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Organic Rankine Cycle-assisted ground source heat pump combisystem for space heating in cold regions

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ABSTRACT

This paper presents an Organic Rankine Cycle (ORC)-assisted ground source heat pump combisystem for the cascaded utilization of low-grade energy and shallow geothermal energy in cold regions. The ORC unit was added to conventional ground source heat pumps to solve the cold accumulation problem, which can lead to performance degradation of heat pumps. The existing types and novel types of the combisystem were then modeled with the Transient System Simulation Program (TRNSYS). During the heating season, the ORC unit and heat pump unit were combined for space heating, and during the non-heating season, the ORC unit was connected to ground heat exchangers for seasonal storage. System performance was simulated over periods of one year and twenty years. The twenty-year simulation results showed that the proposed combisystem could maintain a higher annual average coefficient of performance (COP) of approximately 3.8 because of the steady soil temperature, whereas the annual average COP of the conventional ground source heat pump system decreased from 3.7 to 3.2. Additionally, the total power consumption per unit heating area of the heating system decreased from 2.2×10^3 kW·h/m^2 to 3.3×10^2 kW·h/m^2 when the ORC unit was added to the conventional ground source heat pump. This translates to electricity cost savings of ¥ 908/m^2 over twenty years. Moreover, in the combisystem, the ORC unit provides 55.6% of the total heating capacity; compensates for 78.5% of the heat pump unit's power consumption. And 94.1% of the thermal energy storage from the non-heating season can be used during the heating season by the heat pump unit.

1. Introduction

In recent decades, increasing energy demands in the face of escalating environmental deterioration have generated global concern, and many scholars and engineers have responded by proposing various applications based on relatively clean energy sources. In particular, ground source heat pumps (GSHPs), which use renewable geothermal energy, have received significant attention; however, because these systems suffer from thermal imbalances in cold regions, they are usually used in combination with other energy resources or technologies. To maximize the efficacy of GSHPs, Han et al. [1] presented a solar-assisted GSHP system with a latent heat energy storage tank, and their system exhibited an enhanced coefficient of performance (COP) and operating stability when using solar energy and soil alternately or together as the heat source of the heat pump. Emmi et al. [2] introduced the Transient System Simulation Program (TRNSYS) for studies of solar-assisted GSHPs in different cold climate regions, and they reported that solar thermal collectors could help to ensure that installed systems perform more efficiently. You et al. [3] proposed a new heat compensation unit that uses a thermosiphon to address the decreased heating performance of GSHPs caused by decreased soil temperatures, and to save energy by 15%. Wu et al. [4] introduced a GSHP hybrid that combined a ground source absorption heat pump with a ground source electrical heat pump (GSAHP-GSEHP), and their results demonstrated that the two technologies could complement each other because of their opposing thermal imbalance characteristics in cold regions.

A large number of studies have shown that such combisystems, which use an auxiliary heat source or heat storage methods, can help to maintain the thermal balance in soil and consequently avoid GSHP deterioration; however, few studies have investigated the use of a GSHP system coupled with an Organic Rankine Cycle (ORC) system. In the last few years, interest in ORC technology has increased considerably because of its potential application in distributed generation systems and because of its capacity to exploit low-grade temperature energy [5,6]. In a typical ORC system, a cooling tower or forced air cooling unit is usually used as the heat sink. When an ORC system is used as an

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Nomenclature

A	heat transfer area, m^2
c_p	specific heat capacity, kJ/(kg·K)
Cr	ratio of heat capacity
d_0	external diameter
f	friction factor
F	correction factor
g	gravitational acceleration
h	specific enthalpy, kJ/kg
$\dot{m}$	fluid flow rate, kg/s
p	pressure, kPa
P	power, kW
Pr	Prandtl number
Q	heat transfer quantity, kW
Re	Reynolds number
r_v	internal built-in volume ratio
T	temperature, K
DT_i	temperature differences, K, $i = 1,2$
U	coefficient of heat transfer, $W/(m^2{\cdot}K)$
v	specific volume, m^3/kg
w	specific work, kW/kg
W	work, kW

Greek symbols

α	convective heat transfer coefficient, $W/(m^2{\cdot}K)$
γ	latent heat of vaporization, kJ/kg
ε	efficiency of the heat exchanger
η	isentropic efficiency
λ	thermal conductivity
μ	dynamic viscosity, $(N{\cdot}s)/m^2$
ρ	density, kg/m^3

Acronyms

COP	coefficient of performance
GHE	ground heat exchanger
GSHP	ground source heat pump
NTU	number of transfer unit
ORC	Organic Rankine Cycle
Pi	pump, $i = 1,2$
Vi	valve, $i = 1,2,3,4,5,6$

Subscripts

b	bundle boiling
c	mixture boiling
co	condensation
crit	critical pressure
exp	expander
en	endothermic process
eV	evaporation
ex	exothermic process
in	inlet
h	high
l	low
L	liquid phase
mech	mechanical efficiency
mid	end of isentropic expansion process
min	minimum
max	maximum
natural	natural convection
normal	nominal condition
nb	nucleate pool boiling coefficient
net	net work output
out	outlet
pump	pump
sat	saturation condition
sink	heat sink
source	heat source
tp	two phase
w	wall
wf	working fluid
sf	second fluid
ise	isentropic expansion process
con	constant volume expansion process

auxiliary heat source for a conventional GSHP system, not only can the waste heat from the ORC be used, but also the performance of the GSHP system can be improved.

Dumont et al. [7,8] experimented with the feasibility of using the same scroll machine as both compressor and expander in a reversible heat pump/ORC unit (isentropic efficiencies of 63% and 77% were achieved in the expander mode and compressor mode, respectively), and they found acceptable performance of the heat pump/ORC unit coupled to a horizontal ground heat exchanger (GHE) and an innovative solar roof. Schimpf and Span [9] simulated and optimized a solar-assisted heat pump and ORC combisystem that provided both space heating and domestic hot water by using the scroll compressor of the heat pump as the expansion device; the ORC benefits added up to 20–140 kW·h, which reduced the net electricity demand of the system by 1–9%. In the above references, the solar energy enabled a scroll machine to serve both energy production and heat pump functions, and these systems achieved the successful combination of an ORC system and conventional GSHP system. Although these new systems were confirmed to be feasible, details on the performance metrics of different units (e.g., ground thermal balance, system efficiency, energy transfer processes, etc.) are still scarce.

In general, many scholars have highlighted the importance of equilibrium soil temperatures in GSHP systems, but the potential utilization of waste heat from ORC systems, which could be used for space heating, domestic hot water supplies, or as a heat complement for soil thermal imbalances caused by the continuous operation of GSHPs in cold regions, has largely been neglected. Thus, evidence of the advantages of an ORC-assisted GSHP combisystem in this regard is limited. To solve these problems, this study proposed a novel ORC-GSHP combisystem, which combined an irreversible ORC unit (the expansion device was not used for the compressor function of the heat pump) and a conventional GSHP system for space heating and power production. The combisystem was designed to retain the advantages of both ORC and GSHP technologies, i.e., so that it could achieve low-grade energy cascade utilization, provide longer heat conservation times, and increase the sustainable utilization of shallow geothermal energy sources. Simulations of the proposed ORC-GSHP combisystem system were conducted, and the simulation results were used to compare the performance of the proposed system with a conventional GSHP system. Detailed performance metrics of the ORC-GSHP combisystem units were also obtained and evaluated through the simulations.

2. System description

The main objective of this work was to analyze the combisystem performance of an ORC unit, heat pump unit, and GHEs in cold regions. The ORC unit was used to assist a conventional GSHP system, and the ORC unit and heat pump were combined for space heating during the

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