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# Experimental studies on a combined refrigeration/power generation system activated by low-grade heat

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ABSTRACT

An experimental rig of a combined refrigeration/power generation system was built and investigated. This rig uses an ammonia–water binary working fluid, is driven by low-grade heat, and can function under the absorption refrigeration model and absorption power generation model. When the system was operated under the refrigeration model, the temperatures of the ethylene glycol solution that entered and exited the evaporator were −5.28 °C and −9.07 °C, respectively. The cooling output was 11.67 kW, and the corresponding coefficient of performance was 0.465. When the system was operated under the power generation model, the temperature and pressure of the turbine inlet were 94.66 °C and 8.55 bar, respectively. The turbine outlet pressure was 1.79 bar, the net power output was 1.02 kW (after 1 kW of power consumed by the solution pump was reduced), and the corresponding heat-to-power conversion efficiency was 3.98%. The combined system can achieve cooling and power generation and switch smoothly and easily between refrigeration and power mode. This study provides a feasible and flexible way to produce different products using low-grade heat.



## 1. Introduction

With the gradual over-exploitation of fossil fuel energy, increasing attention has been paid to the utilization of low-grade heat sources, such as industrial waste heat, solar thermal energy, geothermal energy, and low-temperature nuclear energy. These heat sources can be used for power generation by the organic Rankine cycle or Kalina cycle [1–6], as well as for refrigeration by the absorption cycle or ejection cycle [7–13]. These technologies can convert low-grade heat into useful power or cooling energy. To make better utilization of the low-grade heat, researches on the integration of power generation and refrigeration systems have been carried out since the 1990s [14]. Some system configurations have been proposed and investigated in the past decade. According to the types of working fluids, the current power and cooling combined systems can be divided into two classes: single-component and binary-component working fluid systems.

Most single-component working fluid systems are developed from the organic Rankine cycle and ejection cooling cycle. Oliveira et al. [15] built two prototype units of power/cooling cogeneration systems with n-pentane as the working fluid. In these systems, the vapor from the generator is separated into two streams, of which one enters the turbine to expand for power generation, and the other enters the ejector as the primary fluid. Cooling capacities of up to 5 kW and an electrical output of up to 1.5 kW are achieved. The test results show that the systems exhibit low turbo-generator and ejector efficiencies. Nord et al. [16] proposed a power and ejection cooling system intended for space applications. The system uses R134a as the working fluid, and the turbine exhaust vapor is used as the primary fluid of the ejector. This system was also theoretically and experimentally investigated by numerous other researchers [17–20]. Zheng et al. [17,18] analyzed cycle performance with R245fa as the working fluid and developed an experimental prototype with R600a as the working fluid to validate the feasibility of the combined cycle. This experimental system can operate in single power generation mode, single cooling generation mode, and power and cooling cogeneration mode. System performance under these three modes was also tested. Wang et al. [19,20] conducted the parametric and exergy analyses of a new cycle that integrates the organic Rankine cycle and ejector refrigeration cycle through the addition of an extraction turbine

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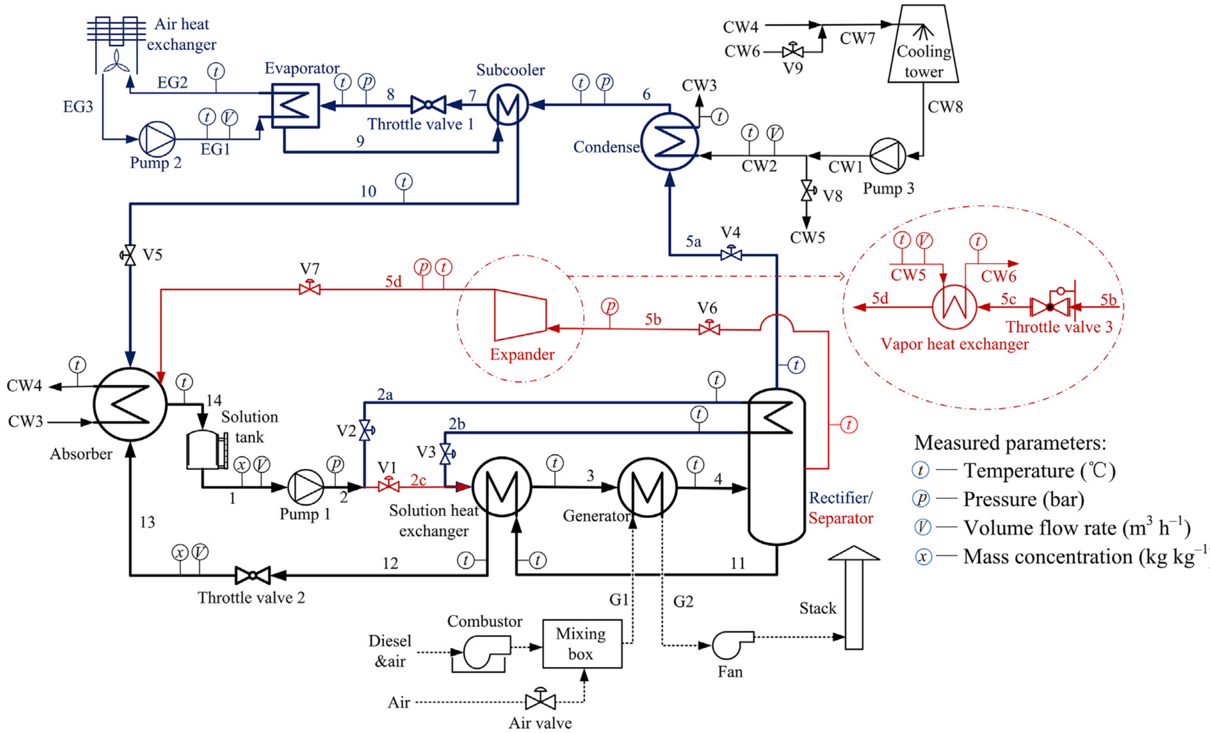


**Fig. 1.** Schematic configuration of the experimental rig.

between the heat recovery vapor generator and ejector. The largest exergy destruction occurs in the heat recovery vapor generator, followed by the ejector and the turbine. System performance can considerably be improved by reducing the exergy destruction of these components. Alexis [21] proposed a system that integrates the Rankine power cycle and ejection refrigeration cycle with water as the working fluid. A stream of steam extracted from the turbine is used as the heat source of the ejection refrigeration system. This system is used for heat sources higher than 360 °C.

Most binary-component working fluid systems are developed from the absorption power cycle or absorption refrigeration cycle with ammonia–water as the working fluid. Goswami et al. [14,22–27] proposed a power and cooling cogeneration cycle based on the ammonia absorption refrigeration system. To decrease the irreversibility in the throttle process, a turbine was used as a substitute for the condenser and throttle valve commonly used in refrigeration systems. Amano et al. [28,29] proposed a hybrid power and refrigeration cycle that integrates an ammonia–water power cycle and an absorption refrigeration cycle. The power cycle provides a strong solution to the rectifier of the refrigeration cycle, thereby improving the performance of the refrigeration cycle. Jawahar et al. [30] proposed a power and cooling cogeneration cycle by introducing an expander into the GAX cycle (Generator Absorber heat eXchanger cooling cycle). The expander is located between the HPGAX (high-pressure generator-absorber-exchanger) and absorber. The power and cooling generation processes are parallel, using the same vapor from the HPGAX. Although the high ammonia purity of vapor is significant in cooling generation, it is unnecessary in power generation. Zheng et al. [31], Zhang et al. [32–34], and Wang et al. [35,36] conducted a number of studies on ammonia–water cogeneration systems for heat source temperatures higher than 300 °C.

The user's energy demands of cooling energy and power may change frequently according to the variation of environmental temperature. For example, cooling energy is unnecessary in the winter, but power is needful. Combination of refrigeration/power generation processes is a feasible way to improve the utilization efficiency of waste heat all the year round. However, little literature were focused on such issue. This paper aims to (1) construct an experimental prototype of a combined refrigeration/power generation system, which uses an ammonia–water mixture as the binary working fluid and is activated by low-grade waste heat; (2) conduct experimental investigations of the system under refrigeration model and power generation model.

## 2. Experimental rig and operation models

Figs. 1 and 2 show the experimental rig of the combined refrigeration/power generation system. The system has a designed cooling capacity of 10 kW when operated under the refrigeration model. Its designed power capacity is 2 kW when operated under the power generation model. The rig comprises five parts: the main body of the combined refrigeration/power generation system, heat source unit, secondary refrigerant unit, cooling water unit, and data measurement and acquisition unit.

The main body of the experimental system includes an absorption refrigeration subsystem and an absorption power generation subsystem. The two subsystems share the same absorber, solution tank, solution pump (pump 1), solution heat exchanger, generator, rectifier, and throttle valve 2. The experimental rig can be operated in three models, including refrigeration model, power generation model and cooling/power cogeneration model. However, the cogeneration of cooling and power is not easy to implement. It involves the accurate distribution of ammonia-water vapor between the power and refrigeration subsystems properly. In this study only the refrigeration model and power generation model were investigated on the experimental rig. Since the cooling and power are different types of energy, two criteria were adopted to evaluate the performance of the system in different operation