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Application of Exergy Analysis to Internal Combustion Engine: A Review

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Abstract—*This paper surveys the publication available in the literature concerning the application of exergy analysis to internal combustion engines. An exergy-based analysis is the analysis of a thermal system based on the second law of thermodynamics that overcomes the limit of an energy based-analysis (first law of thermodynamics). The traditional first law analysis of a system, although it may enable one to determine how the energy is distributed across the boundaries of the system, does not provide the means of evaluating the energy degradation that causes a reduction in work output of system. The use of second law analysis along with the first law analysis provides the capability to identify and catalog those processes which cause energy degradation. Exergy is defined as the maximum useful work obtained as system reaches to dead state. The main objective of the present study is to deal with the review the application of exergy analysis by to internal combustion engine.*

Unlike energy, exergy destroyed as a result of such phenomena as combustion, friction throttling etc. The destruction of exrgy- often termed irreversibility- is the source for the exploitation of fuel into useful mechanical work in engine. The reduction of the irreversibiltites can lead to better engine performance through a more efficient conversion of fuel. To reduce the irreversibiltites, we need to quantify them. That is we need the second law (exergy) analysis. Result of exergy analysis can be used to improve the performance of existing systems as well as to design the new system with higher energy efficiencies.

1. INTRODUCTION

"Reports on detailed use of the second law of thermodynamics (exergy analysis) to study the internal combustion engines have been published for over 50 years. While the use of exergy analysis (second law analysis) is not necessary for general performance computations, the insight provided by exergy analysis is invaluable in understanding the details of the overall thermodynamics of engine operation. The second law of thermodynamics is powerful statement of related physical observations that has wide range of implications with respect to engineering design and thermal system. Exergy analysis is becoming a very powerful strategy to evaluate the real efficiency of a process. Exergy analysis allows the calculation of the exergy losses and thus those systems in which the highest losses are produced can be identified and optimization measures can be taken to minimize those losses. One such approach which identifies and quantities the engine thermodynamic losses, is exergy analysis. Exergy analysis, a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics for the design and analysis of thermal systems. Another term frequently used to identify exergy analysis is availability analysis [20].

The traditional first law analysis of a system, although it may enable one to determine how the energy is distributed across the boundaries of the system, does not provide the means for evaluating the energy degradation that causes as reduction in work output of the system. Based on second law analysis along with the first law analysis provides the capability to identify and catalog those processes which cause energy degradation. Internal combustion engine simulation modelling has long been established as an effective tool for studying engine performance and contributing to evaluation and new developments. Thermodynamic models of the real engine cycle have served as effective tools for compete analysis of engine performance and sensitivity to various operating parameters. On the other hand it has been long understood that traditional first law analysis which is needed for modelling the engine processes, often fails to give the engineer the best insight of engine's operation. In order to analyze the engine performance- that is evaluate the inefficiencies associated with the engine subsystem exergy analysis (second law analysis) can be useful alternative to first law, being able to shed more light and provide better insight into engine processes For second law analysis the key concept is exergy or available energy". The availability of the matter explains it's potential to produce useful work. The main objectives of the application of exergy analysis to internal combustion engines have been:

- To weigh the various processes and devices calculating the ability of each one of these to produce work
- To identify the processes that leads to exergy destruction
- To quantify the various losses and destruction.

- To analyze the effect of various design and thermodynamic parameters on exergy destructions and losses.
- To propose measures for minimization of destruction and losses, to increase the overall efficiency.
- To analyze the effect of various thermodynamics parameters and engine design parameters on exergy destruction.

2. ANALYSIS AND REPORT STUDIES

Over two dozen previous studies employing the second law of thermodynamics or exergy analysis with respect to internal combustion engines were identified. About two – third are completed for diesel engines, and the other one-third are completed for spark engines Following is a chronological presentation of descriptions of these studies. This study is divided into two subsections: early work (1957-2000) and recent work (2000-2015). A brief description of each investigation is provided.

2.1 Early work: 1957 to 2000-

One of the earliest documented studies is a brief report presented by Traupel in 1957. A naturally aspirated diesel engine and a turbocharged diesel engine. It was found that combustion process accounted for destruction of about 22.5% and 21.9% of the fuel's exergy for naturally aspirated and turbocharged diesel engine, respectively. Losses related to cooling, exhaust, mechanical, and aerodynamic process are also reported

Patterson and Van Wylen [28] A pioneering work is reported by Patterson and van Wylen in 1964. Their work described a version of thermodynamic cycle simulation for spark ignition engines in which they included determination of entropy values. With the entropy values, they determined the exergy for the compression and expansion strokes and, most important, they isolated exergy destruction associated with heat transfer and combustion process. Some of simplifications of this early work included (1) idealized induction and exhaust process with instantaneous valve events occurring at top dead and bottom dead center, (2) the induction, compression, and exhaust process were assumed adiabatic, and (3) the cylinder pressure during the induction and exhaust processes is assumed constant and specified.

Ghazikhani et.,al. [11] Experimental investigation was conducted to study the influence of EGR temperature on destruction of the fuel's availability due to combustion process under variable operating engine speeds in IDI diesel engine. They examined the various EGR temperatures and rate at different operating speeds at full load. It was found that about 60 to 70% of fuel's availability or exergy is destroyed by irreversibiltites. They reported that the increase of EGR temperature in leads to reduction in combustion irreversibility.

Primus et. al. [25]: They used the second law analysis to assess the improvements of turbocharging, change air cooling, turbo compounding, and the implementation of a bottoming cycle and the use of insulating techniques. The base line engine for this study was 4-liter direct injection, naturally aspirated, diesel engine rated at 185 kW at 2100 rpm. They showed that as the combustion becomes leaner, the exergy destruction increases due to increased mixing and lower bulk gas temperatures. This happened because the high temperature products of combustion are mixed with the excess air. For mixture closed to or at stoichiometric, this effect is minimized (less excess air, higher temperatures), and hence the conversion of chemical potential to work is more effective. For this reason they found that for turbocharging (with AF ratio) the combustion destruction of exergy was higher.

Flynn et, al. **[11**]: They presented a second law based analysis of the processes within in diesel engine and compared with the traditional first law analysis. Available energy additions, extractions, and destructions are examined and quantified for the various engine processes. To demonstrate the second law analysis technique, a turbocharged after cooled diesel engine used. Conservation of mass and energy is used for calculations. They portrayed the engine processes in T-S plane. This approached can be applied to diagnosis of either the simulation data or experimental data on real operating systems or subsystem within the overall engine system. They stated that the approach, because it used either simulation data or experimental data that supplies working fluid temperatures, pressure, and fuel/air ratio, is easily used in cycle simulation results or an incremental analysis on systems where experimental data are available

Primus and Flynn [**23]** In this study, a turbocharged and after cooled, direct-injected diesel engine is used. They conducted a detailed parametric study which examined the effects of number of engine parameters on various thermodynamic process of engine operation. The examined parameters were engine speed, load, peak cylinder pressure limit, compression ratio, intake air temperature, injection timing and apparent heat release shape. They mentioned the exergy destruction percentage by combustion as increasing from 21.8 to 32.5% as load decreased.

Flynn et. al., [26]: they used a second law analysis to study the turbocharged, intercooled diesel engine. The main purpose of second law analysis was to evaluate low heat rejection engine concepts and secondary heat recovery devices. The engine for this study was a 14-liter, in-line six-cylinder, diesel engine operating at 300 Kw at 2100 rpm. Essentially they used standard thermodynamic cycle simulation to obtain the thermodynamic state for a particular engine cycle. Entropy and exergy is determined for each state point and completed exergy balances are presented for the complete engine cycle. Their research result showed that of the original fuel exergy about 46% was delivered as useful indicated work, 26% was destroyed, 10% was transferred as heat, and 18% was exhausted. The significant result of their work showed that work output per unit of fuel increased as the equivalence ratio became leaner. Also as the equivalence ratio becomes leaner, the destruction of exergy becomes greater. The main reason for this is because exergy transfer due to heat transfers and exhaust flow fall faster as equivalence ratio decreases.

Arai [5] He reported the influence of a disintegrating process and spray characterization of fuel jet injected on fuel- air mixture formation and the influence of that mixture formation and the influence of that mixture on combustion process. The study showed that understanding of disintegrating process and spray characteristics are very important for designing ta high quality diesel engine because combustion in diesel engine is strongly controlled by a fuel spray injected into the combustion chamber. The size and the aerodynamic motion of the fuel spray has great effect on the exergy destruction during combustion and on formation of smoke, unburned hydrocarbon and nitric oxides. His research work is basic study of diesel engine combustion for many researchers.

Kumar [18] reported a useful method in determining all losses associated with an engine using a second law of thermodynamics. In his work, he showed some preliminary results in the application of availability as second law analysis parameter to complete the diesel engine cycle, and that results showed that second law is a very powerful tool in the combustion process analysis which can be quantify the losses and irreversibility's in internal combustion engine.

Alkidas [2] examined the application of a second law analysis for a diesel engine. But his research was different from other investigations on second law analysis. He applied the first and second law to single cylinder open chamber diesel engine. He made two different approaches in his work. The test were run at speed of 1200 and 1800 rpm, at fixed static injection timing of 8^{o}BTDC, and various load. The first law efficiency of the engine, defined as the ratio of brake power to input fuel power varied from 22 to 40 % over the load range evaluated, it showed that the efficiency was increased with increasing with load. The second law efficiency increase with increasing the engine load was reported. It was found that half of the energy of the exhaust gases could be utilized for production of useful work.

Shaporo and Van Gerpen [33] they extended their earlier work to include a two-zone combustion model and applied this model to both a compression-ignition and a spark ignition engine. As before, their study included chemical exergy considerations. Their work considered only the compression and expansion strokes, and included no consideration of intake or exhaust flows. They presented the time resolved values of the exergy for cases with different equivalence ratios, residual fraction, and burning durations.

Gerpen and Shapiro [13] they applied second law analysis on combustion process in a diesel engine for single-zone model.in contrast previous investigation, this work included the "chemical component" of exergy and also included some simplification during the burning process in a cylinder such as initial cylinder conditions at bottom dead center were assumed to be ambient conditions with no residual gases and only compression and expansion strokes were considered (no flows were included. It was found that the chemical exergy is about 15% of total exergy, and for the rich mixture, the exergy was shown to be high as 90% of the total exergy. **Rakopoulos and Andritsakis** [31] presented results for the irreversibility's rates of two four -stroke cycle diesel engine. They used experimental data to determine the fuel burning rate and then they used second law of thermodynamics to deduce the irreversibility rates for each engine. Their experiment showed that the accumulated irreversibility was proportional to the fuel burned fraction for a wide range of engine loads, speeds and injection timings. For the direct injection engine, the destroyed exergy was varied 24-29 %of the fuel exergy.

Rakopoulos et al. [30] they reported on the exergy accumulation and destruction in high speed, direct injection, and natural aspirated diesel engine. They done experiment to determine the fuel reaction rates, and then computed the associated second law quantities including the irreversibility production rate. They limited their considerations to the valve closed period. They completed this work for a range of speeds and loads. They studied limited cooling conditions to determine the implications from a second law perspective on improving the efficiency. They considered the use of exhaust heat recovery devices to utilize the extra exergy present in the exhaust gases for the limited cooling cases.

Rakopoulos. [**29]** described a first and second law analysis of a spark ignition engine using a cycle simulation and experiments. The major parameters studied are compression ratio, fuel air ratio, and ignition advance. They reported that the accumulated irreversibility is proportional to engine load, speeds, and injection timing, for the direct injection engine, the destroyed exergy is about 21 and 30% of the original fuel exergy. For indirect injection engine, the destroyed exergy is between about 24 and 2% of the original value. It was found that indicated that irreversibility's decrease and the exergy of the exhaust gas increases with increasing fuel-air ratio. On the other hand, they reported both the irreversibility's and exergy of the exhaust gas increased with engine speed, and slightly decreased with increasing injection timing.

Al-Najem and Diab [4] presented a short technical note which described brief results for turbocharged diesel engine operated at 243 kW with an air-fuel ratio of 20. They stated that about 50% of the fuel availability is destroyed due to unaccounted factors such as combustion, 15% is removed via exhaust and cooling water, and about 1% is destroyed in the turbocharger

Rakopoulos and Giakoumis [23] they reported on the use of computer analysis to study the energy and exergy performance of an indirect-injection, naturally aspirated diesel engine operating under steady state and transient conditions. Their simulation result includes innovations such as detailed analysis of thermodynamic and dynamic differential equations which accounted for the continuously changing character of transient operations, a more complete analysis than was given earlier treatments of transient mechanical friction, combustion and fuel injection as well the detailed modelling of engine-inertia forces and incorporation of a fully mathematical model of the governor.an exergy balance was applied to subsystem of diesel engine such as cylinder for both closed and open parts of cycle and inlet and exhaust manifold.

Rakopoulos and Giakoumis [32] They investigated the computer analysis to assess the cumulative and availability rate balances of a multi-cylinder diesel engine. They studied a six-cylinder, turbocharged and after cooled, indirect-injection diesel engine at full load and 1500 rpm. They neglected chemical dissociation. They included all individual components from compressor through the cylinder to the turbine. They included all processes for both the closed valve and open valve portion of the cycle. They showed that 21.4% of the fuel's availability left the cylinder with the exhaust, but after the turbine, the exhaust only contained 13.5%. The combustion irreversibility was responsible for destroying 21.9% of the fuel's availability.

Datta and Som [10] developed a theoretical model of exergy analysis, based on availability transfer and flow availability, in the process of spray combustion, to evaluate the total thermodynamic irreversibility. Second law efficiency of the process at various operating conditions was also reported. The velocity, temperature and concentration fields in the combustor, required for the evaluation of the availabilities and irreversibiltites, were computed numerically from two phase separated flow model of the spray along with a suitable reaction kinetics for the gas phase reaction.

3.2 Recent work (2000 to 2015): Following section describes the recent significant work on the application of exergy analysis to internal combustion engine.

C.D. Rakopoulos and D.C. Kyritsis [31]: The first and second law analysis is used to calculate the rate of entropy production as a function of fuel reaction rate. In the modelling of engine, a three-hole injector nozzle was used for dodecane injection. Theoretically, the decomposition of lighter molecules generates less entropy. Using the extensive experimental data available for the case of n-dodecane (n-$C_{12}H_{26}$) injection, which typically represents the diesel fuel in the study of automotive or smaller size diesel engines, the fuel reaction (combustion) rate is determined. A single- zone model is used to simulate the engine operation.

***C.D. Rakopoulos and E.G. Giakoumis(2004):*In** this study the energy and exergy performance of a turbocharged diesel engine operating under transient load condition by performing computer analysis has been studied. The model contains some novel features for the simulation of transient operation, such as, separate consideration for the processes of each cylinder during a cycle ("multicylinder" model), detailed analysis of mechanical friction and mathematical modeling of the fuel pump. The exergy terms were analyzed for the diesel and its subsystem. In this a single zone model is used as the basis for the thermodynamic process evaluation. It was found that specific engine processes and parameters apart from the well-known in-cylinder irreversibiltites (such as the exhaust manifold irreversibiltites, the cylinder wall insulation and the after cooler effectiveness) which could, according to the exergy analysis, improve the engine processes

Giakoumis and Rakopoulos [32] They reviewed the exergy balanced equation of engine cylinder and subsystem with providing the definition of state properties, dead state, flow and fuel exergy. The difference between first law and the second law is also mentioned. The traditional first law is an analysis which is needed for engine modeling, often fails to give the best insight into engine's performance-that is, evaluate the inefficiencies related to varied process-second law must be applied. Exergy is the maximum theoretical work that could extract from the system. Unlike energy, exergy is destroyed within the system. Destruction of exergy is also known as irreversibility- the reduction of the exergy destruction may lead to better engine performance.

Perhan Sekmen, Zeki Yilbasi [27] in this study combination of first and second laws of thermodynamics were employed to analyze the quantity and quality of energy in four-cylinder, direct injection diesel engine by using petroleum diesel fuel and biodiesel fuel. The steady-state tests is used to collect the experimental data for accurate measurements of fuel, air and cooling water flow rates, engine load, and all the relevant temperatures. Balances of energy as well as exergy rates for the engine were determined and then various performance parameters of the engine and energy and exergy efficiencies were calculated for each fuel operation and compared with that of biodiesel.

Canakci and hosonz [34] They reported energy and exergy analysis of diesel engine fuelled with various biodiesels. Here, a four cylinder, turbocharged diesel engine was studied to determine the heat transfer rates and performance parameters during engine operation using diesel, SME(soya bean oil methyl ester), YGME (yellow grease methyl ester), and 20% blends of two bodices. This study concluded that brake specific fuel consumption (bsfc) is inversely proportional with a lower heating value of the fuel" resulting a 12-13% increase in fuel consumption. It was also concluded that the "pure SME and YGME biodiesels yields approximately 1.6% higher thermal efficiencies compared to diesel fuel" due to better combustion characteristics from oxygenated fuels. Overall it was found that "biodiesel and their blends show almost the same energetic performance with diesel fuel in terms of fuel energy and fuel exergy, brake thermal efficiency, combustion efficiency, heat loss, and exhaust loss". The distribution of energy from use of pure biodiesel resulted in approximate differences in heat loss, exhaust loss, and brake work of 2.3%-2.9% and 0.6% respectively when compared to diesel**.**

Jafamrmadar [15] carried the exergy analysis in pre and main chamber of an indirect injection diesel engine by three dimensional model for two load at maximum torque engine speed. Energy analysis during a closed engine cycle by using CFD code has done. Various exergy components including fuel, heat loss, irreversibility's, work exhaust loss, chemical and thermochemical exergy for pre and main chamber were reported. His work demonstrates that multidimensional modeling can be used at complex chamber geometry to gain more insight into the effect of flow fields on combustion process accounting for the second law of thermodynamics.

Jafamrmadar [16] Developed the three dimensional computational code with the appropriate combustion model to study the combustion processes with the chamber of engine from the second law of thermodynamics. It was found that when the gas fuel-air ratio increases from 0.3 to 0.8 by 0.1 increments then the in cylinder temperature, pressure cumulative heat loss increases while the cumulative work exergy and percentage of irreversibiltites decreases

Abassi [1] reported the numerical investigation to study the influence of the nozzle hole diameter in the first and second law balance in a direct injection diesel engine. They found that an increase in the nozzle hole diameter causes an increase in the indicated work and heat loss to walls. With regard to second law terms, they found that an increase in nozzle hole diameter leads to an increase in indicated work exergy, heat loss availability and entropy generation per cycle and decease in combustion irreversibility and exhaust availability.

Ozkan [22] A four stroke four cylinder direct injection CI engine was run using three different injection pressures. It was found that as the injection pressure increases, the indicated power increases because of the increased combustion efficiency, although the brake power decreases at the same time. These results showed that, the power required of an injection pump to pressurize the fuel for a Diesel engine is greater than the increased engine power associated with an increased in the injection pressure. The study showed that it is possible to increase exergetic efficiency of a CI engine by adjusting the injection pressure

Meisami and Ajam [25] They investigated, the first and second laws of thermodynamics to analyze the quantity and quality of energy in a Diesel engine using pure Diesel fuel and various blends of castor oil methyl ester (CME) as biodiesel fuel. It was found that the structural oxygen content of biodiesel improves the combustion efficiency however, the engine's thermal efficiency decreases due to the lower heating value of the biodiesel. It was also found that, destruction of exergy increases when using biodiesel. Exergy analysis was performed by evaluating exer-gies associated with the inlet fuel, heat loss, exhaust loss and destruction. It was reported that the average exergy destruction was about 47% of the inlet fuel exergy, which was mainly due to the irreversibility of the combustion process. They reported that the exergy destruction for biodiesel blends was higher than that of pure Diesel.

3. SUMMERY

This paper has reviewed investigations that have used the second law of thermodynamics in studying internal-combustion engines. The second law of thermodynamics was shown to provide a framework which leads to clear understanding of the energy conversion process, provides a quantitative measure of the capability to produce useful work, and identifies those processes that are destructive to the goals of high performance and high efficiency engines. An important contribution for applying the second law of thermodynamics in engine research was given through application of different and powerful computer simulation programs which provided very accurate engine models to calculate overall thermodynamic values for complete combustion process.

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