International Journal of Refrigeration 86 (2018) 196–202

Contents lists available at ScienceDirect

International Journal of Refrigeration

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

Experimental investigation of a gas engine-driven heat pump system for cooling and heating operation

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ARTICLE INFO

Article history:
Received 7 August 2017
Revised 27 October 2017
Accepted 30 October 2017

Keywords:
Gas engine driven heat pump
Cooling mode
Experimental performance
Domestic hot water
Heat recovery
Energy efficiency

ABSTRACT

The present work aimed at evaluating the performance of a gas engine driven heat pump (GEHP) for cooling and hot water supply. A test prototype working with R134a was built, and the cooling performance with hot water supply were experimented in a range of evaporator water inlet temperature from 12 °C to 22 °C, ambient air temperature from 24.2 °C to 37 °C, and gas engine speeds from 1400 rpm to 2000 rpm. The results show that the effects of evaporator water inlet temperature and gas engine speed on the system performance are more significant than those of ambient air temperature. Average hot water outlet temperatures between 40.7 °C and 61.7 °C are obtained over the considered range of the external operating parameters and this met the temperature demand of domestic water for shaving, residential dish washing, and laundry. Moreover, the primary energy ratio (PER_2) of GEHP system is between 1.14 and 1.45 with waste heat recovery.

1. Introduction

As requirements of indoor environment quality increases, the demand for energy has rapidly risen in recent decades in the world. In addition, more than 80% of the nation electricity generation is contributes to Coal-fired power in China. In order to maintain sustainable economic development and protect the environment, Chinese government pays more attention to energy utilization. Natural gas is considered as a clean energy source, and it will occupy an important part in the energy structure. Heat pumps are considered as the best optimized projects to attain this objective in a wide range of appropriate cooling and heating applications (El-Din, 1999; Shah et al., 2016). In recent years, the gas engine driven heat pump (GEHP) has attracted much attention for its environment-friendly and energy-saving advantages and efficiency (Kamal et al., 2016; Zhang et al., 2014a). Compared with electric driven heat pump, the GEHP, which uses a gas engine as the driving source and recover waste heat of the engine, can relieve the pressure of electricity in the whole year, especially in summer.

Besides, it will satisfy the demands of cooling in summer, heating in winter for buildings, and hot water at the same time (Gungor et al., 2011, 2015; Hepbasli et al., 2009; Liu et al., 2015; Wan et al., 2017; Zhang et al., 2014b). Regarding to the theoretical modeling, Zhang et al. established a steady state model to analyze performances of the GEHP (Zhang et al., 2005). Simulation results proved that the waste heat recovery could account for 30% of the total heating capacity in rated operating condition. Yang et al. set up a thermal model of a GEHP system to heat water, and the performance of the GEHP system was researched by both simulation and experiment (Yang et al., 2013). The experimental and numerical results demonstrated that the coefficient of performance (COP) and primary energy ratio with heat recovery (PER_2) of the air source GEHP system decreased as the gas engine speed and the hot water temperature increased, but increased as the water flow rate increased. Besides, Hao et al. simulated the performance of a new system named solar energy and gas engine driven heat pump for heating supply (Hao et al., 2015). The outcome of simulation confirmed that the evaporation temperature increase linearly with the inlet temperature of evaporator.

Regarding to the above mentioned experimental conditions, Elgendy studied the performance of a GEHP system using R410A as working medium for heating and cooling application. The experimental results proved that PER_2 would increase as engine speed and water inlet temperature decreased (Elgendy et al., 2010). In addition, all heat recovery, cooling capacity and gas heat consumption of system respectively increased by about 28%, 35%, and 44%, while PER_2 decreased by 15% as engine speed increased from

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https://doi.org/10.1016/j.ijrefrig.2017.10.034
0140-7007/

Nomenclature

COP	coefficient of performance without heat recovery (dimensionless)
PER_1	primary energy ratio without heat recovery (dimensionless)
PER_2	primary energy ratio with heat recovery (dimensionless)
LHV	lower Heating Value of natural gas (kJ m^{-3})
V	volume flow rate (m^3 s^{-1})
Q	loads (kW)
W	compressor power (kW)
T	temperature (°C)
c_p	specific heat of water (kJ (kg °C)$^{-1}$)
m	mass flow rate (kg s^{-1})
Superscripts	
HR	waste heat recovery
EC	energy consumption
TH	total capacity
eva	evaporator
in	inlet
out	outlet
cw	coolant water of gas engine
cyl	cylinder
exh	exhaust gas
gas	natural gas
w	water
wp	water pump
fa	fan
Greek letter	
ε	coefficient
Abbreviations	
HP	heat pump
GEHP	gas engine driven heat pump

1200 rpm to 1750 rpm. The performance of GEHP with evaporative condenser in cooling and energy saving were experimentally analyzed by Liu et al. (2016). The conclusions showed that cooling capacity and PER_2 increased as evaporative condenser air velocity increased, and decreased as ambient air temperature increased. Compared the GEHP with air-cooled condenser, the CO_2 emissions saving and energy saving of GHEP with evaporative condenser were 8.8% and 16.3%, respectively. A hybrid-power gas engine heat pump system was proposed by Ji et al. (2016). What's more, Dong et al. (2016) evaluated the heating performance of gas engine heat pump, the results showed that the effect of engine speed on the performance was more significant than the effects of ambient air temperature and condenser water inlet temperature (Dong et al., 2016). Elgendy and Schmidt researched the engine waste heat could be used either to evaporate the refrigerant in the refrigerant circuit or to heat the supply water in winter (Elgendy and Schmidt, 2014). The consequence of experiment demonstrated that maximum PER_2 had been estimated with a value of 1.83 when the recovered engine heat was used in hot water circuit. Moreover, system PER_2 decreases by 15.3% when the engine speed changes from 1300 to 1750 rpm (Elgendy et al., 2011).

As mentioned previously, many simulation and experiment researches had been made on the gas engine-driven heat pumps. There is a lack of experimental data for cooling and hot water with heat recovery on GEHPs working with R134a. This test focused on the performance characteristics of gas engine and GEHP system for cooling and hot water supply. In order to achieve this objective, the design specifications of a gas engine driven heat pump were determined, and the performance of a gas engine driven heat pump were tested by our group under a wide range of operation conditions. Meanwhile, some factors such as gas engine speed, evaporator water inlet temperature, and ambient air temperature were also emphatically introduced.

2. Description of system

A schematic diagram for the experimental equipment is illustrated in Fig. 1, which is composed of three circulations: refrigerant circulation, gas engine heat recovery circulation and evaporator water circulation. And the refrigerant R134a is used as working medium in refrigerant circulations while both air and water are used as secondary heat transfer fluids at the heat sink (condenser) and the evaporator water circulations. The experimental equipment assembled by our group is shown in Fig. 2. The parameters and measuring instruments of major components are exhibited in Tables 1 and 2. All the measured data of the experiment are monitored and record by software. The system includes two water pumps (rated power 1.5 kW) and two axial flow fans (rated power 1.0 kW). And the drive ratio between gas engine and compressor is 1:1, all circuit is thermally insulated to reduce heat loss.

2.1. Refrigerant circulation

The refrigerant circulation is a vapor compression heat pump (VCHP). It comprises an open type compressor, a four-way valve, an oil separator, a condenser, a liquid refrigerant reservoir, an evaporator, and an expansion valve. First of all, the refrigerant, starting as a low-temperature and low-pressure vapor, flows into the compressor, which is driven by a gas engine. Then, the high-temperature superheated refrigerant vapor leaves the compressor and flows through an oil separator and the four-way valve. After that, the ambient air exchanges heat with the refrigerant. In addition, the refrigerant is cooled and condensed to liquid in the condenser. After flowing out the condenser, the refrigerant flows through liquid refrigerant reservoir, electronic expansion valve and evaporator. In the evaporator, refrigerant absorbs heat from the water which flows from the cold water tank and vaporizes. As a result, superheated refrigerant flows into the gas–liquid separator and is sucked by the compressor for the next cycle.

2.2. Gas engine waste heat circulation

The gas engine waste heat circulation includes two secondary heat transfer fluid circuits; namely engine coolant circuit and domestic hot water circuit. In gas engine coolant circuit, ethylene glycol antifreeze is utilized as working mediums. The antifreeze flows between engine cylinder heat exchanger and engine cylinder block to maintain the proper temperature of engine. And the domestic hot water circuit, using water as working medium, is composed of an engine cylinder heat exchanger, an exhaust heat exchanger, a hot water tank, a water pump, a set of well-insulated pipes, and some detectors of temperature and pressure. First of all, when the temperature of engine antifreeze is low (lower than 80 °C), the domestic hot water circuit is turned off. As the engine antifreeze temperature increases (higher than 80 °C), the water which is discharged from hot water tank, is used to recover gas engine waste heat from the engine cylinder heat exchanger and the exhaust gas heat exchanger. Then the high temperature water flows into the hot water tank for next cycle. In addition, the water takes away the heat of antifreeze in engine cylinder heat exchanger to make sure the normal operation and efficiency of the engine.