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Experimental studies on combined cooling and power system driven by low-grade heat sources

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ABSTRACT

An experimental investigation was undertaken to study the actual useful output and performance of a combined power and cooling system that uses low-grade energy. The cycle used was a combination of NH_3-H_2O absorption refrigeration cycle and Kalina extraction turbine cycle. The expected performance characteristics of the dual output system were first evaluated using an energetic and exergetic approach based on the quality of useful outputs; in the experimental confirmation. It was evaluated in Cooling Alone mode (CA mode) and Combined Cooling-Power mode (CCP mode), for the same operating conditions. The weak solution flow rate and generator temperature were maintained constant at 0.237 kg/s and 133 °C respectively throughout the experimental run. The maximum cooling load of 34.26 kW was achieved with a COP's of 0.57 in CA mode. In CCP mode, the system was operated at a split ratio of 0.5 with the useful cooling load of 15.26 kW and estimated expander load of 2.21 kW respectively, with power to cooling ratio of 0.14. The corresponding effective first-law and exergetic efficiencies were 13% and 48%. This study provides a feasible and flexible way to meet the desired combination of power/cooling ratio to generate varying demand profiles using available low-grade heat sources.

1. Introduction

Low and mid-grade grade heat sources (<300 °C) are abundantly available from various heat sources such as solar thermal, geothermal, biomass and waste heat from various thermal and chemical processes. The efficient use of these variable temperature heat sources is a crucial technology, and it can be effectively used for conversion to highly valuable products such as electricity, air-conditioning, and refrigeration. Non-azeotropic nature of ammonia-water binary mixture has a relatively low bubble point temperature and it can evaporate in a wide range of temperatures, making it suitable for low and mid-grade heat source utilization. In addition, the broad evaporation temperature of working fluid can provide cooling as well as refrigeration to end users [1].

Kalina proposed a novel power cycle, using this mixture in bottoming cycle and has claimed higher thermal efficiency of 30–60% than comparable with conventional steam Rankine bottoming cycle [2–4]. In order to validate the feasibility of Kalina cycle, pilot power plants have been built and their performance have been investigated [5]. Using solar thermal energy with a maximum temperature of 130 °C, Kalina cycle was activated, and it was concluded that performance factor was sensitive to the temperature difference between maximum and minimum temperature of the cycle [6]. By utilizing the geothermal resources in Kalina cycle, the energy and exergy analyses were conducted and it was found that the cycle could be optimized for the turbine outlet pressure and mass fraction of the working fluid [7].

Absorption refrigeration cycle using ammonia-water mixture also plays a major role in low-grade heat source recovery. In recent years, integrated combined power and cooling cycles have been proposed for effective utilization of primary energy. Moreover, the integrated cycles are broadly classified into two groups, with both outputs in the same loop and through different loop. In 1995, Goswami [8] proposed an integrated cycle based on conventional Rankine power and absorption refrigeration cycles for simultaneous power and cooling in the same loop. Further researchers studied the thermodynamically performance of Goswami cycle [9,10]. In Goswami cycle, very high concentration of ammonia vapor is expanded in the turbine to a very low temperature without condensation, which is further used for sensible cooling in the evaporator. Although the cycle can provide power and cooling

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outputs in the same loop, but power output as a primary goal. Hence, to obtain larger cooling output in the cycle, the cooling effect produced in the evaporator is achieved through the latent heat of evaporation.

Zheng et al. [11] proposed a novel absorption power and cooling cycle based on the Kalina cycle with improved performance due to its increased capacity for both power and cooling outputs. The cycle was modified by including the condenser and an evaporator was introduced between the rectifier and second absorber. To enhance the purity of the refrigerant, the flash tank in the Kalina cycle was replaced by a rectifier for more refrigeration output. With these modifications the cycle was able to simultaneously provide dual output. Ziegler [12] proposed the double effect absorption cycle for dual output, which was valid when temperature glide in the heat source was large. In the cycle, separate cooling and power production of 1.2 MW and 100 kW respectively was obtained using thermal energy of 1 MW along with freedom to adjust ratio between cooling to power production. Liu and Zhang [13] developed a series connected dual output system, where a splitting/absorption unit was integrated with Rankine cycle and ammonia refrigeration cycle. The cycle could meet different concentration requirements in heat addition and the condensation processes. Zhang and Lior [14] developed three different cycle configurations namely series, parallel and compound for combined power and cooling. The author also summarized some guidelines for integration of refrigeration and power cycles based on energy and exergy efficiencies. Although the energy and exergy efficiencies were appreciably better, the cycles required high driving source temperatures (450 °C). Moreover, the cycles were relatively complicated and necessitated higher capital investment. Wang et al. [15] simplified Zhang's parallel combined refrigeration and power system driven by low-grade heat source. Sun et al. [16] proposed an ammonia-water based power/cooling generation system capable of utilizing low and mid-grade heat sources. Power and refrigeration sub-cycles were driven by high and low temperature portions of cascading waste heat respectively. Compared with the primary energy of separate power and refrigeration systems, the combined system consumed 17.1% less heat with the same output. Yu et al. [17] proposed a novel system with adjustable power to cooling ratios. In the proposed system, a modified Kalina and absorption refrigeration sub-cycles were interconnected by splitters, mixers, absorbers and heat exchangers. Lopez-Villada et al. [18] developed a single-stage power and cooling system and compared it with Goswami cycle. Suitability of different solar thermal collectors as a heat source (partly assisted with a load of the conventional heating system) for CCP system was reviewed with variable power to cooling ratio. A simplified CCP cycle based on Kalina and absorption refrigeration was proposed by Wang et al. [19]. To determine the irreversibilities, the exergy analysis was carried out for the major components in the cycle, in which the condenser and exhausted gas from vapor generator had major exergy destruction of 18.7% and 68.34% respectively.

Experimental studies are of utmost importance to validate the feasibility of combined power and cooling systems. However, very few experimental studies on ammonia water CCP cycles have been found in literature and a majority of the studies is conducted on prototype setup. The first prototype study of CCP cycle based on Goswami cycle was carried out by Tamm et al. [20]; the authors investigated the cycle both experimentally and theoretically. Through the parametric study, the system could be optimized for first and second law efficiencies besides cooling and power outputs. When the real losses were considered in the analysis, the power and cooling outputs, and the thermal efficiency decreased by 11.8%, 37.7% and 20.6% respectively. There was a good agreement between theoretical and experimental results. Martin [21] conducted experimental studies on a combined system driven by low temperature thermal sources (<200 °C). In the Tamm experimental setup, the rectifier and turbine were included to condition the vapour and to extract power from the working fluid respectively, demonstrating that the turbine exhaust was at sub-ambient temperatures. Demirkaya et al. [22] continued the investigation by using the same experimental arrangement, except for the expansion device, which was replaced by a scroll type expander. The experimental results showed that expander isentropic efficiency was between 30 and 50% and it performed well when the inlet vapour was superheated. Han et al. [23] developed an experimental rig for a CCP system in which the power generation was simulated using a vapor heat exchanger since low capacity efficient expanders are not available in the market. The system was able to provide the output based on user energy demand. When the system was operated as a refrigeration model, the cooling output was 11.67 kW with corresponding COP of 0.465, while on power generation model the simulated net output was 1.02 kW at the pressure ratio of 4.

Even though, the combined power and cooling systems are experimentally studied previously by other researchers, the power generation output is maximum of 300–400 W only with cooling output less than 5 kW. In this paper, an attempt is made to design and develop a system which enable the simultaneous production of 15 kW cooling and up to 2 kW net power output and 35 kW only on cooling alone mode. The combined system has integrated generator with solution-cooled rectifier, generator heat exchanger designed to reduce the heat input. By using low-grade heat sources, the CCP system output can be varied from cooling alone to power alone mode along with intermediate operating conditions to meet the demand throughout the year In the CCP system, the experimental study focusses mainly on typical conditions driven by low-temperature heat sources for cooling alone and dual output condition. Additionally, a sensitivity study is also conducted in CCP system for varied heat source temperatures.

2. Experimental setup and procedure

The experimental setup for combined power and cooling cycle driven by a low-grade heat source is shown in Figs. 1 and 2. The designed cooling capacity of the system, at cooling temperature of −10 °C, is 35 kW under the cooling alone and 2 kw of power capacity at power alone condition. The P-T-X diagram, P-h diagram and T-s diagram for the base condition operation of combined cooling and power are shown in Fig. 3. The weak and strong solution concentration values for the base condition are 0.3 and 0.22 respectively. The weak and strong concentration values tally with the equilibrium pressure and temperature conditions of the absorber and the generator.

2.1. Experimental setup

The experimental setup comprises of an integral absorption refrigeration/power generation system, pressurized hot water heat source simulator, cooling water unit and brine solution secondary refrigeration unit. The absorption refrigeration/power generation system includes both cooling and power generation subsystems. The plant operates in a single stage ammonia-water absorption cycle with parallel flow refrigerant supply arrangement for dual output. The condenser, Condensate Pre-Cooler (CPC) and an evaporator are the major components of the cooling subsystem. For power generation subsystem, an efficient expander with low power generation is not available in the market, hence an orifice plate suitable for a typical pressure ratio of 9.0 (pressure ratio = P_{16}/P_{17}) is used to simulate the expansion process in the experimental