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Analysis of Internal Combustion Engine Thermodynamic Using the Second Law of Thermodynamics

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Original scientific paper

The paper presents the research work done by various authors who have done research in the application of the second law of thermodynamics in analysis of the internal combustion engine and in analysis of the thermodynamics of the combustion process in an engine cylinder in spark- and compression-ignition engines.

For several decades now, various authors have been trying to optimize processes in the internal combustion engine, where energy degradations occurs during combustion. It is essential to get a better insight and understanding of the sources for this energy degradation to avoid or diminish them, striving to achieve higher efficiencies of internal combustion engines as the most effective heat engine. One of the most suitable ways in research of energy degradation is application of the second law of thermodynamics in analysis of the process in internal combustion engines.

Through the application of the second law of thermodynamics in analysis of the combustion process, the connection between all thermodynamic data with enthropy was achieved. By applying the numerical simulations in modeling the ICE engine processes together with the analysis by the second law of thermodynamics, we get a very potent tool for better insight and optimization of spark- and compression-ignition engines achieving lower fuel consumption and lower emissions.

Termodinamička analiza motora s unutarnjim izgaranjem koristeći drugi zakon termodinamike

Izvornoznanstveni članak

U radu je dan pregled istraživanja brojnih autora koji su proučavali primjenu drugog zakona termodinamike na analizu motora s unutarnjim izgaranjem i na analizu samog termodinamičkog procesa izgaranja u cilindru motora i to jednako i na otto i na dizelske motore.

Već nekoliko desetljeća brojni autori pokušavaju optimizirati procese u motorima s unutarnjim izgaranjem i to na način da detektiraju mjesta i procese unutar motora gdje se zbiva najveća destrukcija radne sposobnosti radnog medija tijekom izgaranja. To je vrlo bitno jer se boljim razumijevanjem uzroka destrukcije radne sposobnosti, radnog medija dolazi do mogućnosti da se uzroci takvih destrukcija uklone ili smanje kako bi se smanjila ukupna destrukcija radne sposobnosti tj. da se još poveća efikasnost motora s unutarnjim izgaranjem kao najkvalitetnijeg toplinskog stroja za pretvorbu energije. Vrlo prikladan način za detaljnije proučavanje destrukcije radne sposobnosti je uporaba drugoga zakona termodinamike u proračunima i analizama procesa u motorima.

Uporabom drugoga zakona dobiva se veza svih termodinamičkih parametara tijekom procesa izgaranja pa tako i entropije što nije bilo moguće primjenom samo prvog zakona termodinamike. Daljnim korištenjem razvijenih računalnih simulacijskih programa za modeliranje motora s unutarnjim izgaranjem i primjenom drugog zakona termodinamike dobiva se jako moćno sredstvo za kvalitetnije razumijevanje i bolju optimizaciju rada ottovih i dizelskih motora, a samim time postiže se manja potrošnja goriva i smanjenje štetnih spojeva u ispušnim plinovima.

Keywords
Combustion
Internal combustion engine
Second law analysis

Ključne riječi
Analiza primjenom drugog zakona termodinamike
Izgaranje
Motor s unutarnjim izgaranjem

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1. Introduction

Investigations and reports that have used the second law of thermodynamics to analyze the combustion process in internal combustion engines have been published for more than 40 years. Representative results are presented for both compression-ignition and spark-ignition engines to illustrate the type of information obtained by use of second law analysis and instantaneous values for the engine availability or exergy and the overall values for energy and availability are described. A brief description of most of these methods is provided in this work.

The use of second law analysis is not necessarily intended for general performance computations but for understanding the details of the overall thermodynamics of engine operations. The second law of thermodynamics is a powerful statement of related physical observations that has a wide range of implications with respect to engineering design and operation of thermal systems. The second law can be used to determine the direction of process, establish the condition of equilibrium, to specify the maximum possible performance of thermal systems and identify those aspects of processes that are significant to overall performance.

Related to the analysis based on the second law of thermodynamics is the concept of availability or exergy. Availability or exergy is a thermodynamic property of a system and its surroundings and is a measure of the maximum useful work that the given system may obtain as the system is allowed to reversible transition to a thermodynamic state which is in equilibrium with its environment. A very important aspect of availability or exergy is the fact that a portion of a given amount of energy is available to produce useful work, while the remaining portion of the energy is unavailable for producing useful work.

During the combustion process, thermal, mechanical and chemical processes are very important for availability analysis. An example of the thermal aspect of availability analysis is an ideal case where the system temperature is above the environmental temperature, and the availability from the system could be converted to work until the system temperature, equaled the environmental temperature while the remaining energy is an unavailable part of the energy. The mechanical aspect of availability analysis is a system which is at pressure above the environmental pressure. By utilizing an ideal expansion device, the energy of the system could be converted to work until the system pressure equaled the environmental pressure. A third aspect of availability analysis is a chemical aspect, which considers the potential to complete work by exploiting the concentration differences of the various species relative to the related concentrations in the environment. The consideration of the species concentration component of availability is often neglected due to the practical difficulties of implementing such a system and the relatively small amounts of work produced.

Availability or exergy is not a conserved property and can be destroyed by irreversible processes such as heat transfer through a finite temperature difference, combustion, friction and mixing processes.

The majority of different reports and studies have investigated the influence of heat transfer, combustion, friction and mixing processes on availability destruction suggesting different options to reduce energy degradation and increase portion of energy available for useful work.

2. Analysis and report studies

Reviews of a number studies with chronological presentations are shown in the following descriptions of these studies. A pioneering work was reported by Patterson and van Wylen [1] in the early 60's. Their work described a version of a thermodynamic cycle simulation for spark-ignition engines in which they included determination of entropy values. With the entropy values, they determined availability (exergy) for the compression and expansion strokes and, most important, they isolated availability destruction associated with heat transfer and combustion process. They summarized their results by stating that of the availability at the beginning of the compression process, 1/3 was delivered as work, 1/3 was lost due to combustion and heat transfer processes and 1/3 was expelled through exhaust gases.

Clarke [2] also researched availability destruction in engine cycles. He examined the Otto, Joule, Atkinson air-standard cycles from the perspective of availability and the associated availability destruction. He described the possibilities of achieving higher thermal efficiencies by recognizing the fundamental availability loss mechanisms for internal combustion engines. He also reported and explained possibilities to achieve minimum destruction of availability, in which the combustion process should be under conditions of near chemical equilibrium.

A significant research in internal combustion engine thermodynamic analysis was done by Gatowski [3], who analyzed the processes inside the cylinder of an internal combustion engine developing a heat release analysis procedure that maintains simplicity while including the effects of heat transfer, crevice flows and fuel injection. The heat release model developed in his studies uses a one zone description of the cylinder contents with thermodynamic properties represented by a linear approximation. He also presented a new application of the analysis to a single-cylinder spark-ignition engine with a special square cross-section visualization spark-ignition engine, and a direct-injection stratified charge engine.

Edo and Foster [4] reported results on an availability analysis for an engine which utilized dissociated methanol, and the use of dissociated methanol was motivated by the possible potential to capture exhaust energy in exhaust gases by dissociating liquid methanol into more readily used gaseous species such as carbon monoxide (CO) and hydrogen (H2). Such dissociated products can be used as a much leaner reactant mixture and in that way they can improve fuel efficiency. Their study also included availability analysis and availability destruction analysis by using a simple adiabatic analysis with an instantaneous heat release for the combustion process, but with a new element in calculations which includes equilibrium products. They connected availability with equivalence ratio.

Flynn [5] used a second law analysis to study turbocharged intercooled compression ignition engine. The main purpose of second law analysis was to evaluate low heat rejection engine concepts and secondary heat recovery devices. They used a standard thermodynamic cycle simulation to obtain the thermodynamic states for different particular engine cycle. Entropy and availability is determined for each state point and completed availability balances are presented for the complete engine cycle. Their research results showed that only 46% of original fuel availability was delivered as useful work and the rest was non-availability (26% was destroyed, 10% lost through heat transfer 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, there is connection between availability and equivalence ratio which showed that as equivalence ratio becomes leaner, the availability destruction becomes greater. The main reason for this is because availability transfers due to heat transfers and exhaust flow fall faster as equivalence ratio decreases.

Primus [6] also reported on a second law analysis of exhaust systems for turbocharged, intercooled diesel engine. He was investigating the influence of the exhaust manifold cross- sectional area upon a number of characteristic such as frictional losses. His work produced an ability to determine an optimum exhaust manifold diameter which could minimize overall losses.

Primus and Flynn [7] continued their research and in this work they used the second law analysis to assess the improvements of turbocharging, change air cooling, turbocompounding, the implementation of a bottoming cycle and the use of insulating techniques. An important result of their work was that as combustion becomes leaner, the availability destruction increases due to increased mixing and lower bulk gas temperatures. They also showed that for mixtures closer to or at stoichiometry, this effect is minimized.

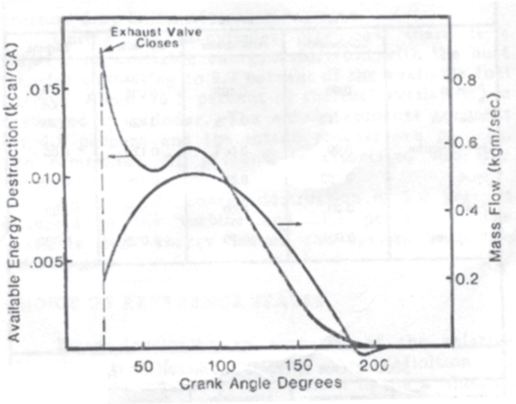

Figure 1. Availability destructions and mass flows during the intake process [5]

Slika 1. Smanjivanje radne sposobnosti i protoka mase tijekom procesa usisavanja [5]

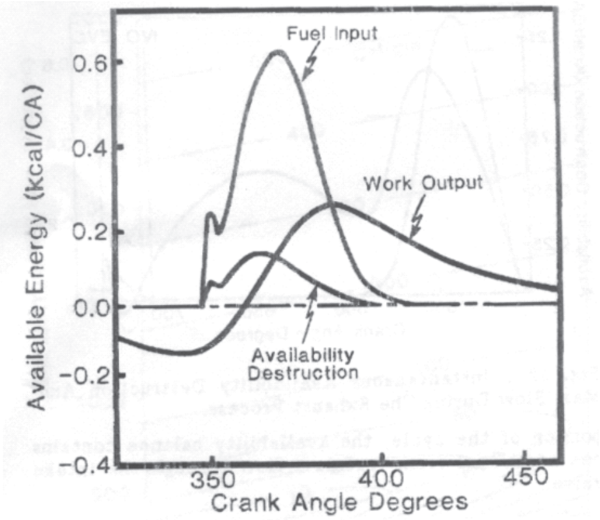

Figure 2. Availability flows during the closed portion of cycle [5]

Slika 2. Radne sposobnosti tijekom zatvorenog dijela ciklusa [5]

Arai [8] showed the influence of a disintegrating process and spray characterization of fuel jet injected on fuel – air mixture formation and the influence of that mixture on a combustion process. The study showed that understanding of the disintegrating process and spray characteristics were very important for designing a high quality diesel engine because combustion in diesel engine was strongly controlled by a fuel spray injected into the combustion chamber. The size and the aerodynamic motion of the fuel spray has a great effect on availability destruction during combustion and on formation of smoke, unburned hydrocarbon and nitric oxides. Arai´s work had a great influence on many engine researches as a basic study of diesel engine combustion.

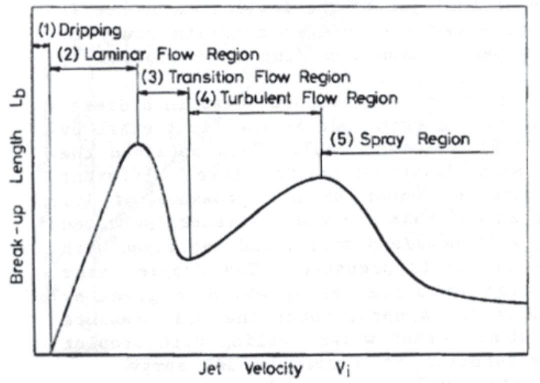

Figure 3. Break-up behaviour of a liquid fuel jet [8]

Slika 3. Ponašanje mlaza tekućeg goriva [8]

Kumar [9] reports results of a useful method in determining all losses associated with an engine using the second law of thermodynamics. In his work, he showed some preliminary results in the application of availability as a second law analysis parameter to a complete diesel engine cycle, and that preliminary results showed that second law is a very powerful tool in the combustion process analysis which can quantify the losses and irreversibilities in internal combustion engines.

Gerpen and Shapiro [10] also used second law analysis with a standard cycle simulation for a diesel engine. But in contrast to the previous investigations, their work included a chemical component of availability and also included some simplifications during the burning process in a cylinder such as initial cylinder conditions at bottom dead center were assumed to be the ambient conditions with no residual gases and only compression and expansion strokes were considered. For the case they studied, they showed that for lean and stoichiometric equivalence ratios, the chemical availability was about 15% of the total availability, and for the rich cases, the availability was shown to be as high as 90% of the total availability.

Shapiro and Gerpen [11] extended their previous work introducing a two – zone combustion model and applied this model to both compression – ignition and spark – ignition engines. This new model also included chemical availability considerations and simplyfications done in previous work. They presented the time resolved values of the availability for cases with different equivalence ratios, residual fractions and burn duration. An important result of their work is that the combustion irreversibilities increases with increasing burn duration.

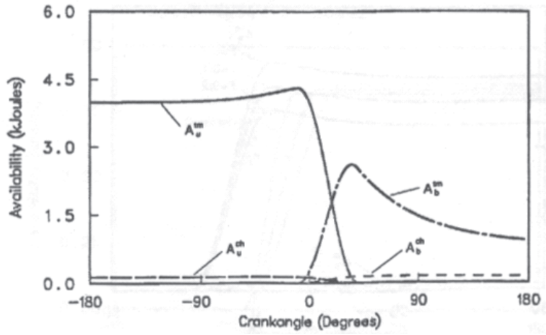

Figure 4. Chemical and thermochemical availability for the unburned and burned zones [11]

Slika 4. Kemijska i termodinamička eksergija u zonama svježe i izgorjele smjese[11]

Alkidas [12] applied second law analysis on diesel engine. But his research was very different from other investigations using second law. He made two different approaches in his work. First the thermodynamic cycle was defined as outside the engine cylinder, and second he used experimental measurements of the energy rejected by the coolant and lubricating oil, brake work and air and fuel rates. Then he calculated availability values from the thermodynamic states based on the measurement values. In his work it is shown that heat transfer was responsible for the greatest availability transfer. Combustion destruction was the second important cause for availability destruction.

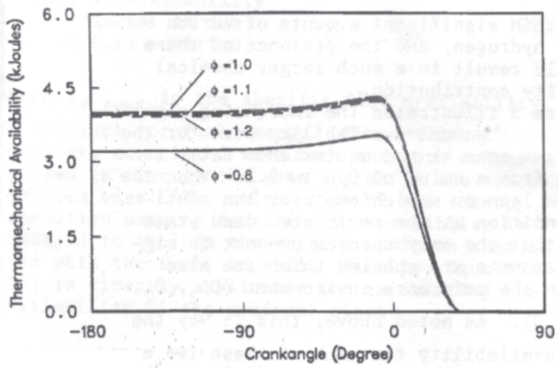

Figure 5. Effect of equivalance ratio on the thermomechanical availability in the unburned zone [11]

Slika 5. Utjecaj pretička zraka na termodinamičku eksergiju u zoni svježe smjese[11]

Nishida and Hiroyasu [13] described a simplified three – dimensional modeling of a mixture formation and combustion process in direct injection diesel engine. They showed that computer modeling of the mixture formation and combustion process in direct injection diesel engine were very useful in predicting engine performance and pollutant emission characteristic. The gas motion, such as the swirl and squish, and the spray behavior were described by a simplified model. Their investigation showed the importance of mixture formation on overall combustion process in an engine cylinder.

Kouremenos [14] presented a thermodynamic analysis of a naturally aspirated, four stroke diesel engine with a swirl prechamber. He used a zero – dimensional energy cascade turbulence model for calculating the heat exchanged between gas and walls in both main chamber and prechamber, using relevant characteristic velocities and lenghts. Combustion in both chambers was attacked by proposing a two zone combustion model. His model gave interesting results in cylinder combustion analysis which evaluate performance data of engine in a wide range of operational conditions.

Gallo and Milanez [15] used a standard cycle simulation to determine the instantaneous irreversibilities and the other second law considerations for spark – ignition engine using ethanol and gasoline. They investigated the effects of ignition timing, duration of combustion, combustion shape factor and equivalence ratio on second law efficiencies. Also they found that combustion irreversibilities were less with ethanol fuel than for gasoline fuel.

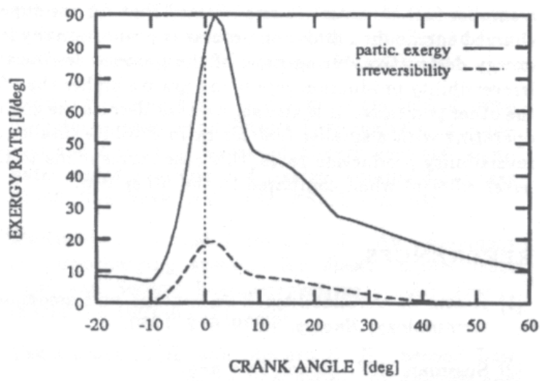

Figure 6. Participating and destroyed exergy rates during combustion

Slika 6. Količina eksergije koja sudjeluje i koja je uništena u izgaranju [15]

Rakoupulos [16] described a first and second law analysis of a spark ignition engine using a cycle simulation and experiment. The main parameters studied were the compression ratio, fuel-air ratio and ignition advance. His model included improvement and development of spherical flame front and he focused on the combustion period when the valves were closed. The author is suggesting possible ways to improve cycle performance by reducing availability losses due to combustion by thorough improvements in combustion chamber designs, better air-fuel mixing and more accurate ignition process.

Rakoupulos and Andritsakis [17] presented results for the irreversibilities rates of two four – stroke cycle diesel engines. 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 availability was between 21% and 31% of the original fuel availability. For indirect injection engine, the destroyed availability was between 24% and 29% of the original fuel availability.

Velasques and Milanez [18] also investigated irreversibility effects on the combustion process in diesel engines by the using second law of thermodynamics. They focused especially on availability destruction connected with air – fuel ratio, and influence of air – fuel ratio on availability destruction increase for overall process during combustion.

Li [19] in his work proposed a thermodynamic model in which an idealized diesel engine is observed. The second law of thermodynamic was carried out by the thermodynamic state parameters calculated by the cycle simulation of engines based on the first law of thermodynamics. The effects of heat transfer losses in the swirl chamber, trothling losses at the connecting passage and the combustion delay in the main chamber on the irreversibilities and availability losses during the engine cycle were analysed in detail. The results of first law analysis indicate that heat transfer losses in the swirl chamber at low load conditions and combustion delay in the main chamber at full load conditions are the main factors impairing the fuel economy of indirect injection diesel engines. Also results of further analysis of the second law indicate that passage trothling is a key factor affecting the fuel economy of indirect injection diesel engines at full load conditions.

Rakoupulos and Giakoumis [20] in their work described improved simulation of transient operations. Their simulation includes innovations such as detailed analysis of thermodynamic and dynamic differential equations which accounted for the continously changing character of transient operations, a more complete analysis than was given in earlier treatments of transient mechanical friction, combustion and fuel injection, as well as detailed modeling of engine – inertia forces and incorporation of a fully mathematical model of the governor. An exergy balance was applied to all subsystems of the diesel engine such as the cylinder for both the closed and open parts of the cycle and the inlet and exhaust manifolds. They described how the exergy changed during transient event, and in their work first applied second law analysis on transient diesel engine operations.

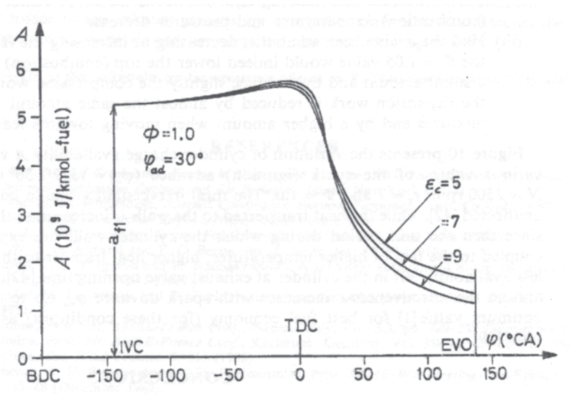

Figure 7. Cylinder charge availability A (per kmol of fuel) vs. crank angle φ at various compression ratios ε_c (wide open throttle, $N = 2500$ min^{-1}) [16]

Slika 7. Eksergija A radnog medija u cilindru (po kmolu goriva) s obzirom na kut koljena φ pri različitim stupnjevima kompresije ε_c (pri punom opterećenju i brzini vrtnje $N = 2500$ min^{-1}) [16]

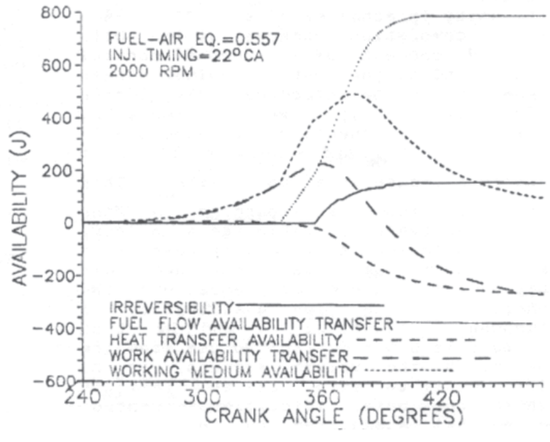

Figure 8. Variation of accumulated, transferred and destroyed availability in the DI diesel engine [17]

Slika 8. Promjena akumulirane, prenesene i uništene radne sposobnosti u dizelskom motoru s izravnim ubrizgavanjem [17]

Stiesch and Merker [21] introduced multi – zone model in their work for heat release and exhaust emission prediction in direct injection diesel engines. They proposed a different approach for fuel spray observation, dividing one fuel jet in numerous packages in a radial and axial direction which contains fuel. The quantity of fuel in each package depends on fuel injection quantity in the cylinder. By using such new model, they achieved better prediction of soot forming and different gaseous pollutants.

Datta and Som [22] 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 irreversibilitiy and second law efficiency of the process at various operating conditions. The velocity, temperature and concentration fields in the combustor, required for the evaluation of the availabilities and irreversibilities, were computed numericaly from two phase separated flow model of the spray along with a suitable reaction kinetics for the gas phase reaction. The thermodynamic irreversibilities associated with the gas phase process in the combustor were obtained from the enthropy transport equation, while that due to the interphase transport process was obtained as a difference of a gas phase irreversibilities from the total irreversibility.

A significant contribution to second law analysis was given by Caton [23], [24], [25] and [26] in several research works. He used second law of thermodynamics to study spark – ignition engine and his work was based on the use of a comprehensive thermodynamic cycle simulation. In one part of his study, he examined the effects of engine load and speed on a number of performances, energy and availability terms. He reported that availability displaced to the cylnder wall through heat transfer (as percentage of the fuel availability) ranged between 15,9 % and 31,5 %. The net availability expelled with the exhaust gases ranged between 21,0 % and 28,1 % and the availability destroyed by the combustion process ranged between 20,3 % and 21,4 %. In addition, his study showed that the mixing of the inlet charge with existing cylinder gases was an additional mechanism for the destruction of availability.

Blair [27] studied spark – ignition engine using different computer programs, by analysing heat release rate during combustion process as a function of crank angle, and also mass fraction burned as function of crank angle. In his calculations he used standard thermodynamic cycle and first law of thermodynamics for transformations inside the cylinder as a function of a time step which was equivalent to a crank angle. Mass fraction burned connected to a time step was given by a Viebe function.

Heywood [28] also contributed to the combustion process analysis. He introduced a zero – dimensional, quasi – dimensional and multi – dimensional model for a combustion process modeling and calculation and he focused especially on scavenging air inlet process and its effects on overall combustion process.

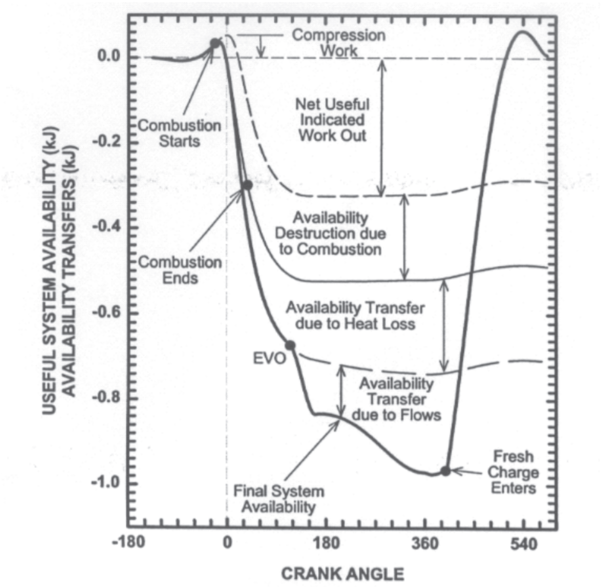

Figure 9. Useful system availability and availability transfers as a function of crank angle for the spark ignition engine [25]

Slika 9. Korisni sustav radne sposobnosti i prijenosa radne sposobnosti kao funkcije kuta zakreta koljenastog vratila kod otto motora [25]

Perkovič [29] introduced a new model of combustion process in a two – stroke marine engine. He used a standard thermodynamic cycle and a mass fraction burned was given by two Viebe functions. He presumed that c_v during combustion process was an independent value of the temperature and reactant mixture, which made the results of his model insufficiently correct for more detailed analysis using second law of thermodynamics.

McClain [30] implemented a MathCAD functions in the combustion process thermodynamic analysis, especially for analysis of overall thermodynamic values transformations during a combustion process. He focused on thermodynamic value transformations of carbon-hydrogen-oxygen-nitrogen mixture.

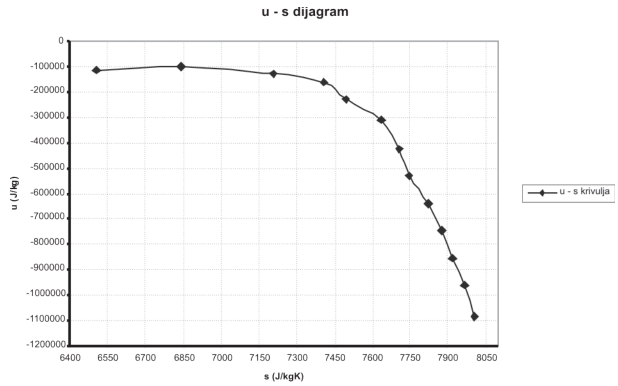

Figure 10. Internal energy change as function of entropy [41]

Slika 10. Promjena unutarnje energije kao funkcija promjene entropije [41]

It is very important to mention the number of PhD theses which deals with second law of thermodynamic applied to the combustion process for both spark – ignition and combustion – ignition engines. Some of these theses are Baeurle [31], Schiessel [32], Bikas [33], Schramm [34], Soltic [35] and Stiesch [36].

Also very important research was done by Medica [37] who developed basic computer simulation program for zero – dimensional model of supercharged diesel engine as a function of time change. His work was significant for more accurate research of all aspects of combustion process in engine cylinder and also basic research for a later PhD thesis. Some of these PhD theses, which also improved thermodynamic analysis of combustion process were Mrakovčić [38] and Skific [39] and Master thesis Račić [40].

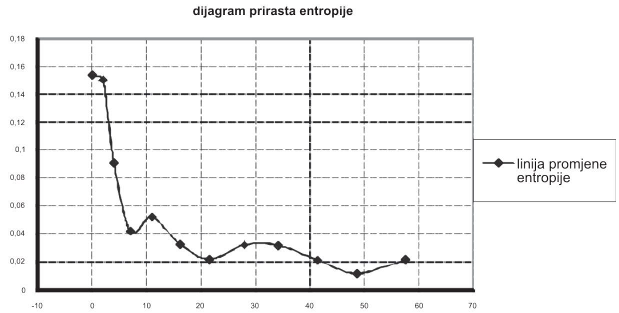

Figure 11. Increase of mixture entropy during combustion as function of crank angle [41]

Slika 11. Porast entropije smjese tijekom izgaranja u funkciji zakreta koljenastog vratila [41]

Jelić [41] used a simplified model without the usual change of combustion process with heat addition. He applied the first and the second law of thermodynamics in process analysis. Indicated pressure values, occurring during combustion process, were calculated depending on fuel combustion dynamic and crankshaft angle position. The method he applied in his work provided the possibility to calculate, beside indicated pressure, all other thermodynamic values during combustion process in IC engine cylinder, including entropy change due to combustion ireversibility. He applied simplifications related to neglect of molecular dissociation during combustion process, which also could be calculated and observed in the process as incomplete combustion in a rich mixture, including octane C_8H_{18} as a fuel. The combustion process was described as a mixture which starts (in step 1) as pure stoichiometric fuel-air mixture at standard pressure and temperature. The combustion process passed through 13 steps starting from mentioned step 1 to step 13 with pure combustion products.

The main difference between the method used in his work and standard IC engine thermodynamic process analysis methods, was in using the first and second law of thermodynamics for irreversible process and, therefore, geting more detailed and more accurate data for the combustion process. The values of temperature, pressure and entropy, calculated on real states for steps 1 to 13 were shown in the diagrams: $u - s$, u -φ, p - φ, ΔQ_L - φand $\Delta S_{irevers}$ - φ.

Ninic [42] in his book applied a new method of calculating all thermodynamic values by using the thermodynamic cycle of internal combustion engine instead of an idealized thermodynamic cycle and he presented results in $h - s$ diagram.

3. Conclusion

Over more than 40 years, various reports on detailed use of second law of thermodynamics have been published. These reports helped to achieve more accurate understanding of all thermodynamic aspects of combustion process in both spark – ignition and combustion – ignition 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.

More accurate understanding of all thermodynamic aspects and possibility to calculate all thermodynamic values resulted in better understanding of availability processes in engine and helped to reduce availability destruction in engine parts and inside the cylinder during the combustion process. This resulted in higher thermodynamic combustion efficiency, less fuel consumption and lower emissions.

This is very important for internal combustion engines as the most efficient heat engines for energy transformation with widespread use in every part of modern life and ensures a future for IC engines comparing them with competitive devices.

It is important to mention significant reasons motivating better efficiency results due to high oil prices and ecology regulations.

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