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# A Review On Waste Heat Recovery Technologies In Internal Combustion Engines

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**Abstract:**In this paper, thewaste heat recovery technologies in internal combustion (IC) engines were reviewed and discussed. The efficiency of a traditional IC engine to convert the heat supplied through fuel is just 15-30%, while the rest heat is expelled to the environment in the form of cooling systems, exhaust gases and other unaccountable losses. This results into entropy rise and formation of greenhouse gases, which indeed lead to environmental pollution.In this scenario, the recovery and proper utilization of waste heat from any source not only conserves the fuel, but also helps in managing and reducing environmental compliances.Several methods for waste thermal energy recovery from internal combustion engine (ICE) have been studied by using supercharger or turbocharger and /or combined.This study also presents an innovative approach to power generation from waste heat of IC engine based on coolant and exhaust. The Rankine cycle used in the exhaust of engines and turbochargers is the most thermal efficient system.Through the study of Rankine cycle it is proved that it is the more perspective than other techniques. Fuel consumption of IC engine could be improved significantly by harvesting waste thermal energy.

**Keywords:**IC Engines,Waste Heat Recovery, Exhaust Gas, Rankine Cycle, Thermo-electric generators,

## 1. INTRODUCTION

Nowadays, diesel engines are widely used due to their abilities and advantages in industries for producing energy, electricity, transportation, etc., but a large amount of their fuel energy is wasted through the exhaust [1-5]. Researchers confirm that more than 30–40% of fuel energy gets wasted from the exhaust and just 15–30% of the fuel energy converts to useful work [6-9]. 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). So, researchers are motivated to recover the heat from the waste sources and increase overall efficiency in engines by using applicable ways [10-16]. Heat recovery not only reduces the demand of fossil fuels, but also reduces the GHG and helps to save energy by the use of advanced materials [17-20].

In spite of the existence of modern technologies for machining of equipments used to improve the working processes in internal combustion engines such as turbocharger systems, direct fuel injection, downsizing, low temperature combustion processes (CAI and HCCI), variable compression ratio, etc., the future requirements for internal combustion engines will be difficult to be met [21-26]. For that reason, waste heat recovery is a good way to increasing the overall engine efficiency, reducing the fuel consumption and $CO_2$ emissions.

## 2.WASTE HEAT RECOVERYTECHNOLOGIES IN ENGINES

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 increase. Researchers attempted to reduce the need of fossil fuels by using the waste heat recovery from the engines. By that some advanced technologies can be applied to improve waste heat recovery efficiency.

### *2.1 Turbocharging*

A turbocharger is a supercharger driven with the exhaust gases energy and increases the engine power by compressing the inlet air to engine (Shown in Fig. 1). 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.But it has some shortcomings, TURBOLAG it is during low speed, acceleration and with heated bearings it can't give same efficiency [27-31]. Another lag is increasing the intake air temperature due to its pressure increase. The warmer intake air has the less density and the less oxygen is available for the combustion event which reduces volumetric efficiency. So the Rankine steam cycle system coupled on the 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.

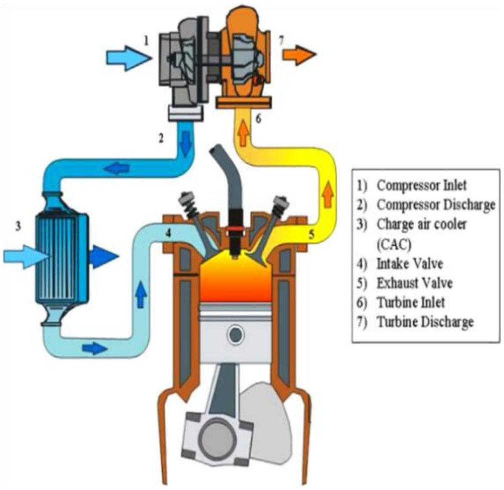


Fig. 1 Schematic view of turbocharging

### *2.2 Turbocompounding systems*

Turbocompounding is an additional waste heat recovery system.They are of two types: mechanical and electrical turbocompounding. In mechanical turbocompounding the turbine shaft is mechanically connected to the engine crankshaft and the energy of the system is added directly to the engine output(Fig. 2)

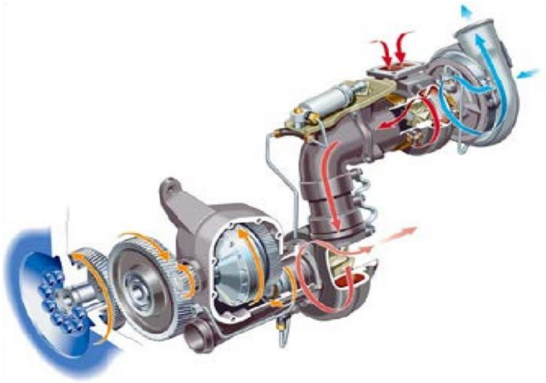

Fig. 2 Mechanical turbo compound

In electric turbocompounding the turbine shaft is connected to a generator. In this case the energy is converted into electricity. The electrical turbocompounding can be developed without additional turbine [32-35]. In this case the generator is mounted directly onto the turbocharger's shaft. (Fig. 3)

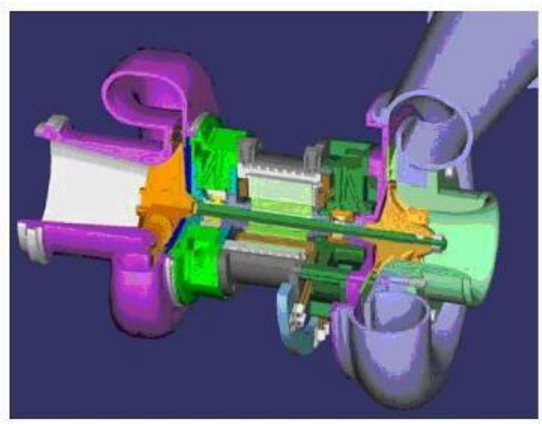

Fig. 3 Electric turbo compound

The disadvantage of such turbocompounding includes an additional turbine that the second turbine creates an additional backpressure in the exhaust system and adversely affects the gas exchange process.The benefits of including turbocompounding are that it increases in attained power by 10-11%,Torque increaseabout 11% and reduction in fuel consumption by 5-11%.

### *2.3Thermo-electric generators*

Thermoelectric generators (TEG) or Seebeck generators are devices which directly convert waste heat energy into electrical energy. See Fig. 4 & 5. Thermoelectric which increase their efficiency to around 5–8% by semiconductor p–n junctions that are made up of new materials such as BiTe (bismuth telluride), CeFeSb (skutterudite), SiGe (silicon–germanium),ZnBe (zinc–beryllium), SnTe (tin telluride) and new nano-crystalline or nano-wire [36-42]. Although TEG devices have many advantages such as clean energy, without sound, without movable component and lesser maintenance costs and only economical when used at high temperatures.

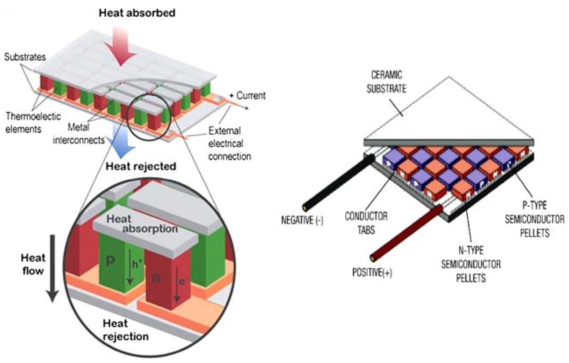


Fig. 4 Schematic view of p-n junction in TEG devices

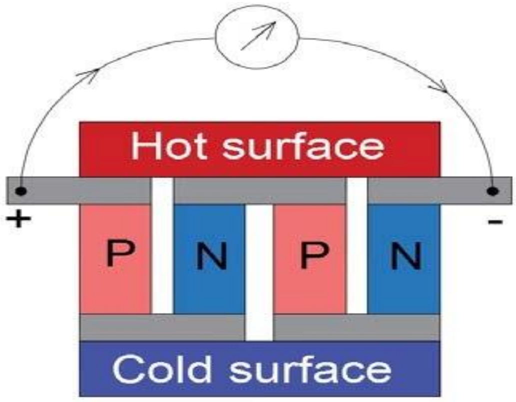


Fig. 5 Thermoelectric Generators

But when the exhaust gases flow through the TEG's heat exchanger, kinetic energy from the gases is lost and causes an increase in pumping losses which is known as back pressure which reduces the engine's performance.

### *2.4.Exhaust gas recirculation*

Recirculation of the exhaust gases into cylinder or EGR is one of the efficient methods to decrease the $NO_x$ level. EGR can be applied internally or externally in the engines [43-45]. EGR is widely used in both gasoline and diesel engines. In a diesel engine, the exhaust gas replaces some of the excess oxygen in the pre-combustion mixture. (See Fig. 6) Since $NO_x$ 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 $NO_x$. Although EGR cannot improve the combustion irreversibility, but it can be assumed as a technique for using the heat of burned gases in the cylinder for another time. Furthermore inmodern diesel engines, the EGR gases are cooled with a heat exchanger in order to enter a greater mass of recirculated gases.

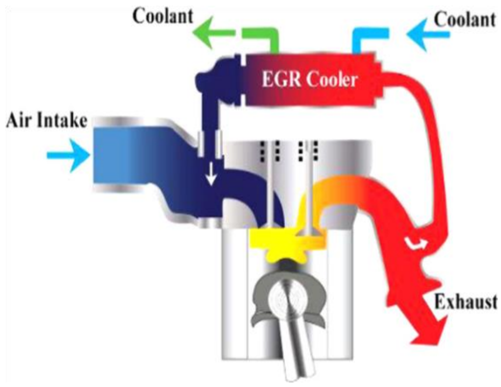


Fig. 6 EGR Principle

### *2.5 Closed-loop thermodynamic cycles*

#### *2.5.1 Stirling cycle*

This closed thermodynamic cycle operates with different types of fluids [46-48]. The most commonly used ones are air, hydrogen or helium. The working process in the Stirling cycle occurs in four stages (Fig. 7):

1-2. T = constant expansion (heat transfer from the external source)

2-3. V = constant regeneration (internal heat transfer from the working fluid to the regenerator)

3-4. T = constant compression (heat rejection to the external sink)

4-1. V = constant regeneration (internal heat transfer from the regenerator back to the working fluid).

#### *2.5.3Rankine cycle*

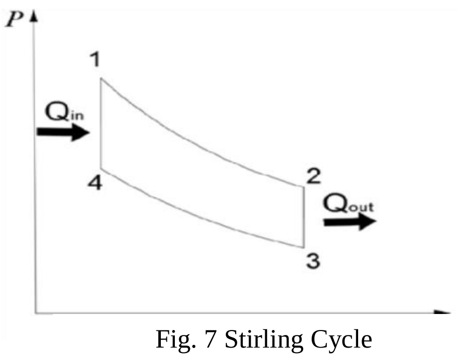


Fig. 7 Stirling Cycle

Stirling cycle has high efficiency when the cycle operates with low heat source. Stirling are suitable for waste heat recovery in internal combustion engines, but there is still a lot of research to be done in order to improve their effectiveness as a waste heat recovery system.

*2.5.2 Erickson cycle*

The Ericsson cycle is similar to the Stirling cycle, except that the two constant-volume processes are replaced by two constantpressure processes [46-48]. The working process in the Erickson cycle occurs in four stages (Fig. 8):

1-2. Isobaric heating of the working fluid - a process in which the temperature of the working fluid increases at constant pressure

2-3. Isothermal expansion - a process in which the fluid expands at constant temperature

3-4. Isobaric cooling - a process in which the liquid temperature decreases at constant pressure

4-1. Isothermal compression - a process in which the fluid is compressed at constant temperature

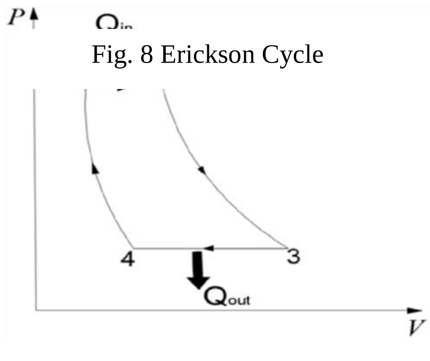


Fig. 8 Erickson Cycle

Among these cycles, Rankine Cycle 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. 9 which contains boiler, expander, condenser, pump and working fluid [49-52]. It is a closed-loop thermodynamic cycle which converts heat into mechanical power. The mechanical power can be used to perform mechanical work or to produce electricity. Separately, this cycle is widely used in the production of electricity by thermal power plants.

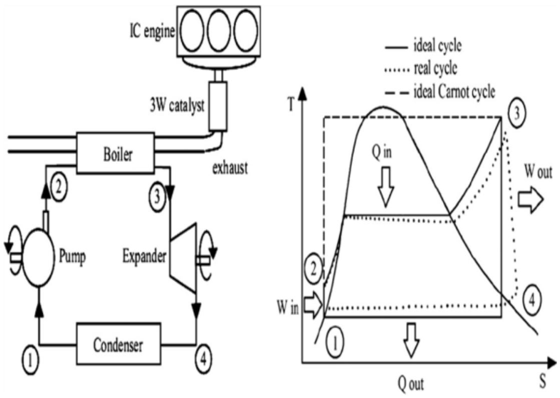


Fig. 9 Rankine Cycle

1-2 Isentropic compression in the pump;

2-3 Working fluid heating and evaporation in the boiler;

3-4 Isentropic expansion in the turbine;

4-1 Working fluid cooling in the condenser.

The Rankine cycle efficiency depends on: the working fluid, boiler (evaporator), expander, condenser and working fluids operating parameters (mass flow rate and pressure).

## 3. FEATURES OF RANKINE CYCLE

### *3.1 Working fluid*

In the development of the Rankine cycle waste heat recovery system, one of the most important stepsis the selection of the working fluid because its operating properties have a great influence on the efficiency, size and design. A number of fluids have been studied such as: water, ethanol, benzene, organic fluids and etc. Water provides high efficiency in the case of a high temperature heat source while organic fluids are more efficient in the case of a low temperature heat source.

The working fluids used in the Rankine cycle can bedivided into three groups according to the slope of the condensation line in the T-S diagram: wet, dry and isentropic.The temperature of the heat source is the main criterion in selecting the working fluid.

### *3.2 Boiler (Evaporator)*

Heat exchangers are devices where heat transfer from one medium to another occurs. In waste heat recovery systems, based on the Rankine cycle transfer of heat from the exhaust gas to the working fluid is carried out in a heat exchanger called the evaporator. The object of a number of studies is to establish the type of heat exchanger which is most suitable for application in the Rankine cycle.

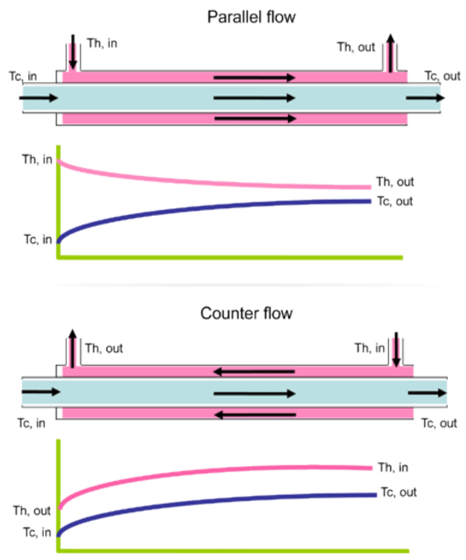


Fig. 10 Parallel flow and Counter flow heat exchangers

Table 1 Review of research of different types of heat exchangers

| Working fluid | Heat exchanger type | Conclusions |
|---|---|---|
| Hossain at al. [1] | Shell and tube | Improving the effectiveness of heat exchanger from 0.44 to 0.76 by optimization design |
| Zhang at al.[12] | Finned tube | The overall heat transfer rate of the evaporator increases with engine powerand reaches 70.4 kW at the rated power |
| Lee at al.[20] | Small fin tube | The heat exchanger that had maximum effectiveness was not necessarily the optimum design |
| Bari at al. [26] | Shell and tube | An additional 23.7% power improvement achieved by using water as the working fluid |
| Pandiyarajan at al.[30] | Shell and finned tube | Nearly 10–15% of total heat is recovered |
| Wang at al.[38] | Multi-coil helical | Total fuel saving was up to 34% under 2000 rpm and 75 Nm |

**4. CONCLUSIONS**

On the basis of the review of the methods for increasing the overall engine efficiency, reducing the fuel consumption and emissions $CO_2$ from internal combustion engines,the exhaust waste heat recovery system based on the Rankine cycle provides higher efficiency than others. The system efficiency can reach 15% to 20% which means that the engine efficiency improvement is between 10% and 12%.The Rankine cycle efficiency depends on: the workingfluid,boiler (evaporator), expander, condenser and working fluidsoperating parameters (mass flow rate and pressure).

**REFERENCES**

[1] Hossain, S.N. and Bari, S., 2013. Waste heat recovery from the exhaust of a diesel generator using Rankine Cycle. *Energy Conversion and Management*, *75*, pp.141-151.

[2] Milkov, N.I.K.O.L.A.Y., Punov, P.L.A.M.E.N., Evtimov, T., Descombes, G. and Podevin, P., 2014, September. Energy and exergy analysis of an automotive direct injection diesel engine. In *Scientific Conference BulTrans-2014* (pp. 149-154)..

[3] Zhao, H. ed., 2009. *Advanced direct injection combustion engine technologies and development: diesel engines* (Vol. 2). Elsevier. 2010: CRC Press.

[4] Sendyka, B. and Soczowka, J., 2004, August. Recovery Of Exhaust Gases Energy By Means Of Turbocompound (Diesel Engines, Performance and Emissions, Heat Recovery). In *The Proceedings of the International symposium on diagnostics and modeling of combustion in internal combustion engines 2004.6* (pp. 99-103). The Japan Society of Mechanical Engineers.

[5] Barik, D. and Murugan, S., 2014. Investigation on combustion performance and emission characteristics of a DI (direct injection) diesel engine fueled with biogas–diesel in dual fuel mode. Energy, 72, pp.760-771.

[6] Thombare, D.G. and Verma, S.K., 2008. Technological development in the Stirling cycle engines. *Renewable and Sustainable Energy Reviews*, *12*(1), pp.1-38.

[7] Kang, S.H., 2012. Design and experimental study of ORC (organic Rankine cycle) and radial turbine using R245fa working fluid. *Energy*, *41*(1), pp.514-524.

[8] Hountalas, D.T., Mavropoulos, G.C., Katsanos, C. and Knecht, W., 2012. Improvement of bottoming cycle efficiency

and heat rejection for HD truck applications by utilization of EGR and CAC heat. *Energy Conversion and Management*, *53*(1), pp.19-32.

[9] Weerasinghe, W.M.S.R., Stobart, R.K. and Hounsham, S.M., 2010. Thermal efficiency improvement in high output diesel engines a comparison of a Rankine cycle with turbo-compounding. *Applied Thermal Engineering*, *30*(14-15), pp.2253-2256.

[10] Roy, J.P., Mishra, M.K. and Misra, A., 2010. Parametric optimization and performance analysis of a waste heat recovery system using Organic Rankine Cycle. *Energy*, *35*(12), pp.5049-5062..

[11] Yu, G., Shu, G., Tian, H., Wei, H. and Liu, L., 2013. Simulation and thermodynamic analysis of a bottoming Organic Rankine Cycle (ORC) of diesel engine (DE). *Energy*, *51*, pp.281-290.

[12] Zhang, H.G., Wang, E.H. and Fan, B.Y., 2013. Heat transfer analysis of a finned-tube evaporator for engine exhaust heat recovery. *Energy Conversion and Management*, *65*, pp.438-447

[13] Barik, D. and Murugan, S., 2016. Experimental investigation on the behavior of a DI diesel engine fueled with raw biogas–diesel dual fuel at different injection timing. Journal of the Energy Institute, 89(3), pp.373-388.

[14] Chen, H., Goswami, D.Y. and Stefanakos, E.K., 2010. A review of thermodynamic cycles and working fluids for the conversion of low-grade heat. *Renewable and sustainable energy reviews*, *14*(9), pp.3059-3067.

[15] Datla, B.V. and Brasz, J., 2012. Organic Rankine Cycle System Analysis for Low GWP Working Fluids.

[16] Vidhi, R., Kuravi, S., Goswami, D.Y., Stefanakos, E. and Sabau, A.S., 2013. Organic fluids in a supercritical rankine cycle for low temperature power generation. *Journal of Energy Resources Technology*, *135*(4), p.042002.

[17] Pei, G., Li, J., Li, Y., Wang, D. and Ji, J., 2011. Construction and dynamic test of a small-scale organic rankine cycle. *Energy*, *36*(5), pp.3215-3223.

[18] Vignesh, G., Prakash, M., Selvam, M. D., and Ragupathi, P. (2018). Frictional Performance of Dimpled Textured Surfaces on a Frictional Pair : An Experimental Study. i-manager’s Journal on Mechanical Engineering, 8(4), 18-24

[19] Zhang, H.G., Wang, E.H. and Fan, B.Y., 2013. A performance analysis of a novel system of a dual loop bottoming organic Rankine cycle (ORC) with a light-duty diesel engine. *Applied energy*, *102*, pp.1504-1513.

[20] Lee, S. and Bae, C., 2008. Design of a heat exchanger to reduce the exhaust temperature in a spark-ignition engine. *International Journal of Thermal Sciences*, *47*(4), pp.468-478.

[21] Boretti, A., 2012. Recovery of exhaust and coolant heat with R245fa organic Rankine cycles in a hybrid passenger car with a naturally aspirated gasoline engine. *Applied Thermal Engineering*, *36*, pp.73-77.

[22] Ragupathi, P., Dennison, M.S. and Ganesan, V., 2018. effect of mineral based cutting fluid on surface roughness of en24 steel during turning operation. International Research Journal of Engineering and Technology (IRJET), 5(2), pp.1008-1011.

[23] Guo, T., Wang, H. and Zhang, S., 2011. Comparative analysis of natural and conventional working fluids for use in transcritical Rankine cycle using low-temperature geothermal source. *International Journal of Energy Research*, *35*(6), pp.530-544.

[24] Ragupathi, P., Sivaram, N. M., Vignesh, G., and Selvam, M. D. (2018). Enhancement of Impact Strength of a Car Bumper Using Natural Fiber Composite Made of Jute. i-manager’s Journal on Mechanical Engineering, 8(3), 39-45.

[25] Nguyen, V.M., Doherty, P.S. and Riffat, S.B., 2001. Development of a prototype low-temperature Rankine cycle electricity generation system. *Applied Thermal Engineering*, *21*(2), pp.169-181.

[26] Bari, S. and Hossain, S.N., 2013. Waste heat recovery from a diesel engine using shell and tube heat exchanger. *Applied Thermal Engineering*, *61*(2), pp.355-363.

[27] Peterson, R.B., Wang, H. and Herron, T., 2008. Performance of a small-scale regenerative Rankine power cycle employing a scroll expander. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *222*(3), pp.271-282.

[28] Barik, D., 2018. Introduction to Energy From Toxic Organic Waste For Heat and Power Generation. Energy from Toxic Organic Waste for Heat and Power Generation, p.1.

[29] Saitoh, T., Yamada, N. and Wakashima, S.I., 2007. Solar Rankine cycle system using scroll expander. *Journal of Environment and Engineering*, *2*(4), pp.708-719.

[30] Pandiyarajan, V., Pandian, M.C., Malan, E., Velraj, R. and Seeniraj, R.V., 2011. Experimental investigation on heat recovery from diesel engine exhaust using finned shell

and tube heat exchanger and thermal storage system. *Applied Energy*, *88*(1), pp.77-87.

[31] Manolakos, D., Kosmadakis, G., Kyritsis, S. and Papadakis, G., 2009. On site experimental evaluation of a low-temperature solar organic Rankine cycle system for RO desalination. *Solar Energy*, *83*(5), pp.646-656.

[32] Brasz, J.J., Smith, I.K. and Stosic, N., 2000. Development of a twin screw expressor as a throttle valve replacement for water-cooled chillers.

[33] Barik, D. and Murugan, S., 2016. Effects of diethyl ether (DEE) injection on combustion performance and emission characteristics of Karanja methyl ester (KME)–biogas fueled dual fuel diesel engine. Fuel, 164, pp.286-296.

[34] Bao, J. and Zhao, L., 2013. A review of working fluid and expander selections for organic Rankine cycle. *Renewable and sustainable energy reviews*, *24*, pp.325-342.
heat. *Renewable and sustainable energy reviews*, *14*(9), pp.3059-3067.

[35] Hung, T.C., Wang, S.K., Kuo, C.H., Pei, B.S. and Tsai, K.F., 2010. A study of organic working fluids on system efficiency of an ORC using low-grade energy sources. *Energy*, *35*(3), pp.1403-1411.

[36] Ragupathi, P., Rajkumar, S. and Hussain, R.S., 2014. Design and Analysis of Diesel Engine Intake Manifold using CFD Simulation. International Journal of Modern Trends in Engineering and Science, 1.

[37] Lakew, A.A., Bolland, O. and Ladam, Y., 2011. Theoretical thermodynamic analysis of Rankine power cycle with thermal driven pump. *Applied energy*, *88*(9), pp.3005-3011.

[38] Wang, E., Zhang, H., Fan, B., Ouyang, M., Yang, K., Yang, F., Li, X. and Wang, Z., 2015. 3D numerical analysis of exhaust flow inside a fin-and-tube evaporator used in engine waste heat recovery. *Energy*, *82*, pp.800-812.

[39] Barik, D. and, Murugan, S., 2013. Performance and emission characteristics of a biogas fueled DI diesel engine(No. 2013-01-2507). SAE Technical Paper.

[40] Tahir, M.B.M., Yamada, N. and Hoshino, T., 2010. Efficiency of compact organic Rankine cycle system with rotary-vane-type expander for low-temperature waste heat recovery.

[41] Barik, D., Satapathy, A.K. and Murugan, S., 2017. Combustion analysis of the diesel–biogas dual fuel direct injection diesel engine–the gas diesel engine. International Journal of Ambient Energy, 38(3), pp.259-266.

[42] P.Ragupathi, Dr.V.R.Sivakumar, "Enhancing Heat Removal by Optimizing Fin Configuration in Air Compressor", International Journal of Engineering Sciences & Research Technology (IJESRT), ISSN: 2277-9655, Volume: 03, Issue: 05, May 2014, pp.111-116.

[43] He, C., Liu, C., Gao, H., Xie, H., Li, Y., Wu, S. and Xu, J., 2012. The optimal evaporation temperature and working fluids for subcritical organic Rankine cycle. Energy, 38(1), pp.136-143.

[44] Bao, J. and Zhao, L., 2013. A review of working fluid and expander selections for organic Rankine cycle. Renewable and sustainable energy reviews, 24, pp.325-342

[45] Barik, D. and Murugan, S., 2014. Investigation on combustion performance and emission characteristics of a DI (direct injection) diesel engine fueled with biogas-diesel in dual fuel mode. Energy (Oxford), 72, pp.760-771.

[46] Fu, J., Tang, Q., Liu, J., Deng, B., Yang, J. and Feng, R., 2014. A combined air cycle used for IC engine supercharging based on waste heat recovery. Energy Conversion and Management, 87, pp.86-95.

[47] Chintala, V., Kumar, S. and Pandey, J.K., 2018. A technical review on waste heat recovery from compression ignition engines using organic Rankine cycle. Renewable and Sustainable Energy Reviews, 81, pp.493-509.

[48] Kim, S., Choi, K., Lee, K. and Kim, K., 2016. Evaluation of automotive waste heat recovery for various driving modes. Energy, 106, pp.579-589.

[49] Rahman, A., Razzak, F., Afroz, R., Mohiuddin, A.K.M. and Hawlader, M.N.A., 2015. Power generation from waste of IC engines. Renewable and sustainable energy reviews, 51, pp.382-395.

[50] Shu, G., Liang, Y., Wei, H., Tian, H., Zhao, J. and Liu, L., 2013. A review of waste heat recovery on two-stroke IC engine aboard ships. Renewable and Sustainable Energy Reviews, 19, pp.385-401.

[51] Saidur, R., Rezaei, M., Muzammil, W.K., Hassan, M.H., Paria, S. and Hasanuzzaman, M., 2012. Technologies to recover exhaust heat from internal combustion engines. Renewable and sustainable energy reviews, 16(8), pp.5649-5659.

[52] Sprouse III, C. and Depcik, C., 2013. Review of organic Rankine cycles for internal combustion engine exhaust waste heat recovery. Applied thermal engineering, 51(1-2), pp.711-722.