Solar Based ORC-Ejector-Absorption Hybrid System for Cogeneration of Power and Cooling using Duratherm 600

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Abstract

Solar operated hybrid system for simultaneous production of power and cooling is one of the promising technologies to resolve the key issues of fossil fuel crisis and serious environmental degradation. Development of this kind of cogeneration offers an effective way to sustainable production of electric power and cooling for hot and dry climatic regions. In the current research proposal, a solar based cogeneration system, which combines the organic Rankine cycle with the ammonia-$LiNO_3$ absorption cooling cycle, is presented which could produce effective cooling with adequate power generation from single source of solar energy at hot climatic conditions. The proposed cycle is quite capable to meet out the energy requirements of some commercial units and industries which need more amount of cooling than power such as cold storages, university building, and shopping complex etc. This cycle employs the solar heliostat field using Duratherm 600 oil as a heat transfer fluid in the receiver which is integrated with the organic Rankine cycle which is superimposed to the vapor absorption refrigeration cycle. Hydrocarbons which are abundantly available in the Kingdom and are environment friendly and chemically stable will be used as working fluid for power generation in the organic Rankine cycle while ammonia-$LiNO_3$ which can produce cooling below 0^oC eco-friendly and effectively will be used as a working fluid in the absorption refrigeration cycle. A mathematical model based on mass, energy, and exergy balance equations will be developed and will be applied to theoretically assess the performance of the proposed cogeneration cycle. The cycle will be further investigated from exergy point of view to identify the locations of thermodynamic losses and to quantify the loss of efficiency in a process that is due to the loss in energy quality. A conceptual design will be presented and analysis will be performed to ascertain the effects of several operating parameters like; direct normal irradiation (DNI), type of working fluid in pure and mixed

form, turbine inlet pressure, and evaporator temperature on energetic efficiency, exergetic efficiency, and cooling to power ratio of the cogeneration cycle. The optimum operating conditions will be established by maximizing the cycle exergy efficiency. The results obtained after completing the proposed research will establish a design-criteria for the development of an integrated system which can harness the solar thermal potential of the India more effectively through cogeneration of cooling and power. The research findings also fill the gap of the open literature through excellent Journal publications from the work proposed.

1. INTRODUCTION

In the last few years renewability and sustainability have become a key factor for economic growth of every nation. Fast depletion of fossil fuel reserves and environmental degradation caused due to rapid combustion of fossil fuels demands for the development of sustainable energy systems. In this context, concentrating solar thermal systems are receiving a considerable attention due to their inherent sustainable merit. However, utilizations of solar thermal technology for power generation are not as competitive as conventional power generation technology because of low solar to electric efficiency and expensive concentrator. To overcome these problems and further to meet out the increasing demand of cooling in hot-climatic regions, combined power and cooling cycles are explored which makes full use of solar thermal energy and offers an effective way to sustainable energy production in hot and dry climates. One of the most common combined power and cooling cycle is a Goswami cycle which is an integrated plant in which evaporator is located at the exit of turbine where the refrigerant is in vapor form of the entrance of evaporator and the cycle is well suited for cold climatic conditions. In hot climatic regions, it is difficult to get cooling through this cycle due to high sink temperature. Integration of organic Rankine cycle with an ejector is an advancement in the area of combined power and cooling production. These cycles utilize the refrigerants which have zero ozone depletion potential using solar energy as a primary input and provides an option to avoid the use of mechanical compressor for energy saving. Ejector which is a key component of the cycle has the disadvantage of low co-efficient of performance which leads to lower solar energy shares towards cooling. Superimposition of solar assisted organic Rankine cycle over the vapor absorption refrigeration cycle emerges as an alternative energy efficient and sustainable solution to the increasing energy demand of the hot areas of the world. In terms of power efficiency, expander size and environmental impact, hydrocarbons have been found as the most suitable working fluids for power generation using the organic Rankine cycles. Ammonia-water mixtures as binary natural refrigerant are environmentally benign materials and have excellent thermo-physical properties as working fluids for vapor absorption refrigeration cycles (VAR). Moreover, ammonia-water absorption refrigeration has wider range of operating temperatures (-60^{o}C to 10^{o}C) and can provide cold for industrial applications when the evaporation temperatures are below 0^{o}C. A big disadvantage of ammonia-water mixture as a working fluid is that it needs rectification which is an energy consuming process that results in the reduction of the system performance. In order to overcome this reduction in performance, ammonia—$LiNO_3$ and ammonia-NaSCN cycles have been explored recently as alternatives to the ammonia-water cycle. These cycles have the advantage of higher co-efficient of performance and requires no energy for rectification. Factors that restrict the applications of ammonia-$LiNO_3$ refrigeration cycle is its high viscosity that exhibit a limited heat and mass transfer in the absorber of the system. An effort is needed to reduce the effect of high viscosity of ammonia-$LiNO_3$ on the absorption refrigeration cycle performance. To this effect, a triple pressure level ejector-absorption cycle is introduced with the application of a liquid vapor ejector at the entrance for the absorber which is expected to improve the cooling performance of the ammonia-$LiNO_3$ cycle. In order to promote the use of solar thermal driven combined power and cooling cycles, further developments are required to improve their performance and reduce their high initial cost.

In view of the above, in the current research, a novel solar based integrated system for cogeneration of power and cooling is proposed which integrates the organic Rankine with the triple pressure level ammonia-$LiNO_3$ ejector-absorption refrigeration cycle where a liquid vapor ejector is employed at the entrance of the absorber. This cycle is an effort for the smart use of solar thermal energy and may be described as: solar radiations falls on the heliostat field and reflected on the aperture area of central receiver which is located on the top of the tower. The concentrated rays that fall on to the receiver results in its high temperature which is used to heat the oil (Duratherm 600). The oil flows through the pipes which transfer the thermal energy from central receiver to the HRVG and generator of the vapor absorption cycle. Superheated refrigerant vapor of hydrocarbon fluid enters the turbine and expands to a low pressure to produce electricity by rotating the shaft connected to an electric generator. Afterword, the turbine exhaust is condensed to liquid in the condenser by rejecting heat to the environment. The liquid hydrocarbon fluid from the condenser is compressed by the pump and fed back to the vaporizer through economizer. The organic Rankine cycle is integrated with the triple pressure level ejector-absorption refrigeration cycle where the generator works at high pressure and the evaporator at low pressure, while the absorber operates at an intermediate pressure. In the generator, ammonia vapor is generated from strong solution, using the exiting Duratherm 600 oil from the heat exchanger as a high temperature heat source. The weak solution leaving the generator passes through the solution heat exchanger (SHX) before entering the ejector (the primary low stream) and draws into the ejector the vapor from evaporator (the secondary flow stream). The mixed stream is discharged from ejector into the absorber. The strong solution leaving the absorber and pumped back to the generator through the solution heat exchanger. In the generator, the strong solution splits into $LiNO_3$ and ammonia, where ammonia goes to the condenser and then as condensate it is fed to the evaporator through the expansion valve where it vaporizes, and the desired cooling effect is produced.

Deployment of the proposed solar based combined power and cooling cycle is expected to meet the increasing energy demand of the Gulf region in an energy efficient and reliable manner because no compressor is needed and the solar thermal cycle does not need any external power input for producing the desired electric power and cooling. The proposed cycle further provides the way for promising and sustainable use of hydrocarbons for power generation instead of burning them as they are abundantly and cheaply available in most of the West Asian countries. Integration of triple pressure level ejector-absorption cycle as a bottoming cycle produces a much better cooling effect than the conventional ammonia-water cycle, not only because of higher energy and exergy efficiency, but also because this cycle does not need rectification. Proposed energy-efficient and sustainable cogeneration cycle offers an excellent opportunity to produce electric power and cooling for the hot climatic regions of the world and provides an alternative environment-friendly solution to utilize hydrocarbons and organic fluids for sustainable energy production.

Concept of exergy yields a method of analysis based on the second law of thermodynamics and its aim is to identify the magnitudes and the locations of thermodynamic losses which pinpoint the locations of system imperfections. Exergy analysis paves the way to quantify the loss of efficiency in a process that is due to the loss in energy quality and hence the information obtained from exergy analysis can be used to guide investment decisions that weigh which research efforts will produce the greatest efficiency gains, i.e., which loss mechanism is the most worthwhile to address.

In the recent past, cogeneration of power and cooling systems caught the attention of many researchers but very few investigations are reported on the exergy analysis of these systems. Therefore, research carried out in the proposed study on the novel solar based integrated system will result in the preparation of some excellent research papers for publication in peer reviewed Journals of international repute. Current proposal is the advancement in the existing low temperature heat source based cogeneration cycles which can be observed as:

- Deployment of solar power tower technology to harness low grade solar energy for the operation of cogeneration cycle which produce electric power and cooling in a carbon-free manner.

- Super imposition of organic Rankine cycle over the triple pressure level absorption refrigeration cycle boost the cycle efficiency and explores the possibility of utilizing abundantly available hydrocarbons and organic substances as a working fluids for the simultaneous production of power and cooling.

- Cascade utilization of energy and exergy techniques to investigate how the pure and mixed working fluids affect the cogeneration cycle performance and its design parameters.

2. Literature

Among all the concentrating solar thermal technologies investigated, solar power tower technology has been receiving more and more attention due to its inherent sustainable merit [Barlev et al. (2011)]. In order to utilize the solar thermal potential of hot areas of the world and to protect the environment along with the conservation of energy, cogeneration cycles for combined production of power and cooling have been explored.

Exergetic analysis, which combines the law of conservation of mass and energy along with the second law of thermodynamics has been widely embraced by the researchers over traditional energy methods in both industry and academia, has been applied to cogeneration cycles which produce both power and cooling simultaneously [Torio et al. (2009)].

In this context, a novel cycle that employs ammonia-water mixture as a working fluid was proposed by Goswami (1998). This cycle can produce both power and cooling simultaneously, and it can utilize low temperature heat sources. Xu et al. (2000) carried out a parametric study for this cycle and suggested a range of operating conditions. Hasan (2002) applied energy and exergy methodology to optimize the performance of such a cogeneration cycle. They established the optimum operating conditions by maximizing the cycle efficiency for the case of a solar heat source.

Zheng et al. (2006) developed a novel absorption power and cooling cycle. They reported 24% of cycle efficiency at a maximum temperature of 350^{o}C. But, the cycle proposed was complex in nature. Wang et al. (2008) designed a combined power and refrigeration cycle, which described the features of Rankine cycle and absorption refrigeration cycle and uses a binary ammonia-water mixture as the working fluid. They reported 20.5% cycle efficiency at the source temperature of 300^{o}C. These cycles found to be suitable for cold climatic conditions and it is difficult to get cooling from them in hot areas. With the intention to produce power and cooling effectively for hot and humid areas of the world and to avoid the use of mechanical compressor, few investigations have also been carried out on cogeneration cycle which integrates the organic Rankine cycle with an ejector. Dai et al (2009) proposed and analyzed a cogeneration cycle where an ejector was employed between the turbine and condenser to produce the desired cooling along with the power generation. Li et al. (2012) analyzed and compared the performance of double organic Rankine cycle and found its thermal performance superior to organic Rankine cycle with ejector. Khaliq et al (2012) presented the first and second law analyses of a novel low temperature energy source operated organic Rankine cycle integrated with ejector-absorption cooling cycle which yields a considerable gain in both energy and exergy efficiencies of the cycle. Habibzadeh (2013) conducted a thermodynamic study on organic Rankine cycle with ejector and computed its first and second law performance for different working fluids. They obtained the optimum operating conditions by minimizing the total thermal conductance of the system. Zhang and Mohamed (2015) presented a promising combined cycle configuration for cogeneration of power and cooling using low grade solar energy. Their theoretical analysis showed that much research efforts are needed to optimize the design and performance of the combined power and cooling cycle for its successful application in hot climates. Grosu et al. (2015) carried out the exergy analysis of a cogeneration cycle which combines the organic Rankine cycle with the single effect LiBr-H_2O absorption cooling cycle. They highlighted the components of maximum exergy losses and their impact on the performance of cogeneration cycle. Absorption refrigeration systems using LiBr-H_2O as a working fluid are suitable for air-conditioning and other high temperature applications. Using water as a refrigerant the system becomes unfunctional for the applications where the evaporator is below 0^oC. Ammonia-water mixture is an environmentally benign substance which has excellent thermo-physical properties and is commonly used as working fluid for absorption cooling cycles to produce cooling for industrial applications when the evaporator temperatures are below 0^oC [Yu et al. (2014)]. However, application of ammonia-water mixture as a working fluid in cogeneration cycle requires energy for rectification which is an energy consuming process and hence causes a reduction in system's energetic performance. To alleviate these problems, ammonia – $LiNO_3$ is proposed as alternatives to the ammonia-water mixture. A brief is reported on the combined first and second law analyses of ammonia $LiNO_3$ operated cooling cycle by Farshi et al. (2014). Their analysis clearly shown that ammonia- $LiNO_3$ cycle yields higher performance and do not require purification of the refrigerant vapor. But the performance of this cycle is also limited due to the high viscosity of ammonia- $LiNO_3$ mixture that can limit heat and mass transfer in the absorber of the system. Efforts are needed to reduce the effect of high viscosity of ammonia $LiNO_3$ on system performance.

3. Conclusion

From the foregoing literature review, it is seen that no research is reported that deals with the proposal and analysis of a solar based cogeneration cycle which integrates the organic Rankine cycle with the ammonia-$LiNO_3$ ejector-absorption cooling cycle by using Duratherm 600. Therefore, in the current research proposal an attention is focused on the development of an alternative energy-efficient cogeneration system that can utilize the abundantly available hydrocarbons and organic substances of the Kingdom as a working fluid for sustainable production of power and cooling. The proposed solar based cogeneration cycle will be designed and studied thermodynamically from both energy and exergy point of view to check its feasibility at hot climatic conditions (25^oC-48^oC). Pure hydrocarbons and their mixtures will be used as a working fluid and the results will be compared to see how mixed working fluids affect system performance and key design parameters. Results obtained based on developed mathematical model will be displayed and partially validated with the reported experimental data of the literature.

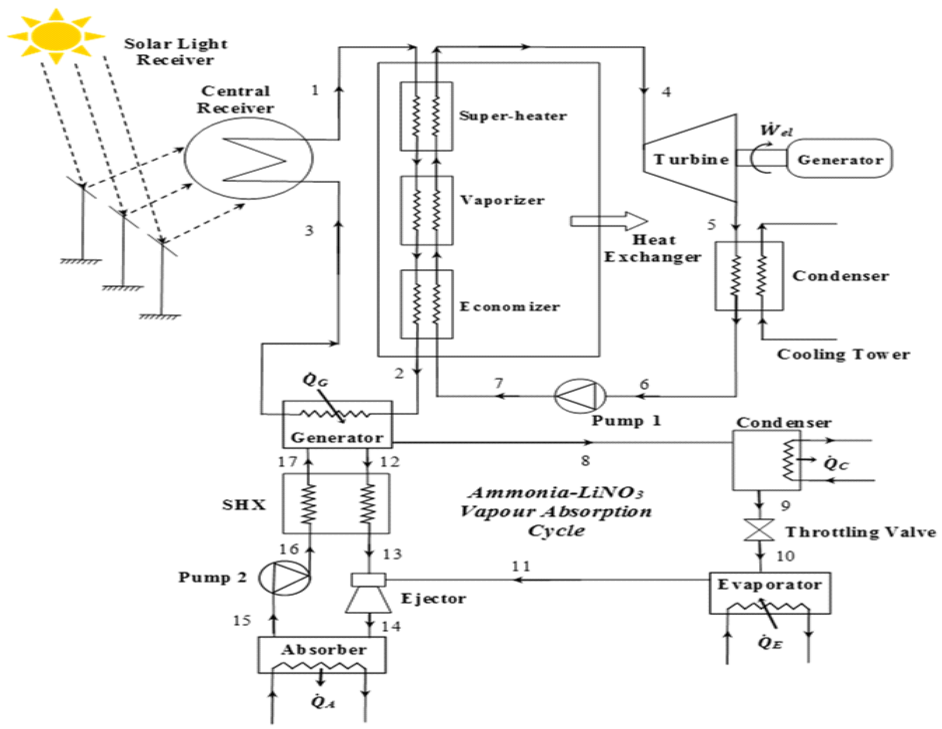

Fig. 1: Proposed diagram

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