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Simulation of a solar assisted combined heat pump – Organic rankine cycle system ☆

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ABSTRACT

A novel solar thermal and ground source heat pump system that harnesses the excess heat of the collectors during summer by an Organic Rankine Cycle (ORC) is simulated. For the ORC the heat pump process is reversed. In this case the scroll compressor of the heat pump runs as a scroll expander and the working fluid is condensed in the ground heat exchanger. Compared to a conventional solar thermal system the only additional investments for the combined system are a pump, valves and upgraded controls. The goal of the study is to simulate and optimize such a system. A brief overview of the applied models and the evolutionary algorithm for the optimization is given. A system with 12 m^2 of flat plate collectors installed in a single family house is simulated for the locations Ankara, Denver and Bochum. The ORC benefits add up to 20–140 kW h/a, which reduces the net electricity demand of the system by 1–9%. Overall 180–520 € are saved over a period of 20 years, which can be enough to cover the additional investments.

1. Introduction

The coupling of a ground source heat pump and solar thermal collectors in a solar combisystem providing both space heating and domestic hot water is established technology [1]. As there is no demand for space heating during summer the area of the collector array becomes over dimensioned and the collectors come to a standstill whenever the maximum temperature of the storage is reached. This is potentially harmful since the stagnation can lead to an aging of the heat transfer medium and put a critical temperature strain on the components of the collector loop. The stagnation can however be circumvented by addition of an ORC which harnesses the excess heat. The domestic application of solar ORCs comprising either flat plate or evacuated tube collectors has been studied both experimentally [2–4] and theoretically [5–7]. In this study a scroll expander is used as expansion device. The application and performance of scroll machines as expanders has been experimentally examined [8–10] but their use is not yet a prevalent and market-proven technology. Dumont et al. demonstrated that it is possible to use the same scroll machine both as compressor and as expander in a reversible heat pump/ORC unit. They experimentally studied the heat pump/ORC unit [11] and modeled the system performance of the unit coupled to horizontal ground heat exchanger and an innovative solar roof [12]. While the modeling of the heat pump/ORC unit is very detailed, only simple models for the solar and ground loop are used.

The goal of this study is to simulate and optimize a solar combisystem providing both space heating and domestic hot water with an additional ORC using the scroll compressor of the heat pump as expansion device. The simulation results are used to evaluate the energetic and economic benefit of the ORC. Since a conventional solar combisystem, equipped with flat-plate or evacuated tube collectors and a ground source heat pump coupled to a vertical ground heat exchanger, is the basis for the addition of the ORC, no fundamentally novel system is designed from scratch. In fact, the aim of this study is to enhance the efficiency of market-proven technology with minimal additional investments.

2. System description

A schematic overview of the system is given in Fig. 1. The system mainly consists of flat plate collectors, a multi-node storage tank, a radiant floor heating system, a reversible heat pump/ORC unit, and a ground heat exchanger. The storage tank provides both domestic hot-water by a coiled tube heat exchanger and space

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Nomenclature

A	area, m^2
B	diffuse radiation, W/m^2
c	coefficient
c_p	isobaric heat capacity, J/m^2 K
D	direct beam radiation, W/m^2
E	electric energy, kW h
f	solar fraction
$F'(\tau\alpha)_{en}$	conversion factor
$\dot{H}$	enthalpy flow
i	node index
$K_{\theta b}(\theta)$	incidence angle modifier, direct beam
$K_{\theta d}$	incidence angle modifier, diffuse
L	Laplace transform
$\dot{m}$	mass flow, kg/s
$\dot{Q}$	heat flow, W
$\dot{q}$	specific heat flow, W/m
R_V	volumetric ratio
s	entropy
T	temperature, K
t	time, s
$\dot{V}$	volumetric flow rate, m^3/s

Greek symbols

β	collector tilt angle
η	efficiency
μ	average mean value
σ	standard deviation

Subscripts and superscripts

amb	ambient
avg	average
build	building
coll	collector
cond	condensation
DHW	domestic hot water
elec	electric heating at the outlet of the DHW coil
evap	evaporation
ex	external port
ext	extracted
i	inside
in	inlet
inj	injected
ins	insulation
is	isentropic
o	outside
pi	pinch-point
SH	space heating
sub	subcooling
sup	superheating
trans	transmission
vent	ventilation
λ	conductive term

heating. If the temperature at the outlet of the coiled tube is lower than the desired temperature additional electric heating is applied afterward. The ground-source heat pump can deliver heat for space heating purposes directly without passing the tank or charge the tank for the generation of domestic hot water. Solar energy is coupled into the tank by means of two coiled tube heat exchangers.

When a predefined temperature in the storage tank is reached the ORC is started and solar heat is used to evaporate the working fluid in the condenser of the conventional heat pump cycle. The fluid is afterward expanded in the scroll compressor/expander and condensed in the brine heat exchanger recharging the ground. The heat injection could lead to a reduced borehole depth or an increased COP at the beginning of the next heating period by counteracting the thermal degradation of the ground. These benefits are discussed in detail in another work by the authors [13].

A disadvantage of the addition of the ORC is that an active or passive cooling of the building with the heat pump is complicated as the soil temperature increases due to heat injection. In addition, the operation of the ORC might overlap with the cooling periods. In this study the installation of the solar heat pump–ORC combisystem in a single-family house with a floor space of 150 m^2 built according to the German low energy standard KfW 70 is examined for the locations Bochum, Ankara and Denver. Characteristic climate data for these locations are listed in Table 1.

Table 1 indicates that all locations have a heating dominated climate. At Bochum the cooling demand is negligible whereas at Ankara and Denver the energy demand for cooling approximately equals one sixth of the total energy demand of the system. For a first evaluation of the feasibility of the addition of an ORC to a combined solar system the cooling demand will be neglected for all locations. If it is desired to include the cooling demand in future works, a detailed thermal building model accounting for the impact of solar thermal gains is required. The model should allow for a prediction of the exact times when cooling demands occur and therefore for an assessment to what extent an interference with the operating times of the ORC will exist.

The heating power of the heat pump depends on the outdoor design temperature and lies between 3.78 kW and 6.49 kW. The borehole lengths of 59 m in Ankara, 66 m in Bochum and 90 m in Denver have been determined according to the German guideline VDI 4640 [14] without consideration of long-term effects. The absorber area of the collector array amounts to 12 m^2 of flat plate collectors. The volume of the storage tank is 0.9 m^3 and the daily demand for domestic hot water with a temperature of 318.15 K is 0.2 m^3. The domestic hot water profile was adopted from Jordan and Vajen [15], who developed a realistic profile for single-family houses on behalf of Task 26 of the International Energy Agency. The profile is based on a study considering German and Swiss consumption patterns. The flow rates for each minute of the year are determined by a stochastic algorithm, which results in daily water consumptions that spread around the mean daily average consumption of 0.2 m^3 with a Gauss-distribution.

Datasheets describing all relevant parameters of the collectors, the pipes of the solar loop, the storage tank, the ground heat exchanger, the heat pump and ORC as wells as the building are given in Appendix A. In order to protect the scroll machine and the lubricant the maximum temperature at the expander inlet is set to 373.15 K. From May to September the ORC is started if the temperature at the domestic hot water sensor exceeds 333.15 K. From October to April it is instead more beneficial to fully charge the tank up to the high-temperature cut-off of 368.15 K in order to bridge a gap between days with no or insufficient solar radiation.

3. Modeling and simulation of the combined system

In order to simulate the novel combined heat pump/ORC system appropriate models for the components of the system are required.