Waste Heat Recovery Technologies in Diesel Engines for Energy Conservation

Jigar Trivedi[a]
[a]MTech, Faculty of E&M, CME, Pune. (jigar38@gmail.com)

Abstract: Waste heat is the energy that is generated in various engineering processes which is not put into any practical use and is lost, wasted and dumped into the environment, which is an infinite sink. Recovering the waste heat can be conducted through various waste heat recovery technologies to provide valuable energy sources and reduce the overall energy consumption. In this review paper, a wide-ranging evaluation is made of waste heat recovery technologies in engines, in general and for exhaust waste heat recovery processes, in particular. By considering inputs from various review papers in the domain of waste heat recovery, a revision of the current practices and procedures is evaluated. The review is conducted on the operation and performance of the commonly used technologies in exhaust gas waste heat recovery. Though most of the topics covered in this review paper are available in open domain, in order to maintain the uniqueness, the latest trends and researches in the spectrum of waste heat recovery has also been discussed in this paper.

1. Introduction

Currently, diesel engines are widely used due to their abilities and advantages in residential, commercial and industrial domain for producing energy, electricity, transportation, etc., but a large amount of their fuel energy is wasted through the exhaust. 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 [1,2]. 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 [3] 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. Exhaust of the engines is one such 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 can be then used in the cycles such as Organic Rankine Cycle (ORC), combined heating and power (CHP), combined cooling, heating and power (CCHP), etc. M. Hatami et al. [4] carried out an exhaustive review of different heat exchangers designs for increasing the diesel exhaust waste heat recovery. In all these applications, requirement of a heat exchanger is necessary to transmit the heat from hot gases to working fluid at excellent efficiency. The current paper aims to introduce the ways to recover heat from engines. The experimental set up for testing and evaluation of one such waste heat recovery system has also being undertaken as a project.

2. Waste Heat Recovery Technologies In Engines

A review of the technologies for heat transfer from engines is presented in this section. 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 also increase. Researchers have attempted 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. [5] 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) and exhaust heat exchangers (EHXs). A brief 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 [6]. 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% [5].

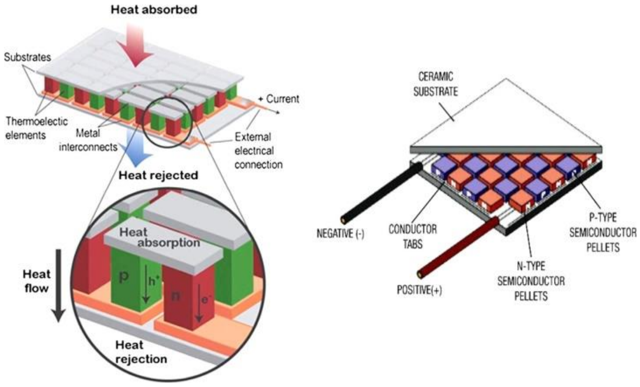


Fig. 1. Schematic view of p–n junctions in TEG devices

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°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 [5]. For instance, Karri et al. [7] studied two cases of exhaust waste heat recovery using TEGs. Also, Zhang and Chau [8] reported that using TEG has low effect on engine performance and it can improve the engine power up to 17.9%.

2.2.Organic Rankine Cycle

A number of thermodynamic cycles such as Kalina, trilateral flash, Goswami and Rankine are presented in the literature for exhaust waste heat recovery from engines [5]. Among these cycles, Organic Rankine Cycle (ORC) can be introduced as the most efficient cycle for low temperature sources such as engine exhaust. A schematic of the ORC is shown in Fig. 2 which 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], Chen et al. [11] and Wang et al. [12]. Most of these works are based on the effect of working fluid type on the ORC performance.

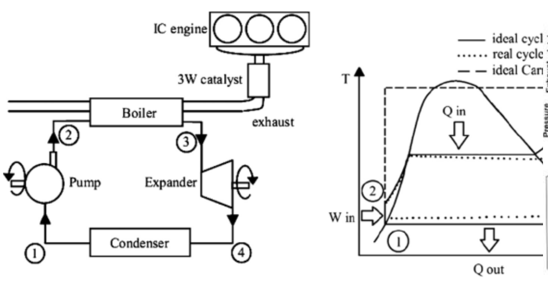


Fig. 2. Schematic of Organic Rankine Cycle (ORC)

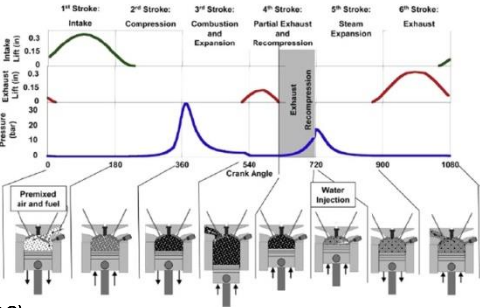


Fig. 3. Six stroke engine operation

2.3.Six Stroke Engines

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 [5], but in one of them proposed by Conklin and Szybist [13], 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°.

2.4.Turbocharging

The first idea of turbochargers was proposed by Dr. Alferd J. Buchi in 1915 which he developed it on a diesel engine [5]. 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.

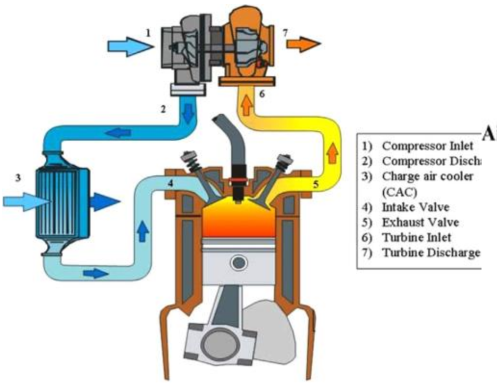


Fig. 4. Schematic view of turbocharging

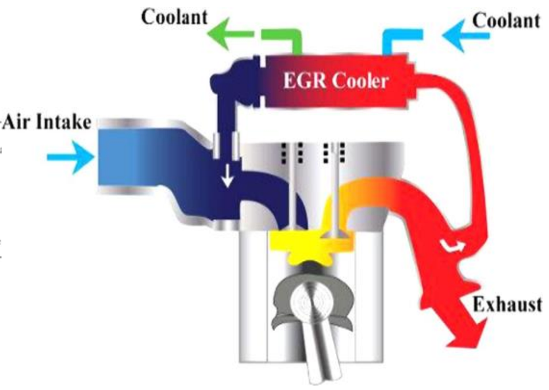


Fig. 5. EGR principle

A novel exhaust steam recovery called steam turbocharging is presented by Fu et al. [14]. 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 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 % or more.

2.5.Exhaust Gas Recirculation

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. [15] and Zheng et al. [16], 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. Furthermore in modern diesel engines, the EGR gases are cooled with a heat exchanger in order to enter a greater mass of recirculated gases (Fig. 5).

2.6. Engine Heat Exchangers (Hxs)

One of the most common ways to recover heat from engines is using the heat exchangers. Although heat exchangers are used in ORC cycles, they can separately be used for obtaining the heat from the exhaust for other applications such as hot water for domestic uses or utilizing as injection in cylinder, turbocharger, EGR, etc. Due to the high applications of heat exchangers, researchers have tried to improve heat transfer through special design of heat exchangers.

2.6.1 HXs in Cylinder

Cylinder is the highest temperature source for heat recovery in engines. Although cylinders were commonly cooled by radiators, but Ghazikhani et al. [17] considered a separate circuit for cylinder cooling to reduce the brake specific fuel consumption (BSFC) in a two stroke SI engine. They reported the effect of engine speed and torque on exergy balance and irreversibility. Their outcomes reveal that when torque or speed increases, the pressure and temperature in the cylinder will rise and makes an increase in exhaust gas availability and as a result the internal irreversibility decreases. So, more exergy will be recovered in higher load and speeds.

2.6.2. HXs in Radiator

Another main application of HXs in engines is radiators constructed of a pair of header tanks, linked by a core with many narrow passageways, giving a high surface area relative to volume. Engines are often cooled by circulating a liquid called engine coolant through the engine block. Engine coolant is usually water- based, but may also be oil or nanofluid for increasing the heat transfer rate.

2.6.3. HXs in Exhaust

Some researchers attempt to enhance the rate of heat transfer by a special design of HXs in the exhaust of diesel engines due to their high applications. Zadsar and Gorji-Bandpy [18] used a twisted tape in the exhaust of an OM314 diesel engine in order to increase the recovered heat and their usage in a refrigeration cycle experimentally. Pandiyarajan et al. [19] designed a finned-tube heat exchanger as shown in Fig. 6. They used a thermal energy storage using cylindrical phase change material (PCM) capsules and found that nearly 10–15% of fuel power is stored as heat in the combined storage system in different loads as seen in Fig. 7.

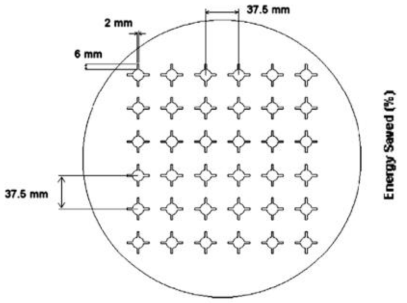


Fig. 6. Heat exchanger designed by [19]

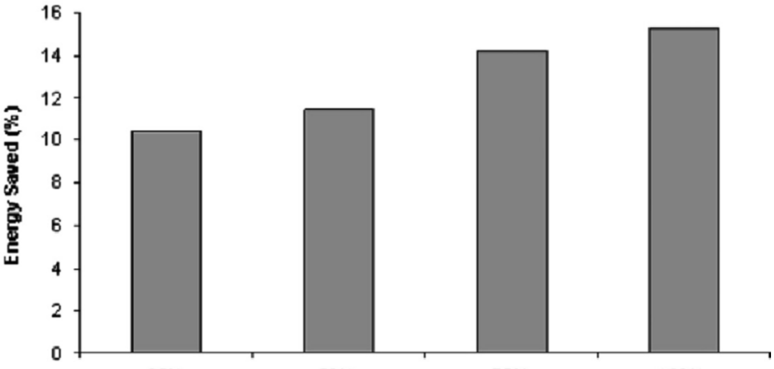


Fig. 7. Heat recovery rate

Furthermore, Lee and Bae [20] made a small heat exchanger with fins in the exhaust by design of experiment (DOE) technique. They reported that fins should be in the exhaust gases passage for more heat transfer (Fig. 8) and designed 18 cases with different fin numbers and thicknesses and found the most effective cases as shown in Fig. 8. Zhang et al. [21] modeled a finned tube evaporator heat exchanger for an ORC cycle as shown in Fig. 9. They concluded that waste heat recovery efficiency is between 60% and 70% for most of the engine's operating region and also they mentioned that heat transfer area for a finned tube evaporator should be selected carefully based on the engine's most typical operating region.

Ghazikhani et al. [22] used a simple double pipe heat exchanger in a diesel engine and performed an exergy analysis for finding the relation between irreversibility and exhaust sound level. Recently, they [23] estimated an experimental work that BSFC could be improved approximately up to 12% in different loads and speeds of an OM314 diesel engine by utilizing the recovered exergy from a simple double pipe heat exchanger in exhaust (Fig. 10). Also, they showed that exergy recovery will be enhanced by increasing the engine loads and speeds especially in high speeds.

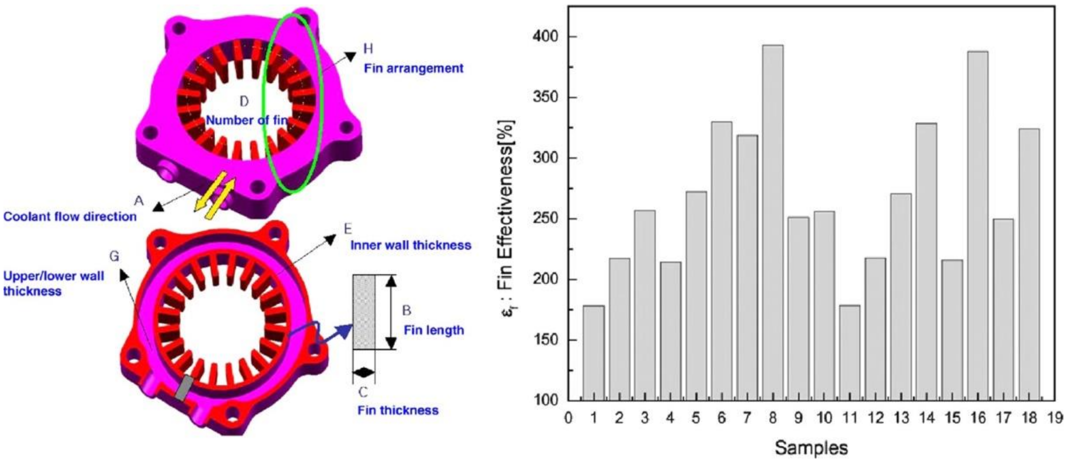


Fig. 8. Heat exchanger designed in Ref [20]

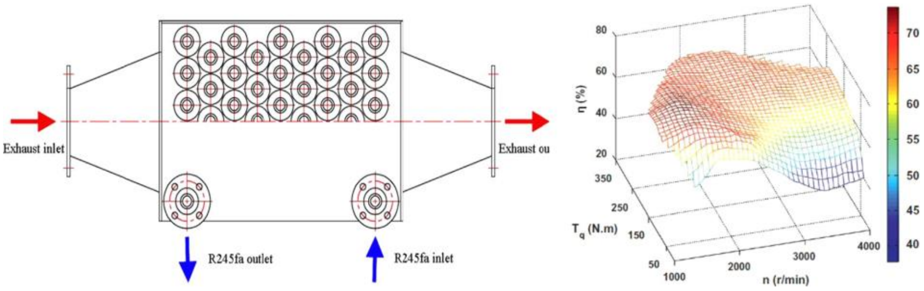


Fig. 9. Finned tube heat exchanger designed by Zhang et al. [21] for ORC application

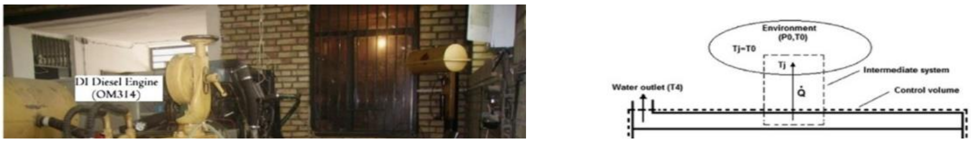


Fig. 10. Double pipe heat exchanger used in Ref. [23]

The thermoelectric modules for heat recovery need two heat sources, cold and hot. So, HXs can be a suitable device for providing these sources which can simultaneously produce electricity and hot water. Weng and Huang [24] designed a heat exchanger with radial fins and TEG device as illustrated in Fig. 11 and studied the effect of HX length and TEG number on heat recovery. Lu et al. [25] designed a heat exchanger on exhaust automobile as Fig. 12 in different outlet and inlet pipe numbers. Furthermore, Yang et al. [26] invent a heat pipe for cooling the exhaust of a large bus and modeled it numerically and finally obtained a good agreement between numerical and experimental outcomes. Wang et al. [27] suggested a heat exchanger as shown in Fig. 13, it seems that this kind of HX has high back pressure, but in their study the total fuel saving of the engine reached up to 34% under some of the operating conditions. Recently, Hossain and Bari [28,29] applied a new HX for a diesel engine presented in Fig. 14 experimentally and numerically. After that they optimized the working fluid pressure and the orientation of heat exchangers and found the additional power increased from 16% to 23.7%. Also, they investigated the parallel and series configurations of HXs and as a result obtained additional power are shown in Fig. 14. Mavridou et al. [30] examined two groups of configurations: (a) a classical shell with a tube heat exchanger using staggered cross-flow and (b) a cross-flow plate heat exchanger which is initially placed with finned surfaces on the exhaust gas and then is covered with metal foam instead of the fins. They attempt to minimize the volume and weight of the arrangement and simultaneously keep the heat transfer from the gas side at a maximum range. Kauranen et al. [31] used phase change materials (PCM) and latent heat accumulator (LHA) for diesel exhaust waste heat recovery which help to decrease the fuel consumption and also its emission reduction. In a different study, Baker et al. [32] designed a multi pass duct shape heat exchanger (Fig. 15) for a diesel engine by numerical finite difference method (FDM) and examined the effects of TEG, porous structure and fins for the amount of heat recovery. Then, they found that 1.06 kW is the maximum net electrical power which can be achieved for the three parallel flow paths in a counter-flow arrangement. Also, Deng et al. [33] designed two thermoelectric HXs models by CFD simulation and used Wilcox k-ω model to discuss on different internal structures, lengths and materials on the HX performance. The same study has been performed by Kumar et al. [34] which modeled three HXs (rectangular, triangular and hexagonal) by CFD FLUENT software and experimentally produced and tested the best model.

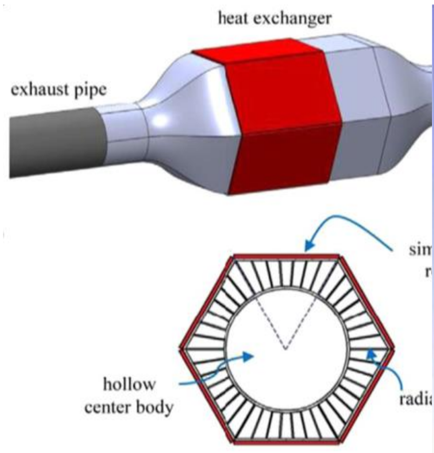


Fig. 11. HX designed with thermoelectric and radial fins [24]

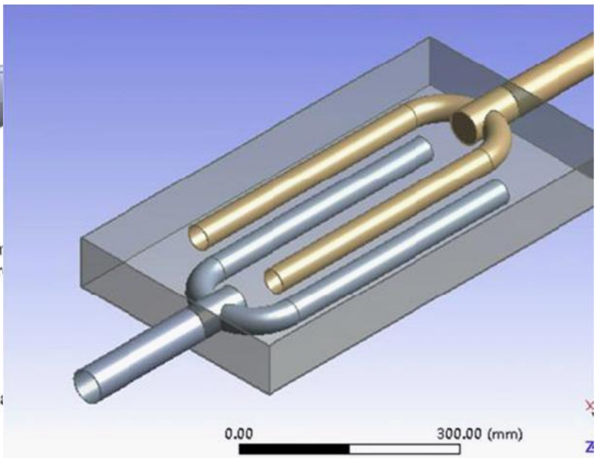


Fig. 12. TEG heat exchanger designed by Lu et al.[25]

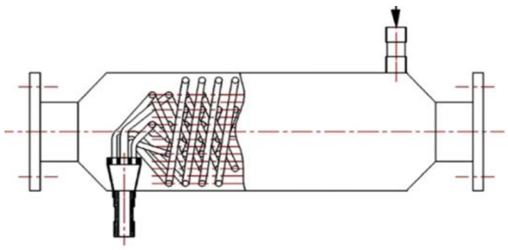


Fig. 13. Exhaust HX used in Love et al. [27]

Fig. 14. HX used by Hossain and Bari [28]

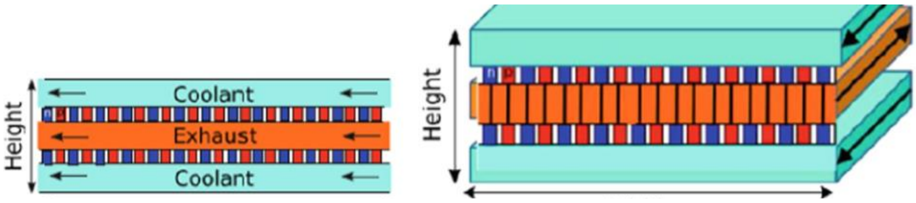


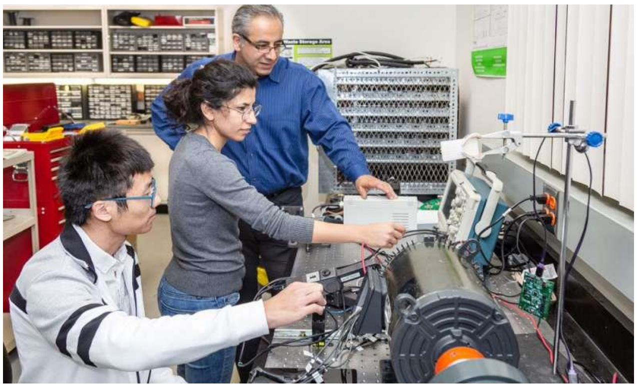
Fig. 15. Duct shaped HX designed by Baker et al. [32] for studying TEG

3. Latest Trend

Two of the recent researches in the field of waste heat recovery are given below. These researches will be forerunner for efficient conversion of the waste heat into more useful form of energy.

3.1 Generator To Convert Waste Heat Into Clean Electricity

University of Texas at Dallas researchers have developed a generator prototype in Oct 2019 that uses liquid metal to convert waste heat from sources such as electric cars or data-centres into clean electricity. Data centres, electric car batteries and appliances such as air conditioners generate a largely untapped potential energy source. This project zeroes in on sources that generate lower temperature heat, between 80 and 115°F, which have been more challenging to convert to electricity. The researchers started with a magneto-hydrodynamic power (MHD) generator, a device that generates electricity by moving fluid through a magnetic field. The technology has many potential applications. The technology also could improve the efficiency of electric vehicles by converting heat from the car batteries and exhaust into electricity.



Researchers at University of Texas, Dallas

3.2. Latest Trend: Aqua ammonia based thermally activated combined power and cooling system

According to research published in Sep 2019 in Progress in Industrial Ecology, An International Journal, it should be possible to generate electricity and refrigerate simultaneously using low-grade waste heat from industry. The key is a system based on an ammonia-water mixture. Mechanical engineer Kolar Deepak of Vardhaman College of Engineering, in Hyderabad, India, has proposed a system that exploits thermodynamic phenomena encapsulated in the Kalina cycle to generate power and cool a system at the same time using evaporation and condensation of an ammonia-water working fluid.

The system does mechanical work, which can drive a dynamo type device to generate electricity, while the refrigeration effect is produced by the working fluid from the turbine exit. A thermal efficiency of almost 20% at an operating temperature of 135°C was achieved which is the sort of temperature for "waste" heat streams from industrial plants and gas turbine exhaust, as well as municipal incinerators, or renewable energy sources, including geothermal brine.

4. Conclusion

In this paper, a brief review of heat recovery technologies in engines and heat exchangers has been presented. It seems that in most of these technologies (ORC, TEG, EGR, HXs and turbo- charging), heat exchangers have an important role to transfer heat should be applied in accordance with this fact that heat transfer increases when pressure drop is in the allowable limit. Rising focus of the regulatory regime toward sustainable development and longterm benefits of decarbonisation, have significantly boosted the demand for waste heat recovery systems. On-going initiatives toward reducing carbon dioxide emissions along with favourable government policies toward adoption of energy efficient systems and solutions will further enhance the industry growth. Global Waste Heat Recovery System Market is expected to surpass USD 80 Billion by 2025, as reported in the latest study by Global Market Insights, Inc. Shifting focus toward emission control coupled with stringent government regulations will stimulate the adoption heat recovery systems. Technology advancement, greater operational flexibility and subsequent cost reduction are few prominent features that will significantly contribute toward expansion of global waste heat recovery market size.

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