Energy Conversion and Management 75 (2013) 141–151

Contents lists available at SciVerse ScienceDirect

Energy Conversion and Management

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

Waste heat recovery from the exhaust of a diesel generator using Rankine Cycle

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ARTICLE INFO

Article history:
Received 10 March 2013
Accepted 7 June 2013

Keywords:
Waste heat recovery
Rankine Cycle
Diesel generation
Heat exchanger

ABSTRACT

Exhaust heat from diesel engines can be an important heat source to provide additional power using a separate Rankine Cycle (RC). In this research, experiments were conducted to measure the available exhaust heat from a 40 kW diesel generator using two 'off-the-shelf' heat exchangers. The effectiveness of the heat exchangers using water as the working fluid was found to be 0.44 which seems to be lower than a standard one. This lower performance of the existing heat exchangers indicates the necessity of optimization of the design of the heat exchangers for this particular application. With the available experimental data, computer simulations were carried out to optimize the design of the heat exchangers. Two heat exchangers were used to generate super-heated steam to expand in the turbine using two orientations: series and parallel. The optimized heat exchangers were then used to estimate additional power considering actual turbine isentropic efficiency. The proposed heat exchanger was able to produce 11% additional power using water as the working fluid at a pressure of 15 bar at rated engine load. This additional power resulted into 12% improvement in brake-specific fuel consumption (bsfc). The effects of the working fluid pressure were also investigated to maximize the additional power production. The pressure was limited to 15 bar which was constrained by the exhaust gas temperature. However, higher pressure is possible for higher exhaust gas temperatures from higher capacity engines. This would yield more additional power with further improvements in bsfc. At 40% part load, the additional power developed was 3.4% which resulted in 3.3% reduction in bsfc.

1. Introduction

Compression Ignition engines, also known as diesel engines, are a major type of Internal Combustion (IC) engines. These diesel engines have a wide field of applications and frequently used because of their higher thermal efficiency. Trucks, buses and earth moving machineries use high speed diesel engines and output of these engines can be as high as 740 kW. Diesel engines are also used in small power generating units or as standby units for medium capacity power generations. Power generation using diesel engines became popular in the last four decades. The main applications of these diesel generators are auxiliary or backup power plants in hospitals, airports, hotels and industries those need to ensure reliable power supply at all times. Engine based power production today represents some 10–15% of the total installed capacity in the world [1].

A brief analysis of heat balance of a diesel engine indicates that the input fuel energy is divided into three major parts: energy that converts to useful work, energy that loses through the exhaust gas and energy that dissipates to the coolant. In general, diesel engines have a thermal efficiency of about 35% and thus the rest of the input energy is wasted. A considerable amount of energy is expelled to the ambient environment with the exhaust gas despite recent improvement of diesel engine efficiency. In a water-cooled engine about 25% and 40% [2] of the input energy are wasted into the coolant and exhaust gases, respectively. Johnson [3] found that the total waste heat dissipated can vary from 20 kW to as much as 40 kW from a typical 3.0 l engine having a maximum output power of 115 kW. It is also suggested that for a typical and representative driving cycle, the average heating power available from the waste heat is about 23 kW.

Due to strict regulations on polluting emissions and energy savings, diesel engine is being an object of intensifying research to improve its thermal efficiency and to make it more environmentally friendly. The thermal efficiency of a diesel engine can be increased by improving the thermodynamic efficiency of the operating cycle and/or reducing the mechanical losses [4,5]. These techniques result in a reduction in the brake-specific fuel consumption (bsfc), but it appears that the potential for further improvement is limited [6]. An attractive alternative option for further improvement of bsfc and reductions of specific polluting emissions can be waste heat recovery (WHR). There are several WHR technologies available and the dominating ones are:

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http://dx.doi.org/10.1016/j.enconman.2013.06.009

Nomenclature

ε	heat exchanger effectiveness
$\dot{m}$	mass flow rate, kg/s
P	power, kW
η_{ts}	turbine isentropic efficiency
h	specific enthalpy, kJ/kg
e	specific exergy, kJ/kg
u	specific internal energy at exhaust temperature, kJ/kg
u_0	specific internal energy at dead state temperature, kJ/kg
p_0	dead state pressure, bar
p	exhaust pressure at the end of combustion
v	specific volume at exhaust temperature, m^3/kg
v_0	specific volume at dead state temperature, m^3/kg
$\overline{R}$	universal gas constant, kJ/mol K
M	molecular weight of exhaust gas, kg/mol
$s^0(T)$	absolute entropy of ideal gas at T temperature, kJ/kg K
$s^0(T_0)$	absolute entropy of ideal gas at T_0 temperature, kJ/kg K
$\dot{E}_d$	exergy destruction rate, kW
c_p	specific heat at constant pressure, kJ/kg K
u, v, w	velocity components in x, y and z direction, respectively, m/s
T	temperature, °C
λ	conductivity coefficient at bulk temperature of fluid, W/m K
ρ	cold fluid density, kg/m^3
τ	shear stress, N/m^2

Subscripts

c	cold fluid
h	hot fluid
1	hot fluid inlet
2	hot fluid outlet
3	cold fluid inlet
4	cold fluid outlet

- *Mechanical turbo-compounding*: an additional power turbine is utilized in the downstream of the turbocharger and it is mechanically coupled to the engine crank shaft by a gear train to increase the engine power output [4,6]. By using mechanical turbocompounding, Caterpillar [7] reported an average bsfc reduction of 4.7% for a 50,000 mile extra urban driving test in the USA. They used an axial-flow power turbine on a 14.6 l diesel engine. Scania [7] also applied the same technology in a 11 l, six cylinder turbo charged diesel engine and found 5% improvement in bsfc at full load. Hountalas et al. [6] performed engine simulation to study the performance of mechanical turbocompounding and reported 4.8% improvement in bsfc at full engine load.
- *Electrical turbo-compounding*: a system that converts waste exhaust energy to shaft work using a turbine which is coupled to an electric generator [8,9]. The electricity produced from the generator is used to run a motor fitted to the engine crank shaft. Caterpillar has considered this concept in their research programme [9,10] providing an indication of 5% reduction in bsfc whereas Hountalas et al. [6] found 3% bsfc reduction using the same principle.
- *Thermoelectric system*: this technology directly converts a portion of the exhaust gas heat to electrical power through thermoelectric phenomenon without the utilization of mechanical components [6,11]. Due to the low conversion efficiency of the system ranging from 6% to 8% [12], the thermoelectric system can improve the bsfc by less than 1%. Since the cost of the thermoelectric semiconductor materials is relatively high, the thermoelectric system is not yet suitable for practical applications.
- *Turbocharger*: a turbocharger is an exhaust gas driven supercharger. In this system, the available energy in the engine's exhaust gas is used to run the turbine of the turbocharger which runs the compressor to increase the inlet air density. The clear objective of the turbocharger is to increase the specific power output and torque of the engine [4,13,14] with no or slight reductions of bsfc which is less than 1%. Even a turbocharged diesel engine still rejects 35–40% of input energy through the exhaust gas [15,16]. Because of this fact, applications of WHR can also be found in turbocharged engines [4,17] as well.
- *Rankine Cycle* (RC): a steam generator is employed to generate steam using the exhaust heat which is expanded in a turbine to produce additional power. If an organic fluid is used instead of water then the system is called Organic Rankine Cycle (ORC). Hountalas et al. [6] performed engine simulation to study a RC based WHR system and reported 9% improvement in bsfc at full engine load. They utilized the heat from both Exhaust Gas Recirculation (EGR) and Charge Air Cooler (CAC). Recently, Hountalas et al. [18] reported 5.5% bsfc improvement utilizing heat from the exhaust gas of a Heavy Duty (HD) truck diesel engine using RC based WHR system. Katsanos et al. [19] did a theoretical study to investigate the potential improvement of the overall efficiency of a HD truck diesel engine equipped with a bottoming RC to recover heat from the exhaust gas. They were able to improve the bsfc by 7.5% at full load of the engine using water as the working fluid. Likewise, Dolz et al. [20] was able to achieve 8.5% improvement in bsfc using exhaust heat utilizing a RC based WHR system.

From the aforesaid analyses of different WHR technologies, it is clear that mechanical turbo-compounding and RC based WHR systems are the most promising candidate for improving bsfc of diesel engines. However, increase in engine backpressure and pumping losses [21] are the fatal disadvantages of mechanical turbo-compounding. Consequently due to these disadvantages, mechanical turbo-compounding system is not widely used. Between RC and mechanical turbo-compounding systems, Weerasinghe et al. [22] made a numerical simulation comparing their power output and fuel savings. Their results revealed the relative advantages of RC over mechanical turbo-compounding. According to their study, 7.8% power was recovered by using RC system whereas only 4.1% power was recovered by using mechanical turbo-compounding system. Vaja and Gambarotta [23] performed thermodynamic analysis to investigate WHR systems using RC into stationary diesel engine and reported 6% improvement in bsfc utilizing heat from both exhaust and coolant.

With the exception of mechanical turbo-compounding, RC- and ORC-based heat recovery systems need to utilize heat exchangers to extract energy from the waste heat. The heat exchanger design is critical as it needs to provide an adequate surface area in order to cope with the thermal duty. The pressure loss across the heat exchangers also needs to be reasonable to avoid back pressure that will have a negative impact on the net engine power and efficiency. These are the challenges need to be investigated to design an effective heat exchanger to extract heat efficiently with low pressure drop from the exhaust of the diesel engines. The pressure of the working fluid also needs to be investigated to find out the optimum pressure for any particular application. However, studies of