CODEN STJSAO
ZX470/1482
ISSN 0562-1887
UDK 621.431.019:62-222:536.75

Thermodynamic Analysis of Diesel Engine Combustion Process*

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Keywords
Availability
Combustion
Decomposition model
Diesel engine

Ključne riječi
Dizelski motor
Izgaranje
Model rastavljanja
Radna sposobnost

Received (primljeno): 2009-04-30
Accepted (prihvaćeno): 2010-10-29

Original scienfic paper

New method of working fluid availability analysis during cylinder combustion process is described in this thesis. This new method uses a new approach to thermodynamic combustion process by applying a decomposition model. A decomposition model substitutes one realistic process with two identical imaginary processes due to the equivalent change of working fluid and external influences.

Such a new developed method, has advantages to detect exact positions of working fluid availability destruction. Also, there is a possibility to calculate complete thermodynamic values including entropy changes during combustion steps.

Experimental results are obtained by analysing a four – stroke compression ignition engine and results are shown in diagrams: *u-s*, *u-φ*, *s-φ* and ΔW_{indic},ΔQ-φ.

In the last chapter of this thesis certain group of results are compared and availability destruction positions are located. The method, developed in this thesis, can be used for further optimisation and development of compression ignition engines.

* Defended Doctoral Thesis (2008.)

Termodinamička analiza procesa izgaranja u dizelskom motoru*

Izvornoznanstveni članak

U doktorskoj disertaciji je opisana nova metoda termodinamičke analize procesa izgaranja u cilindru motora. Nova metoda koristi model rastavljanja kao novi pristup termodinamičkom procesu izgaranja.

Sam model rastavljanja temelji se na zamjeni realnog procesa izgarnja u cilindru motora s dva identična fiktivna procesa, koji su jednaki realnome po izmjeni radne tvari i promjeni vanjskih utjecaja.

Nova metoda opisana u disertaciji sadrži prednosti u boljem otkrivanju točnih mjesta degradiranja radne sposobnosti radnog medija tijekom procesa igaranja. Također postoji mogućnost proračuna svih ostalih termodinamičkih veličina stanja tijekom pojedinih faza izgaranja, uključujući i entropiju.

Eksperimentalni podaci su dobiveni obradom četverotaktnog dizelskog motora i prikazani su u dijagramima: *u-s*, *u-φ*, *s-φ* i ΔW_{indic},ΔQ-φ.

U završnom poglavlju disertacije rezultati su uspoređeni, a istaknuta su i mjesta majvećih gubitaka radne sposobnosti radnog medija.

Metoda koja je razvijena u disertaciji može se koristiti za daljnju optimizaciju i razvoj dizelskih motora.

* Obranjena doktorska disertacija (2008.)

1. Introduction

Compression ignition engines achieve thermodynamic efficiency of 50 % and have low specific oil consumption and emissions. These engines are very technically developed heat engines but due to rising oil prices and high demanding ecology regulations, research process is focused on further increasing thermal efficiency and lower oil consumption.

A standard approach to compression ignition process analysis is based on the assumptions [1, 2] where it is necessary to know the distribution of value ΔQ_R during the combustion process. Such distribution in, for example spark ignition engine, is referred to as the Viebe function.

Knowledge of heat transfer value ΔQ_L to the cylinder walls is obtained from the equation:

$$\Delta Q = \Delta Q_L + \Delta Q_R \quad (1)$$

an equation which connects Nusselt and Reynolds number [2] can be used.

A standard approach to compression ignition process analysis is not accurate enough because it simplifies the assumption of fuel chemical energy release ΔQ_R as

Symbols/Oznake

p	- pressure, Pa - tlak	T	- temperature, K - temperatura
q	- specific heat, J/kg - specifična toplina	u	- specific internal energy, J/kg - specifična unutarnja energija
Q	- heat, J - toplina	U	- internal energy, J - unutarnje energija
Q_{gor}	- fuel chemical energy release, J - toplina oslobođena izgaranjem goriva	V	- volume, m^3 - volumen
Q_{gubit}	- heat loss, J - gubitak topline	w	- work, J - rad
Q_{pozit}	- heat release, J - oslobođena toplina	φ	- crank angle, ° - kut akreta koljenastog vratila
s	- specific entropy, J/kg·K - specifična entropija		

external heat addition and excludes the possibility to detect availability losses during combustion process.

A modern approach to compression ignition process analysis, used in this thesis, is more accurate because there is a presumption that combustion process starts when first part of reactants are burned.

Applying the second law of thermodynamics to a modern approach of analysis gives the possibility of calculating all thermodynamic values including entropy. Also combination of a modern approach and second law of thermodynamics detect places of availability losses during combustion process.

In this thesis compression ignition engine is modeled as two – zone, zero – dimensional combustion process with computer simulation program developed by Medica [4].

Assumptions of zero – dimensional model and descriptions of compression ignition engine mathematical model with decomposition method are given in [2]

2. Decomposition method of thermodynamic analysis

For better understanding of the decomposition method, described in [2], it is important to know that heat loss through a cylinder wall can be temporarily neglected to focus on combustion irreversibility research. Such process is shown in Figure 1:

In this diagram in Figure 1 two steps of combustion process are described. Work done in equilibrium combustion process is u_1 - $u_{1'}$, and irreversibility loss is concentrated in u_2 - $u_{1'}$. But irreversibility of realistic process 1-2, concentrated in process 1*-2 has also additional effects, which in a certain way improves work loss in u_{1*}-$u_{1'}$.

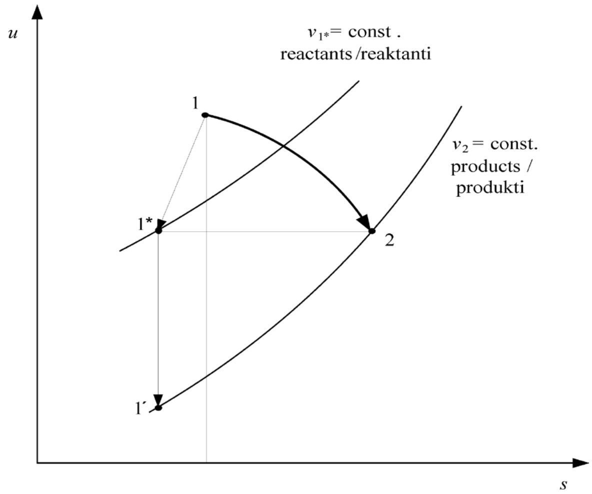

Figure 1. Decomposition method applied on two steps

Slika 1. Primjena metode rastavljanja na dva koraka

The following presumptions are important:

- the result of process $u_1 - u_{1*}$ is equilibrium work done (volume work done), and the additional work done can be obtained in equilibrium chemical reaction by V = const., like fuel cell process.
- completely equilibrium process 1-1´ would decrease pressure value over the next piston move, because form $p_{1'} < p_2$.

It can be assumed that, in the next step, the equal amount of fuel is burned in both processes, in equivalent 1-1´´ and in realistic 2-3. That fact determines connection between lanes 2*-3 and 1**-3´.

For the equivalent volume change, volume part of equivalent work done would be, following decomposition method, $u_{1'}$ - u_{1**}, and realistic work done would be u_2 – u_{2*}.

Due to form $p_{1'} < p_2$, equation is:

$$p_2(V_3 - V_2) > p_1(V_3 - V_2). \tag{2}$$

Following the diagram in Figure 1, work done in equilibrium process by the end of volume V_3 would be higher then work done in realistic process:

$$u_1 - u_{1''} > u_1 - u_3. \tag{3}$$

But volume work done would be lower in equilibrium process 1-1´´ due to lower pressure values in the process.

The decomposition method, described in this thesis, gives opportunity to compare the sum of volume work done $\sum_{i=1}^{n-1} w_{\text{vol,real},i}$ obtained in realistic process 1-2-3 in Figure 1, with sum of volume work done obtained in equilibrium process 1-1´-1´´, where both processes have equivalent scheme of fuel combustion:

$$\sum_{i=1}^{n-1} w_{\text{vol,ravnot},i} = p_1\left(V_2 - V_1\right) + p_{1'}\left(V_3 - V_2\right), \tag{3}$$

where: n - number of equilibrium states

n-1 - number of steps in realistic combustion process

Comparison result is:

$$\sum_{i=1}^{n-1} w_{\text{vol,real},i} > \sum_{i=1}^{n-1} w_{\text{vol,ravnot},i}. \tag{24}$$

This method gives possibility for modeling different fuel combustion schemes, which would provide maximum sum of volume work done.

3. Four – stroke compression ignition engine analysis

A four stroke diesel engine is used for complete analysis of all thermodynamic values during combustion process with two – zone combustion model approach, described in [2]. Specifications of four stroke diesel engine MAN 826LD LOH15 are:

- number of cylinders: 6 ,
- bore: 0.1080 m,
- stroke: 0.125 m,
- connecting rod: 0.1872 m,
- compression ratio: 18.0
- power: 162 MW,
- engine speed: 1800 s^{-1},
- inlet valves open: 703.0 °CA,
- inlet valves closes: 933.0 °CA,
- exhaust valve open: 483.0 °CA,
- exhaust valve closes: 745.0 °CA,
- fuel LHV: 42,490 MJ/kg,
- cylinders are cooled with fresh water with additives,

The change of all thermodynamic values is observed at the beginning of the process, which starts 90° CA before TDC, and ends 90° CA after TDC. Average load of analysed four stroke diesel engine is 60 %.

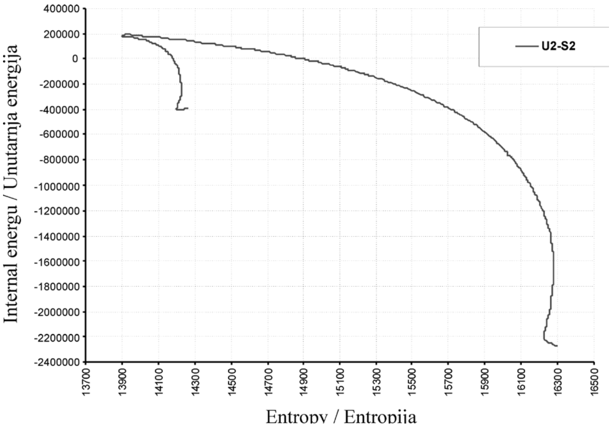

Figure 2. Internal energy change as function of entropy change

Slika 2. Dijagram ovisnosti promjene unutarnje energije o promjeni entropije

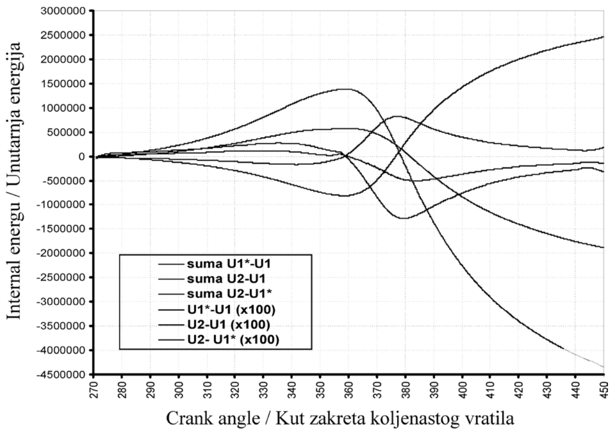

Figure 3. Internal energy and sum of internal energy changes as function of crank angle

Slika 3. Dijagram promjena unutarnjih energija i suma unutarnjih energija

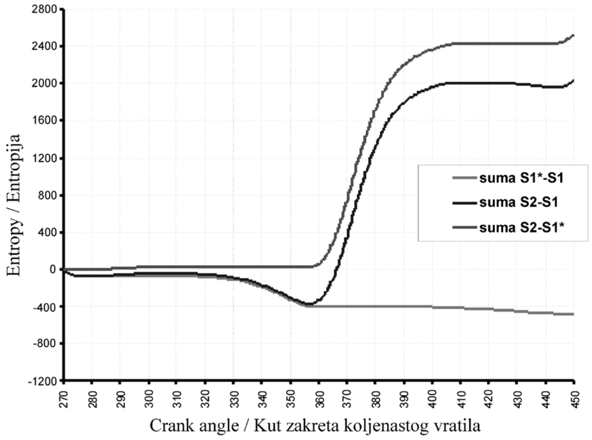

Figure 4. Sum of entropy changes as function of crank angle

Slika 4. Dijagram promjene suma entropija

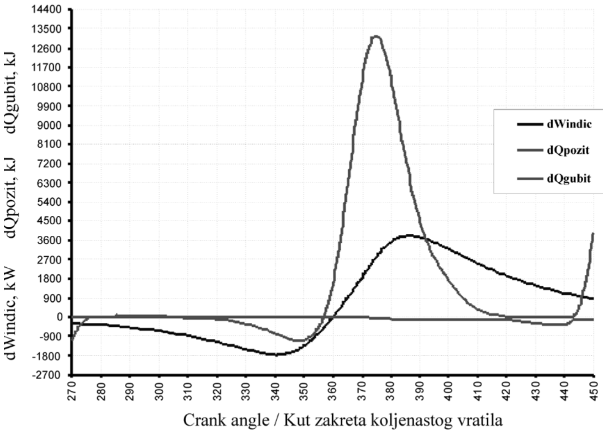

Figure 5. Indicated work, heat release rate and heat loss as function of crank angle

Slika 5. Dijagram indiciranog rada, pozitivne oslobođene topline i ukupnih gubitaka izgaranja

4. Analysed and compared results

Due to compared data results in analysed diagrams, it can be observed that the higher heat loss occurs few degrees before TDC. Such heat loss will increase the difference of internal energies U2-U1*, which represents direct work loss during combustion process and occurs a few degrees after TDC.

The difference of internal energies U2-U1* can be decreased due to an increase of cylinder wall temperatures.

Such results are shown in Figure 6:

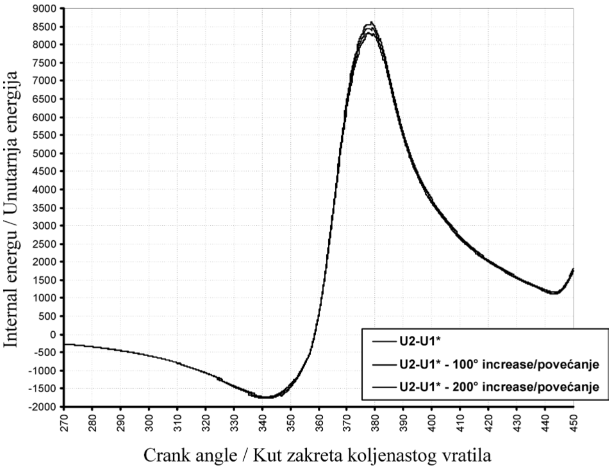

Figure 6. Difference of internal energies U2-U1* due to increase of cylinder wall temperatures

Slika 6. Razlike unutarnjih energija U2-U1* pri povišenju temperature stijenki cilindra

Cylinder wall temperatures are increased by 100° and 200° in four stroke compression ignition engine due to average load of 72 %.

Also sum of internal energy differences U2-U1* can be shown in the following diagram:

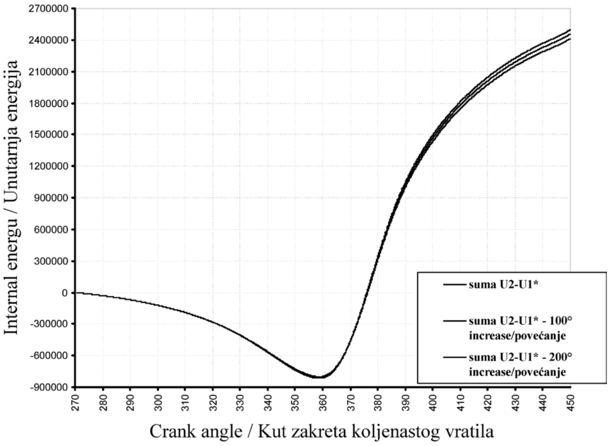

Figure 7. Sum of internal energy differences U2-U1* due to increase of cylinder wall temperatures

Slika 7. Razlike suma unutarnjih energija U2-U1* pri povišenju temperature stijenki cilindra

It can be observed that such temperature increase of cylinder walls will decrease direct work loss during the combustion process. Work loss decrease is not very significant , but it can´t be neglected.

5. Conclusion

Due to high oil prices and high demanding ecology regulations, research of compression ignition engine combustion process is focused on lower fuel oil consumptions and on higher thermal efficiency.

During the combustion process, a large amount of energy is transferred out of the cylinder system by heat loss rate, which has its maximum values a few degrees before TDC. In thermodynamic analysis of combustion process heat loss is described as heat transferred through to the cylinder wall and heat used to prepare fuel mixture.

Destruction of working fluid availability is possible to reduce by decreasing heat loss rate in the combustion process, and decreasing heat loss rate can be obtained by decreasing cylinder wall and cylinder head temperatures. Higher cylinder wall and cylinder head temperatures results in lower energy transfer through to the cylinder wall and thus lower heat loss rate.

Such approach has a disadvantage because any temperature rise will increase the combustion temperature and that demands better and more expensive construction materials in engine cylinder.

Better materials which can withstand very high temperatures of combustion are special steel and ceramic material and must be used for certain parts of the engine such as cylinder head and piston head. Ceramic materials has a disadvantage for such use due to its very high ability to accumulate heat.

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