Applied Thermal Engineering 89 (2015) 833–842

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Thermodynamic analysis and performance assessment of an integrated heat pump system for district heating applications

Reza Soltani[*], Ibrahim Dincer, Marc A. Rosen

Faculty of Engineering and Applied Science, University of Ontario Institute of Technology (UOIT), 2000 Simcoe St. North, Oshawa, ON L1H 7K4, Canada

HIGHLIGHTS

- A new integrated heat pump system is developed for district heating applications.
- An analysis and assessment study is undertaken through exergy analysis methodology.
- A comparative efficiency evaluation is performed for practical applications.
- A parametric study is conducted to investigate how varying operating conditions and state properties affect energy and exergy efficiencies.

ARTICLE INFO

Article history:
Received 10 March 2015
Accepted 21 June 2015
Available online 27 June 2015

Keywords:
Buildings
Heat pump
Energy
Exergy
Efficiency
District heating

ABSTRACT

A Rankine cycle-driven heat pump system is modeled for district heating applications with superheated steam and hot water as products. Energy and exergy analyses are performed, followed by parametric studies to determine the effects of varying operating conditions and environmental parameters on the system performance. The district heating section is observed to be the most inefficient part of system, exhibiting a relative irreversibility of almost 65%, followed by the steam evaporator and the condenser, with relative irreversibilities of about 18% and 9%, respectively. The ambient temperature is observed to have a significant influence on the overall system exergy destruction. As the ambient temperature decreases, the system exergy efficiency increases. The electricity generated can increase the system exergy efficiency at the expense of a high refrigerant mass flow rate, mainly due to the fact that the available heat source is low quality waste heat. For instance, by adding 2 MW of excess electricity on top of the targeted 6 MW of product heat, the refrigerant mass flow rate increases from 12 kg/s (only heat) to 78 kg/s (heat and electricity), while the production of 8 MW of product heat (same total output, but in form of heat) requires a refrigerant mass flow rate of only 16 kg/s.

1. Introduction

District energy generally involves heating and/or cooling for more than one building, in which either hot/cold water or low pressure steam is used as the working fluid [1]. District heating/cooling is employed to provide heat/cold and distribute it through piping systems for users. The primary energy source for this purpose may be either fossil fuels or other energy sources, or combinations of systems with more than one energy input like natural gas, biomass fuels, municipal or industrial waste heat, depending on what is economically feasible [2]. Rezaie and Rosen [3] have comprehensive studied technology enhancements for district heating and cooling; they review various definitions, classifications and applications of district energy systems and conclude that environmental benefits are one of the main advantages of district energy systems over conventional distributed heating/cooling systems. They also discuss available technologies. In another study, Rezaie et al. [4] have examined environmental and economic aspects of district energy systems with a focus on assessing and comparing various energy resources; they propose an approach considering carbon dioxide emissions and economics which can be developed for energy suppliers.

Numerous studies have been carried out through on new types of district energy systems, especially integrated energy

---

[*] Corresponding author.

E-mail addresses: reza.soltani@uoit.ca (R. Soltani), ibrahim.dincer@uoit.ca (I. Dincer), marc.rosen@uoit.ca (M.A. Rosen).

http://dx.doi.org/10.1016/j.applthermaleng.2015.06.048
1359-4311/

systems. For instance Ref. [5] proposes an integration of a conventional geothermal district heating system with a biogas power generation cycle and report a 7.5% efficiency enhancement energy wise and a 13% increase in exergy efficiency for the integrated system compared to the geothermal system. Also, hybridization of a geothermal driven absorption cooling system with solar-assist systems has been studied in Ref. [6]; the authors conduct energy and exergy analyses of the new cycle, as well as sensitivity analyses of important system factors. Geothermal heating systems are discussed in Refs. [7,8], while an exergoeconomic study [7] is reported of a geothermal system for district heating purposes. It is observed that relating energy losses and capital costs provides clear insights into the thermoeconomics of energy systems.

Heat pumps are important energy systems that can be used to provide heat/cold directly for users or for specific components in an integrated system for various applications. These devices permit heat from low- and moderate-temperature sources to be used by raising its temperature. Ground, water (surface or well waters), air and waste heat can be used as energy sources for heat pumps. Most heat pumps operate on vapor compression cycles [9], although district heating applications can also be met using engine heat pumps [10], which also utilize vapor compression cycles, and absorption heat pumps [11].

Rankine cycle-driven heat pumps [9], which have an organic Rankine cycle (ORC) as the prime driver, can be applied in conjunction with industrial waste heat recovery systems, especially for low-temperature waste heat. Such systems have not, to the best of our knowledge, been reported in the literature as a component of district heating systems. A Rankine cycle-driven heat pump for generation of superheated steam is thus a focus of this article and is modeled for district heating purposes.

Water (liquid or vapor) is a common heating medium in district heating systems. The most appropriate medium depends on many factors, including the type of customer. If the heating if or a hospital or an industry, steam is often the choice as a distribution medium, whereas for systems serving large commercial buildings hot water is usually more attractive [12]. Since steam systems rely on latent rather than sensible heat, the mass flow rate of working fluid is almost 10 times lower for steam systems than liquid water systems. Note that for superheated steam systems even lower flow rates result.

The purpose of this study is to extend a Rankine cycle-driven integrated heat pump for district heating and to improve understanding of the performance of such systems through energy and exergy analyses. These can determine the most inefficient parts of systems quantitatively and clearly. A comprehensive parametric study is performed to determine the impact of variations in design parameters on the overall system behavior, performance and size. To determine the best designs and operating conditions, a trade-off between system size, efficiency and other parameters is needed; this is best accomplished with multi-objective optimization, but that is beyond the scope of this study.

2. System description

The proposed Rankine cycle-driven heat pump system considered here for district heating is modified from the system proposed in Ref. [13] for process heating, with the aim of providing domestic hot water and superheated steam for space heating. This system can provide superheated steam from low-temperature waste heat between 100 °C and 200 °C.

The system considered here has a Rankine cycle (specifically an ORC) as the primary mover. The ORC drives the compressor of the system for heat recovery from industrial waste heat. As can be seen in Fig. 1, waste heat from a nearby process or industry is split into two streams, one for the ORC evaporator and the other for the water evaporator (points 5 and 7). The water evaporator delivers saturated steam to the compressor (point 9), after which superheated steam at or below 180 °C (based on district heating temperature limitations [9]) is conveyed in a pipe to district heat users (point 10). The district heat users act in essence as a desuperheater and condenser for this system; condensed hot water at a saturated condition returns to the cycle (point 11). In order to extract heat from the low-temperature waste heat in the steam evaporator, the hot returning water must be expanded to lower pressure (point 12). In component j (Fig. 1), high-temperature return water is subcooled, becoming low-quality steam (point 14). The heat exchange between expanded water and hot return water decreases the amount of waste heat required for generating the same amount of saturated steam in the evaporator. In the evaporator, the steam generation process continues using the waste heat stream.

The ORC drives the steam cycle compressor. The refrigerant R113 is used. As a dry refrigerant, using R113 results in better performance than using wet and isentropic refrigerants for extracting energy from waste heat streams [14]. The compressed liquid refrigerant is evaporated in the ORC evaporator and saturated vapor enters the turbine (point 2). This turbine is designed to satisfy the work needs of the pump and the compressor, and excess electricity can also be generated in a generator connected to the turbine. The exiting working fluid is desuperheated in the domestic hot water generator (component e) and enters the condenser as a saturated vapor with low temperature. An air-cooled condenser removes the latent heat of the working fluid and releases it to the ambient environment, and the condensed refrigerant enters the pump (point 4). The desuperheater is taken to generate hot water at 60 °C. The mass flow of this hot water is a function of the overall system and is not the design point, so it varies with other design considerations. Thus, it might not be able to satisfy 100% of the needs of the district for hot water.

Other design and analysis assumptions are listed as follows:

- The compressor isentropic efficiency is taken to be 0.84 [15].
- The ORC turbine isentropic efficiency is taken to be 0.87 [15].
- The ORC pump isentropic efficiency is taken to be 0.88 [16].
- All processes are steady state and steady flow, potential and kinetic energy effects are negligible, and there are no chemical reactions.
- The waste heat is considered to be combustion products of natural gas and these are taken to have a low temperature. This waste stream is simplified as dry air, even though for this system it generally can be any kind of waste heat with temperatures between 100 °C and 200 °C.
- Air behaves as an ideal gas with constant specific heat.
- The waste heat stream enters both evaporators at 180 °C and the temperature drop through these heat exchangers is 80 °C. The waste stream therefore exits at 100 °C. Owing to presence of sulfur in natural gas, corrosive sulfuric acid can be formed when the products of combustion are sufficiently cooled [17].
- The ORC turbine provides primary mechanical energy for the compressor and the circulating pump without any loss. It also can be set to generate export electricity.
- The saturation temperature of the refrigerant in the ORC evaporator is considered to be 5 °C below the waste heat stream line mean temperature: