International Journal of Scientific Research & Engineering Trends
Volume 8, Issue 1, Jan-Feb-2022, ISSN (Online): 2395-566X

A Review on Performance Optimization of Absorption Refrigeration Systems Using Box-Behnken Design and Central Composite Design

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Abstract-The decrease of fossil fuels such as natural gas, coal, oil and the increase of the negative impact of these fuels increase the need for renewable energy sources day by day. Therefore, in the last few years, the use of absorption refrigeration systems (ARSs) instead of vapor compression refrigeration systems is currently gaining momentum.The most important advantages of ARSs are as follows: They do not destroy the ozone layer depending on the working fluid pairs used in the system and can benefit from various renewable energy sources (i.e., geothermal energy or solar energy).

Keywords-Absorption Refrigeration Systems, optimization, BBD, CCD

I. INTRODUCTION

The decrease of fossil fuels such as natural gas, coal, oil and the increase of the negative impact of these fuels increase the need for renewable energy sources day by day. Therefore, in the last few years, the use of absorption refrigeration systems (ARSs) instead of vapor compression refrigeration systems is currently gaining momentum.The most important advantages of ARSs are as follows: They do not destroy the ozone layer depending on the working fluid pairs used in the system and can benefit from various renewable energy sources (i.e., geothermal energy or solar energy).

Tugcu et al. (2016) optimized the single stage geothermal energy assisted ARS, working with NH3-H2O, for different solution concentrations and design parameters. In this study, for the optimum design, COP of the system was determined as 57.22% while the exergy efficiency was calculated as 62.01%.

Saleh and Mosa (2014) examined the single-effect ARS powered by a flat-plate collector for hot regions and optimized the performance of the system. They found that the overall system performance takes its optimal value at temperatures between 75 ^{o}C and 80 ^{o}C, adopting typical values encountered in hot regions.In literature, there are many studies on the thermodynamic analysis of ARSs and the performance characteristics of the cycle.

Karamangil et al. (2010) presented a comprehensive literature review on the ARS and they examined the influence of the effectiveness's of solution, refrigerant and solution-refrigerant heat exchangers (SHE, RHE and SRHE), the operating temperatures (generator, evaporator, condenser, and absorber) and the selection of working fluid (LiBr-H2O, NH3-H2O, NH3-LiNO3) on the system performance indicators (COP and circulation ratio, CR). In that study, it was concluded that SHE has the most significant effect on COP since it increases the system COP by 66% compared to RHE and SRHE.

Li et al. (2017) performed a thermodynamic analysis of a novel air-cooled non-adiabatic ejection-absorption refrigeration cycle with R290/oil mixture driven by exhaust heat.

Ouadha and El-Gotni (2013) performed the thermodynamic analysis of an ARS driven by waste heat from a Diesel engine. The thermodynamic study of the cycle performed for several working conditions by changing the temperatures of generator, condenser, absorber and evaporator. They determined that higher performance of the system is obtained at high generator and evaporator temperatures and also at low condenser and absorber temperatures.

Kaynakli and Yamankaradeniz (2003) investigated the effect of heat exchangers, which are used to recover heat energy in the ARS, on the coefficient of performance (COP). In this study, it was found that the solution heat exchanger (SHE) is the most effective heat exchanger on the system performance.

Abed et al. (2015) focused on the optimization of the utilization of the internal heat recovery of the ejector-flash tank-ARS working with NH3-H2O. They found that the refrigeration capacity increment of the proposed cycle with added RHE is 4.85%.

Sencan (2007) performed the performance analysis of NH3-H2O ARS based on the artificial neural network model. Novella et al. (2017) performed the thermodynamic analysis of an absorption refrigeration cycle used to cool down the temperature of the intake air in an internal combustion engine using the exhaust gas of the engine as a heat source. In general, in these studies, the different parameters affecting the first law efficiency of the ARS were examined and the effects of the system on the COP were analyzed.

Bademlioglu et al. (2018) examined the impact weights of parameters on ORC's first-law efficiency by utilizing Taguchi and ANOVA methods. In this study, the most efficient parameters on the thermal efficiency of the ORC (evaporator temperature, condenser temperature and turbine isentropic efficiency) were determined and the total effect ratios of these parameters were calculated to be 70%.

Coskun et al. (2012) analyzed the performance of waste heat recovery application with the aid of the Taguchi method, and determined the significant parameters and optimum operating conditions. Arslanoglu and Yigit (2017) examined the parameters that have the most significant effect on the optimum insulation thickness, in accordance with the importance order by utilizing Taguchi method. Moreover, impact ratio for each parameter was determined with the help of ANOVA.

II. DESCRIPTION OF VAPOUR ABSORPTION SYSTEM

Below is a description of the main parts of the system.

1. Evaporator:
Water as the refrigerant enters the evaporator at a very low pressure and temperature. Since very low pressure is maintained inside the evaporator the water exists in a partial liquid state and partial vapor state. This water refrigerant absorbs the heat from the substance to be chilled and gets fully evaporated. It then enters the absorber.

2. Absorber:
A concentrated solution of lithium bromide is available in the absorber. Since water is highly soluble in lithium bromide, solution of water-lithium bromide is formed. This solution is pumped to the generator.

3. Generator:
Heat is supplied to the refrigerant water and absorbent lithium bromide solution in the generator from the steam or hot water. The water becomes vaporized and moves to the condenser, where it gets cooled. As water refrigerant moves further in the refrigeration piping and though nozzles, its pressure are reduced along with the temperature. This water refrigerant then enters the evaporator where it produces the cooling effect. This cycle is repeated continuously. Lithium bromide on the other hand, leaves the generator and re-enters the absorber for absorbing water refrigerant.
As seen in the image above, the condenser water is used to cool the water refrigerant in the condenser and the water-Li Br solution in the absorber. Steam is used for heating water-Li Br solution in the generator. To change the capacity of this water-Li Br absorption refrigeration system the concentration of Li Br can be changed. The lithium bromide absorption refrigeration system uses a solution of lithium bromide in water. Water is being used as refrigerant whereas Li-Br is a highly hydroscopic salt, used as absorbent. The Li-Br solution has a strong affinity for water vapour because of its very low vapour pressure. Also it is corrosive; hence Lithium chromate is often used as an inhibitor. The absorber and evaporator are placed in one shell which operates at same low pressure of system, while generator and condenser are placed in another shell which operates at same high pressure of system.Water for air conditioning coils pumped through chilled water tubes, is chilled in evaporator by giving up heat to refrigerant water sprayed over the tubes.

Since evaporator pressure is maintained very low, therefore refrigerant water evaporates and the vapours are absorbed by strong Li-Br solution which is sprayed in absorber. This absorption makes the solution weak and maintains high vacuum in evaporator. The weak solution is pumped to generator where it is heated up using steam or hot water in heating coils. This leads to evaporation of some portion of water thereby making the solution strong. Now this solution is sent back to absorber for spraying as mentioned above.

The weak solution going to generator is passed through heat exchanger where it absorbs heat from the strong solution coming from generator. This reduces steam requirement for the generator to heat the weak solution.
The refrigerant water vapours formed in generator are passed to condenser. Cooling water for condensing is pumped from cooling water pond or tower, and this water goes first to the absorber for taking away heat of condensation and dilution, and then to the condenser.

The condensate from condenser is sent to evaporator to compensate the loss of refrigerant water through evaporation and is pumped and sprayed on the chilled tubes, thus completing the cycle.The pressure reducing valve reduces the condensate pressure from condenser to evaporator pressure. The pressure for spray is created using the pressure difference between generator and absorber, and the gravity due to height difference of the two shells.

III. ADVANTAGES OVER VAPOUR COMPRESSION SYSTEM

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 useful refrigeration by using a heat operated

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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 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 absorption system differs fundamentally from VCR system in the method employed for compressing the refrigeration. In the absorption system, the compressor is replaced by the combination of an absorber, a generator, and a pump.

The combination called aqua ammonia was used in absorption systems years before LiBr-water combination become popular. The absorption systems have experienced many ups and downs. The absorption was the predecessor of the vapour compression system in 19th century and aqua- ammonia system enjoyed wide applications In domestic refrigerators and large industrial installations in the chemical and process industries. The LiBr-water system was commercialized in the middle of the 20th century as water chillers for large buildings air-conditioning. In the LiBr-water system water is the refrigerant. This imposes restriction on its use for applications requiring temperatures below 0^{o}c.

And the LiBr being a salt has a re-crystallization zone when it becomes solid and hence imposes flow restrictions .The vapour absorption system practically LiBr-water system has bounced back with the use of solar energy and the recent emphasis on co-generation which makes available, the otherwise waste heat , for external direct heating source in vapour absorption system The analysis of this system is relatively easy as the vapour generated in the generator is almost pure refrigerant (water), unlike ammonia-water systems where both ammonia and water vapour are generated in the generator.

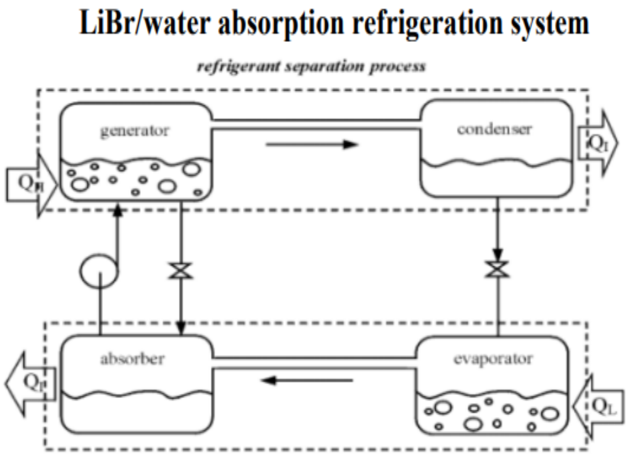

Fig 1. Li-Br/ water absorption system.

IV. THEORETICAL STUDIES REPORTED IN THE LITERATURE

Extensive studies have been carried out on the compression-absorption systems by various researchers regarding the first law analysis of the system as reported in the literature which are explained in the following section.

Saleh and Mosa (2014) examined the single-effect ARS powered by a flat-plate collector for hot regions and optimized the performance of the system. They found that the overall system performance takes its optimal value at temperatures between 75°C and 80°C, adopting typical values encountered in hot regions.

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Aman et al. (2014) developed a thermodynamic model based on a 10 kW air-cooled NH3-H2O absorption chiller driven by solar thermal energy. In this study, the first and second law analyses were conducted to evaluate the performance of this residential scale cooling system and it was found that the absorber is the component where the most exergy loss occurs (63%) followed by the generator (13%) and the condenser (11%).

Joybari and Haghighat (2016) performed the exergetic analysis of a base case single effect LiBr-H2O absorption system. In this study, it was determined that as the mass flow rate of water circulated in the system became lower, the exergy losses in the main components of the system decreased.

Modi et al. (2017) investigated the energetic and exergetic performance of the absorption refrigerant system in LiBr-H2O solution for each component. For this purpose, they developed a numerical program for energy and exergy calculations of the ARS.Kumar et al. (2017) performed a thermodynamic analysis of the single effect NH3-H2O ARS. They determined the optimum generator temperature corresponding to maximum COP and minimum exergy loss.

Fernandez-Seara and Sieres (2006) investigated the effects of the ammonia purification, the liquid entrainment and blow-down from the evaporator in the ARS. They developed a mathematical model based on a single stage system with complete condensation. It was concluded that small values of liquid entrainment or blow-down fractions increase the operating range of the absorption system significantly, and smoothes the efficiency requirements of the distillation column. In these studies, the energetic and exergetic performance of the ARS were investigated and the effect of different parameters on COP and eCOP was examined.

Kaynakli and Kilic (2007) performed a detailed thermodynamic analysis of the LiBr-H2O ARS. They investigated the impacts of operating temperature and effectiveness of heat exchanger on the system performance. In this study, it was obtained that the SHE increases the COP value up to a maximum of 44%, while the RHE had an effect of only 2.8%.

Ketfi et al. (2015) studied on the modeling and simulation of a 70 kW Yazaki absorption refrigeration machine working with LiBr-H2O solution. They examined the effect of system parameters on the coefficient of performance (COP).

In general, analysis of variance (ANOVA) and Taguchi method are used to determine the impact weight of the parameters statistically by considering the possible combinations of the parameters affecting the system. However, studies on the statistical analysis of parameters affecting the performance of thermal systems are limited in the literature. In many of these studies, the design parameters of heat exchangers were determined, and performance analyses were performed with the help of Taguchi and ANOVA methods.

Turgut et al. (2012) determined the optimum design parameters of the concentric heat exchanger with injector turbulators using Taguchi experimental design method. They investigated the effects on the heat transfer and pressure loss of the injector-shaped turbulators having different angles, diameters and numbers.

Verma and Murugesan (2014) analyzed the performance of a solar assisted ground source heat pump using Taguchi technique. In the study, the design parameters were optimized to obtain solar collector area and ground heat exchanger length for space heating application with optimum COP.

Yakut et al. (2006) examined the effects of various kinds of design parameters on the heat transfer and pressure-drop characteristics of the heat exchanger using the Taguchi method. Zeng et al. (2010) investigated the influence of various design parameters on the heat transfer and flow friction characteristics of a heat exchanger with vortex-generator fins and optimized the parameters of vortex-generator fin-and tube heat exchangers by using the Taguchi method.

Bademlioglu et al. (2018) examined the impact weights of parameters on ORC’s first-law efficiency by utilizing Taguchi and ANOVA methods. In this study, the most efficient parameters on the thermal efficiency of the ORC (evaporator temperature, condenser temperature and turbine isentropic efficiency) were determined and the total effect ratios of these parameters were calculated to be 70%.

Coskun et al. (2012) analyzed the performance of waste heat recovery application with the aid of the Taguchi method and determined the significant parameters and optimum operating conditions.

Arslanoglu and Yigit (2017) examined the parameters that have the most significant effect on the optimum insulation thickness, in accordance with the importance order by utilizing Taguchi method. Moreover, impact ratio for each parameter was determined with the help of ANOVA. Another important statistical analysis method, which is different from Taguchi and ANOVA, is Grey Relational Analysis (GRA).

In general, the GRA model allows the simultaneous evaluation of different objective functions and enables the determination of the optimum parameters for all purpose functions.

Naqiuddin et al. (2018) performed a computational fluid dynamics analysis to evaluate the performance of a micro-channel heat sink. In that study, the effects of various design parameters on the heat transfer and flow characteristics were optimized using Taguchi-GRA method.

Celik et al. (2018) experimentally investigated the corrugated tape type turbulators with different pitches, weights and thicknesses inserted in a concentric pipe heat exchanger. In that study, the multi-performance analysis was carried out by using GRA method for heat transfer and pressure loss.

Acir et al. (2017) determined the optimum factors having an impact on the first and second law efficiencies for a unique design solar air heater using the GRA method. They calculated the contribution ratios of each parameter on the system performance by using ANOVA.

Kuo et al. (2011) performed the design by determining the optimal operating parameters of the flat-plate collector with the help of the Taguchi method and GRA. Chamoli et al. (2016)investigated the effect of processing parameters on the performance of a heat exchanger tube with the help of the Taguchi based GRA. In addition, they conducted an experimental study by using the optimal design condition.

V. CONCLUSION

Studies in the literature show that there are various parameters affecting the energetic and exergetic performance of ARS such as the generator, evaporator, condenser and absorber temperature, the effectiveness of SHE, RHE and SRHE and pump isentropic efficiency. Nonetheless, a detailed study analyzing all these parameters and determining their contribution ratios on the system's performance with a statistical approach has not been encountered in the literature.

For this reason, the purpose of this study is to examine the parameters that present the most significant effect on the ARS's COP values and determine the importance order of these parameters by utilizing RSM method. Moreover, the best and worst working conditions are determined by different statistical analysis methods and the results are compared.

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