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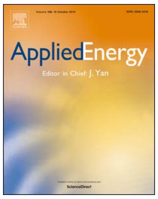

Assessment of a novel heat-driven cycle to produce shaft power and refrigeration

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HIGHLIGHTS

- A novel closed, low-grade heat-driven combined cooling and power system is presented.
- Evaporative cooling and refrigeration cycles are combined to enhance the cooling effect.
- Sensible and latent loads are decoupled by means of a liquid desiccant cycle.
- A parametric analysis is performed to study the system performance sensitivity.
- System is more energy-efficient than separate systems providing the same services.

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ABSTRACT

This paper proposes a novel combined cooling and power (CCHP) system based on a composition of a Rankine, gas refrigeration (reverse Brayton), liquid desiccant, ejector, and evaporative cooling cycles. The two proposed configurations, called the original cycle (OC) and the enhanced cycle (EC), utilize heat rejected by the Rankine cycle via its condenser in order to regenerate the liquid desiccant cycle. The desiccant cycle allows the cooling systems to decouple sensible and latent loads, and potentially reduce water consumption relative to pure evaporative cooling. Based on our thermodynamic calculations, the OC and EC are more feasible from an energy-saving viewpoint compared with separate systems that provide the same services for sensible heat ratios (SHR) less than 14% and 39%, respectively. At a fixed heat source input of about 2.4 $\mathrm{MW_{th}}$ at 210 °C, the OC is capable of generating 103 $\mathrm{kW_e}$ of electrical power, 181 $\mathrm{kW_{th}}$ of sensible cooling, 1631 $\mathrm{kW_{th}}$ of latent cooling capacity, and fresh water at 2.7 $\mathrm{m^3/h}$ capacity. At a SHR of 10%, the OC can achieve an exergy efficiency and primary energy saving ratio (*PESR*) of 24% and 28%, respectively. Similarly, and at the same thermal energy input, the EC can supply 354 $\mathrm{kW_e}$, 400 $\mathrm{kW_{th}}$, and 1199 $\mathrm{kW_{th}}$, and 1.8 $\mathrm{m^3/h}$ of electrical power, sensible cooling capacity, latent cooling capacity, and fresh water capacity, respectively, at a SHR of 25%. Furthermore, the EC is more efficient than both the OC and stand-alone conventional systems as it shows a higher exergy efficiency of 53% and *PESR* of 29%.

1. Introduction

Residential, commercial, and industrial buildings all over the world consume a significant fraction of energy in the form of electricity, cooling, and heating. On-site polygeneration and district systems remain atypical, perhaps due to historical, economic, or practical considerations and preferences of building managers. Consequently, fuel consumption escalates, which ultimately increases energy demand, fuel cost, air pollution, and carbon emissions [1]. Combined cooling, heating, and power (CCHP) systems have been identified as energy efficient and an effective strategy in the face of rising fuel costs with less negative environmental impact compared to conventional stand-alone systems [2–6].

Polygeneration has occupied the attention of many researchers and governments focusing on possible configurations of different technologies into one combined system. In fact, the European Union (EU) considers polygeneration as a strategic technology plan with the intention of reducing greenhouse gas emissions and the total cost of energy [5]. As one potential configuration, we present this work that proposes a novel combined cooling and power (CCP) system.

About 85% of electricity production worldwide is generated using a Rankine power cycle [7]. However, the thermal efficiency of the Rankine cycle becomes very low and unacceptable from an economic standpoint when the steam temperature is below 371 °C [7]. Hence, at

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Nomenclature

C_p	specific heat at constant pressure [kJ kg^{-1} K^{-1}]
COP	coefficient of performance
E	exergy flow rate [kW]
h	specific enthalpy [kJ kg^{-1}]
h_{fg}	enthalpy of vaporization [kJ kg^{-1}]
M	molar mass [kg mol^{-1}]
$\dot{m}$	mass flow rate [kg]
P	pressure [kPa]
$\dot{Q}$	heat flow rate [kW]
s	specific entropy [kJ kg^{-1} K^{-1})
T	temperature [C^{-1}]
W	power [kW]

Greek letters

α	moisture removal effectiveness [%]
η	efficiency [%]
χ	desiccant solution concentration [$kg_{LiCl}\ kg_{solution}^{-1}$]
ω	humidity ratio [$kg_{water}\ kg_{dry\ air}^{-1}$]

Abbreviations

CCP	combined cooling and power
CCHP	combined cooling, heating, and power
EC	enhanced cycle
EES	Engineering Equation Solver
F	fuel
LiCL	Lithium Chloride
OC	original cycle
PESR	primary energy saving ratio [%]

Subscripts

a	air
b	boiler
diff	diffuser
ele	electrical
entr	entrainment
hs	heat source
lat	latent
nozz	nozzle
o	dead state
s	solution or isentropic process
sen	sensible
th	thermal
w	water

these temperatures, the key to making a Rankine cycle financially feasible is to harness the reject heat for a secondary cycle or applications. Indeed, studies show that such Rankine combined systems can be made worthwhile, and so we choose a Rankine cycle as the basis for the power generating subsystem.

Cho et al. [8] presented a broad review of performance improvement methodology for combined cooling, heating, and power (CCHP) systems using energy and exergy analyses. They found that CCHP systems are usually analyzed and optimized in a wider context using various techniques and criteria such as primary energy savings, total cost rate, greenhouse gas emissions, and energetic and exergetic efficiencies. They concluded that major trends in recent literature regarding CCHP systems are utilizing alternative power sources, applying novel thermodynamic techniques, and improving system selection with new working schemes.

Demirkaya et al. [7] explored in a review paper the feasibility of improving the overall energy conversion efficiency of different combined power and refrigeration cycles, in which heat rejected by the power cycles can be recovered to provide refrigeration. They concluded that, in most applications, refrigeration is a more expensive product than power since it requires purchasing both power and equipment to produce. Consequently, the extra refrigeration reduced by the combined power and refrigeration cycles is more beneficial than standalone conventional power plants.

Liu et al. [9] surveyed state-of-the-art CCHP systems in which the survey was divided into three parts. In the first part, they presented the development and operation strategies of CCHP systems. Secondly, they introduced prime movers (steam turbines, reciprocating internal combustion (IC) engines, and fuel cells) that provide reject heat and thermally activated cooling technologies (absorption and adsorption chillers, and desiccant dehumidifiers) that can utilize that heat. In the third part, they presented the recent research progress on the management, control, optimization, and sizing of CCHP systems.

In a similar work, Al Moussawi et al. [10] classified different types of trigeneration systems based on the prime mover, size, and energy sequence usage. They showed in detail a methodology for selecting the optimum heat recovery equipment (cooling or heating) that is suitable and compatible with a given prime mover. Additionally, they considered various thermal energy storage systems and heat transfer fluids to be employed in order to reduce the trigeneration system's size and capital cost. In their detailed review, they found that CCHP systems often have positive performance impacts compared with separate systems that provide the same services.

Because cooling demand varies frequently, Han et al. [11] compared two operating strategies of small-scale gas turbines, namely turbine inlet temperature (TIT) and compressor inlet air throttling (IAT), to improve the overall performance of combined cooling and power (CCP) systems. A single-effect LiBr-H_2O absorption refrigeration system was considered to harness the high-temperature exhaust of the gas turbine in order to meet the cooling demand. The result showed that, when the gas turbine is operated at 50% rated power output, the IAT operating strategy can increase the overall system performance by 10% compared with the TIT strategy.

Rostamzadeh et al. [12] presented energy and exergy analyses of a combined cooling and power (CCP) cycle based on a combination of the organic Rankine cycle (ORC) and ejector refrigeration cycle (ERC). In three different configurations of the ORC, the ORC reject heat was harnessed to drive the ERC. Aiming to identify the best configuration based on energy and exergy performances, they selected (1) isobutene as the refrigerant for the ERC, (2) R123 as the ORC working fluid for the ORC, and (3) a configuration with recuperation and turbine bleeding.

Kang et al. [13] proposed a coupled combined heat and power and heat pump (CHP-HP) system of which a domestic hot water heater utilizes the waste heat from a ground source heat pump (GSHP) condenser and exhaust heat of a gas turbine engine. The result indicated that the proposed system can generate more power compared to the reference system. In a recent work by the same authors [14], the proposed system was optimized by a genetic algorithm based on several parameters such as primary energy saving ratio (PESR), CO_2 emission reduction ratio (CER), and annual total expense saving ratio (ATESR). The result showed that the comprehensive performance (CP) metric of the proposed system reached a maximum of 26.76% when the prime mover capacity was 1.136 MWe, where the corresponding PESR, CER, and ATESR were 23.24%, 35.13%, and 21.93%, respectively.

In this paper, we propose a novel cooling, dehumidification, and power cycle that is composed of four subsystems based on a gas