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Research Paper

Performance analysis of diesel engine heat pump incorporated with heat recovery

N.N. Shah *, M.J. Huang, N.J. Hewitt

Centre for Sustainable Technologies, Ulster University, Newtownabbey, Co. Antrim BT37 0QB, UK

HIGHLIGHTS

- Diesel engine heat pump with heat recovery.
- Water-to-water source heat pump based on R134a.
- Possibility for different flow temperature for heat distribution system.
- Possible retrofit application in off-gas or weak electricity network area.
- Potential to diversify use of fossil fuel, primary energy and CO_2 emission savings.

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ABSTRACT

This paper presents experimental study of diesel engine heat pump (DEHP) system to find potential as retrofit technology in off-gas or weak electricity network area to replace existing gas/oil/electric heating system in domestic sector. Test set-up of diesel engine driven water-to-water heat pump system was built which included heat recovery arrangement from the engine coolant & exhaust gas. The system was designed to meet typical house heating demand in Northern Ireland. Performance of DEHP was evaluated to meet house-heating demand at different flow temperature (35, 45, 55 & 65 °C), a typical requirement of underfloor space heating, medium/high temperature radiators and domestic hot water. The performance was evaluated against four-evaporator water inlet temperature (0, 5, 10 & 15 °C) and at three different engine speed 1600, 2000 & 2400 rpm. Experiment results were analysed in terms of heating/cooling capacity, heat recovery, total heat output, primary energy ratio (PER), isentropic efficiency, etc. Test results showed that DEHP is able to meet house-heating demand with help of heat recovery with reduced system size. Heat recovery contributed in a range of 22–39% in total heat output. It is possible to achieve high flow temperature in a range of 74 °C with help of heat recovery. Overall system PER varied in a range of 0.93–1.33. Speed increment and flow temperature has significant impact on heat recovery, total heat output and PER. A case scenario with different flow temperature to match house-heating demand has been presented to show working potential with different heat distribution system. In addition, DEHP shows good potential to save primary energy consumption and CO_2 emissions, a helpful technology to achieve national emission reduction target.

1. Introduction

Future challenges of secure fuel supply, fuel prices, climate change and CO_2 emissions requires collective efforts towards use of more efficient technology along with increased share of renewable energy. In the UK, domestic sector is responsible for 64.2 $MtCO_2e$ emissions by consuming 38.2 Mtoe of energy in 2014 [1,2]. The domestic heat demand exists mainly due to space heating and hot water production mostly met by natural gas. Hence, there is a great potential to diversify use of fossil fuels, improve energy efficiency, reduce primary energy consumption and emissions in domestic sector.

Vapour compression heat pumps are such mature and efficient technology to provide space heating and hot water for various applications. Different application of heat pumps with other renewable technology and energy storage has shown promising results [3,4]. However, the most heat pumps are driven by electric motor that uses electricity called electric heat pumps (EHPs). If major deployments of EHPs (10–20% penetration) were carried

* Corresponding author.
E-mail address: n.shah@ulster.ac.uk (N.N. Shah).

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out then it would require attention to existing electricity distribution network [5,6]. In addition, poor insulated UK housing stock and single-phase electricity supply adds additional cost to components/sizing of EHPs [7]. To take advantage of oil/gas boiler replacement in existing housing stocks, EHPs faces several challenges such as oversized radiator and flow temperature requirement (above 60 °C). as a retrofit application [8–10].

Engine driven heat pumps (ENHPs) is such potential technology to overcome issues of EHPs due to waste heat recovery and speed modulation [11]. Extensive literature search on web of science gave output of around 110 articles from year 1980–2016 on engine heat pump. A literature search shows four focus area of ENHP articles: (1) Application/experimental work: commercial, industrial, transport (e.g. green house heating, drying, etc.); (2) Theoretical studies: reviews, energy/exergy analysis, etc.; (3) Novel application: hybrid system, tri-generation, use with renewable technology or technology combination; (4) Simulation/modelling, controller, control strategy for optimum operation, cost and emission savings.

For example, Hepbasli et al. [12] have presented a review on gas engine heat pump (GEHP) application in residential and industrial sector showing benefits of GEHP over conventional system. In addition, there are opportunities to use various fuel based on renewable sources such as biogas and biofuels with use of waste heat from the engine [13,14]. Additionally, many authors presented advantages of ENHPs over EHPs mainly due to waste heat recovery and engine speed modulation for various applications [15–20]. There are various literatures available on ENHPs application for commercial and industrial applications [21]. Most literature focuses on system parameters influence mainly on primary energy ratio in heating, cooling and hot water application [22–25]. Few other investigations focused on GEHP's simulation and/or experiment in heating or hot water application showing heat recovery contribution (30%) in total heat output [26] and 37% emission reduction compared to gas boiler [27]. Mostly, all investigations focused on gas engine and air-to-water or air-to-air system for heating/cooling/hot water application. There is very little investigation on ENHPs domestic application with water-to-water heat pump and/or use of diesel engine. Lian et al. showed benefits water-to-water based engine heat pump with reduced payback period [28] but still no application for domestic sector. Additionally, there is not any small engine heat pump system (e.g. 10 kW) commercially available in Europe as the main market players of engine heat pump system are from ASIA (mainly Japan) with capacity from 14 to 175 kW [29].

Hence, this work presents novel domestic application with <10 kW size heat pump (water-to-water) driven by diesel engine. The performance analysis of system aims to address retrofit challenges in domestic sector. It provides information for various flow temperature required for conventional radiator (high temperature), medium temperature and underfloor heating system. The study on high temperature application (65 °C flow temperature) for retrofit application has been shown by author's previous work [30]. This paper presents detailed work related to flow temperature, engine speeds and their comparative analysis at respective evaporation temperature conditions.

2. DEHP test set-up development and test procedures

2.1. Design criteria

Diesel engine driven heat pump (DEHP) system component size, selection and design mainly depends on average/peak heating demand. It is also important to estimate heat recovery percentage that helps to reduce heat pump system components size and hence, the cost. The domestic heat demand mainly occurs due to space heating and hot water that varies with dwelling types, occupancy, season, etc. For the test set-up development, heat demand (Fig. 1) of a typical three bedroom 105 m^2 test-houses in Carrickfergus, Northern Ireland was considered [31]. The house heating demand varies between 4.2 kW and 8.5 kW at air temperature of −10 °C to 20 °C. DEHP system was designed to meet 7.1 kW heat demand at 0 °C ambient temperature to provide flow temperature in a range 55 °C to 65 °C (above 60 °C to avoid legionella) with the help of heat recovery. Based on the heating demand other system components were designed, selected and assembled together.

2.2. System components

DEHP system has two major components; the diesel engine and open reciprocating compressor. Both components were selected/checked simultaneously to match their torque and speed requirement. Based on initial analysis, commercially available diesel engine Kubota EB300-E [32] was selected to drive open reciprocating compressor with help of flexible coupling. R134a was used as a refrigerant due to higher temperature limit and lower torque requirement for the compressor/engine. The engine gives 4.14 kW continuous power at maximum speed of 3000 rpm whereas compressor has a speed range of 750–3000 rpm.

The engine came with thermosiphon water-cooled system accompanied by radiator fan. Therefore, the engine was modified to accommodate coolant heat recovery. A low temperature thermostatic valve, pump, and plate heat exchanger replaced fan & radiators arrangements. This enabled coolant heat recovery when temperature of coolant rises above 60 °C.

Heat pump circuit consisted a brazed plate heat exchanger as condenser/evaporator, thermostatic expansion valve (TEX), filter/-drier and liquid receiver. TEX converts high pressure liquid into low-pressure vapour-liquid mixture at outlet whereas liquid receiver helps to store and provide refrigerant during load change and pump down conditions. Heat recovery circuit has plate heat recovery for coolant heat recovery, exhaust gas heat recovery heat exchanger (shell-tube type), pumps and three-way valve. Fig. 2 presents schematics of DEHP set-up where it shows the arrangement of various components and instrumentations for DEHP system. Primary circuit represents refrigeration cycle and heat pump related components/instruments. In secondary circuit, water temperature at inlet of evaporator and outlet of condenser maintained constant with the help of PID controller. This PID controller oper-

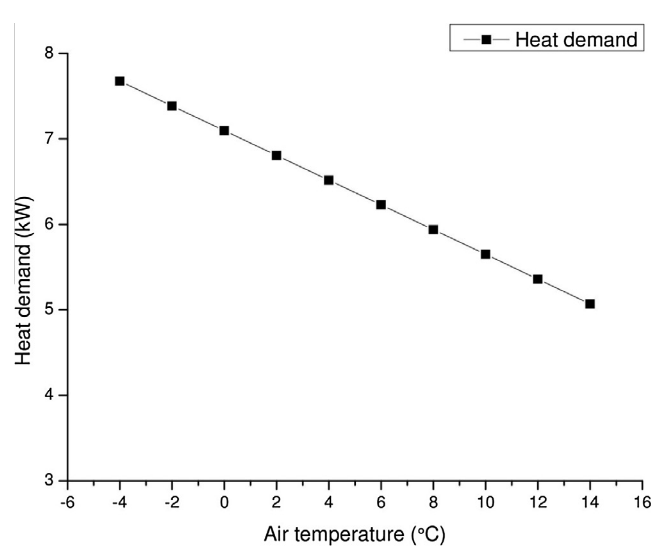

Fig. 1. Typical house heating demand (incl. DHW demand) [31].