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Research Paper

# Experimental study of a diesel engine heat pump in heating mode for domestic retrofit application

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

*Centre for Sustainable Technologies, University of Ulster, Newtownabbey, County Antrim BT37 0QB, UK*

## HIGHLIGHTS

- Diesel engine heat pump test set-up was developed <10 kW heating capacity.
- R134a based water-to-water source heat pump was designed considering waste heat recovery.
- Influence of engine speed and evaporation temperature was evaluated.
- DEHP optimisation to match heating demand and comparison with conventional heating system.
- DEHP application potential by reducing primary energy consumption and $CO_2$ emission.

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## ABSTRACT

An engine driven heat pump (ENHP) can provide better efficiency compared to electric heat pump (EHP) considering primary energy consumption. The present work aimed to find suitability of diesel engine heat pump as a domestic retrofit application for off or weak gas/electricity network area. For this work, water-to-water heat pump test facility was developed which consisted heat pump, diesel engine and heat recovery arrangements. The system performance was evaluated for 65 °C flow temperature from condenser at three different engine speeds (1600, 2000 and 2400 rpm) and four evaporator water inlet temperatures (0, 5, 10 and 15 °C). The system performance was evaluated by heating capacity, isentropic efficiency, coolant heat recovery, exhaust gas heat recovery and PER. Performance analyses showed that heat recovery contributed 33% in total heat output where heat recovery was in a range of 1.7 to 3.7 kW. PER varied in the range of 0.9 to 1.4 showing good potential in terms of 35–65% primary energy saving and 23–42% $CO_2$ emissions reduction compared to conventional systems. DEHP optimisation showed ability to meet water flow temperature requirement of 65–73 °C by speed variations and heat recovery providing good potential to meet heating demand during winter and summer periods in retrofit settings.


## 1. Introduction

To address global issues of greenhouse gas (GHG) emission, climate change, depleting fossil fuel resource and security of supply, sustainable growth which includes increased share of renewable energy and efficient technology is essential. Heat pump based on vapour compression cycle is such efficient and mature technology which can provide heating/cooling/DHW in domestic, commercial and industrial sectors. Mostly, heat pumps driven by electric motors are known as electric heat pump (EHP). However, heat pump can be driven by gas/diesel/Stirling engine too. The concept of engine driven heat pump (ENHP) was developed during 1970s to balance gas and electricity demand during winter and summer. ENHP concept was presented by Colosimo where he showed benefits of waste heat utilisation from the engine to improve overall efficiency compared to EHPs [1]. From the year 1980 to 2015, data gathered from the ISI Web of Knowledge, it was found that almost 115 articles have been published in scientific Journals and/or conferences related to engine heat pump systems. The published articles mainly consisted of simulation, experimental analysis, controller side, thermodynamic analysis and novel application with other technologies etc. From the concept to product development, various investigations and applications have been presented through literatures.

For example, Hepbasli et al. [2] have presented a review on gas engine heat pump application in residential and industrial sectors. Advantages of ENHPs over EHPs due to heat recovery and engine

*Abbreviations:* ENHP, Engine driven heat pump; DEHP, Diesel engine driven heat pump; GHP/GEHP, Gas engine driven heat pump; EHP, Electric heat pump; PER, Primary energy ratio; COP, Coefficient of performance; H.H.V., Higher heating value of fuel (MJ/kg); HEX, Heat exchanger; TEX, Thermostatic expansion valve; DE, Diesel engine; H.R., Heat recovery; CHR, Coolant heat recovery; EGHR, Exhaust gas heat recovery.

* Corresponding author. Tel.: +44 0 2890366122; fax: +44 0 2890368239.
*E-mail address:* n.shah@ulster.ac.uk (N.N. Shah).

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speed modulation have been presented by various authors [3–8]. Gas engine heat pump performance in heating, cooling and for hot water production has been discussed by Elgendy's research group showing influence of condenser/evaporator inlet/outlet temperature and engine speed variation on heating/cooling capacity and primary energy ratio [9–11]. In addition, few other investigations are on simulation/thermodynamic analysis and experimental work together. For example, Yang et al. presented simulation and experimental results of GEHP for water heating application which showed that GEHP operation reduced running cost and emission in a range of 30–37% compared to gas boiler [12]. Similarly, Zhang et al. presented a steady stage model based on exprimental and manufacturer data for air-to-water heat pump in heating mode showing 30% waste heat recovery contribution in total heat ouptut at rated conditions [13].

Hence, from literature it was found that most of the studies have been carried out on gas engine, air-to-water heat pump and commercial/industrial applications. There is not enough investigation on diesel engine based water-to-water heat pump or ENHPs for retrofit application in the domestic sector. In addition, Lian et al. showed that there is no currtent water-to-water based engine heat pump readily available in the makret and they presented benefits of gas engine heat pump with water loop system with reduced payback period [14]. Additionally, the main market players of engine heat pump system are from Asia (mainly Japan) with capacity from 14 to 175 kW [15]. Hence, there is no current manufacturer from Europe of small scale engine heat pump systems which can provide heating capacity in a range of 10 kW, which is the typical house heating demand of UK dwellings.

In addition, despite having higher efficiency, heat pumps are not so common in the UK due to gas and electricity price and other factors such as poor insulation, housing stock, weather etc. [16]. Moreover, in the UK domestic sector, gas and oil boilers are the most common technologies providing space heating and domestic hot water (DHW) through a central heating system, which contributes almost 78% in domestic energy consumption and 40% in domestic heat related emission [17,18]. A retrofit technology (e.g. heat pump) needs to meet certain criteria to replace existing heating systems as existing wet radiator systems require higher flow temperature to meet their heat demand [19]. In addition, poorly insulated housing stock in the UK influences sizing of heat pump, and EHPs' vast deployment (10–20% penetration) would require attention to existing electricity distribution network [20,21]. EHP requires high start-up current whereas most of the houses in the UK have single-phase supply that may add further cost to the system [16]. In the domestic sector, along with electricity consumption, natural gas consumption is the most dominant fuel to provide space heating and hot water. Natural gas supply and demand side has also issues due to depleting resources. Natural gas production is decreasing in the UK, where UK has become a net importer of natural gas since 2005 instead of a net exporter [22]. In addition, there is a limitation of gas and electricity network, and further extension or new production requires huge investment.

Hence, to address above mentioned issues, experimental study on diesel engine heat pump (DEHP) based on water-to-water source has been presented in this paper. The novelty of this work presents in terms of capacity (small scale; less than 10 kW) water-to-water source heat pump, domestic retrofit application and potential for off gas grid area with possible use of renewable sources. The selection of diesel engine proves beneficial due to higher compression ratio and higher density of diesel fuel compared to gas/petrol engine. In addition, there is a possibility of using vegetable oil, biodiesel or waste oil with diesel engine, which could make it a technology based on renewable sources. Generally, vegetable oil or biodiesel has higher viscosity than diesel fuel, which affects engine performance and components [23]. However, pre-heating of such oil helps to reduce viscosity and makes it possible to use such vegetable oil, biodiesel or waste oil in diesel engine directly. Pradhan et al. used waste heat from exhaust gas to preheat *Jatropha curcas* oil to improve fuel properties which helped to reduce emissions [24]. Similarly, many other investigators used waste heat from exhaust gas and/or jacket water to improve fuel properties of various fuels for diesel engine [25–28]. Hence, it shows good operational potential in remote area or off-gas grid network area to use vegetable oil or waste oil with possible use of waste heat recovery when not used for heating/DHW.

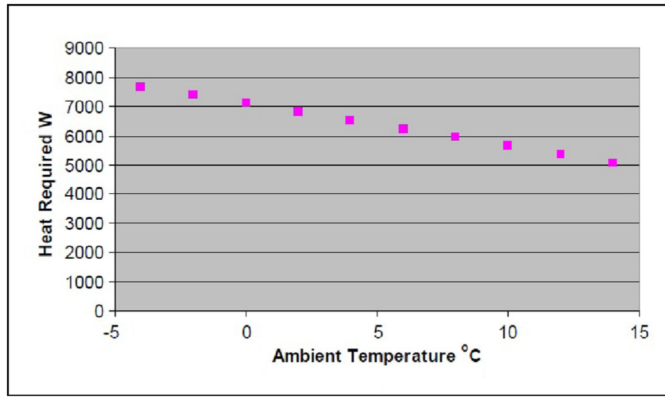


**Fig. 1.** Typical house heating demand (incl. DHW demand) [29].

The diesel engine was modified and fitted with low temperature thermostat along with other heat recovery arrangements to run with water-to-water source heat pump. This paper presents detailed performance analysis of DEHP showing influence of engine speed and evaporation temperature on heating/cooling capacity, primary energy ratio, isentropic efficiency, coolant heat recovery and exhaust heat recovery. In addition, DEHP performance was compared with conventional technology to show potential in terms of primary energy and $CO_2$ emission savings.

## 2. Experimental set-up

### 2.1. Design consideration

Diesel engine driven heat pump (DEHP) design and component selection criteria are dependent on many parameters. However, the most important parameter is heating load/demand along with other parameters such as function, thermal comfort, temperature requirement, heat loss, size, mobility, ergonomics, maintenance, monitoring, control, total cost etc. Heat demand in the domestic sector is mainly for space heating and for hot water. Heat demand varies based on type of dwellings, sizes, occupants, etc. For the development of laboratory test set-up, heating load and DHW demand were taken into consideration. Huang et al. presented the heating demand for typical three bedroom 105 $m^2$ test-houses in Carrickfergus, Northern Ireland [29]. Fig. 1 shows the house heat demand against ambient temperature curve. The heating demand (including hot water) varied from 8.5 kW at −10 °C to 4.2 kW at 20 °C. The demand side management and capacity control both play vital roles at different ambient conditions. Therefore, considering these points, the DEHP system was designed to meet house heat demand of 7.1 kW at 0 °C ambient temperature. This can supply hot water in a temperature range of 55 °C to 65 °C (more suitably, above 60 °C to avoid legionella formation) in existing wet radiator hydronic system as a retrofit technology. Based on heating demand, all components of DEHP system such as the engine, compressor, heat exchanger etc. have been selected. Water-to-water heat pump was designed to see their feasibility with context to ground source heat pump as well.