Review of Waste Heat Recovery Mechanisms for Internal Combustion Engines

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The demand for more fuel efficient vehicles has been growing steadily and will only continue to increase given the volatility in the commodities market for petroleum resources. The internal combustion (IC) engine utilizes approximately one third of the chemical energy released during combustion. The remaining two-thirds are rejected from the engine via the cooling and exhaust systems. Significant improvements in fuel conversion efficiency are possible through the capture and conversion of these waste energy streams. Promising waste heat recovery (WHR) techniques include turbocharging, turbo compounding, Rankine engine compounding, and thermoelectric (TE) generators. These techniques have shown increases in engine thermal efficiencies that range from 2% to 20%, depending on system design, quality of energy recovery, component efficiency, and implementation. The purpose of this paper is to provide a broad review of the advancements in the waste heat recovery methods; thermoelectric generators (TEG) and Rankine cycles for electricity generation, which have occurred over the past 10 yr as these two techniques have been at the forefront of current research for their untapped potential. The various mechanisms and techniques, including thermodynamic analysis, employed in the design of a waste heat recovery system are discussed. [DOI: 10.1115/1.4024882]

1 Introduction

The IC engine is approximately one third efficient at converting the energy in fuel to mechanical work. The remaining energy is lost through waste heat that is predominantly rejected from the engine through the cooling and exhausts systems [1]. To improve the fuel economy in automobiles with IC engines, various techniques to recover this waste heat energy are being investigated. Two of the most promising techniques that will be discussed in this paper are thermoelectric generators and the Rankine cycle.

Depending on operating conditions, engine type, and location of the temperature measurement, exhaust gas temperatures average between 500 °C and 600 °C, with maximum values up to 1000 °C [1–4] while the coolant fluid temperatures range between 100 °C and 130 °C [1,5,6]. The heat energy found in the exhaust ranges from 4.6 to 120 kW and from 9 to 48 kW for the coolant system. An illustration of the heat balance of a 1.4 l gasoline engine at two operating conditions can be seen in Fig. 1 [1] while a graph showing exhaust gas temperatures over different engine speeds and torque from a four cylinder gasoline engine can be seen in Fig. 2. [6].

The Carnot cycle, that takes into account the average exhaust gas/coolant fluid temperatures with ambient air temperatures, states that the maximum amount of energy that ideally can be recovered ranges from 1.7 to 45 kW for the exhaust and from 0.9 to 4.8 kW for the coolant system [1].

The recovered exergy or, available useful energy, can be recycled back into the vehicle system either mechanically or electrically. This paper will focus on the use of thermoelectric generators and Rankine cycles as WHR systems that generate electricity. It has been estimated that a WHR system that produces 1.3 kW of electricity can replace the alternator of a small passenger vehicle [7]. Reduction of the engine's mechanical load needed to operate the alternator would result in an increase in vehicle fuel economy. The potential energy that could be recovered would indicate that the net fuel consumption of hybrid vehicles can be improved by as much as 32% [1].

A 2.0 l midsize production vehicle was tested on a chassis dynamometer by Mori et al. [8]. Figure 3 shows the proof of concept of supplying external electric power to the electrical system over three different driving cycles. The improvement in fuel economy could exceed 15% for certain cases. The improvement in the fuel economy was the direct result of supplementing the electrical load

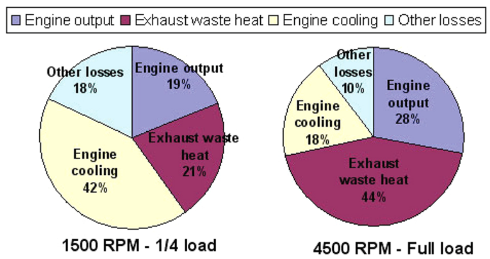

Fig. 1 Heat balance of a 1.4 l spark ignition internal combustion engine [1]

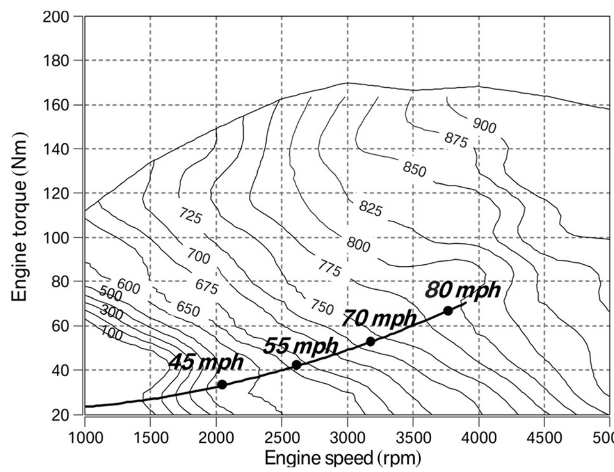

Fig. 2 Exhaust gas temperatures from a four cylinder gasoline engine with stoichiometric combustion [6]

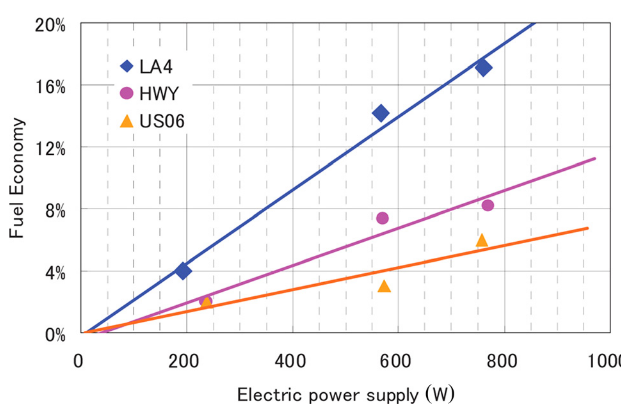

Fig. 3 Effect of external electric power supplied to a 2.0 l midsize production vehicle [8]

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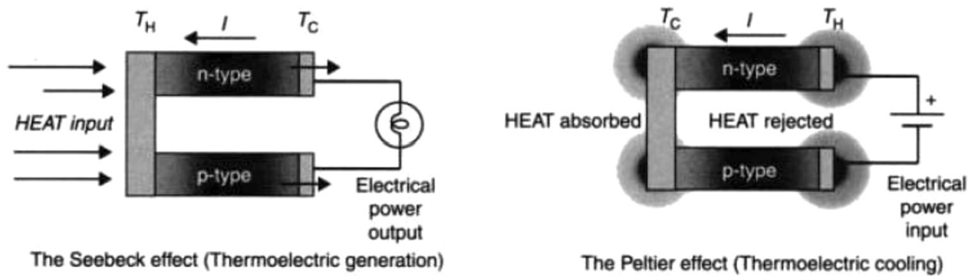

Fig. 4 Schematic of a TE system demonstrating the Seebeck and Peltier effect [9]

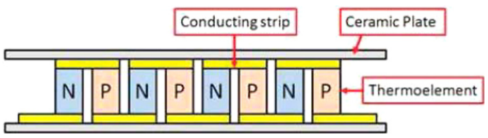

Fig. 5 Schematic showing cross-section of a typical multicouple thermo-electric module [7]

on the engine from the alternator and thus reducing the mechanical load on the engine.

2 Background

2.1 Thermoelectric Principles. Thermoelectric systems are solid state devices that can be used in two basic modes based on either the Peltier effect or the Seebeck effect [9], shown in Fig. 4. The mode that uses the Peltier effect has current going through the TE module which causes absorption of heat on one side of the device and an expulsion of heat on the other. The mode that uses the Seebeck effect has a temperature gradient across a TE module that causes the TE module to generate an electric current. TE modules are made from alternating elements of n-type (negative) and p-type (positive) semiconductors connected electrically in series and thermally in parallel [10]. This can be seen in Figs. 5 and 6.

To measure the efficiencies of these TE modules to generate electricity, a term is defined called the dimensionless figure of merit (ZT) [11]. The equation to calculate the ZT value can be found in Eq. (1). Where S is the Seebeck coefficient, σ is the electrical conductivity, T is the average operating temperature, and κ is the thermal conductivity

$$\mathrm{ZT} = \frac{S^2 * \sigma * T}{\kappa} \quad (1)$$

The current value of ZT for TE systems is around 1.0. To be competitive with current mechanical recovery systems, such as turbochargers, the ZT value for TE systems needs to be around 34 [11]. It should be noted that Srinivasan and Praslad [12] have stated that the ZT needs to be equal to or greater than 8 to compete with conventional electricity generators or vapor compression refrigerators. Although these levels of ZT are not available at this time, lab studies of TE systems that use new materials have been recording ZT values that have exceeded 2 with evidence that it could be improved with additional research. It was estimated in 2008 by Heading et al. [10] that higher efficiency TE systems will be commercially available within the next 5–10 yr. This rapid advancement of TE materials that has increased the ZT for operation around 500 °C has made TEG good candidates for waste heat recovery for automotive purposes [10].

The thermal efficiency of any exhaust-based TEG is controlled by four main factors; heat exchanger geometry, heat exchanger materials, the installation site of the exhaust-based TEG, and the coolant system of the exhaust-based TEG [13].

2.2 Rankine Cycle Principles. The Rankine cycle is a thermodynamic cycle dedicated to generate mechanical work from heat. This mechanical work can be converted into electrical energy [1].

The ideal Rankine cycle, seen in Fig. 7, consists of the following processes [1]:

1–2: compression of a working fluid in a pump
2–3: constant pressure heat addition in a boiler
3–4: isentropic expansion through a turbine
4–1: constant pressure heat rejection in a condenser

Irreversibilities, such as fluid friction and heat transfer, contribute to differences between the actual cycle efficiency and the ideal Rankine cycle prediction.

The choice of the working fluid in the Rankine cycle for automotive WHR systems is important. The use of water as the working fluid becomes inefficient for WHR at temperatures below 370 °C [14,15]. The use of an organic fluid instead of water to recover heat energy at temperatures below 370 °C increases the Rankine cycle efficiency [14–16]. A graph of efficiencies of numerous working fluids over a range of the inlet temperature of the turbine can be seen in Fig. 8. A Rankine cycle that utilizes organic fluid is termed an organic Rankine cycle (ORC). The three

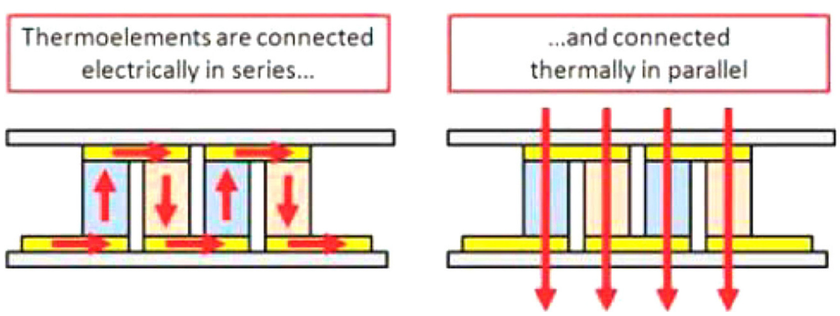

Fig. 6 Electrical and thermal conduction paths of a multicouple thermo-electric module [7]

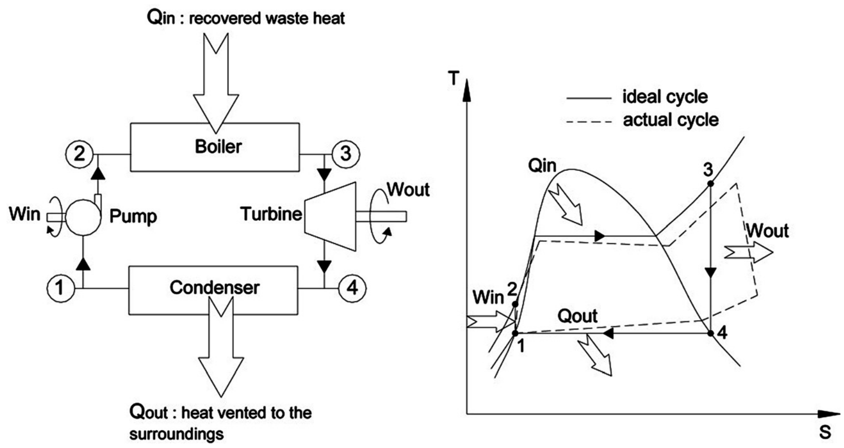

Fig. 7 Rankine cycle system and its ideal—actual cycle [1]

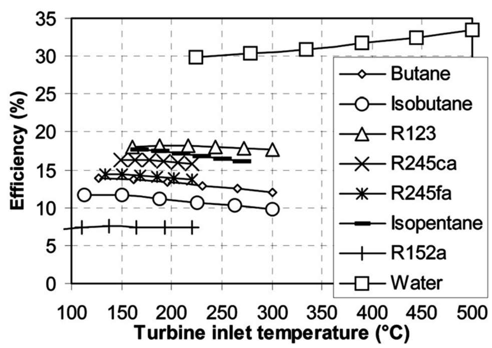

Fig. 8 Rankine cycle efficiency for various turbine inlet temperatures [1]

categories of working fluid are dry, wet, and isentropic. They are determined by the slope (dT/ds) of the saturated vapor line on the temperature-entropy (T–s) diagram; dry is positive, wet is negative, and isentropic is infinite as shown in Fig. 9. ORC systems use dry or isentropic type for the working fluid because they are superheated after isentropic expansion. This eliminates the need of a superheated apparatus because there is no longer a concern that liquid droplets would form on the turbine blades [15].

3 Design Considerations to Address

There is a considerable number of design and technological issues within these two WHR techniques but these techniques also have unique issues of their own.

3.1 Common Issues Related to WHR Systems

3.1.1 Backpressure. With the installation of a WHR system in a vehicle exhaust system, the engine backpressure will increase resulting in reduced engine volumetric efficiency and thus reduced fuel conversion efficiency. This restriction is caused by direct obstruction of the exhaust gas flow, or by the reduction in temperature of the exhaust gas or by a combination of both [8]. An experiment conducted by Mori et al. [8] on a 2.0 l midsize production vehicle showed the effect of additional mean backpressure to the fuel economy during three different driving modes. The results of the study are shown in Fig. 10.

However, the effect of increased back pressure within the coolant system on fuel economy was negligible [8].

3.1.2 Weight. The added weight of WHR systems on an automobile will negatively affect the total gain in fuel economy. It has been a widely published concern although the additional weights of these systems have not been disclosed.

3.1.3 Thermal Power Fluctuations. The thermal power sources of waste heat in an IC engine are highly dynamic. They are a function of mass flow rate and temperature. The dynamic changes that occur with the mass flow rate and temperature will greatly affect the heat transfer to the WHR system. This will cause the overall performance of the WHR system to degrade from its optimum [17].

3.1.4 Cold Reservoir Reliability. To properly recover the wasted heat from the exhaust, a compact heat exchanger similar to a radiator would need to be integrated. The air flow on the underside of the car is not consistent compared to the airflow that is being applied to the coolant system radiator. Due to this fact, it is difficult to regulate dependable heat transfer to the cold reservoir (ambient air) which will diminish the efficiency of the system [18].

3.1.5 Type of Engine. The comparison of two engine types for light-duty vehicles concluded that spark ignition engines are more favorable for WHR systems because they generally have higher exhaust gas temperatures and lower exhaust gas flow rates [19].

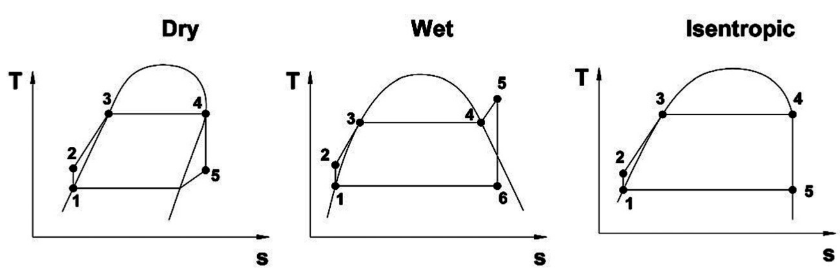

Fig. 9 T-s diagram for dry, wet, and isentropic fluids [1]

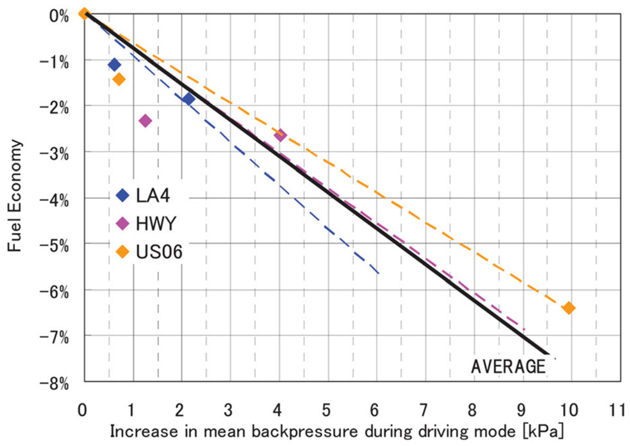

Fig. 10 Effect of backpressure supplied to a 2.0 l midsize production vehicle [8]

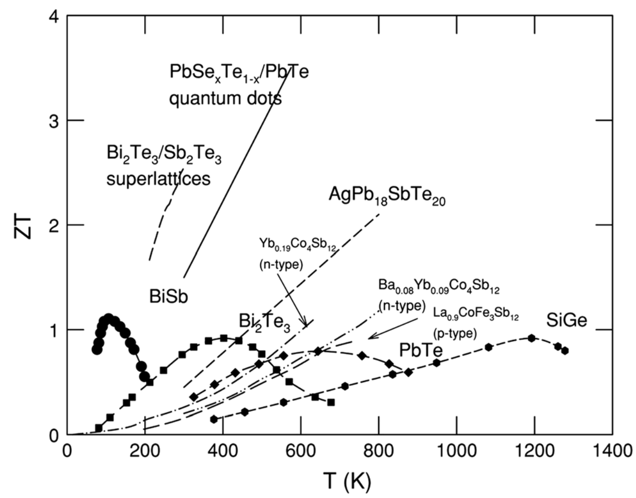

Fig. 11 "ZT versus T for state-of-the-practice (symbols with lines) and state-of-the-art materials (lines only)" [3]

3.1.6 Coolant or Exhaust Energy Streams. As was stated earlier, the exhaust system has a greater potential to convert waste heat into mechanical work compared to the cooling system. Thus, the location of the WHR system generally resides in the exhaust system [20].

The highest temperatures and heat energy in the exhaust system would be found before and in the catalytic converter. Although this would permit larger amounts of WHR, it is not recommended to remove heat from the catalytic converter since this could decrease its conversion efficiency if enough energy was extracted. [8]

3.1.7 Expense/Complexity/Size. The added expense, complexity, and size of WHR systems have hindered significant implementation. Generally, to utilize a larger quantity of waste heat would require an increase in the system complexity and thus increased expense and size [1,6].

As was stated by Smith and Thornton [21], "Current TE system costs of \$3000 to 6000/kW must be reduced substantially, to about \$450/kW for the class 8 truck platform application, to become economically justifiable." They went on to mention that this reduction in cost might come as a result of using thin-film devices that use expensive TE junction materials more efficiently.

3.2 Thermoelectric Device Issues

3.2.1 Thermoelectric Materials. A high ZT value of TE materials over certain temperature ranges is crucial to the success of TEG as WHR systems. The key to this WHR technique will continue to be the development of new TE materials with increased TE efficiency [22].

3.2.2 Longevity. Although thermoelectrics have been known to have long productive life spans in certain applications, a great deal of planning must be done to get the most power out of these devices while protecting their durability. "Efficient operation of the TEG heat exchangers over the life of 10 yr–30 yr of a vehicle is a concern. The effect of material buildup on the heat exchanger surfaces from exhaust gas, coolant, or air is basically unknown and needs research to ensure that it does not excessively degrade system operation" [3].

As seen in Fig. 11, the ZT values of high-ZT materials peak only relatively lower than the material degradation (melting, sublimation, etc.) temperatures. This is a cause for concern since the goal of TEGs as WHR systems is to maximize the amount of electrical energy generated. As the temperature decreases from the optimum setting, the ZT value decreases significantly. Therefore, the efficiency of the TEG will be proportionally lower at these lower temperatures. The materials in the TEG must be able to either withstand the highest possible temperatures found in either the coolant or exhaust systems or must be protected from these potentially devastating high temperatures by other means [4,17].

3.2.3 Stress. Most thermoelectric materials are brittle semiconductors. Any microfractures in the thermoelectric materials will reduce the TEG's ability to generate electricity. In the case of using TEG's in automotive applications, the stresses from thermal gradient, thermal cycling, and vibrations may cause; fractures within the TE materials, increases in the electrical resistivity, decreases in the material's ZT value, and reduction in the lifetime of the TEG [3,4].

3.2.4 DC-DC Converter Loses. The relatively low output voltages of thermoelectric WHR systems will need to be raised to a level that is compatible with the vehicle's electrical system. The dc–dc converter losses will affect the total increase in fuel economy. The issue of dc–dc converter losses becomes more important when high voltages are needed for Hybrid Electric Vehicle applications [23].

3.3 Rankine Cycle System Issues

3.3.1 Working Fluid Selection. Most organic fluids suffer chemical decomposition and deterioration at high temperatures and pressures. Although water does not have this issue, it does have shortcomings of high operating boiling pressure, low condensing pressures, and high triple-point temperatures that does not make it an ideal fluid for Rankine bottoming cycles for automotive applications [1].

The environmental aspects of the organic working fluid such as global warming potential and ozone depletion potential have to be a consideration in selecting the working fluid [1]. Organic fluids prevent freezing and air infiltration problems that can occur in similarly designed steam Rankine systems [1].

3.3.2 Components Design. The working fluid and operating conditions can greatly influence the design of the turbine since they influence the power density, pressure ratio, volumetric flow, and maximum operating pressure [1]. The heat exchanger (boiler and condenser) dimensions and cost are dependent on the thermal properties of the operating fluid, mass flow rates, operating pressures, and the Rankine cycle system efficiency. The mass flow rate is significant because higher mass flow rates require large collectors and flow passages in order to avoid excessive pressure drop. The operating pressure of the working fluid is influential as it will affect the heat exchanger mass due to the metal thickness that will be required [1].

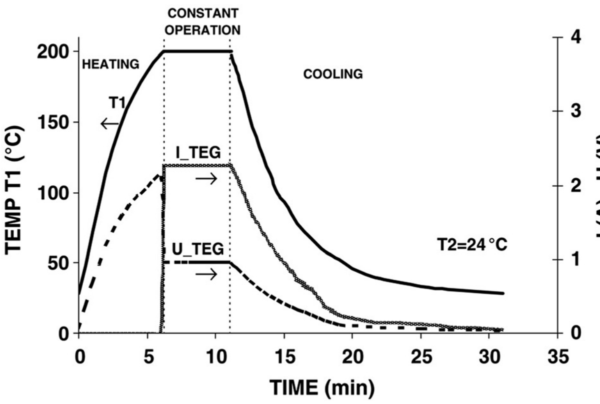

Fig. 12 The heating–cooling cycle performed [4]

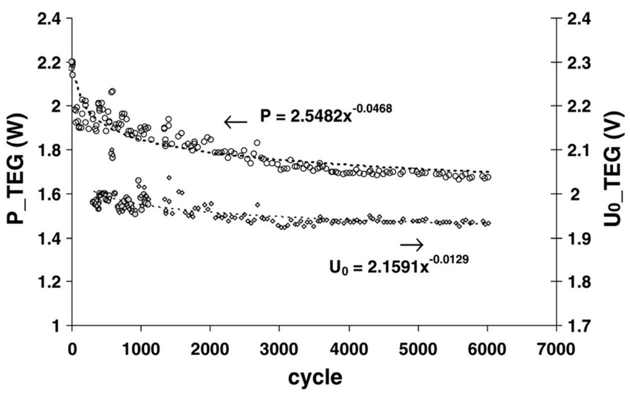

Fig. 13 "TEG's maximum gained power (P) and EMF (U_0) during the reliability test" [4]

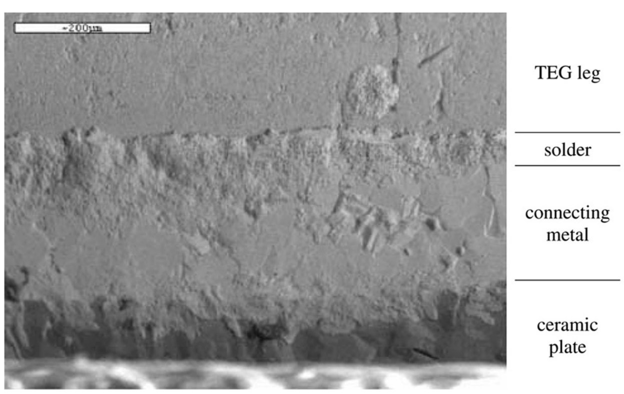

Fig. 14 Scanning electron microscope micrograph for a TEG before 6000 thermal cycles [4]

3.3.3 System Pressure. The efficiency of the system increases as the system pressure increases; however, it may not be realistic to pursue this direction due to cost, complexity, and material selection of the components [1].

3.3.4 Safety. The safety aspects of toxicity, maximum operating pressure, and flammability have to be considered [1].

4 Technology Advancements/Studies

4.1 Thermoelectric. There was a study performed by Hatzikraniotis et al. [4] to determine the longevity of a TEG in an environment similar to that found in vehicles. This test involved 6000 sequential heating–cooling cycles over a time period of 3000 h.

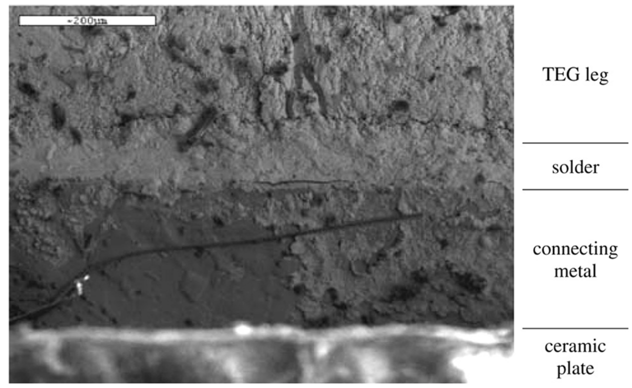

Fig. 15 Scanning electron microscope micrograph for a TEG after 6000 thermal cycles [4]

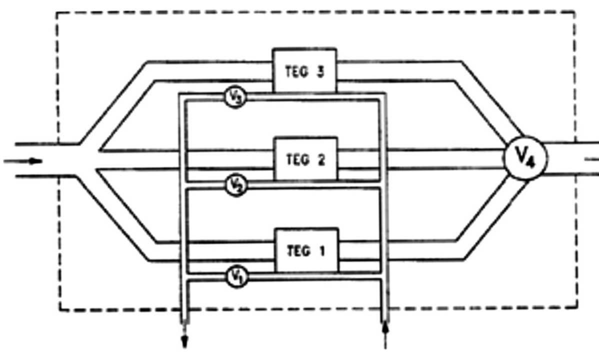

Fig. 16 Schematic diagram of a multiple section TE power generator system without an intermediate loop [17]

The TE material used was 2.5 cm × 2.5 cm Bi2Te3–based modules (Melcor HT9 – 3 – 25) and the module consisted of 31 thermocouples. The hot reservoir fluctuated from 30 °C to 200 °C while the cold reservoir stayed constant at 24 °C. The graph of the thermal cycle and the generated amperage and volts can be seen in Fig. 12.

The abrupt changes in the first 15 cycles could have been the contribution by the thermal grease being deteriorated caused by the elevated temperatures. The ZT value decreased from 0.74 to 0.63 and was accompanied by a 6.6% decrease in the average leg thermal conductivity, a 3.8% decrease in the Seebeck coefficient, and a 16.1% increase in resistivity. The gained power and electromotive force (EMF) was reduced by 14% and 3.3%, respectively [4]. These results of the experiment can be found in Fig. 13.

Using a scanning electron microscope, Figs. 14 and 15 reveal the physical effects of 6000 thermal cycles on the tested TEG. Notice how the TE material degraded and there is evidence of a microfracture in the connecting metal.

Realizing that TE systems are only optimized for a small range of temperature and mass flow rate, an experiment by Crane and Bell [17] utilized a three section system that had each section optimized for different operating conditions. The multiple sections allowed for the TE system to adjust to the constantly changing environment to insure the maximum amount of electricity could be generated. This system would be regulated with a controller and valves. An example of such a system can be seen in Fig. 16. To minimize the influence of fluctuations in the operating conditions, an intermediate loop was added to the system, which is shown in Fig. 17.

Improvement in the power output percentage was consistently increased over an exhaust gas mass flow rate range of 5–40 g/s. The largest increases occurred when the exhaust gas mass flow was very low (5 g/s). The lowest improvement was around the

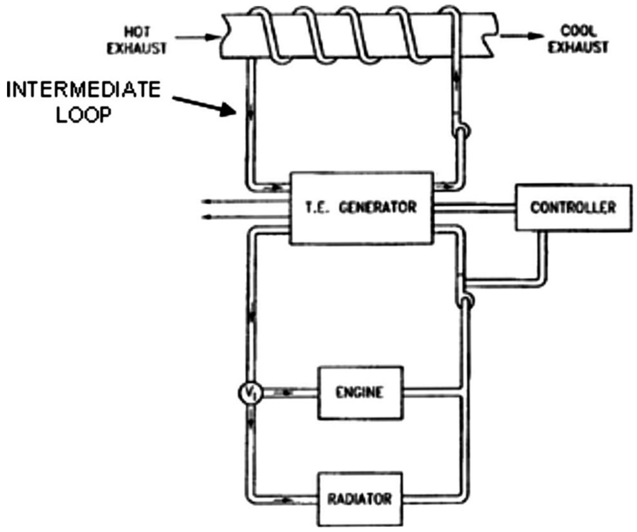

Fig. 17 The schematic for a multiple TE power generator system with an intermediate loop between the exhaust pipe and the TE generator [17]

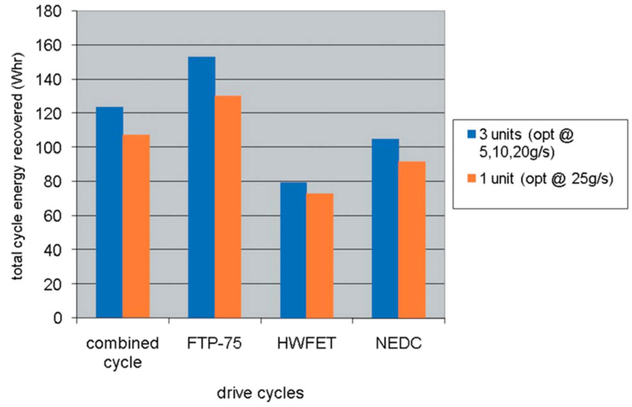

Fig. 19 Comparing the total cycle energy recovered (W/h) for four different drive cycles that used a single section system (optimized at 25 g/s) to that of a three section system (optimized at 5, 10, and 20 g/s) [17]

exhaust gas mass flow rate of 20–25 g/s but increased as the mass flow rate increased or decreased from this amount. The performance improvements over traditional single section TE devices are in the range of 90% at low mass flow rates and 25% for high mass flow rates. These data can be found in Fig. 18.

The total cycle energy recovered was measured on four different drive cycles for both a single section TE system and a three section TE system. These drive cycles were FTP–75 city cycle, the HWFET highway cycle, the combined city and highway cycle, and the European NEDC drive cycle. The results found in Fig. 19 show that the three section TE system outperforms the single section TE system for all four drive cycles because the three section TE system can be optimized for three different heat energy conditions instead of just one.

The performance improvement for the four different drive cycles can be found in Fig. 20, which illustrates an increase from roughly 9–18%.

A system level optimization study by Mori et al. [5] that used a validated model was performed to find the potential of a cross flow heat exchanger that had hot reservoir characteristics of the coolant flows of an IC engine. The system would take the place of a traditional radiator and thus would have the cold reservoir consisting of ambient air flowing over the heat exchanger. The schematics of the simulated system can be seen in Figs. 21 and 22. "The results show that a net power output of 1 kW can be achieved for a modestly sized heat exchanger core such that the net power density based on heat exchanger volume is 45 kW/m^3. Optimization for a power/cost ratio objective function with a minimum net power requirement of 1 kW indicated that the power per cost can reach as high as 1.1 kW/$10,000" [5].

4.2 Rankine Cycle. A study conducted by Arias et al. [24] evaluated the potential energy recovery in a practical hybrid implementation. The Toyota Prius hybrid was used as inputs for the vehicle/energy recovery model. It was found that the exhaust temperatures for this vehicle were lower than what was expected. This lower temperature accounted for a poor average recovery rate of 0.8% of the total fuel energy and about 1.8% of the total available waste heat. The system was modified to utilize the heat from the engine block, seen in Fig. 23. The engine block was used to boil the working fluid in the power cycle and the high temperature exhaust gases were then used to superheat the fluid. This

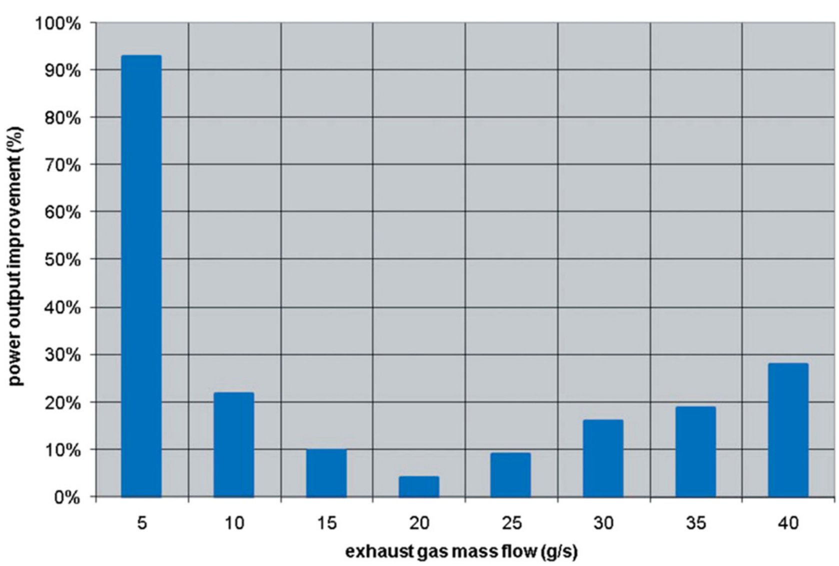

Fig. 18 The power output improvement (%) for a given exhaust gas mass flow (g/s) by using a three section system compared to a single section system [17]

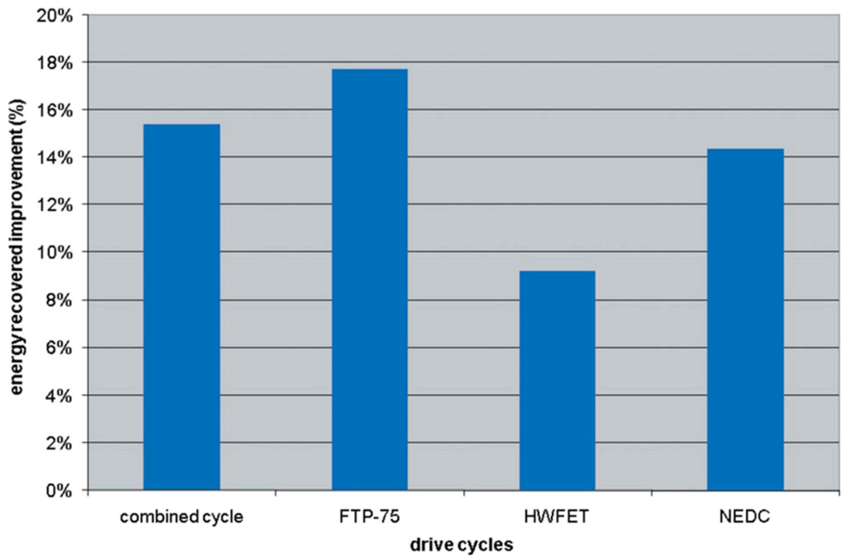

Fig. 20 The percent improvement of energy recovered for the four drive cycles for the three section system over the single section system [17]

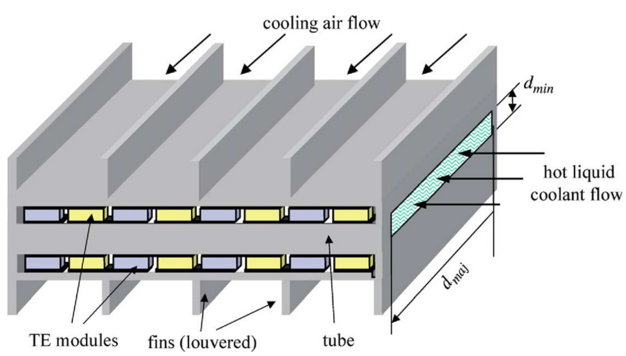

Fig. 21 Schematic showing layout of subsection of thermoelectric heat exchanger [5]

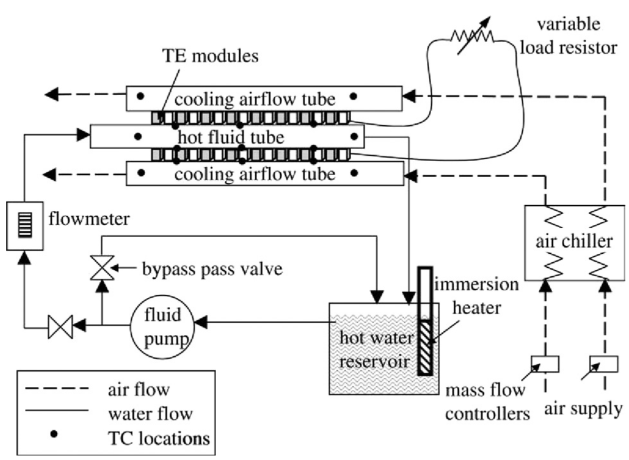

Fig. 22 Schematic of counter flow TE heat exchanger [5]

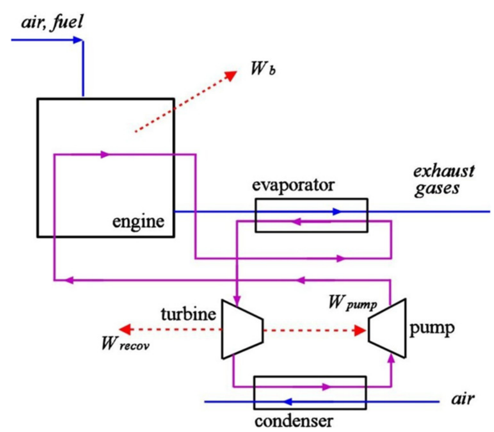

Fig. 23 Schematic of the Rankine cycle utilizing the engine and exhaust gas waste heat [24]

combination of WHR resulted in an average recovery rate of 5.5% of the total fuel energy and about 7.5% of the total available waste heat.

In a study from Teng et al. [25], an ORC system was proposed for a heavy-duty diesel engine. The working fluid that was used was categorized as a dry fluid with a critical pressure less than 70 bars. This ORC WHR system had different pressures in the charge air cooler, the low-temperature exhaust gas recirculation (LT-EGR), the exhaust cooler, and the high temperature exhaust gas recirculation (HT-EGR) cooler. This was done to improve system performance, reduce system cost, and avoid possible phase change in the EGR coolers. It was decided that heat rejection from the radiator would be excluded in the WHR system because its energy level was close to that of the ambient. The negative effect of requiring a larger condenser size, if the heat rejection from the radiator was included, also helped the decision to exclude it. A schematic of the proposed system can be found in Fig. 24.

"The case study showed that up to 20% increase in the engine power could be achieved by the WHR system without additional fuel consumption. It was demonstrated that, with the hybrid power system of the diesel engine and the Rankine engine operated with waste heat, substantial enhancement in the engine power, improvement in fuel economy, and deduction in specific emissions can be achieved" [25].

A study by Mago et al. [26], explored how the use of regenerative ORC over a basic ORC would affect the amount of exergy destroyed during the Rankine cycle process. Reducing the amount of exergy destroyed during the Rankine cycle would help increase the efficiency of the entire WHR system. The schematic of a regenerative ORC can be found in Fig. 25.

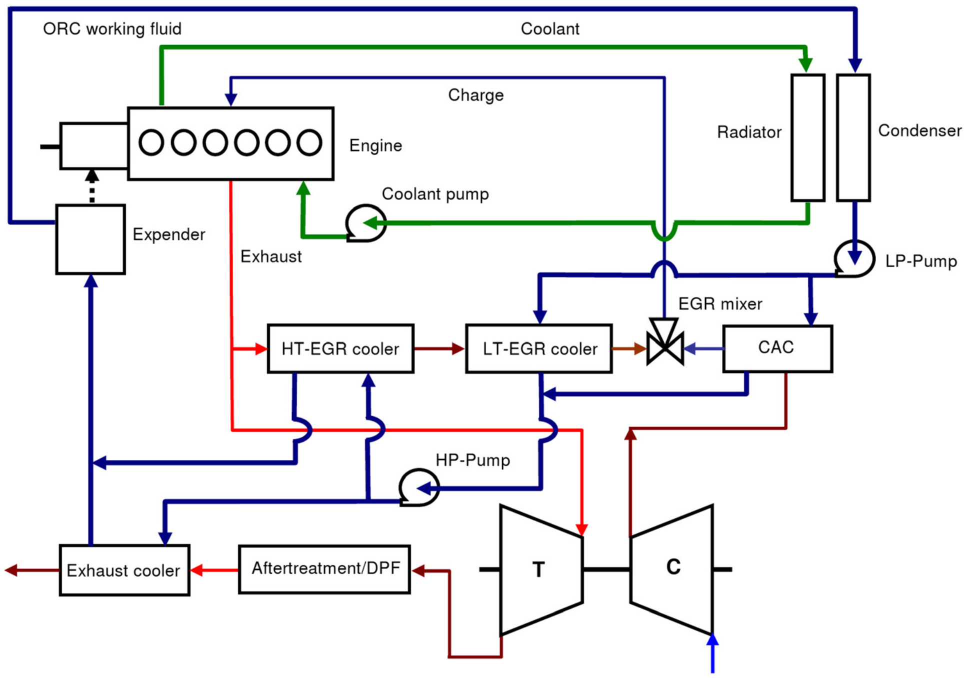

Fig. 24 An ORC-WHR system with integrated low-temperature cooling loop [25]

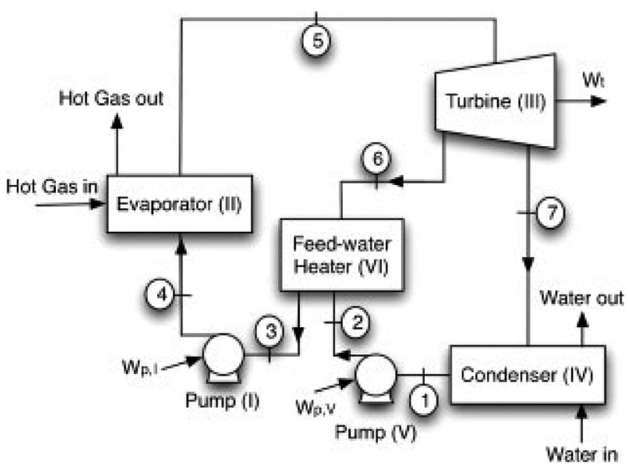

Fig. 25 Schematic of a regenerative ORC [26]

The regenerative ORC produced higher thermal/exergy efficiencies, a higher degree of thermodynamic perfection, and a lower total system exergy loss compared to the basic ORC system.

It was found that the evaporator is the component, in ORC systems, with the highest influence coefficient and highest exergy loss with respect to the overall system exergy loss. The exergy loss was reduced in regenerative ORC systems from 77% to 40.4% because the working fluid was more gradually warmed up by the presence of the feed-water heater.

The thermal and exergy efficiencies increase along with a decrease in system total exergy loss with the increase in the evaporator pressure. The increased evaporator pressure will bring the temperature of the organic fluid closer to the temperature of the hot gas entering the evaporator with heat transfer occurring over a lower temperature difference.

5 Conclusions

The use of waste heat recovery systems in automobiles has shown substantial potential to increase fuel economy. The two main WHR systems for automotive applications were found to be thermoelectric generators and Rankine cycle electrical generators. The design considerations for these systems include; backpressure, weight, thermal power fluctuations, cold reservoir reliability, dc–dc converter loses, type of engine, coolant or exhaust energy streams, expense, complexity, and size. Additional considerations for thermoelectric material, longevity, and stress are needed for thermoelectric generators while working fluid selection, component design, system pressure, and safety are needed for Rankine cycles. Over the past 10 yr, these issues have been addressed by a number of different case studies and advances in technology which will assist in making these techniques for waste heat recovery in automobiles economically and technologically a reality.

Nomenclature

CAC = charge air cooler
EGR = exhaust gas recirculation
EMF = electromotive force
HT = high temperature
IC = internal combustion
LT = low temperature
ORC = organic Rankine cycle
P = power
U_0 = electromotive force
s = entropy
S = Seebeck coefficient
T = operating temperature
TE = thermoelectric
TEG = thermoelectric generator
WHR = waste heat recovery
ZT = dimensionless figure of merit
κ = thermal conductivity
σ = electrical conductivity

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