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Waste Heat Recovery Technologies In Turbocharged Automotive Engine – A Review

Alias Mohd Noor [a*], Rosnizam Che Puteh [b] and Srithar Rajoo [a]

Significant waste heat recovery technologies have been developed to recover exhaust heat and turn it into useful energy such as in downsizing the engine or to regain the auto-electricity. Extensive work and research in energy recovery have been identified in the automotive sector; therefore the main objective of this paper is to assess each waste heat recovery technology based on current developments, research trends and its future in an automotive application. The study looked into potential energy recoveries, performances of each technology and other factors affecting the implementation. As a result, the article drew the conclusion that waste heat recovery and its utilization will remain a good prospect in future automotive engine application.

Field of Research: Waste Heat Recovery, Turbo-Compounding, Thermoelectric Generator, Rankine Cycle, Automotive.

1. Introduction

Internal Combustion Engine (ICE) remain the most dominant method of world transportation since its invention in early 19th Century. Extensive research and technology development by engine manufacturers concentrate on two main methods available to improve engine thermal efficiency: one is to improve cylinder indicated efficiency by optimizing the combustion process, and the other is to recover waste heat energy of the engine. Jianqin et al. (2011) explained that Waste Heat Recovery has attracted a significant interest due to substantial potential of the amount of heat that can be recovered. Ma et al. (2012) mentioned in their work by recovering useful energy, in the form of electrical power from engine exhaust waste heat would directly reduce system fuel consumption, increase available electric power and improve overall system efficiency by adding the power produced by the engine. This paper presents a short study on different waste heat recovery systems available for application in automotive engines. Utilising a waste heat recovery technology is becoming an increasingly viable means of reducing fuel costs by increasing the energy output from an internal combustion engines.

The content of this paper is basically divided into seven main parts. The first part introduces the reader to the waste heat recovery and its utilization. The second part provides the literature reviews on mechanical turbocompounding.

Then literature reviews of electrical turbocompounding followed by thermoelectric generator as well as steam rankine cycle and organic rankine cycle. Finally, the last

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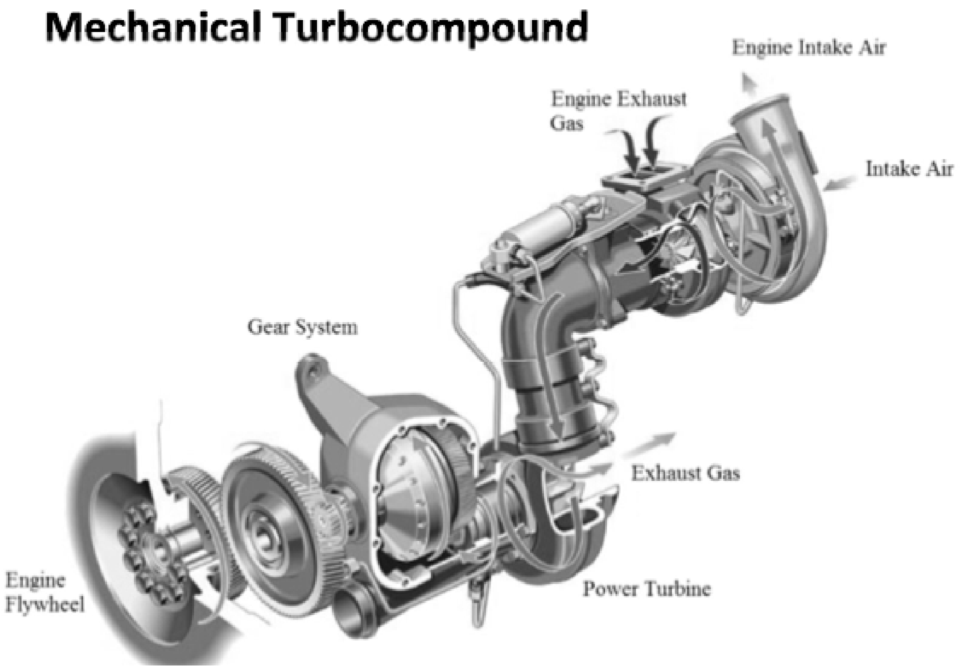
[a] Transportation Research Alliance, Faculty of Mechanical Engineering,
Universiti Teknologi Malaysia, Skudal, Malaysia.
[b] Royal Malaysian Navy, Navy Headquarters, Ministry of Defence, Kuala Lumpur, Malaysia
[*] Corresponding Author: alias@mail.fkm.utm.my,

part covers conclusions drawn based on the technology outlines with possibilities of future works on the similar subject.

2. Mechanical Turbo-Compounding

Mechanical turbo-compounding includes a conventional turbocharger which recovers exhaust energy in a turbine to boost the air coming into the engine in a conventional fashion. Downstream of the turbocharger turbine, the exhaust gas goes through a second turbine as shown in Figure 1. Sendyka and Soczwka (2004) mentioned that the energy recovered is added to the engine torque through a system of shafts, gears and a fluid coupling.

Figure 1: A Typical Layout of Mechanical Turbo-Compounding, Sendyka and Soczwka (2004)



At present, Volvo, Detroit Diesel, Iveco and Scania truck manufacturer in United States of America (USA) has already produced engine utilising the system primarily for long-hauled truck. Tennant and Walsham (1989) explained that Caterpillar has used an axial power turbine on a 14.6-liter diesel and reported an average Brake Specific Fuel Consumption (BSFC) reduction of about 4.7% for a 50,000 miles extra-urban driving test in the USA. The paper also reported that Scania applied this technology on an 11 liter displacement 6-cylinder turbocharged diesel engine and reported providing a 5% improvement of BSFC at full load. Whilst Brands et al. (1981) mentioned that Cummins used a radial flow power turbine and reported 6% maximum improvement of BSFC at full load and 3% at part load. However, in a more recent work by Patterson et al. (2009) clearly pointed that mechanical turbo-compounding systems are an energy consumer at low loads and idling speed, thus pulling down the average BSFC.

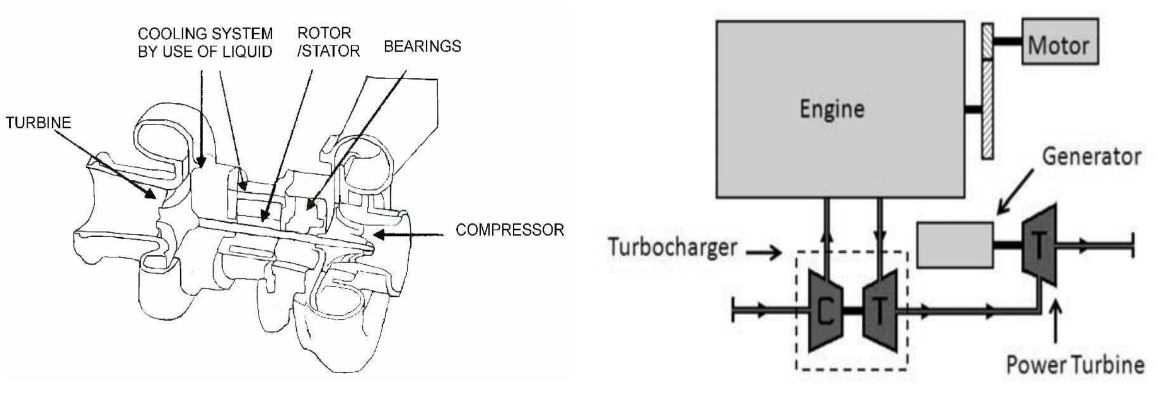
For Mechanical turbocompound, engine manufacturers is keen on improving the fuel economy by improving the design and material used in the engine-turbocompound setup. Wilson (1986) reported that Caterpillar has used an axial power turbine on a 14.6-liter diesel and reported an average BSFC reduction of about 4.7% for a 50,000 miles extra-urban driving test in the US. Cummins used a radial flow power turbine and reported 6% maximum improvement of BSFC at full load and 3% at part load. In an more detail work by Hountalas et al. (2007) mechanical turbo-compounding can offer a maximum BSFC reduction of 0.5%-4.5% as load increases from 25% to 100% for a power turbine efficiency of 80%.

A research done by Southwest Research Institute by Callahan et al. (2012) on Detroit Diesel 15 engine shows the work produced by mechanical turbocompound unit offsets the pumping losses in certain range of operation, particularly at 1400rpm at fullload, the axial turbine provides an estimated 2.5% increase in power and a corresponding decrease in BSFC. Koyess (2011) in his master research done in Cranfield University on an F1 Cosworth vehicle, it was found a power increase of about 7% over the useful range of the engine, from 8,000 to 10,000 rpm. The peak power increase by 8% which results in a 2% increase in engine efficiency.

3. Electric Turbo-Compounding

The mechanical turbo-compounding technology has been utilized in diesel engines, but the system hardware is rather complex. The increasing demands of ancillary electrical equipment and the rise of hybrid power-train vehicles have led to a growing electrical energy requirement in vehicle. As a result, the electric turbo-compounding system offers a better solution and attracts more attention. The firm Caterpillar researcher, Hoppman and Algrain (2003) has setup a system of electric turbo-compounding consist of an air compressor, turbine, and a generator mounted in between. Another design by company John Deere through Vuk (2005) is using the turbogenerator in parallel with engine turbocharger. Both designs are shown in Figure 2.

Figure 2: Electrical Turbocompound (A) Caterpillar Setup (B) John Deere Setup, VUK (2005)



(a) (b)

Both models show results in achieving overall engine efficiency in the range of 3-5%.

Previous research by Bumby et al. (2006) shows an increase of 6% fuel economy of a 12 tonne city bus depending on operating conditions by introducing motor generator within the vehicle's engine turbocharger.

A number of significant issues remain to be resolved. Much of it deals with applying high speed generator technology to exhaust high temperature environment. The high frequency of the generator output is also challenging. The added flexibility of the electric turbo-compounding system makes the control and optimization of the system more complicated. In a report released by the United States Department of Energy (US DOE) 2010 (Kruiswyk, 2010) stated that the efficiency of the electrical machine on the turbo shaft fell short of the target values, and partially as a result of this the turbo generator had a tendency to overheat at higher power levels. However, in a next phase action plan this issue will be tackled by Caterpillar in collaboration with Barber-Nichols Inc. to design and analyze of the new generation of electric turbo-compounding turbo-generator.

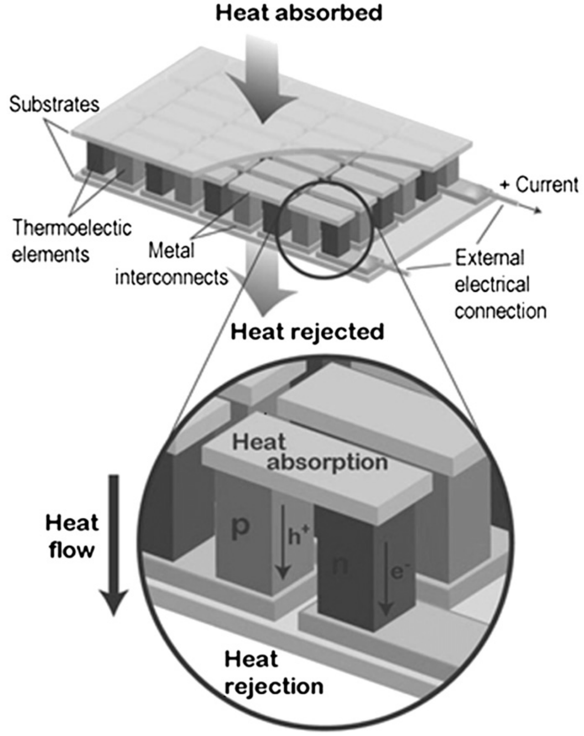
Rajoo and Martinez-Botas (2008) explained that power turbine and engine's turbocharger requires suitable turbomachinery design in order to achieve maximum efficiency for energy retrieval from the exhaust flow. Relevant research in this field has been done to mitigate this issue. In a recent work by renowned truck manufacturer, Navistar through Ojeda and Rajkumar (2012), the engine base turbochargers were upgraded with high efficiency turbine wheels to reduce the back pressure to accommodate the inclusion of the turbo-compounding system. Both modeling and experimental validation helped determine the optimum geometries for best air- to-fuel ratio capability and lowest engine back pressure.

Zhuge et al. (2011) reported in a collaboration work by Tsinghua University and General Motors Global R&D, a gasoline electric turbocompound have been studied and evaluated under United States Environmental Protection Agency (US EPA) standard US06 and FTP75 driving cycles. The test was done using Fixed Geometry Turbine (FGT) against Variable Nozzle Turbine (VNT) through engine performance GT DRIVE software. Results show that optimization of the turbo generator turbine geometry design cannot simultaneously meet the requirement of engine practical high loading and low loading driving cycles such as US06 and FTP75 driving cycles. The ETC system with VNT can improve the engine efficiency at engine high load operating conditions and increase the electric power generation, but has no significant effect on engine fuel economy improvement under practical driving cycles. Further research will be done to manufacture the ETC system and test the system performance on the gasoline engine.

4. Thermoelectric Generator (TEG)

The thermoelectric power generation is based on the Seebeck effect – *If heat is applied to a circuit at the junction of two different conductors, a current will be generated.* TEG device offers the conversion of thermal energy into electric current in a simple and reliable way. Figure 3 shows a typical thermoelectric setup, where the device is sandwiched between a heat source and a heat sink. Riffat and Ma (2003) show in their result shows heat flow will induce thermoelectric element to produce an electrical charge. Advantages of TEG include free maintenance, silent operation, high reliability and involving no moving and complex mechanical parts.

Figure 3: A Typical Thermoelectric Device, Riffat and Ma (2003)



Stobart et al. (2010) reviewed the potentials in fuel saving of thermoelectric devices for vehicles. They concluded that up to 4.7% of fuel economy efficiency could be achieved. Studies on thermoelectric devices are still an ongoing matter. BMW has been developing a thermoelectric generator for waste heat recovery (GreenCar Congress 2011), for a number of years, and has suggested 2 location of TEG devices; integration to exhaust gas recirculation (EGR) and integration in the exhaust manifold. The result shows 2% improvement in fuel economy and they targeted by improving the system it can show further reduction of BSFC to 5%.

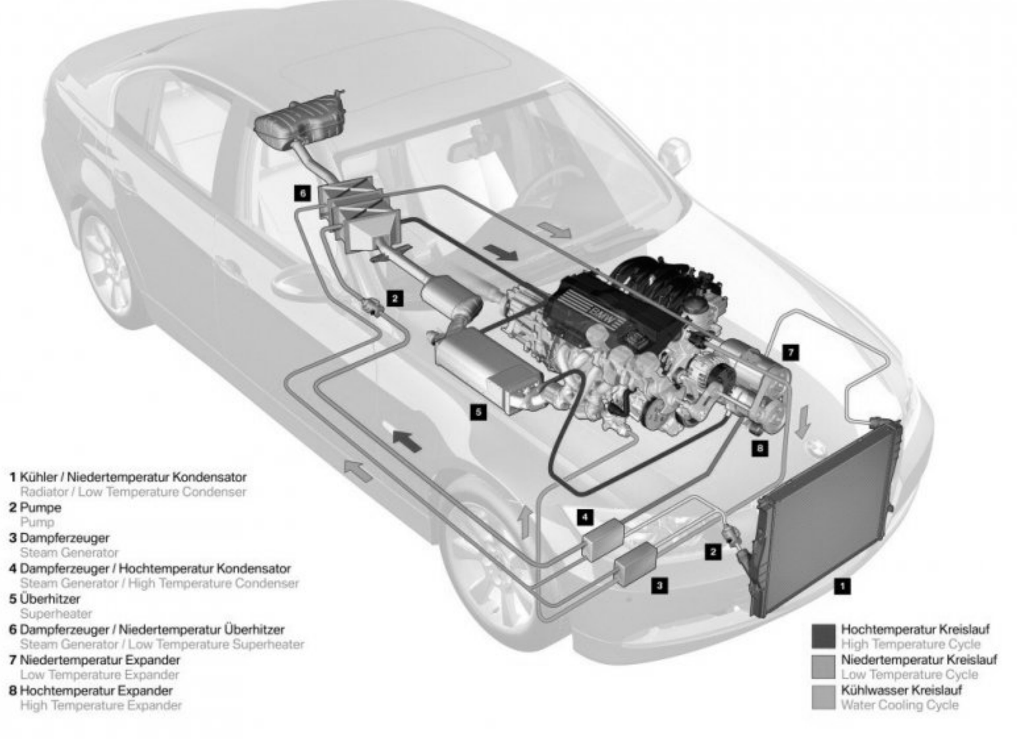
Stobart and Weerasinghe (2006) stated that the primary challenge of using TEG is its low thermal efficiency (typically Z_{tho} 4%). Thermoelectric materials efficiency depends on the thermoelectric figure of merit, Z; a material constant proportional to the efficiency of a thermoelectric couple made with the material. Karri et al. (2011) stated that future thermoelectric materials show the promise of reaching significantly higher values of the thermoelectric figure of merit, Z, and thus higher efficiencies and power densities can be obtained. Crane and Jackson (2004) in their work mentioned that materials such as BiTe (bismuthtelluride), CeFeSb (skutterudite), ZnBe (zinc–beryllium), SiGe (silicon–germanium), SnTe(tintell- uride) and new nano-crystalline or nano-wire thermoelectric materials are currently in development stage to improve the conversion efficiency of TEGs. Yang (2005) mentioned BiTe-based bulk thermoelectric material is mostly used in waste heat recovery power generation due to its availability in the market and high applicability in low and high exhaust gas temperature range. The performance of a thermoelectric material can be expressed as $ZT=S^2T/k\rho$, where S is the thermopower, T the absolute temperature, k the total thermal conductivity,and ρ the electrical resistance.

In automotive industry TEG could be coupled with various other devices to maximize its potential. Yu and Chau (2009) has proposed and implemented an automotive thermoelectric waste heat recovery system by adopting a Cuk converter and a Maximum Power Point Tracker (MPPT) controller into its proposed system as tools for power conditioning and transfer. The other exciting development of TEG is the combination of thermoelectric and photovoltaic (PV) systems which can be called as a hybrid system. Zhang and Chau (2011) proposed the TE-PV system coupled with MPPT controller to achieve maximum power output. They reported that the power improvement is recorded from 7.5% to 9.4% when the hot-side temperature of the TEG is heated from 100 ^{O}C to 250 ^{O}C and the irradiance of PV generator (PVG) is fixed at 1000W/m^2.

5. Steam Rankine Cycle

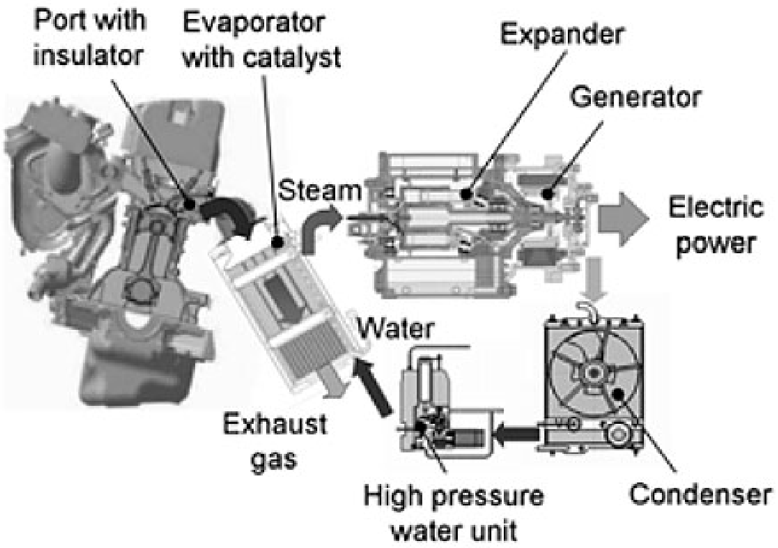
The Rankine cycle is named after William John Macquorn Rankine (July 5, 1820 - December 24, 1872), a Scottish engineer and physicist. Rankine developed a complete theory of the steam engine and indeed of all heat engines. The Rankine cycle is the fundamental thermodynamic underpinning of the steam engine. Steam Rankine cycle is widely used in power generation plants and also as waste heat recovery system for large and slow speed ship's two stroke or four stroke diesel engine propulsion plant.

Figure 4: BMW Turbosteamer, BMW 2011



In automotive application, BMW introduces Turbosteamer (Figure 4) in 2005 (GreenCar Congress 2011) which uses a steam engine to convert waste heat energy into supplemental power for the vehicle. The turbosteamer device salvages the heat wasted in the exhaust and radiator and uses a steam piston or turbine to relay that power to the crankshaft. BMW claimed that the system produces 10 kW power and 20 Nm of torque at peak, yielding an estimated 15% gain in fuel efficiency. Ringler et al. (2009) from BMW Group Research and Technology reported that steam Rankine cycle able to produce 10% additional power output at typical highway cruising speeds .

Figure 5: Honda Rankine Cycle Engine, Rosebro (2008)

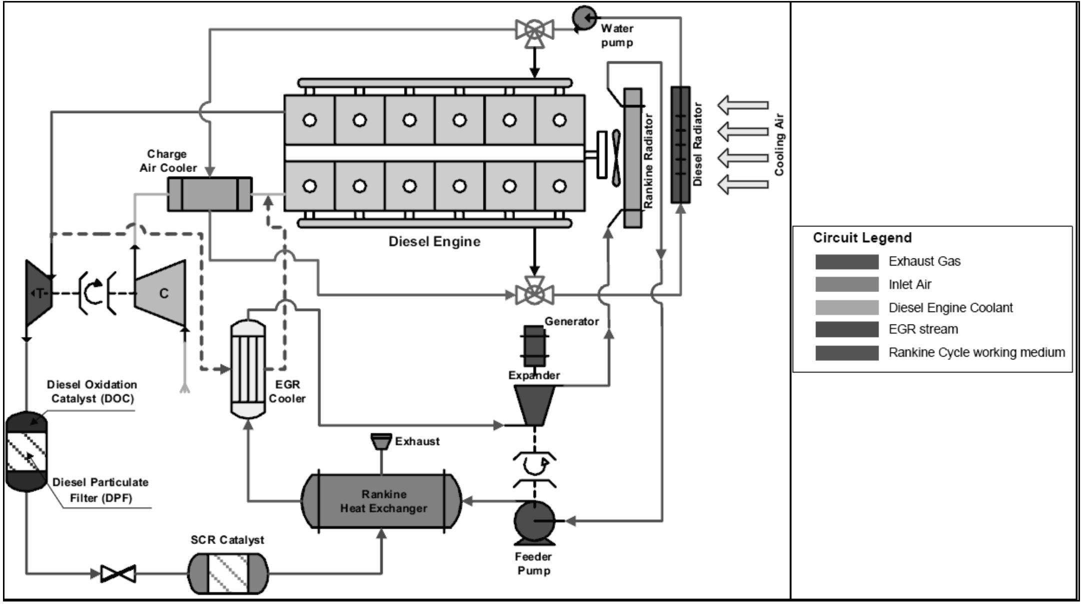


Rosebro (2008) in a Honda's heat-recovery system mentioned (Figure 5) is based on the Rankine cycle, which is also used in most steam-driven power plants. First, heat from the car's catalytic converter is used to boil water. The high-temperature steam (400-500°C) produced then turns an electric generator, before a condenser finally cools the steam back into water. According to Honda, under normal driving conditions, the steam system recovered three times as much electric power as the hybrid's regenerative braking system. Unfortunately, however, the 4% improvement in overall vehicle efficiency that resulted is not high enough to warrant commercialization.

6. Organic Rankine Cycle

The Organic Rankine Cycle (ORC) system is based on the steam generation in a secondary circuit using the exhaust gas thermal energy to produce additional power by means of a steam expander. A special case of low temperature energy generation systems is the use of certain organic fluids instead of water in so-called Organic Rankine Cycle (ORC). This technique has the advantage compared with turbo-compounding that does not have so an important impact on the engine pumping losses and with respect to thermoelectric materials that provides higher efficiency in the use of the residual thermal energy sources. Vaja and Gambarotta (2010) explained that organic fluids are to be preferred to water when the required power is limited and the heat source temperature is low, as these fluids often have lower heat of vaporization and can better follow the heat source to be cooled, thus reducing temperature differences and therefore irreversibilities at the evaporator.

Figure 6: General Layout for the Arrangement of ORC System in On A HD DI Diesel Engine Installation



Hountalas and Mavropolous (2011) in their work (Figure 6) stated that ORC system in a heavy duty direct injection diesel engine was able to achieve 9 to 11% BSFC reduction using 70% expander efficiency. However, the research also concludes that more research are required to address the issue of toxicity, thermal and chemical instability of the organic working fluid.

The selection of a suitable working fluid is quite a daunting task. For most of the organic fluids the vapor tables and saturation curves are unknown. Without the knowledge of the saturation pressures and temperatures it is not possible to evaluate the suitability of a fluid in any given application. Chen et al. (2010) described that each (organic) fluid has its own specific properties. Hence not every fluid can be used in a certain application. Depending on the type of heat source (hot water, exhaust gases) and its temperature level, a suitable working fluid with appropriate evaporation and condensing temperatures has to be selected.

7. Conclusion

From the review, it has been identified that each waste heat recovery technologies offers considerable benefits for practical application. Waste heat recovery defines capturing and reusing the waste heat from internal combustion engine can be utilised thermally, mechanically or electrically and turn into useful energy. It would also help to recognize the improvement in performance and emissions of the engine. If these technologies were adopted by the automotive manufacturers on a commercial basis then it will be result in more efficient engine performance and reduction in low global emission. Future research and improvements on cycle efficiency, materials advancement and packaging will make the system more attractives to policy maker. Mechanical turbo-compounding has long found its way on land applications and companies such as Scania, Volvo, Daimler and Detroit Diesel has already produced their mechanical turbo-compounding engine for long haul usage. The technology still needs to address the issues of low BSFC at low speeds. Electric turbo-compounding have a good future in vehicle application which provides better BSFC reductions with simplicity in design compared to mechanical turbo-compounding. Caterpillar and John Deere are in their final stage of developing production engines with electric turbo-compounding for commercial market. Future work will concentrate to issues such as the efficiency of both electrical machine and turbomachine. TEG generates a lot of research interests lately due to its simplicity, ability to generate electricity in lower heat temperature, involves no moving parts and require less maintenance. BMW also show great interest in their research of TEG for vehicle application. However, their efficiencies are limited due to its dependancy on thermal and electrical properties of material used. It will take quite some time before the technology become prevalent. Steam Rankine offers the highest reduction in BSFC compared to ORC as shown by BMW research group. As for ORC future improvement, factors such as expander efficiency, toxicity and stability of the working fluids remain an interested subject for researchers.

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Appendix 1: Abbreviation

BiTe	Bismuth Telluride
BSFC	Brake Specific Fuel Consumption
CeFeSb	Skutterudite
EGR	Exhaust Gas Recirculation
FGT	Fixed Geometry Turbine
FTP75	US EPA Federal Test Procedure for city driving cycle
GT DRIVE	Gamma Technology Drive
ICE	Internal Combustion Engine
MPPT	Maximum Power Point Tracker
ORC	Organic Rankine Cycle
PbS	Plumbum Sulphide or Lead Suplhide or Galena
rpm	revolution per minute
SCR	Selective Catalytic Reduction
S	thermopower, volts per kelvin (V/K)
SiGe	Silicon Germanium
SnTe	Stanum Telluride
T	absolute temperature, kelvin (K)
TE – PV	Thermoelectric and Photo Voltaic
TEG	Thermoelectric Generator
PVG	Photo Voltaic Generator
US06	Supplemental Federal Test Procedure (SFTP)
US DOE	Unites States Department of Energy
US EPA	United States Environmental Protection Agency
VNT	Variable Nozzle Turbine
Z	Figure of Merit
Z_{tho}	Figure of Merit for low thermal efficiency
ZnBe	Zinc Beryllium
ZnSb	Zinc Antimonide
ρ	Electric resistance, ohm metre (Ω m)