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Review on Exhaust Heat Recovery Systems in Diesel Engine

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Abstract— *Exhaust heat recovery system converts the thermal losses in the exhaust zone in engines into energy for work. This technology also reduces exhaust emission from engines. This review paper extends the classification of various methodologies on EHR in diesel engine. In spite of their indigenous benefit for various technologies, it has some limitation over applications to different context. From the current researches the variation in usage of exhaust heat from the diesel engine is evaluated and compared to find which methodology is suitable to attain high efficiency in thermal recovery for power generation. Finally a novel method of an EHR system is proposed to increase high percentage of heat recovery from the exhaust gas in diesel engines.*

Keywords*— *Exhaust heat recovery system, diesel engine.

I. INTRODUCTION

Diesel engines are used in varied applications and it is also a part of a widely networked global system defined by the concepts of ''resources'' and ''environmental pollution''. It is based purely on energy and economics aimed at minimizing the heat losses that fails to satisfy present day demands specified by the ecological imperative according to which energy and material must always be converted with maximum efficiency while minimally polluting the environment [1]. Just like gasoline engines, diesel engines are, in principle, energy converters that convert chemically bound fuel energy into mechanical energy (effective work) by supplying the heat released by combustion in an engine to a thermodynamic cycle. The heat released from the engine can be recovered to appropriate work. 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 aspect the toxic emissions from the exhaust gases leads to public awareness of the finiteness of fossil fuel. It has receded into the background somewhat after being raised in the 1970s; the impact of pollutant and CO_2 input into the earth's atmosphere is again making the need for a longer-range environmentally compatible energy policy with concrete goals evident to suppress the greenhouse effect. For a better future, both challenges conserving resources and protecting the environment would require an approach that endeavors to take full advantage of the ample potentials to save energy and additionally intensify the utilization of inexhaustible energy sources. These challenges will necessitate the research on various waste heat recovery schemes that accumulate on diesel engine through various forms for conserving the primary energy of the fuel and protecting the environment.

Exhaust heat recovery system

Exhaust heat recovery system is an energy recovery heat exchanging process that recovers heat with high potential energy in sources like diesel engine for improving its efficiency. In the present scenario there is a substantial demand of energy for global applications, so the usage of conventional fuels and its toxic exhaust gases will increase the effect of global warming. With the aspect to dwindle the usage of fossil fuels many researchers attempt to recover the waste heat from diesel engines. Various forms of heat can be categorized from engines on their origin

- Heat losses from the exhaust gas through exhaust pipeline,
- Waste heat produced as cooling energy to protect engine seize,
- Waste heat from intercooling to boost engine power and net efficiency,
- Waste heat convected through the engine surface.

During combustion cycle in engines the exhaust gases are dissipated through gas exchange process at a range of 300-500°C. Other sources of waste heat from engine will be transferred to the surroundings with the aid of coolant. Heat transfer occurs through the coolant medium (air, water or oil) at various points of engine to recover its complex issues. The cooling energy is transferred through heat exchangers. In case of the exhaust gas loaded with particulate matter and soot particulates is more critical in heat transfer through HXs. Aerated heat from the under hood parts usually transfer heat through radiation and convection or heat pump which works on thermal absorption cycle. To implement the heat recovery for different temperature operating conditions in engines, various technologies has been proposed by many researchers. In this paper, a short review of the technologies for heat recovery from engines is presented.

Review on EHR systems

Thermo electric generators

Thermoelectric generators (TEG) or See beck generators are devices, which directly convert waste heat energy into electrical energy. These devices work on See beck effect, which was discovered by Thomas Johann See beck in 1821 [4]. 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 Bi-Te (bismuth telluride), CeFeSb (skutterudite), Zn-Be (zinc–beryllium), Si-Ge (silicon–germanium), Sn-Te (tin telluride) and new nano-crystalline or nanowire thermoelectric which increase their efficiency to around 5–8%. 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 (4200 1C) and when only small amounts of the power (a few mill watts) are needed. TEG's advantages motivated many of the researchers to use it in automobile waste heat recoveries which can be seen in [5]. For instance, Karri et al. [6] studied two cases of exhaust waste heat recovery using TEGs. Also, Zhang and Chau [7] reported that using TEG has low effect on engine performance and it can improve the engine power up to 17.9%due to their smaller size of energy absorbing ratio.

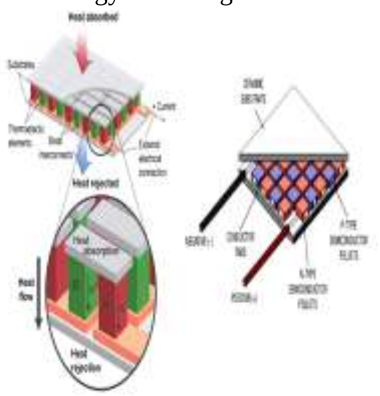

Fig.1. Detailed view of p-n junction semiconductor device

In this work, the heat exchanger connected with TEGs for recovering waste heat from an automotive channel is analyzed. As per the assention between the infrared experimental results and the CFD simulation, a brass heat exchanger with accordion shape and surface territory (660 mm 305 mm) is chosen to form the hot side.It can reduce the thermal resistance between the exchanger and the TEMs and obtain a relatively high surface temperature and uniform temperature distribution to improve the efficiency of the TEG as shown in **fig.2.**The current study focuses on the structural optimization of the heat exchanger and the coolant system to improve the efficiency of the vehicular exhaust gas heat. In the later study, the way of the simulation modeling and the infrared experimental verification that has been introduced in this article needs to be combined with the heat transfer theory, to make further structural design and optimization to improve the overall exhaust heat utilization [8].

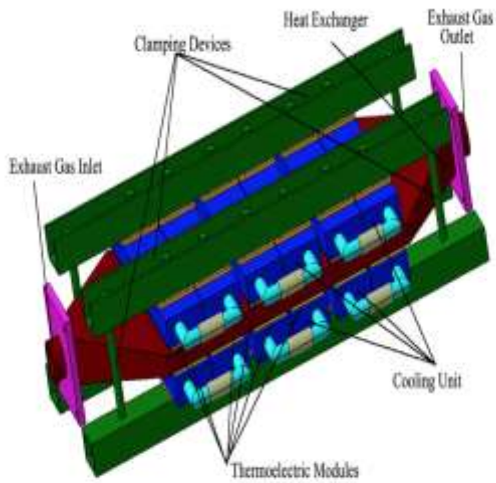

Fig.2: Schematic of automotive exhaust based TEG

Organic Rankine Cycle

Among these cycles, Organic Rankine Cycle (ORC) can be introduced as the most efficient cycle for low temperature sources such as engine exhaust. Simple ORC is contains boiler, expander, condenser, pump and working fluid [9]. Many works are performed in this field and complete reviews of them are presented by Sprouse et al.[10] and Wang et al. [11]. Most of these works are based on the effect of working fluid type on the ORC performance. The different types of working fluids are wet, dry and isentropic fluids with their T–S diagram slopes being positive, negative and infinite. Chen et al. [12] by comparing 35 kinds of working fluids reached to the fact that suitable working fluid depends on the operating condition and a working fluid does not have maximum efficiency at all conditions. Dai et al. [13] mentioned that organic working fluids are more suitable for low temperature sources such as engine exhaust from the knowledge that wet fluids are never recommended for ORC due to the interaction between fluid particles and turbine blades. With a complicated system, Teng and Regner[14] exploited waste heat from the EGR system of a class-8 truck diesel engine to operate a supercritical RC with R245fa as working fluid, as demonstrated in Fig. 9. The fluid was superheated upstream of the expander, which was coaxially assembled with the alternator. The system achieved a 15.8% Rankine efficiency, which could

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reach to 25.5% with ethanol as a substitute fluid. The composite fuel savings over the ESC 13-mode test cycle was up to 5%.

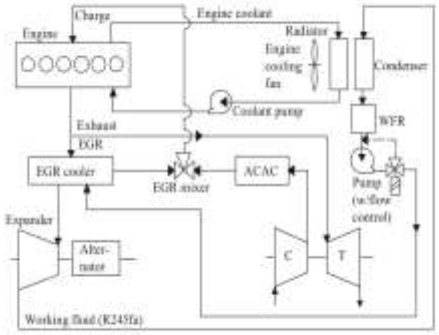

Fig.3: ARC system for waste heat recovery from diesel engine

Five stroke cycle

The concept of five-stroke engine, invented by Schmitz [15], does not reduce compression but increases expansion. The 5-stroke engine is a three-cylinder in which two cylinders perform a four-stroke cycle and alternatively a second expansion of the burnt gases is performed in the third cylinder. Turbocharger is adopted to deliver the boost pressure and the system is controlled by an innovative system called smart waste gate. It consist of variable valve timing of the two valves of the low pressure cylinder. [16].

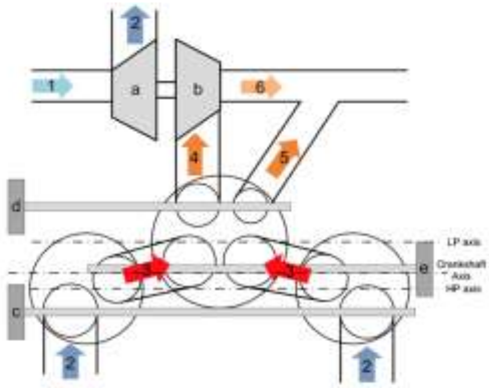

Fig.4: Architecture of the 5-stroke engine showing the valves location and the smart waste gate

Six stroke cycle

The six-stroke engine is a type of internal combustion engine based on the four-stroke engine but with additional complexity intended to make it more efficient and reduce emissions. Three types of six-stroke engines have been developed since the 1890s [17], but in one of them proposed by Conklin and Szybist [18], the engine captures the heat lost from the four-stroke diesel engine and uses it to generate an additional power without more fuel consumption. A schematic of the operation of this engine is shown in Fig. 3. As seen, there are two power strokes: one with fuel, the other with water injection by using the waste heat of burned gases in the previous stroke. Water injection is occurred after compressing the burned gases from first stroke when the crank shaft angle is 720°. Mean effective pressure (MEP) of these engines will be increased by increasing the injected water amount. The main advantages of this engine is reducing the emissions and using from two main waste heat sources because injected water can be preheated by using an exhaust heat exchanger.

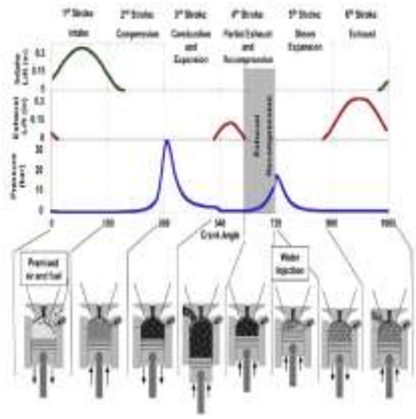

Fig.5: Six stroke engine cycle

Turbo charging

Dr. Alferd J. Buchi proposed the first idea of turbochargers in 1915, which he developed it on a diesel engine. Actually, a turbocharger is a supercharger driven with exhaust gases energy and increases the engine power by compressing the inlet air to engine. Fig. 4 shows a turbocharger with its appurtenances. A turbocharged engine is more powerful and efficient than a naturally aspirated engine because the turbine forces more air and proportionately more fuel into the combustion chamber than atmospheric pressure alone, but it has some shortcomings. Turbo- lag i.e., (hesitation or transient response) during low speed acceleration and major concerns with heated bearings are two main shortcomings in turbochargers which are approximately solved by using two stages turbochargers and variable geometry turbines (VGT) [19]. Another concern in turbochargers is increasing the intake air temperature due to its pressure increase. The warmer intake air has the less density and the less oxygen is available for the combustion event which reduces volumetric efficiency, it also leads to engine knock or detonation known as a destructive factor in engines. So, turbocharger units often use an intercooler (also known as a charge air cooler) to cool down the intake air as shown in Fig. 4. Recently, a novel exhaust steam recovery system (steam turbocharging) is presented by Fu et al [20]. They set a Rankine steam cycle system coupled on engine exhaust pipe, which utilizes the exhaust energy of engine in order to generate steam and

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then drive the turbine. Their results show that IC engine power can theoretically be improved by 7.2% at most and thermal efficiencies can be raised up to 2 percent or more.

EGR system

Recirculation of the exhaust gases into cylinder or EGR is one of the efficient methods to decrease the NOx level. EGR can be applied internally or externally in the engines. EGR is widely used in both gasoline and diesel engines reviewed by Wei et al. [21] and Zheng et al. [22], respectively. In a diesel engine, the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture. Since NOx is formed primarily when a mixture of nitrogen and oxygen is injected into high temperature circumstances, the lower temperatures of combustion chamber caused by EGR reduce the amount of the NOx. EGR cannot improve the combustion irreversibility, but it can be assumed as a technique for using the heat of burned gases in the cylinder for another time [23]. Furthermore in modern diesel engines, the EGR gases are cooled with a heat exchanger in order to enter a greater mass of recirculated gases.

Pneumatic power system

Pneumatic hybridization of ICEs was first discussed in the 1990s [24,25]. HPPS generally consists of an ICE, an air compressor, a pressure tank, and a high-efficiency turbine. A concept schematic setup of HPPS is shown in Figure 4. The main working principle of pneumatic hybridization engines is to recover energy from a braking phase or from a combustion phase by pumping the exhaust gas or the pressurized air into the air tank, and then the air tank can then be restored to start the engine or charge the engine during the strong transient accelerations or short-term high-power output period. An advantage of the pneumatic hybridization engine is that the pressurized air can be pumped into the combustion chamber to overcome the turbo-lag problem during the speedup period of the turbocharger, which can maximize the performance of the turbocharger. Pneumatic hybridization engines also offer improved fuel economy and reduced emissions. Compared with a conventional diesel vehicle for the drive cycles of NEDC, UDDS, HWFET, and JAPAN10-15, Chen and Xu believed that the parallel pneumatic hybrid vehicle could decrease emissions by 58.84% (NEDC), 38.76% (UDDS), 14.54% 4(HWFET), and 66.59% (JAPAN10-15), and save energy by 13.12%, 14.06%, 16.27%, and 28.06%, respectively [26]. According to simulation results, the overall efficiency of HPPS can be expected to increase by approximately 20% [27]. Donitz et al. even concluded that, the combination of engine downsizing and pneumatic hybridization yields a fuel consumption reduction of up to 34% for the MVEG-95 drive cycle [28]. However, the merging problem between the high- pressure flow in the air tank and the high-temperature exhaust gas in the ICE must also be considered. Huang et al. [29] studied the effects of the level of compressed air pressure (P_{air}) and the contraction of the cross-section area at the merging position on the flow energy merger and found that exhaust gas energy recycling efficiency and merger flow energy are significantly dependent on the optimum adjustment of the cross-section area for changes in Pair.

Thermal distillation system

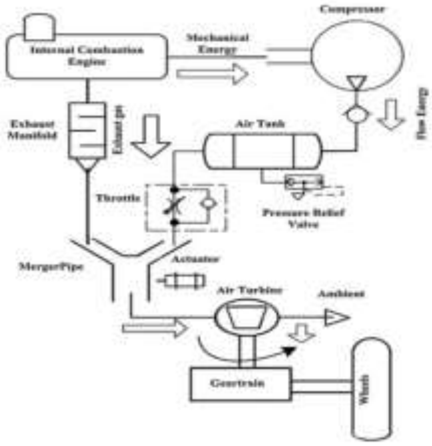

Fig.6: Schematic view of hybrid pneumatic power system

The aim of this work is to utilize the heat energy wasted in exhaust gas of an internal combustion engine of low capacity for desalination using a submerged horizontal tube straight pass evaporator and a condensing unit, without the aid of any external energy. A horizontal tube straight pass evaporator and water-cooled condenser for condensing the evaporated steam were designed and fabricated. The experiments were conducted in a 5 hp diesel engine to analyze the performance of the submerged horizontal tube straight pass evaporator (SHTE) under various load conditions. It is evident that 3.0 l/h of saline water can be desalinated from the engine exhaust gas without affecting the performance of the engine. More over nearly 24 litre of water is heated, up to 60 °C in the condenser unit. By utilizing the heat energy in condenser water in addition to waste exhaust gas heat energy the overall efficiency of the system is enhanced and thermal pollution is also reduced considerably [30].

Combined air cycle power generator

A combined air cycle is designed for

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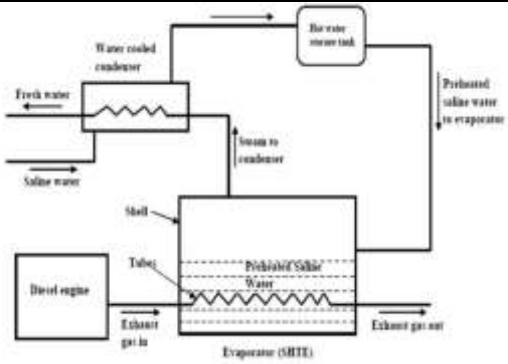

Fig.7: Circuit view of thermal distillation from EHR system

Internal combustion (IC) engine supercharging. The setup consists of IC engine working cycle and bottom cycle of waste heat recovery (WHR). IC engine exhaust gas is used to run the bottom cycle and its power used to drive the gas compressor. Numerical calculation were performed for both the heat transfer and thermodynamic processes of combined air cycle for different cycle parameters and IC engine operating conditions. Results show that the cycle efficiency and exhaust gas energy recovery efficiency depend largely on the working pressure and their maximum values appear at the working pressure of 0.35 MPaand 0.2 MPa respectively. This approach can make the fuel utilization efficiency of IC engine increase by 8.9% points and 4.1% points at most respectively compared with the naturally aspirated (NA) engine and turbocharging engine due to the reduction of exhaust gas pressure. [31]. Gao et al. [32]have proposed a WHR system where a high speed turbocharged diesel engine acts as the topper of a combined cycle with exhaust gases used for a bottoming Rankine cycle. And the result shows that heat recovery system can increase the engine power output by 12%, when diesel engine operates at 80 kW/2590 rpm.

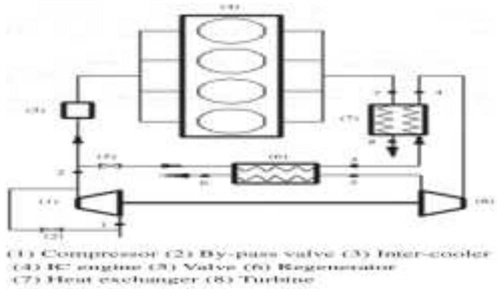

Fig.8: Schematic view of combined air cycle EHR system

Thermal storage system

Schatz [33] introduced the concept of a heat battery to store the engine waste heat using a PCM. They reported that the possible way of recovering the waste heat from the IC engine coolant and storing the heat in a PCM heat battery through experiments.This stored heat is used during engine cold start condition by transferring heat from PCM to the engine coolant, which ensures the engine to attain operating temperature substantially faster. The energy available in the exit stream of many energy conversion devices goes as waste, if not utilized properly. The exhaust gas from an internal combustion engine carries away about 30% of the heat energy of combustion. The major technical constraint that prevents successful implementation of waste heat recovery is due to its intermittent and time mismatched demand and availability of energy. In the present work a shell and finned tube heat exchanger combined with an IC engine setup to is used to recover the heat from the exhaust gas and a thermal energy storage tank used to store the excess energy available is investigated in detail. A combined sensible and latent heat storage system is designed, fabricated and tested for thermal energy storage using cylindrical phase change material (PCM) capsules. The performance of the engine with and without heat exchanger is evaluated. Results shows that nearly 10–15% of fuel power is stored as heat in the combined thermal storage system. The performance parameters pertaining to the heat exchanger and the storage tank such as amount of heat recovered, heat lost, charging rate, charging efficiency and percentage energy saved are evaluated and reported in this paper [34].

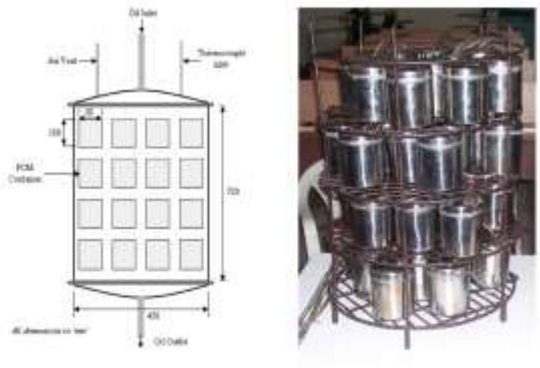

Fig.9: Layout setup of thermal storage PCM tank

Proposed methodology

The proposed methodology is an integration of thermoelectric generator with shell and tube heat exchangers for exhaust heat recovery system. The model consists of a shell and tube heat exchanger with a modified slot for TEG device i.e. (current conducting medium) placed on the middle of heat exchanger. The surface of the p-n junction device will be in contact with the thermo-electric fluid (ionic fluid) acts as a carrier medium. This absorbs the heat losses from the exhaust gas produced in the diesel engine and the cold fluid from the radiator outcome. With this integration effect, we can achieve a greater efficiency in HER system. The typical circuit of the proposed heat exchanger is shown in **Fig.10.**

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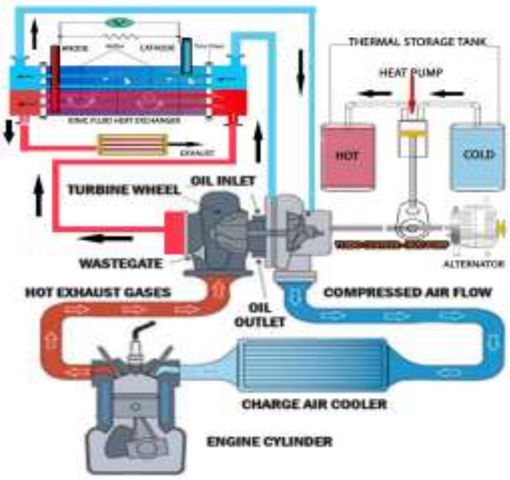

Fig.10: Layout of proposed pumping heat recovery system

II. CONCLUSION

In this paper, a short review of heat recovery technologies in engines and heat exchangers has been presented. It seems that in most of these technologies (ORC, TEG, EGR, and turbo- charging), heat exchangers have an important role to transfer heat for recovering process, so a suitable design for heat exchanger should be applied in accordance with this fact that heat transfer increases when pressure drop is in the allowable limit. Some experimental and numerical researches about various heat exchangers designs existed in the literature which all of them have been reviewed here. It can be concluded that using fins is more applicable and appropriate than foams and porous materials due to the lower pressure drop and higher heat transfer rate. Also, it seems that other methods for increasing the heat transfer such as vortex generators, nanofluids, using the PCM as heat storage source, etc., in addition to lower TEGs in downstream of HEX, design parallel HEXs or HEX with one inlet and two outlets, selecting the best solid materials, TEGs material and working fluids can enhance the exhaust heat recovery and save the fuel costs for future works.

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