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Optimum utilization of recovered heat of a gas engine heat pump used for water heating at low air temperature

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ABSTRACT

Engine waste heat recovery represents one of the main advantages of gas engine heat pump (GEHP) as compared to conventional heat pump. At lower air ambient temperature, engine waste heat can be used either to evaporate the refrigerant in the refrigerant circuit (mode-I) or to heat the supply water (mode-II). In this paper, the performance of a gas engine heat pump integrated with heat recovery subsystem for both modes are experimentally investigated. In order to achieve this objective, a test facility was developed and experiments were performed over a wide range of engine speed (1300:2200 rpm), ambient air temperature (−3.3:22 °C) and condenser water inlet temperature (27:48 °C). Performance characteristics of the gas engine heat pump were characterized by outlet water temperature, heating capacity and primary energy ratio. The results showed that the effect of condenser water inlet temperature on the system performance is more significant than the effects of ambient air temperature and engine speed. Maximum primary energy ratio has been estimated with a value of 1.83 when the recovered engine heat is transferred to water while it is limited to 1.25 as the recovered engine heat is transferred to refrigerant circuit.

1. Introduction

Gas engine heat pump (GEHP) consists basically of a gas engine and a vapor compression heat pump. Typically, the produced mechanical energy by the gas engine is used to drive the vapor compression heat pump. Moreover, the engine waste heat from both engine cylinder jacket and exhaust gas has been recovered to enhance the system heating capacity. The overall efficiency of GEHP system is significantly improved by 15–25% when waste heat from the engine coolant and exhaust gas is recovered as reported by Nowallowski and Busby [1]. Furthermore, the easy modulation of compressor speed by adjusting the gas supply represents another advantage of the GEHP over the conventional heat pump system.

Hepbasli et al. [2] reviewed GEHP systems for residential and industrial applications. They confirm that GEHP systems become more efficient when used both in water and space heating especially as appropriate control systems and equipments is adopted. Performance characteristics of the GEHP in heating mode were evaluated by many investigators using theoretical modeling [3–7] and experimental approach [8–12]. Regarding to the theoretical modeling of the GEHP, Zhang et al. [3] examined the effect of both ambient air temperature and engine speed on the heating performance of an air to water GEHP based on steady state model. Their results proved that the waste heat of the gas engine can take about 30% of the total heating capacity in rated operating condition. Furthermore, the engine speed had remarkable effects on both the engine and heat pump, but the ambient air temperature had a little influence on the engine performance. An intelligent control simulation model for the GEHP system in heating mode was established by Zhao et al. [4]. The model aimed at analyzing the dynamic characteristics of the GEHP system. The results showed that the model was very effective in evaluating the effects of the control system. Moreover, the steady state accuracy of the intelligent control scheme was higher than that of the fuzzy controller. Sanaye and Chahartaghi [5] predicted the performance of the GEHP under cooling and heating operating modes. Simulation results were compared with experimental data for various amounts of suction and discharge pressures, fuel consumption and coefficient of performance. The results reported that error percentages of suction and discharge pressures, fuel consumption and coefficient of performance were 3.4%, 4%, 6.7% and 7.2% for cooling mode, respectively, and 3.7%, 5.4%, 8.1% and 7.8% for heating mode, respectively.

Abbreviations: GEHPs, gas engine heat pumps; WP, water pump.

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Nomenclature

e	error
F	flow meter
h	specific enthalpy (kJ/kg)
LHV	lower heating value (kJ/m^3)
$\dot{M}$	mass flow rate (kg/s)
N	rotational speed (rpm)
PER	primary energy ratio
q	quantity
$\dot{Q}$	heat flow rate (kW)
V	valve
$\dot{V}$	volume flow rate (m^3/s)
ρ	density (kg/m^3)
ϑ	temperature (°C)

Subscripts

amb	ambient
av	average
con	condenser
eng	engine
HR	heat recovery
hw	hot water
ref	refrigerant
w	water
p	primary
s	secondary
sub	subcooler
tot	total

Superscripts

meas	measured

Regarding to the experimental studies of the GEHP, Boye et al. [8] evaluated the performance characteristics of the GEHP used for air conditioning. The effect of the outside air temperature on the primary energy ratio (PER) of the GEHP system was studied without engine heat recovery. As the outside air temperature changed from −2.5 °C to 12.5 °C, the PER increased from 0.8 to 1.4 during winter season. Lazzarin and Noro [9] evaluated the performance of 'S. Nicola' plant in Vicenza during three years of operation. Plant heating load are supplied using a GEHP and two condensing boilers. The economic analysis has been taken into account while the energy efficiencies were not taken into considerations. Recently, Wu et al. [10] investigated a novel GEHP which could independently provide heating, cooling and hot water for the buildings with its autonomous power supply system using mixture refrigerant R134a/R152a. Maximum COP and PER has been estimated with 8.88 and 1.69.

However, at low ambient air temperature the amount of heat transfer to a given evaporator is low and the recovered engine heat could be used to enhance the system performance by one of two options. It could be used to compensate the evaporator capacity or increase directly the supply water temperature and heating capacity. Thus, the present work is carried out with the aim of evaluating the performance characteristics of the GEHP used in water heating at low ambient air temperature. In order to achieve this aim, a test facility of the GEHP is constructed and equipped with the necessary instrumentation. This paper is organized as follows. The experimental apparatus to estimate the performance of characteristics of the GEHP is described in Section 2 while the data reduction manipulation is given in Section 3. This is followed by the experimental results and discussion in Section 4. Finally, error analysis and conclusions based on the present work results are reported in Sections 5 and 6, respectively.

2. Test facility

The experimental apparatus consists mainly of two units one outdoor and the other is indoor. The outdoor unit contains the engine, heat recovery heat exchangers and the evaporator while the indoor unit contains the condenser, measuring instruments and operational and safety control devices. The engine is reciprocating with displacement of 0.952 L and its rated power is 7.5 kW. Actually, the system is incorporated with heat recovery subsystems and its performance characteristics in cooling, heating and simultaneous cooling and heating modes are experimentally investigated in previous work [13–15]. However, at low ambient air temperature its operation mode should be optimized and this is major aim of the present work. In order to optimize the utilization of the recovered engine heat, two options of heat recovery utilization have been applied according to the ambient air temperature. The first choice is to use the recovered engine heat to evaporate the refrigerant in the primary cycle (mode-I) while the other option is to heat the supplied water (mode-II). Fig. 1 shows a schematic diagram of the experimental test rig in mode-I and mode-II.

Refrigerant R410A is used as a primary working fluid while both water and air are used as secondary heat transfer fluids at the heat source (evaporator) and the heat sink (condenser). In engine coolant circuit, both ethylene–water mixture (65% by volume) and propylene–water mixture (45% by volume) are used as cooling mediums. Pre-calibrated PT100 sensors are used to measure operating temperatures while digital pressure gauges are used to record the operating pressures at four locations in the refrigerant circuit of the heat pump. All the measuring instruments have been installed and connected to 64 channels in the data acquisition cards. The control system is established using PRIVA software which provides several possibilities for indoor unit selection and consequently system operation. All the measured data are recorded using DIAdem software and analyzed using an EES program [16] to evaluate the system performance.

2.1. Primary working fluid circuit

The primary working fluid circuit is a vapor compression heat pump. It comprises an open compressor, a condenser, a sub-cooler, an expansion device and an evaporator. The compressor is a scroll open type with swept volume of 104 cm^3/rev whereas the expansion device is an electronic expansion valve. The indoor and heat recovery heat exchangers are brazed plate heat exchanger with heat transfer area of 4.6 and 0.75 m^2 respectively. In order to reduce the heat transfer to and from the surroundings, the primary fluid pipeline circuit is thermally insulated.

As the refrigerant flows to the compressor (state point 1), the compressor raises the pressure of the refrigerant and delivers superheated vapor (state point 2) to the condenser (state point 3) through an oil separator and a reversing valve. The condensation heat of refrigerant vapor is released to the water flowing through the condenser. Thus, R410A vapor condenses (state point 4) and its mass flow rate is measured using flow-meter F_1 before it flows to the sub-cooler. The liquid refrigerant is sub-cooled (state point 6) by transfer its heat to the throttled refrigerant flowing through valve V_1. Then, the refrigerant is throttled using expansion devices V_2 and V_3 and evaporated inside both the evaporator and the heat recovery heat exchanger using the heat transferred from ambient air and the recovered heat from the engine, respectively (Fig. 1A).