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Waste heat recovery systems for internal combustion engines: A review

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Abstract

Energy and ecology are the most critical issues the world has been facing for the decades. With the progress of the modern world, the shortage of the energy content become acute when a significant portion goes to waste. The necessity for the fuel efficient vehicles is getting intensified not only to save the fuel but also to preserve the ecology. The effective energy conversion from a conventional IC engine is nearly 30-35% and the rest of the energy is expelled through the waste heat dissipation and engine cooling. To minimize the energy loss, thereby, to maximize the efficiency of the internal combustion engine and waste heat recovery systems (WHS) are being researched a lot, especially for the application in automobiles. Various techniques have been developed for the waste heat recovery, namely thermoelectric generator, Rankine cycle electricity generation, drying processes which finally help not only to save fuels but also for reducing the overall exhaust gas emission as well as the global greenhouse gas (GHG) reduction. This paper organizes and summarizes the main themes along with the recent progress and developments about different types of direct and indirect waste heat recovery systems, their quality of energy recovery and field of applications for internal combustion engines.

Introduction

Waste heat losses arise both from equipment inefficiencies and from thermodynamic limitations on equipment and processes. For instance, the need for many systems to reject heat as a by-product of their operation is fundamental to the laws of thermodynamics. Figure 1 shows the energy balance of an IC engine. However, instead of being "wasted" by release into the ambient environment, sometimes waste heat (or cold) can be utilized by another process (such as using hot engine coolant to heat a vehicle), or a portion of heat that would otherwise be wasted can be reused in the same process if make-up heat is added to the system. Currently, up to 65% of the heat energy produced in internal combustion engines (ICEs), whether gasoline or diesel is wasted [1]. The exhaust heat is the largest source of waste energy in ICEs [2].

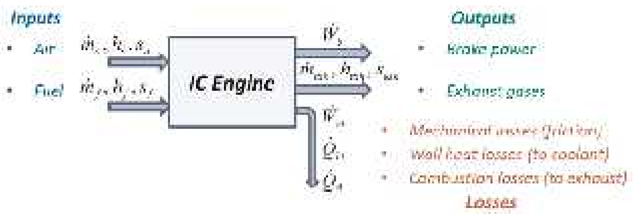

Figure 1. Block diagram for IC engine energy balance [2].

However, there is a dire lack of information on the source of the largest waste heat losses in different sectors and processes and the nature of different waste heat sources (e.g., the waste heat quality and chemical composition) — knowledge of these factors is critical in determining the feasibility and extent of opportunity for waste heat recovery. This study summarizes the main themes along with the recent progress and developments about different types of direct and indirect waste heat recovery systems, their quality of energy recovery and field of applications for internal combustion engines. This study can be used further by researchers working in the field of research and development sectors of waste heat recovery of internal combustion engines.

Factors Affecting Waste Heat Recovery Feasibility

Evaluating the feasibility of waste heat recovery requires characterizing the waste heat source and the stream to which the heat will be transferred. Important waste stream parameters that must be determined include—

- Heat quantity
- Heat temperature/quality.
- Composition.
- Minimum allowed temperature.
- Operating schedules, availability, and other logistics.

These parameters allow for analysis of the quality and quantity of the stream and also provide insight into possible materials/design limitations.

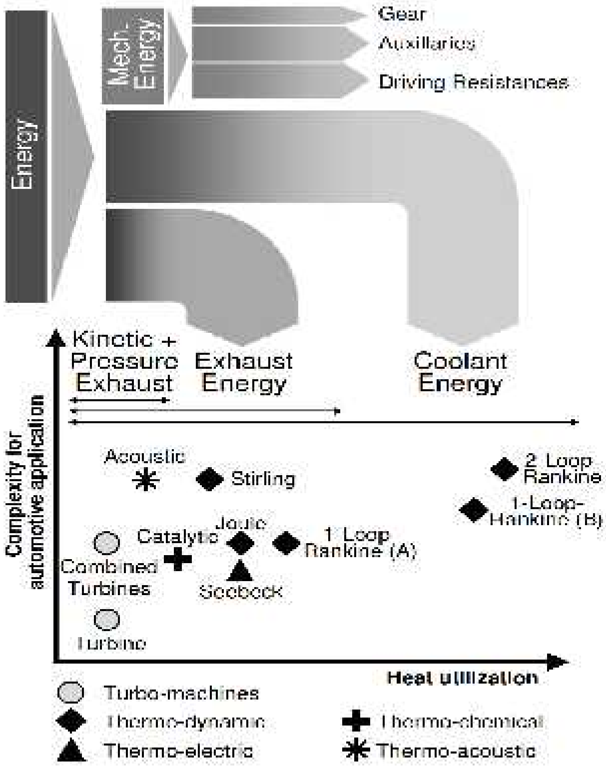

Figure 2. Energy utilization vs. complexity of different heat recovery systems [3].

Waste Heat Recovery Technologies for IC engines

There are numerical ways of waste heat recovery technologies for ICEs. The most important ones: direct and indirect are discussed here.

Direct Electrical Conversion Devices

Thermoelectric Generation

A TEG usually consists of pairs of doped n- and p-type semiconductors connected thermally in parallel and electrically in series. When one of the junctions is at a different temperature than the other, a direct electric current flows in the circuit. The magnitude of the current depends on the specific thermoelectric properties of the two materials and on the temperature difference between the two junctions. The operating temperature range of a TEG depends on the materials employed. For example, a bismuth-tellurium system is suitable for relatively low temperature operation (room temperature to 200°C), whereas silicon-germanium alloys work best for high temperature applications (>800°C). For moderate temperature (T = 500 to 800°C), heat sources such as a vehicle's exhaust and industrial waste heat, half-Heusler types are the material of choice.

In 2015, a demonstration of the TEG's ability to convert a vehicle's waste heat into electricity was performed for the Army's TARDEC (Tank Automotive Research, Development and Engineering Center) program. For that program, GMZ Energy successful demonstrated a 1,000 W TEG designed for diesel engine exhaust heat recapture. The company integrated five 200W TEGs into a single 1,000 W diesel engine solution that directly converts exhaust waste heat into electrical energy, which increases fuel efficiency and lowers overall costs. Figure 3(a) and 3(b) show the construction and interconnections of the 1000W TEG [4].

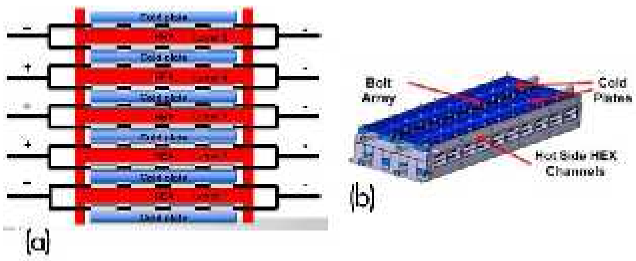

Figure 3. 1000W TEG module showing a) the complete module, and b) Interconnection of individual TEG8-1.0 units [4].

Thermionic Generation

Thermoelectric generators have the capability to directly convert waste heat from the hot engine exhaust into electricity that can power vehicle auxiliary loads and accessories. Thermoelectric generators consist of an array of semiconductor elements that produce a voltage when placed across a temperature gradient without releasing the carbon dioxide and other emissions that typically result from fossil fuel consumption.

Recently, Zhang, an assistant professor with Boise State's department of mechanical and biomedical engineering, worked on a project "Nanostructured High-Temperature Bulk Thermoelectric Energy Conversion for Efficient Automotive Waste Heat Recovery". The process developed by Zhang and his research partner uses post catalytic converter heat exchangers to remove heat from the exhaust gases and deliver it to the thermoelectric devices, which convert the heat to electricity [5].

Exhaust gas heat recovery system (EGHR)

The system was first used used on 2016 Chevrolet Malibu Hybrid. Unlike other technologies, it doesn't generate electrical energy from waste heat to recharge the battery. Instead, the electrified Malibu uses waste heat to warm the cabin interior as well as the engine, raising the latter to peak operating temperature quickly, and keeping it there. While that may all sound underwhelming, the boost to fuel economy – especially in the colder months – is measurable. It also allows for a further reduction of NO_2, almost as big an opponent to clean air as carbon. The EGHR system in the 2016 Chevrolet Malibu is kind of like that old Native American principal of using every part of the buffalo; what once was waste is wasted no longer.

Generating Power via Mechanical Work

Rankine Cycle

The 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 uses 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. Waste heat recovery from rankine cycle operated at low temperature difference using unconventional fluids (refrigerants, CO_2, binary mixtures) is shown in Figure 4. At very low heat source temperature the trans-critical CO_2 cycle produces highest net power output [9]. Rankine bottoming cycle techniques maximize energy efficiency; reduce fuel consumption and green-house gas emissions.

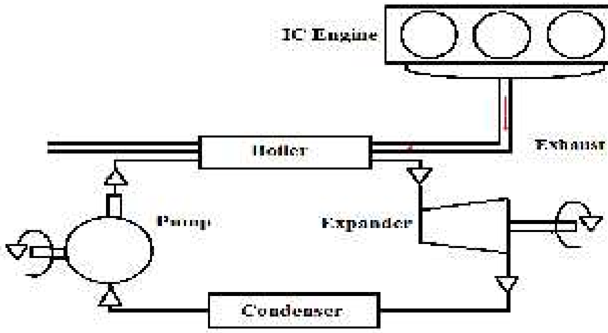

Figure 4. Rankine cycle.

Recovering engine waste heat can be achieved via numerous methods. The heat can either be reused within the same process or transferred to another thermal, electrical, or mechanical process [8]. Analysis shows that evaporator pressure gives better efficiencies. Pinch point temperatures, heat exchangers cost, critical temperature of working fluid would be a restriction for maximum working pressure of cycle. Organic rankine cycles as in Combined Heat and Power units are options to improve total efficiency and reduce the cost [10]. Waste heat recovery using Organic rankine cycle is an efficient method compared with the other techniques; so automobile manufacturers use this method to enhance the efficiency of their products [11]. The heat recovery is can be done and increases with increasing exhaust mass flow rate [12].

Stirling Cycle

A Stirling engine is a heat engine operating by cyclic compression and expansion of air or other gas, the working fluid, at different temperature levels such that there is a net conversion of heat energy to mechanical work [13]. Free Piston Stirling Engine is shown in Figure 5. Developments of gamma type Stirling engine which operate at high temperature difference to find out the optimum temperature difference at which model would give maximum thermal efficiency [14]. Waste heat recovery from internal combustion engine analyzed with two different fluids by using organic rankine cycle. The best performance was obtained when R-123 was applied as the working fluid. [15-16]. The free piston Stirling engine couples with a pneumatic cylinder And results by simulation shows the Output power from numerical simulation was higher than that of experiment according to theoretical assumptions [17]. Gamma type Stirling engine was design and developed for application of waste heat recovery system. The performance of low temperature difference Stirling engine was investigated. A twin power piston gamma configuration low temperature differential Stirling engine is tested with non-pressurized air by using solar simulator and conclude that Stirling engine working with relative low temperature air of potentially attractive future engine [18]. Figure 5 shows the construction principle of a free piston Stirling cycle.

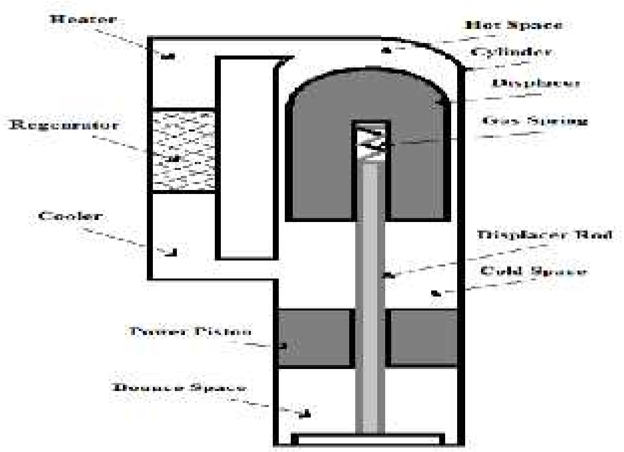

Figure 5. Free Piston Stirling Cycle.

Vapour Absorption Refrigeration Cycle

Many researches have been conducted regarding vapour absorption refrigeration cycle on IC engine [19-30]. In vapour absorption refrigeration cycle, heat is provided at generator which generates the refrigerant vapours. These vapours are then condensed in condenser by losing heat. The high pressure liquid refrigerant is then throttled through expansion valve to lower pressure at evaporator. The refrigerant at such lower pressure and temperature evaporates and produces cooling effect. The refrigerant vapours then pass to absorber. The weak solution in absorber absorbs the refrigerant vapours and the solution is pumped to higher pressure to generator by a pump. The weak solution from generator is fed back to absorber where it absorbs the refrigerant vapours coming from evaporator.

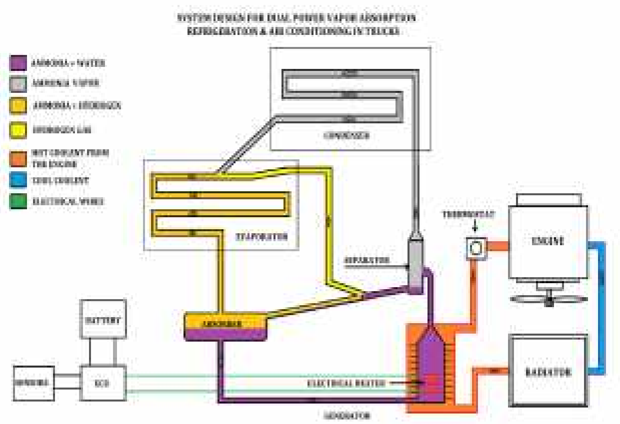

Figure 6. Vapour Absorption Refrigeration Cycle for an IC engine [6].

Turbo-compounding

In a turbocompound engine, a power turbine is added in the exhaust line to extract energy from the wasted exhaust. Fig. 1 shows a conventional turbocompound engine in which a power turbine is added after the turbocharger turbine and it is connected to the engine crankshaft mechanically. The main drawback of turbocompounding is its high exhaust back-pressure in the exhaust manifold before the turbocharger turbine which makes the expelling of the burned gasses from the combustion chamber difficult. This means that the engine needs to work more to expel these burned gasses. In contrast to Rankine cycles and thermoelectric generators, the turbocompound interacts with the exhaust flow and causes back-pressure on the engine. This results in negative pumping work (pumping loss) on engines [31].

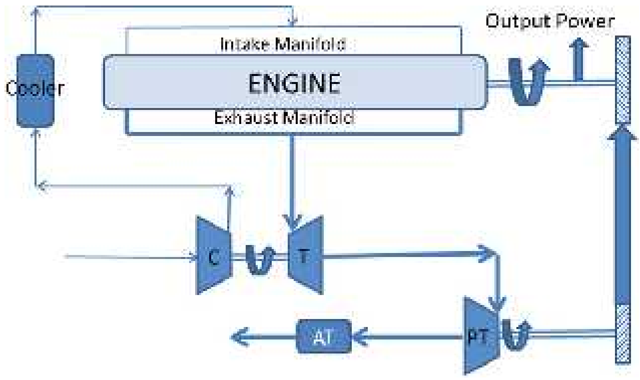

Figure 7. Mechanical (conventional) turbocompounding [33].

This leads consequently to lower brake specific fuel consumption (BSFC) reduction compared to other WHR systems. In addition to the pumping loss, higher exhaust back-pressure on the engine results in increased residual gases, delayed combustion, increased heat transfer in the cylinder, and disruption of global engine thermodynamic balance [32].

Other Technologies

Other technologies are being researched at present for the utilization of waste heat of IC engines. Other technologies include utilization of heat exchangers, recuperator, regenerator, passive air preheaters, and finned tube heat exchanger for ICEs exhaust waste heat recovery. Waste heat energy can be utilized not only for increasing the efficiency of the engine, but also for other applications, for example, the waste heat of stationary ICEs can be utilized for food drying technology.

Conclusion

Now-a-days, different automobiles, including passenger cars (BMW, Honda, Exoes, Barber Nichols, FVV) and trucks, are being industrially manufactured with waste heat recovery technology [34-37]. But the research should be carried on for the betterment of waste heat recovery system and thereby optimizing fuel utilization and maximizing environment sustainability.

References

[1]https://www.asme.org/engineering-topics/articles/automotive/using-waste-engine-heat-in-automobile-engines (Last access: 31 January, 2017).

[2]Chiara, F. & Canova, M. A., Review of Energy Consumption, Management and Recovery in Automotive Systems with Considerations of Future Trends, *Proceedings of Institution of Mechanical Engineers: Journal of Automobile Engineering*, **227**, 2013, 914-936.

[3]Ringler, J., Seifert, M., Guyotot, V. & Hübner, W., Rankine Cycle for Waste Heat Recovery of IC Engines, *SAE International Journal of Engines*, **2** (1), 2009, 67-76.

[4]http://powerelectronics.com/thermal-management/thermoelectric-devices-convert-waste-heat-dc-power (Last access: 31 January, 2017).

[5]https://phys.org/news/2013-11-aims-cars-efficient.html (Last access: 31 January, 2017).

[6]http://www.i4c.co.in/idea/getIdeaProfile?idea_id=3645 (Last access: 31 January, 2017).

[7]Jadhao, J. S., & Thombare, D. G., Review on Exhaust Gas Heat Recovery for I.C. Engine, *International Journal of Engineering and Innovative Technology*, **2 (**12), 2013, 93-100

[8]Saidur, R., Rezaei, M., Muzammil, W. K., Hassan, M. H., Paria, S. & Hasanuzzaman, M., Technologies to Recover Exhaust Heat from Internal Combustion Engines, *Renewable and Sustainable Energy Reviews*, **16**, 2012, 5649–5659.

[9]Galanis, N., Cayer, E., Roy, P., Denis, E. S. & Désilets M., Electricity Generation from Low Temperature Sources, *Journal of Applied Fluid Mechanics*, **2**, 2009, 55-67.

[10]Drescher, U. & Bruggemann, D., Fluid Selection for the Organic Rankine Cycle (ORC) in Biomass Power and Heat Plants, *Applied Thermal Engineering.*, **27**, 2007, 223–228.

[11]Kumar, R., Sonthalia, A. & Goel, R., Experimental study on waste heat recovery from an internal combustion engine using thermoelectric technology, *Thermal Science*, **15** (4), 2011, 1011-1022.

[12]Xuejun, H. & Deli, G., Computational Models Analysis of Diesel Engine Exhaust Waste Heat Recovery, *International Conference on Ecology*, **7**, 2012.

[13]Zulkifli, S. A., Karsiti M. N. & Aziz, A. R. A., Starting of a Free-Piston Linear Engine-Generator by Mechanical Resonance and Rectangular Current Commutation," *IEEE Vehicle Power and Propulsion Conference (VPPC)*, 2008, Harbin, China.

[14]Mehta, A. V., Waste Heat Recovery Using Stirling Engine, *International Journal of Advanced Engineering Technology*, **3**, 2012, 305-310.

[15]Wu, D. W. & Wang, R. Z., Combined Cooling, Heating and Power: A Review, *Progress in Energy and Combustion Science*, **32**, 2006, 459–495.

[16]Jia, H., Hong, G., Cheng, N. & Li, W., Key Techniques for Designing Free Piston Stirling Engine, *Power and Energy Engineering Conference (APPEEC)*, 2012, Asia Pasific.

[17]Kwankaomeng, S., & Promvonge, P., Investigation on a Free-Piston Stirling Engine and Pneumatic Output, *The First TSME International Conference on Mechanical Engineering*, 2010.

[18]Dadi, M. J., Molvi, I. M. & Mehta, A. V., The Most Efficient Waste Heat Recovery Device: A Gamma Type Stirling Engine, *International Journal of Advanced Engineering Technology*, **3**, 2012, 189-195.

[19]AlQdah, K., Performance and Evaluation of Aqua Ammonia Auto Air Conditioner System Using Exhaust Waste Energy, *Energy procedia*, **6**, 2011, 467-476.

[20]Manojprabhakar, S., Ravindranath, R.,Vinothkumar R., Selvakumar, A. & Visagavel, A., *International Journal of Research in Engineering and Technology*, **3**, 2014, 299-304.

[21]Sowjanya, S. L., Thermal Analysis of a Car Air Conditioning System Based on an Absorption Refrigeration Cycle Using Energy from Exhaust Gas of an Internal Combustion Engine, *Advanced Engineering and Applied Sciences: An International Journal*, **3** (4), 2013, 47-53.

[22]Pathania, A. & Mahto, D., Recovery of engine waste heat for utilization in air conditioning system in an automobile: An investigation, *Global journal of researches in engineering Mechanical and Mechanics engineering*, **12**, 2012.

[23]Vicatos, G., Gryzagoridis, J. & Wang, S., A Car Air-Conditioning System Based on an Absorption Refrigeration Cycle Using Energy From Exhaust Gas of an Internal Combustion Engine, *Journal of energy in Southern Africa*, **19** (4), 2008, 6-11.

[24]Mathapati, S., Gupta, M. & Dalimbkar, S., A Study on Automobile Air-Conditioning Based on Absorption Refrigeration System Using Exhaust Heat of a Vehicle, *International Journal of Engineering Research and General Science*, **2** (4), 2014 , 80-86.

[25]Maurya, S., Awasthi, S. & Siddiqui, S., A Cooling System for an Automobile Based on Vapour Absorption Refrigeration Cycle Using Waste Heat of an Engine, *International Journal of Engineering Research and Applications*, **4** (3), 2014, 441-444.

[26]Keinath, C., Delahanty, J. Garimella, S. & Garrabrant, M., Diesel Engine Waste-Heat Driven Ammonia-Water Absorption System for Space-Conditioning Applications, *International Refrigeration and Air Conditioning Conference*, 2014.

[27]Singh, R., Vats, S., Baghel, N. & Kumar, R., Integration of Water-Lithium Bromide Absorption Refrigeration System with Diesel Engine: A Thermodynamic Study, *International Conference of Advanced Research And Innovation*, 2014, 150-154.

[28]AlQdah, K., Alsaqoor, S. & AI-Jarrah, A., Design and Fabrication of Auto Air Conditioner Generator Utilizing Exhaust Waste Energy From a Diesel Engine, *International Journal of Thermal and Environmental Engineering*, **3** (2), 2011.

[29]Krishnadasan, V. & Sajid, N. M., *International Journal Of Advanced Research Trends in Engineering and Technology*, **2** (10), 2015, 868-872.

[30]Bangotra, A. & Mahajan, A., Design Analysis of 3 TR Aqua Ammonia Vapour Absorption Refrigeration System, *International Journal of Engineering Research and Technology*, **1** (8), 2012.

[31]Wurm, J., Kinast, J. & Bulicz, T., Assessment of Positive Displacement Supercharging and Compounding of Adiabatic Diesel. *SAE Technical Paper*, 1984.

[32]Ismail, Y., Durrieu, D., Menegazzi P., Chesse P. & Chalet D., Potential of Exhaust Heat Recovery by Turbocompounding, *Proceedings of the SAE 2012 International Powertrains, Fuels and Lubricants Meeting*. 2012.

[33] Aghaali, H & Ångström, H., A Review of Turbocompounding as a Waste Heat Recovery System for Internal Combustion Engines, *Renewable and Sustainable Energy Reviews*, **49**, 2015, 813–824.

[34]http://paultan.org/2005/12/11/bmw-turbosteamer/ (Last access: 31 January, 2017).

[35]http://www.exoes.com/EN/exhaust-heat-recovery.html (Last access: 31 January, 2017).

[36]http://www.barber-nichols.com/products/heat-engines/rankine-cycles (Last access: 31 January, 2017).

[37]http://corporate.renault-trucks.com/en/press-releases/the-renoter-project-reducing-consumption-by-recovering-heat-from-exhaust-gases.html (Last access: 31 January, 2017).