muñoz and Flores (2014)
Ammonia+ water	Toxicity of ammonia, unstability	Fluoride refrigerants are suggested due to their good solubility, non-corrosive, completely miscibility with organic solvents such as N,N′-dimethylformamide (DMF) and N,N′-dimethylacetamide (DMAC).	Fatouh et al. (1993)

LiBr- water

In H_2O–LiBr pair, LiBr is used as an absorbent and water as a refrigerant. For refrigeration processes below 0 °C this system can't be used which therefore limits its performance. The lithium bromide solution has a low vapor pressure and it develops a strong affinity towards water vapor. However, this system is used mainly for air-conditioning purposes. The system also undergoes the problems of crystallization as well and the viscosity of the solution increases at low pressure and eventually a difficulty arises with the system. For solving these problems, a proper design of the system should be done. Kaynakli and Kilic (2007) performed an analysis of a H_2O–LiBr VARS and they concluded that" VARS performance improves with increasing evaporator and generator temperatures, while it reduces with increasing absorber and condenser temperatures. They also found that it is the solution heat exchanger which affects the performance of the system". Joudi and Lafta (2001) developed a model for studying the similar properties on the system using hot water for generating heat. Priedeman et al. (2001) experimentally tested an ammonia-water chiller with a suitable heat exchanger with which they obtained a COP of 0.7 and a cooling capacity of 17.6 kW. Kilic and Kaynakali (2007) pointed that highest exergy destruction occurs in the generator. Gomri and Hakimi (2008) presented the advantages of double effect VARS as high ratio of volatility, good affinity, greater stability, much increased safety, and sufficient amounts of latent heat. Arunkumar and Ragavendran (2016) reported that "when solar energy is used, a good COP of up to 0.7–0.8 could be achieved and due to such better COP the system could readily be used not only for domestic purposes but also for industrial purposes". Therefore, it could be interpreted that this technology is beneficial in those refrigerating operations where a temperature greater than 0 °C is required.

Alternative refrigerants

Due to many advantages of the absorption systems, many researchers are focusing on modeling development as well as on heat transfer additives, heat and mass transfer analysis and several other experiments for improving the COP of the vapor absorption refrigeration system by introducing new mixtures of refrigerants. Sohel et al. (2006) carried out a research study on improving the thermal performance of the Diffusion Absorption Refrigerator (DAR) by addition of alumina nanoparticles into the ammonia/water solution, and reported that the "system with the nanoparticles provided better absorption of heat from the generator". Lee et al. (2017) studied on the effect of nano-sized oil droplets and found that introduction of nano emulsion fluid increased the COP of the DAR system to as high as 15%. Wang et al. investigated binary refrigerant R23/R134a and reported that "the refrigerating temperature level of -40 °C using low-grade thermal energy can be obtained". Ayou et al. (2014) also concluded that "the ionic liquid based working pairs can replace the conventional H_2O + LiBr working pairs to avoid crystallization and corrosion and they have a better performance". Chen and liang performed a thermodynamic analysis of IL/H_2O and IL/CH_3OH systems were compared with those of LiBr/H_2O system. COPs and η_{ex} of both systems are lower than by less than 10%. DMAC is an organic compound which is considered as an absorbent because of its good solubility as quoted by (Smirnova et al. (2007). Another author Chen et al. (2016) compared the refrigerant $bmimZn_2Cl_5/NH_3$ with $bmimZn_2Cl_5/NH_3$ and found that $bmimZn_2Cl_5/NH_3$ systems have a slightly higher COP than that of the $NaSCN/NH_3$ system when the generation temperature is high. The findings also indicated that an absorption system using $bmimZn_2Cl_5/NH_3$ as a working pair could be used for cooling and heating applications. Lastly Boman et al. (2015) suggested that a "heat pump designed to operate in a location where temperatures remain above 0°C would be able to utilize the H_2O-mmimDMP working pair, while one intending to operate in both cooling and heating modes in a colder climate would tend towards an NH_3-H_2O or NH_3- $LiNO_3$ working pair". Hence there are many more newer researches on combinations of different types of refrigerants for absorption cycle out of which anyone could be selected according to the requirement.

APPLICATIONS OF VARS

Considering the issue of fuel demand and depletion of fossil fuels, most of the refineries have started to opt for an alternative system that could provide the same output by consuming less amount of energy or by utilization of waste heat sources. Due to several advantages such as its huge working capacity (even for above 1000 TR) and less maintenance VARS is widely used in various industries.

Cold storage

Cold storages are needed for the purpose of storing perishable food items at temperature below 10°C. This helps to increase the shelf life of the food commodities. Since this storage system is intended for long operating hours, vapor absorption system proves to be more of economical. A single stage vapor absorption refrigeration cycle requires heat input at a minimum temperature of 100°C. Problems such as crystallization, corrosion, vacuum operation in water–lithium bromide, rectification and incompatibility with copper in ammonia–water systems are observed many a times. Arivazhagan et al. (2005) gave a suggestion to use R134a and DMAC as the working fluid pair. The COP came between 0.35–0.46. They also concluded that the COP of is system was 25% higher than that of the ammonia–water cycle without the condensate pre-cooler and 35% higher with the condensate pre-cooler. A similar study of design on solar powered absorption refrigeration technology was studied by Said et al. (2012) it was concluded that continuously operating refrigeration systems with refrigerant storage have comparatively low mass requirement and high COP and it can provide day as well as night cooling. Similarly, Agyenim et al, (2010) calculated the average COP of the system running on solar energy as 0.58 from a 12 m^2 Thermomax DF100 vacuum tube collector as observed on a hot sunny day with average peak insolation of 800 W/m^2. Along with solar technology some hybrid technologies are also there as just in case where Panja and Ganguly (2010) designed a system for running cold storage using biomass energy and solar thermal for storing potatoes. The COP varied between 0.70 and 0.82. It could be inferred from the above values of COPs and performance evaluation that the absorption refrigeration can resolve the issue of hunger, losses of food items due to lack of preservation, milk spillage, can provide food security to the poor countries, can also help to increase the shelf-life of the perishable food items.

Road transport vehicles

The refrigeration units incorporated in maximum of the road transport vehicles is of the vapor compression type. But here also vapor absorption technology can be used as waste heat energy as a power source. Koehler et al. (1997) developed a prototype of an absorption system for truck refrigeration using heat from the exhaust-gases of diesel engine and as a result of the COP measurements; he concluded that an absorption system for truck refrigeration systems is an interesting alternative for operating conditions with long distances. On this note Horuz and Callander (2004) further explained that “the design of a heat exchanger is capable of extracting the maximum waste heat with minimum pressure loss in the exhaust systems”. Automotive air conditioning systems are those equipment’s that excessively use CFC compounds, and the leakage of these badly affects the environment, the absorption cycle is found to be an ideal option. Aqeeli and Gandhidasan (2002) designed an air conditioning system for automobiles using the Open Cycle Absorption System, and suggested that “using the exhaust gas to pre-heat the weak desiccant we can minimize the power losses”. Further AlQdah et al. (2011) remarked that “the COP values of automobile air conditioners are directly proportional with increasing generator and evaporator temperatures”. Trucks used for the transportation of food items such as milk, vegetables, fruits, and meat must be equipped with refrigeration systems. Using the absorption technology, it saves our environment from pollution and it also reduces the cost of operation thereby reducing global warming.

Industrial chillers

Presently there is a huge attention towards absorption refrigeration systems because of not using CFC and HCFC refrigerants, and providing a solution to the problems of overload power grids during the warm seasons. Industrial chillers working on ARS uses waste heat generated in the industry for cooling purposes. Bruckner et al. (2009) pointed out that absorption chillers are profitable only when applied for at least 2500 h per year and electric heat pumps are profitable for more than 4000 h/a and absorption heat pumps with 3000 h/a. Lake et al. quantified the effect of concentration of Lithium Bromide in an absorption chiller using exergy analysis and found that "internal temperatures changes by 3 to 7 °C with an increase in the concentration". Lu et al., (2008) analyzed a heat driven absorption refrigeration technology and concluded that optimal COP of the absorption chiller is about 0.825 when the generator temperature is 60°C and the maximum COP of the system under 10°C. Switching on towards solar energy, Shirazi et al. (2013) conducted a multi-objective optimization of solar absorption chillers. The results revealed that the double-effect chiller has the best economic, energetic and environmental performance of the system; it also reduces the annual primary energy use and CO_2 emissions by 44.5–53.8% and 49.1–58.2%. Hence, we can infer that an absorption chiller provides us with alternative energy sources for refrigeration and chilling water.

CONCLUSION

Due to ever increasing energy demands of refrigeration and air conditioning these days the vapor absorption refrigeration system proves as a solution to the energy deficit challenges. As the resources are depleting and the world is switching more towards alternative renewable energy sources this technology is gaining importance, since it could be driven from low grade heat inputs like solar energy and biogas combustion are capable of driving the refrigeration systems which will also be useful in unelectrified rural areas where grid supply is yet not present.

New combinations of refrigerants helps in overcoming the drawbacks of LiBr-H_2O and NH_3- H_2O like by using binary nanofluids heat and mass transfer enhancement for H_2O/LiBr falling film absorption process could be done. And for ammonia water Fluoride refrigerants are suggested since they have a good solubility and non-corrosive nature. Ionic liquid pairs can readily replace the conventional refrigerant pairs. The optimum generator temperature of the absorption system should lie between 80-90°C so as to improve the system performance.

FUTURE SUGGESTIONS

Vapor absorption technology is a very promising technique by using which we can protect our mother Earth from harmful gaseous emissions like Chlorofluorocarbons which are continuously depleting the ozone layer. The heat exchangers should be properly designed and incorporated within the system so that the heat losses could be reduced and hence the performance of the system will improve. Also the heat input source should be designed in a manner that it is in conjunction with the systems requirement. Waste heat can be recovered in its most efficient way through VARS technology thereby providing an alternate nonconventional energy source and helping to save energy. Cold storage, water chillers, domestic purpose chillers and automotive vehicles are some examples of waste heat utilization through vapor absorption refrigeration systems for cooling purposes using a clean energy pathway.

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