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A review of different heat exchangers designs for increasing the diesel exhaust waste heat recovery

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ABSTRACT

In this paper, after a short review of waste heat recovery technologies from diesel engines, the heat exchangers (HEXs) used in exhaust of engines is introduced as the most common way. So, a short review of the technologies that increase the heat transfer in HEXs is introduced and the availability of using them in the exhaust of engines is evaluated and finally a complete review of different HEXs which previously were designed for increasing the exhaust waste heat recovery is presented. Also, future view points for next HEXs designs are proposed to increase heat recovery from the exhaust of diesel engines.

Contents

Abbreviations: BSFC, brake specific fuel consumption; LHA, latent heat accumulator; CCHP, combined cooling, heating and power; LMTD, log mean temperature difference; CFD, computational fluid dynamic; MEP, mean effective pressure; CHP, combined heating and power; MHD, magneto-hydrodynamic; CI, compression ignition; ORC, Organic Rankine Cycle; DI, direct injection; PCM, phase change materials; DOE, design of experiment; RNG, renormalization-group; EGR, exhaust gas recirculation; SST, Shear-Stress Transport; EHD, electro-hydrodynamic; SI, spark ignition; FDM, finite difference method; TEG, thermoelectric generator; GHG, greenhouse gases; VGT, variable geometry turbines; HEX, heat exchanger; WHR, waste heat recovery

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Nomenclature

C_p	specific heat at constant pressure (kJ/kg K)
e	specific exergy (kJ/kg)
g	gravity acceleration (m^2/s)
h	specific enthalpy (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
M	molecular weight of exhaust gas (kg/mol)
p	pressure (bar)
P_b	brake power (kW)
$\dot{Q}$	heat flux (W)
$\overline{R}$	universal gas constant (kJ/mol K)
s	absolute entropy of ideal gas (kJ/kg K)
T	temperature (°C)
u,v,w	velocity components (m/s)
U	overall heat transfer coefficient (W/m K)

Greeks

ε	heat exchanger effectiveness
ρ	density (kg/m^3)
τ	shear stress (N/m^2)
η	second law heat exchanger efficiency
ν	specific volume (m^3/kg)

1. Introduction

Nowadays, diesel engines are widely used due to their abilities and advantages in industries for producing energy, electricity, transportation, etc., but a large amount of their fuel energy is wasted through the exhaust [1]. Researchers confirm that more than 30–40% of fuel energy gets wasted from the exhaust and just 12–25% of the fuel energy converts to useful work [2,3]. On the other hand, statistics show that the production of a large number of internal combustion engines increases the presence of harmful greenhouse gases (GHG) which is a cause of concern. So, researchers are motivated to recover the heat from the waste sources in engines by using applicable ways. Heat recovery not only reduces the demand of fossil fuels, but also reduces the GHG and helps to save energy. Rakopoulos [4] mentioned that one of the main aims of the second law of thermodynamic, in engines, is identifying the source of destruction and suggesting ways to convert these destructions to useful work or to use them. Combustion is one of the main sources of energy destruction in engines which many researchers aimed to reduce its irreversibility property. For example, Li et al. [5] investigated the effect of swirl chamber on combustion irreversibilities and concluded that increasing the chamber volume increases the irreversibilities due to lower temperature and pressure in the cylinder. Ghazikhani et al. [6] investigated the exhaust gas recirculation (EGR) effect and mentioned that EGR cannot improve the combustion process from the second law view point. Primus et al. [7] tried to reduce the irreversibilities by insulating the cylinder. They observed a 3.7% increase in the indicated work and 49% increase in exergy of exhaust gases, but their study showed that NOx also increases which is not appropriate. Many studies are done on using the alternative fuels to improve the combustion process. Approximately all of them reveal that hydrogen enrichment can improve the combustion process [8–10]. Alasfour [11] showed that 30% Butanol added to gasoline makes a 7% reduction in the second law efficiency and was not appropriate from the second law view point, while Rakopoulos and Kyritsis [12] reduced the combustion irreversibilities by using methane and methanol. Also, Ghazikhani et al. [13] confirmed that just 5% ethanol can improve the combustion process through the second law view point in an experimental work.

It is evident that exhaust of the engines is another main source from which a large amount of energy gets wasted through it. This energy can be recovered by using the heat exchanger in exhaust and this recovered heat is then used in the cycles such as Organic Rankine Cycle (ORC), combined heating and power (CHP), combined cooling, heating and power (CCHP), etc. In all these applications, requirement of a heat exchanger is necessary to transmit the heat from hot gases to working fluid at excellent efficiency. On the other hand, since exhaust heat exchanger may cause a pressure drop and affects the engine performance, its design is of great importance. The current paper aims to introduce the ways to recover heat from engines. Also, a review of previous heat exchangers designs is performed and suggestions for future developments are presented.

2. Waste heat recovery technologies in engines

In this section, a short review of the technologies for heat transfer from engines is presented. In the current status of the world the requirement of energy is increasing especially for transportation applications, so the usage of fossil fuels and consequently harmful greenhouse gases (GHG) will increase. Researchers attempt to reduce the need of fossils fuels by using the waste heat recovery from engines. As of now, six technologies are presented for engines waste heat recovery of which Saidur et al. [14] have performed a complete review of four of them. These six technologies are thermoelectric generators (TEG), Organic Rankine Cycle (ORC), six stroke engines, turbocharging, exhaust gas recirculation (EGR) andexhaust heat exchangers (HEXs)and a short introduction to each of them is given below.

2.1. Thermoelectric generators

Thermoelectric generators (TEG) or Seebeck generators are devices which directly convert waste heat energy into electrical energy. These devices work on Seebeck effect which was discovered by Thomas Johann Seebeck in 1821 [15]. Recently, for increasing the efficiency of these devices, semiconductor p–n junctions were added (Fig. 1)that are made up of new materials such as BiTe (bismuth telluride), CeFeSb (skutterudite), ZnBe (zinc–beryllium), SiGe (silicon–germanium), SnTe (tin telluride) and new nano-crystalline or nano-wire thermoelectric which increase their efficiency to around 5–8% [14]. Although TEG devices have many advantages such as clean energy, without sound, without movable component and lesser maintenance costs, they are however only economical when used at high temperatures (> 200 °C) and when only small amounts of the power (a few milliwatts) are needed. TEG's advantages motivated many of the researchers to use it in automobile waste heat recoveries which can be seen in [14]. For instance, Karri et al. [16] studied two cases of exhaust waste heat recovery using TEGs. Also, Zhang and Chau [17] reported that using TEG has low effect on engine performance and it can improve the engine power up to 17.9%. But, in another research, Yu and Chau [18] revealed that when the exhaust gases flow through the TEG's heat exchanger, kinetic energy from the gases is lost and causes an increase in pumping