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Review Paper on Inverted Brayton Cycles

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Abstract:*The exhaust gas from an internal combustion engine contains approximately 30% of the thermal energy of combustion. Waste heat recovery (WHR) systems aim to reclaim a proportion of this energy in a bottoming thermodynamic cycle to raise the overall system thermal efficiency. One of promising heat recovery approaches is to employ an inverted Brayton cycle (IBC) immediately downstream of the primary cycle. However, it is a little-studied approach as a potential exhaust-gas heat-recovery system, especially when applied to small automotive power-plants.The experiments of the IBC prototype were conducted in the gas stand. The correlated IBC model can be utilized for the further development of the IBC system. Researchers were reviewed core paper on Inverted Brayton Cycles (IBC) and concluded that there were possibility of heat recovery system in that for changing different mechanical components.*
Keywords*: I C Engine; Inverted Brayton Cycle; Waste Heat Recovery; Prototype; Postoperative*

I. Introduction

The development of sustainable energy technologies is a key part of the global scientific agenda and is one of the most difficult challenges facing engineers today. Observing that internal combustion engines are the most widely used source of primary power for machinery critical to the transportation, construction and agricultural sectors, one of the greatest areas for impact is the improvement in engine technology due to its extraordinary growth, especially in rapidly industrializing nations. Notably in transportation applications, the amount of CO_2 gas released from engine takes up 25% of global CO_2 emissions [1]. In addition, the global demand of vehicles increases steadily and dramatically.

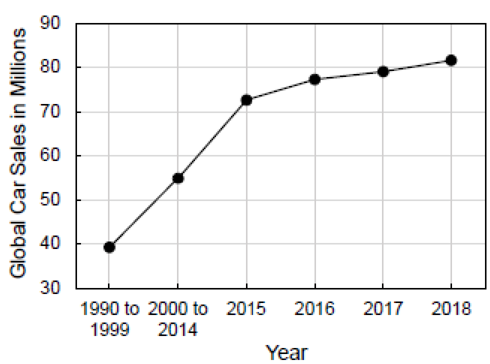

Figure 1 Number of vehicles sold worldwide from 1990 to 2018

Figure 1 shows the number of passenger and commercial vehicles sold worldwide from 1990 to 2017, and a forecast for 2018 [2]. The number of the total vehicle production significantly increased in 2015, then kept at a stable and sustainable pace from 2015 to 2017. In 2018, it is expected to reach at around 81 million. Despite developments in fuel cell and electric vehicle technology, it is now widely recognized that a large fraction of future vehicles will still rely on the internal combustion (IC) engine.

II. IC Engine Energy Flow

To achieve the thermal efficiency improvement, the energy balance and exergy balance in IC engine should be analysed, which allows engineers focus on addressing the most significant parasitic losses of the fuel energy. Extensivestudies on the energy flow reveal that waste heat produced during the thermal combustion process could be as high as 30-40% which is rejected to the environment through an exhaust pipe in the form of heat, while only 12-30% of the available energy in a fuel can be converted to the mechanical work or brake work [3-5]. One reason for this is that maximum compression ratio of IC engines is limited by several factors, such as engine knocking, even though the high compression ratio is desired due to the resulting efficient combustion and subsequent expansion stroke. Thus, the combusted gases released by the combustion chamber, referred as the exhaust gas, still contains various forms of energy due to an insufficient expansion stroke. Especially under part load, the energy contained by the exhaust gas is up to around 36% of the fuel energy. However, the exhaust gas energy is considered by some to be low-grade energy due to its high temperature but low pressure [6].

Liu et al. [7] presented an energy flow analysis in a turbocharged, gasoline direct-injection (GDI) engine. As shown in Figure 2 (a), energy utilization efficiency of a modern gasoline engine is still low. The fuel energy can be divided into several parts – effective work, exhaust gas energy, coolant energy and other loss (unburned fuel energy and engine surface heat transfer). Under part load, the percentage of effective work changes from 27.8% to 33.5%, while that of exhaust gas energy varies between 23.7% and 35.8%. In most cases, exhaust gas energy almost equals effective work in quantity. However, the exhaust gas energy cannot be fully reused since it is a kind of low-grade energy. Therefore, engine exergy balance analysis was carried out, shown in Figure 2 (b). It can be observed that the percentage of exhaust gas exergy is always lower than that of effective exergy, but it is larger than the percentage of heat transfer exergy under most of conditions. Under part load, the percentage of exhaust gas exergy changes from 9.4% to 16.8%, and it demonstrates a great potential for engine fuel economy improvement by the exhaust gas energy recovery.

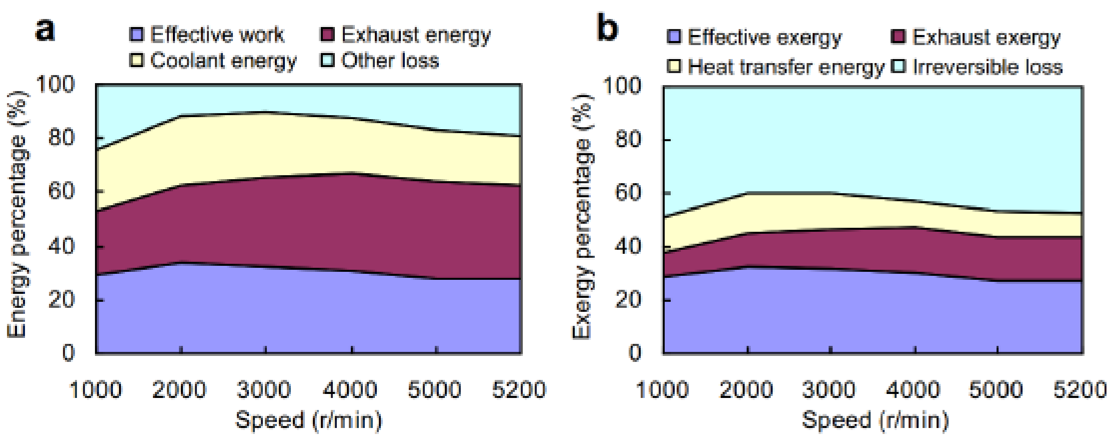

Figure 2 Energy and exergy distribution of a turbocharged, direct injection gasoline. (a) Energy distribution of GDI engine. (b) Exergy distribution of GDI engine. [7]

Ozkan et al. [8] analysed the energy balance and exergy balance of a Ford 1.8 L, four-cylinder, four-stroke, direct-injection compression ignition diesel engine. The test has been performed at the engine speed of 2000 rpm and the engine load of 50%. According to the energy distribution shown in Figure 3, the percentage of energy contained by the exhaust gas is 32%, which is only slightly lower than that utilized by the drivetrain. Furthermore, the exergy distribution of the considered diesel engine, shown in Figure 4, reveals that 7.94% exhaust gas exergy is expected.

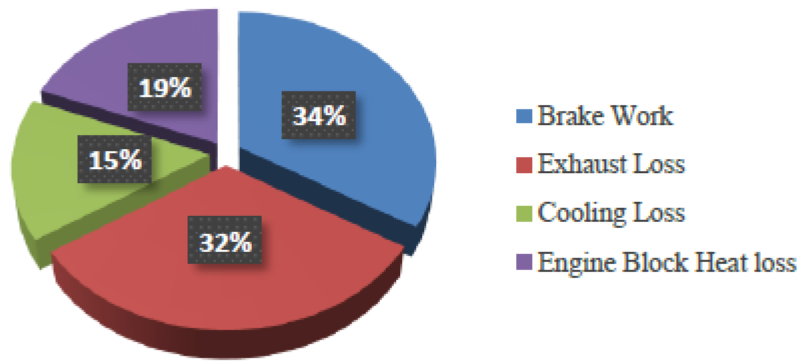

Figure 3 Energy distribution of a Ford diesel engine

In order to quantify exhaust energy available for the heat recovery system, exhaust gas from a typical light duty 4 cylinder spark ignition engine has been analysed by Chammas and Clodic [9]. The results show that the corresponding available exhaust gas energy ranges from 4.6 to 120 kW depending on the engineoperating conditions. However, given the conversion efficiency and the parasitic losses of the exhaust-gas heat-recovery systems, the maximum recoverable work is from 1.7 to 45 kW when the regeneration system operates between the average temperature of the exhaust gases and the outdoor temperature.

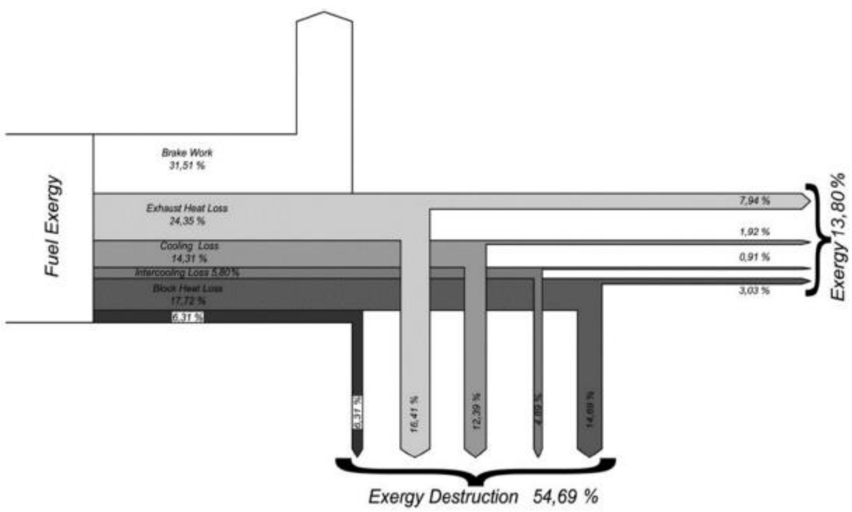

Figure 4 Exergy distribution of a Ford diesel engine [8]

These observations in terms of the energy quantity and quality of the gasoline and diesel engines exhaust gas have given rise to a recent trend for wasted heat recovery, as they point to the significant amount of energy in exhaust gas could be recovered that is otherwise simply wasted by discharging exhaust gas to the ambient.

III. Exhaust Gas Energy

As a major part of the loss from an internal combustion engine, the exhaust gas contains various forms of energy, and the main characteristic of the exhaust gas energy is unsteady caused by the working cycle and engine various operating conditions. Generally, the exhaust-gas flow energy can be classified into terms of kinetic energy, pressure energy, and thermal energy [7]. The kinetic energy can be neglected since it only accounts for small proportion of the total exhaustgas energy, or more precisely, is lower than 0.6% at most engine operating conditions [6]. The remaining pressure energy in the exhaust gas is high-grade mechanical energy and can be directly recovered by an expansion process like that which occurs within a turbo-compounding turbine placed in the exhaust system. Theoretically, the recovery efficiency is limited by the component efficiency and the parasitic energy losses of an expansion device. After expansion, the remaining thermal energy could be considered as low-grade thermodynamic energy that can be recovered by some indirect or direct methods. In fact, the thermal energy occupies more than

90% of the exhaust energy under full load conditions and also represents the largest proportion under part load [6]. However, this thermal energy is impossible to completely convert into high-grade energy such as mechanical energy and electrical energy, and the corresponding recovery efficiency is limited by cycle and heat transfer efficiencies [10].

IV. Waste Heat Recovery System

Although various vehicle-mounted thermal utilities adopted to recover energy from exhaust gas have been intensively investigated, the exhaust steam still contains high-grade heat content. The turbocharger is an example of this since it is widely employed to IC engines as an exhaust-gas energy-recovery device. The direct recovery method used by the turbocharger mainly aims to reclaim the pressure energy resulting from 'blowdown' at the end of the expansion. The blowdown event refers to the pressure pulse in the exhaust gas forming as the exhaust valve is opened. To be specific, due to the cylinder expansion ratio usually being insufficient to fully expand the gas to ambient pressure, the pressure in the cylinder is much higher than that in the exhaust manifold when the exhaust valve opens, especially before the piston reach top death centre. Therefore, once the exhaust valve is opened, any remaining combustion pressure in the cylinder is suddenly released producing a sudden pressure rise in the manifold [11]. The energy extracted by the turbine is used to compress the engine intake air, thereby allowing more fuel to be burnt and an increased engine power density. Thus, the employment of the turbocharger can offer a route to fueleconomy through downsizing. However, at many engine operation conditions, there is much more energy available to a turbine than that consumed by a compressor. The waste gate of the turbine, therefore, is introduced to divert a fraction of the exhaust gas, thereby reducing the power driving the turbine wheel to match the power required for a given boost level. By doing so, energy that could have been reclaimed is wasted. Thus, a significant amount of heat energy is available for a waste heat recovery (WHR) system conceived as bottoming cycle. Similar to the first stage of the exhaust-gas energy-recovery system, bottoming WHR cycles could further profitably exploit this discharged heat not only by direct recovery through exhaust gas expansion but also indirect recovery through heat transfer.

The aim is to introduce IBC system as a bottoming WHR cycle of a turbocharged engine, instead of replacing the turbocharger. This is because that the turbocharger is not only designed for reducing the engine fuel consumption in some engine operating envelope, but achieve significant power gains and, therefore, provide a route towards engine downsizing. The benefits of engine downsizing are friction reduction as well as reduced thermal loss. Moreover, any reduction in engine mass can, in turn, lead a reduction in chassis, drivetrain and suspension masses. Thus, given that the turbocharger is highly beneficial to engine performance, the IBC system is designed and mounted downstream of the turbocharger turbine, even though an IBC system is able to recover more wasted energy without the turbocharger due to the higher exhaust temperature.

V. Inverted Brayton Cycle

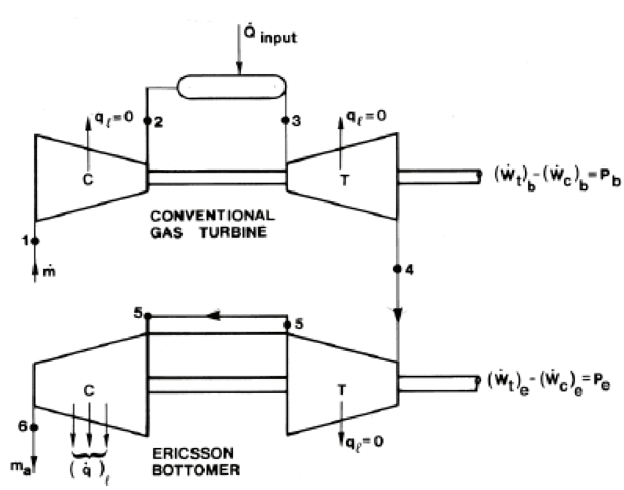

Figure 5 Layout of a combined Brayton and Ericsson bottomer gas turbine

Due to the drawbacks of the turbo-compounding system, a simple modification of the turbo-compounding system with a downstream heat exchanger and compressors with intercooling, termed as the Braysson cycle, has been proposed by Frost et al. The Braysson cycle, shown in Figure 5, consists of a conventional gas-turbine worked as the high-temperature heat addition process and the Ericsson cycle as the low-temperature heat rejection process. Frost et al. performed the First Law analysis for the Braysson cycle. The exergy analysis of an irreversible Braysson cycle has also been studied by Zheng et al. Furthermore, performance analysis and optimum criteria of anend reversible and irreversible Braysson heat engine have been intensively studied by using a concept of the finite-time thermodynamic for a typical set of operating condition. The corresponding results revealed that there is a window of pressure ratio in the upper Brayton cycle where the Braysson cycle shows a significant improvement over the best that can be achieved with either the non-regenerative or the regenerative Brayton cycle, even over the conventional combined gas and steam turbines in a certain range of operating condition. However, the high vacuum (up to 0.04 bar) in the bottom cycle requires a large turbine and the cooling technique implemented with the compression process to obtain isothermal compression that may hinder the practical application especially considering the added manufacturing difficulty and cost. Thus, given the feasibility of Braysson cycle application, the Ericsson cycle should be improved by adding a heat sink – heat exchanger and replacing intercooled compressors with conventional compressors. In other words, the novel proposed architecture consists of a conventional turbine, heat exchangers, and compressors, referred as inverted Brayton cycle (IBC). The schematic diagram of the basic IBC system with an IC engine is shown in Figure 6.

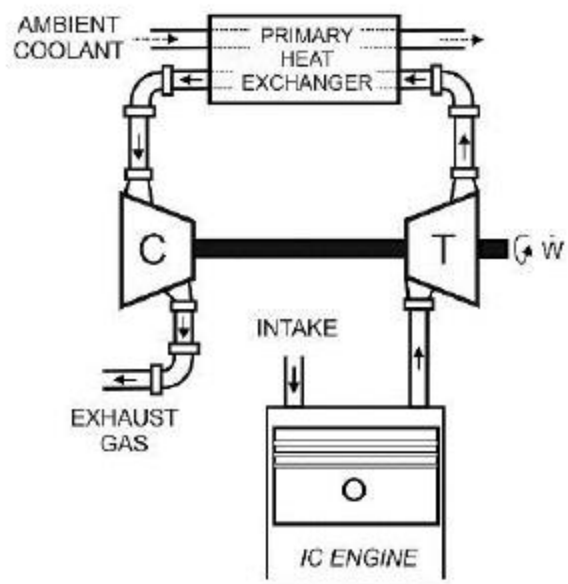

Figure 6 Layout of inverted Brayton cycle mounted immediately downstream of an IC engine

As far as authors' knowledge, the concept of inverted Brayton cycle has been first proposed and studied by Kohler in 1919. Instead of utilizing a heat exchanger,a steam generator and condenser were employed to cool the working fluid after expansion. In 1944, the alternative cooling applications, using surface or spray type coolers, were studied by Hingst to improve the overall performance. In 1955, the function of IBC inlet temperature and turbine pressure ratio was established by Hodge, to evaluate the IBC overall thermal efficiency and specific power output. The function shows that the cycle inlet temperature plays a vital role in the IBC performance, as both the thermal efficiency and the optimum pressure ratio increases with the cycle inlet temperature. Thus, given the characteristic of IBC cycle, the preferable primary cycle should deliver high temperature exhaust gas in order to enhance the hear-recovery capability of IBC cycle.

Preliminary analysis on the IBC has been concentrated on the case of an IBC as a bottoming cycle to a gas turbine, which is dubbed the mirror gas turbine. The first investigation was performed by Wilson and Dunteman, who were inspired from a business case about a Ruston and Hornsby commercial gas turbine. In order to increase the overall energy generated by this gas turbine system, a waste-heat boiler was incorporated as a heat source for other uses by harvesting some remaining heat from the turbine exhaust. The downside of the additional heat boiler is that the parasitic pressure drop contributes to the increase of the turbine exhaust pressure, thereby reducing the pressure ratio across the turbine and, therefore, the corresponding power output. One customer attempted to eliminate this negative influence of the waste-heat boiler by employing a downstream induced draft fan to reduce the turbine exhaust pressure back to atmospheric. The customer reported that although the induced draft fan consumed the electric power to remain the atmospheric pressure at the turbine exit, the overall net power benefited from the increased power generated by the gas turbine itself. The resulting power gain encouraged Wilson to further improve this architecture by introducing an additional turbine between the main turbine and a waste-heat boiler, that is, inverted Brayton cycle as a bottoming cycle. In Wilson's research, the thermodynamic performance and return on investment of IBC system were investigated based on the reasonable assumptions with respect to the technology at the time. The results showed that there is a window of IBC inlet temperature and pressure ratio where the cycle iscompetitive with other methods of waste-heat utilization. Moreover, the average return on investment for the IBC device was up to 30 percent. This large return on investment was calculated on the assumption that the exhaust gas would be discharged into IBC at any operating points. It should be noted that the resulting back pressure will be negligible at design point, but undoubtedly increase at off-design points. However, the gas turbine power loss caused by the back pressure was ignored in their research. Consequently, the return on investment were overestimated. The other limitation of their study is that the IBC system was only evaluated at one operating condition. In addition, a proper optimisation of the pressure ratio of the IBC turbine should be employed to maximum the IBC heat-recovery capability in their study.

Afterwards, Holmes conducted a thermodynamic analysis of the combined system of marine gas turbine and IBC, in order to investigate performance, efficiency and fuel-consumption effects on marine gas turbine. The results showed a maximum increase in power and efficiency of around 12%. In addition, he reckoned that the upper cycle, which was marine gas turbine in his research, should be optimised to gain benefits from the employment of an IBC system. Thus, a matching process should be conducted when IBC system is introduced to any existing upper cycle.Tsujikawa at el. performed a comprehensive parametric study of IBC system to reveal the influence of the IBC inlet temperature, pressure ratio, turbo machinery efficiencies, and the stage number of intercooling. Then, a conventional gas turbine and IBC system - mirror gas turbine were optimised to maximize the power output and thermal efficiency of the combined system.

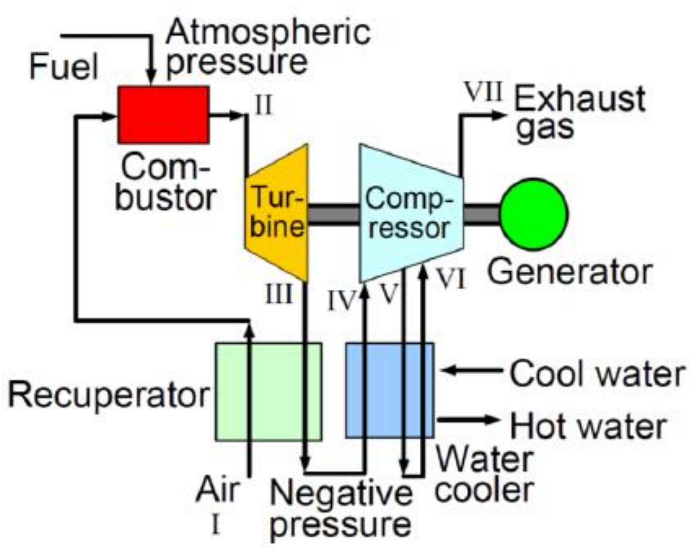

Figure 7 Schematic diagram of APT

The results showed that even at atmospheric pressure the waste energy can be recovered successfully from the high temperature gas by employing IBC system as a bottoming heat-recovery cycle. Moreover, by introducing three stages intercooling, the IBC thermal efficiency can be improved by approximately 10 percent when the IBC overall pressure ratio was limited up to 10. Finally, they found that the optimal combined system of a Brayton cycle and IBC was able to deliver up to 60% thermal efficiency in the case of a turbine inlet temperature of 1500°C. However, since the IBC inlet pressure in the combined system was fixedas 1 bar in their research, the influence of IBC inlet pressure on the whole system was not revealed. It should be noted that the benefit of multi-stages IBC, constructed from a expander followed by multiple heat exchangers and compressors, was also investigated by Kaneko. The results showed that the improved systematic performance could be expected by an increase in the number of compression stages. In addition, a combined system between two-stage IBC and a combustor, referred as two-stage atmospheric pressure turbine (APT), was able to achieve maximum overall thermal efficiency of 65%. Figure 7 shows the basic configuration of an APT. Basically, it consists of a combustor and IBC system. The unpressurized burned gas with high temperature discharged by combustor is utilized as the energy source for IBC system. Thus, research above showed that multi-stages IBC are promising and should be considered as a potential bottoming heat recovery cycle.

VI. Conclusion

As per given data of different research paper for Inverted Brayton cycle (IBC) in which studied different methodology of heat recovery system and effect of improving different component in cycle like centrifugal pump. Try to replace existing mechanical component which are not compatible to system for improve system with reference to energy concern.

In this research, inverted Brayton cycle (IBC) has been comprehensively studied by simulations and tests. It was considered as the exhaust-gas heat-recovery systems for a commercial 2-litre turbocharged gasoline engine. Based upon intensively 0D, 1D, and 3D simulations of the IBC system, the IBC prototype was designed, manufactured, and tested in this research. This is the first experiment of IBC system designed for the automotive use. More important, decent heat-recovery capability of the IBC system was demonstrated experimentally.

The basic IBC system consists of a turbine, a heat exchanger, and a compressor in sequence. The use of IBC turbine is to fully expand the exhaust gas available from the upper cycle to below atmospheric pressure, thereby harvesting the wasted energy. The remaining heat in the exhaust after expansion is rejected by the downstream heat exchanger. Then, the cooled exhaust gases are compressed back up to the atmospheric pressure by the compressor and discharged to the ambient. The network produced by IBC system is defined as the power differential between the power harvested by the IBC turbine and that consumed by the IBC compressor. The use of the heat exchanger is to minimize the inlet temperature of the IBC compressor.

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