Applied Thermal Engineering 93 (2016) 155–165

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Design and feasibility study of combined heat and power systems integrated with heat pump

Heejin Cho *, Riasat Sarwar, Pedro J. Mago, Rogelio Luck

Department of Mechanical Engineering, Mississippi State University, MS 39762, USA

HIGHLIGHTS

- We present a design study of a CHP system integrated with a heat pump (CHP-HP).
- CHP-HP can be effectively used to reduce energy cost in cold climate zones.
- CHP-HP enhances heat pump operations in cold climate using recovered heat.
- Recovered heat is mainly used to supplement auxiliary heater energy in heat pumps.
- CHP-HP can provide an attractive payback period in cold climate zones.

ARTICLE INFO

Article history:
Received 16 April 2015
Accepted 10 September 2015
Available online 3 December 2015

Keywords:
CHP
Combined heat and power
Heat pump
Residential building

ABSTRACT

This paper presents the design and feasibility analysis of a combined heat and power system integrated with a residential heat pump (CHP-HP). The proposed CHP-HP model consists of a power generation unit (PGU) driving a heat pump and a heat recovery system for the PGU used to offset the heat pump heating load and the domestic water heating requirements. The proposed system is evaluated for a single family residential building in ten different U.S. locations representing different climate zones. The performance of the proposed system is compared to the performance of conventional systems in the same locations. Two parameters, the electrical power ratio ($PR_{elec.}$) and the electricity to fuel cost ratio (EFCR), are used to investigate the effect of the electricity consumed by the auxiliary heater and energy prices on the CHP-HP operation. Results show that the proposed CHP-HP system can be effective in cold climate zones by supplementing the auxiliary heater energy consumption with the recovered waste heat from the PGU.

1. Introduction

With the rise of fuel cost and global environmental concerns, the importance of research focused on waste heat recovery technologies has been recognized and emphasized over several decades. Combined heat and power (CHP) systems are one of the widely used technologies, in which waste heat from an on-site power generation unit (PGU) can be recovered and used to meet the facility's thermal demand. A small scale or micro CHP system is a promising technology to satisfy the electrical and heating demand of residential and small-scale commercial buildings. Many researchers have investigated energy savings, and environmental and economic benefits of micro CHP systems [1–8]. In addition, many studies focused on CHP system design optimization and control strategy development to maximize the potential benefits from micro CHP systems [9–16]. Prime movers, such as internal combustion (IC) engines, fuel cells, or Stirling engines, can be used in residential CHP applications and the waste heat from these prime movers could be recovered and used to provide space heating and hot water energy demand. Among different types of available technologies, IC engines are well suited for residential CHP applications because they represent mature, robust, and well-proven technology [17], and they have a wide range of sizing and fuel options [18].

Space cooling and heating can be achieved using different means, such as heat pumps, absorption chillers, boilers, heat exchangers, and thermal energy storage. Numerous technologies have been investigated for energy efficient space conditioning [19,20]. In residential applications, heat pumps are favored because they can meet both heating and cooling demands at a relatively lower installation cost. Thus, small-scale CHP systems integrated with heat pumps can be promising in residential applications as these systems can be implemented with existing systems to potentially obtain energy and cost savings.

Although heat pumps are a relatively mature technology, still there is a continuous effort to improve its performance. Chua et al. [21] reviewed recent advancement in heat pump systems and

* Corresponding author. Tel.: +1 662 325 1959; Fax: +1 662 325 7223.
E-mail address: cho@me.msstate.edu (H. Cho).

http://dx.doi.org/10.1016/j.applthermaleng.2015.09.027

broadly categorized works based on energy efficiency, hybrid systems, and novel applications. One of the main shortcomings of heat pumps is their poor heating performance in cold climate zones. Specifically, heating in very cold climate zones using a heat pump represents a great challenge where ambient temperature can reach as low as −30 °C [22]. Several studies have been carried out in order to overcome this issue associated with heat pumps. Bertsch and Groll [23] investigated the performance of a two-stage heat pump using R-410 refrigerant in a very cold climate zone and observed four problems associated with its operation in low ambient temperature: insufficient heat output due to lower mass flow rate of refrigerant at high compressor pressure ratio, introduction of auxiliary electric heater at lower temperature resulting to lower overall system efficiency, rapid decrease of the coefficient of performance (COP), and finally over-sizing of heat pump in cold regions, which leads to transient operation instead of steady state during moderate temperature. Guoyuan et al. [24] investigated heat pump technology that split the refrigerant flow after condensation to provide heating in low ambient temperature with acceptable COP values. Researchers have also investigated the performance and feasibility of ground source heat pump (GSHP) in cold regions and have found that GSHP can be effectively used in cold climate areas, however the higher initial cost is one of the major barriers for successful implementation [25–29]. The potential of using CHP systems in cold climate regions to meet building electric and heating energy consumption has also been investigated in different studies. A CHP system coupled with a heat pump (CHP-HP) was studied by Mancarella [30] where fuel energy savings and greenhouse gas emission reductions were evaluated for different operational schemes. Aussant et al. [31] studied the feasibility of IC engine based CHP systems in Canada. They determined that their proposed system was not favorable in terms of operation cost, however it had the potential of reducing the capital investment on electricity generation, transmission, and distribution infrastructure.

CHP-HP systems have the potential to reduce the heat pump energy consumption during the heating period in cold climate zones by taking advantage of the heat recovered from the PGU and using it as a source of auxiliary heat. This could improve the overall system performance along with savings in operational costs. This study presents the design and feasibility study of a CHP system coupled with a heat pump in a single family residential building. The proposed CHP-HP system is specifically designed and configured to enhance the heat pump operations in cold climate and to effectively retrofit heat pumps that are already installed in the existing homes in cold climate. The proposed system is operated following the electric load of the heat pump (FEL_{HP}) and the recovered heat from the PGU is used to provide the heating energy required by the HP auxiliary heater and a domestic hot water system. The potential of the proposed system to reduce the energy consumption is evaluated in ten different U.S. climate locations. In addition, both monthly and yearly cost savings potentials are estimated in the selected locations and a simple payback period is determined for each location.

2. Conventional heat pump and hot water system model

This section presents the mathematical description used to model a conventional heat pump and a domestic hot water system in a residential building. Fig. 1 demonstrates the basic operation of a conventional heat pump and a hot water system. The auxiliary heater is in operation only during the heating period when the heating energy supplied by heat pump is not sufficient to meet the space thermal load. In this study, it is assumed that the conventional heat pump with the auxiliary heater is powered by electricity from the grid. A natural gas fired boiler is used to meet the hot water demand of the building.

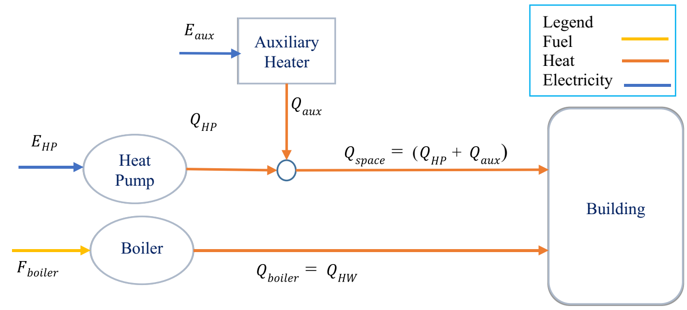

Fig. 1. Schematic diagram of conventional heat pump and hot water system.

2.1. Conventional heat pump operation

The required building thermal load (Q_{space}) is the total thermal energy supplied by the heat pump (Q_{HP}) plus the thermal energy supplied by the auxiliary heater (Q_{aux}) as expressed in Eq. (1):

$$Q_{space} = Q_{HP} + Q_{aux} \tag{1}$$

If the thermal energy supplied by the heat pump is not sufficient to meet the building thermal load, an auxiliary electric heater supplies the required additional heat (Q_{aux}) as shown in Eqs. (2) and (3).

$$\text{If } Q_{space} > Q_{HP}, \quad then \quad Q_{aux} = (Q_{space} - Q_{HP}) \tag{2}$$

$$\text{If } Q_{space} = Q_{HP}, \quad then \quad Q_{aux} = 0 \tag{3}$$

The total electric power required to operate the heat pump (E_{HP}) includes the power consumed by the heat pump compressor (W_c) and the supply air fan (W_{fan}):

$$E_{HP} = W_c + W_{fan} \tag{4}$$

The heat pump coefficient of performance (COP) is determined as the ratio of thermal energy supplied by the heat pump (Q_{HP}) to the power input (E_{HP}) as shown in Eq. (5).

$$COP = \frac{Q_{HP}}{E_{HP}} \tag{5}$$

If an auxiliary electric heater is used to supply the additional heat needed, the electric power required to operate the heater is given by Eq. (6).

$$E_{aux} = \frac{Q_{aux}}{\eta_{aux}} \tag{6}$$

where η_{aux} is the efficiency of the auxiliary heater.

The electrical power ratio ($PR_{elec.}$) is defined in this analysis as the ratio of the power consumed by the auxiliary heater to the power consumed by the heat pump:

$$PR_{elec} = \frac{E_{aux}}{E_{HP}} \tag{7}$$

2.2. Domestic hot water demand and boiler fuel consumption

The hot water demand (Q_{HW}) in the residential facility considered in this analysis arises from appliances like sinks, bath, shower, dish washer, and cloth washer. In the conventional systems, a natural gas fired boiler is used to satisfy the hot water demand (Q_{boiler}). The total energy supplied by the boiler can be expressed as