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Three-dimensional modeling and exergy analysis in Combustion Chambers of an indirect injection diesel engine

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HIGHLIGHTS

- We carried out exergy analyses in pre and main chambers of an IDI diesel engine by three dimensional model.
- At 50% and full load cases 56% and 77% of total irreversibility are related to combustion in main chamber, respectively.
- When load increases from part to full load, the amount of exergy flow in throat increases to 56%.
- At part and full load cases, 65.7% and 55% of total heat loss exergy concern to heat loss in main chamber, respectively.

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ABSTRACT

In this investigation, the energy and exergy analyses are carried out in pre and main chambers of a Lister 8.1 indirect injection diesel engine (IDI) diesel engine for two loads (BMEP of 2.96 bar and 5.9 bar as 50% and full load operations) at maximum torque engine speed (730 rpm). The energy analyses are carried out during a closed engine cycle by using a computational fluid dynamics (CFD) code. The results for the pressure in cylinder for two loads are compared with the corresponding experimental data and show good agreement. Also, for the exergy analysis in the chambers, a developed in-house computational code is applied. Various exergy components are identified and calculated separately with crank position at both loads. The results show that at partial and full load operations 56% and 77% of total irreversibility are related to combustion process in main chamber, respectively. This work demonstrates that multidimensional modeling can be used at complex chamber geometry to gain more insight into the effect of flow field on the combustion process accounting for the second-law of thermodynamics.

1. Introduction

In general, the first-law of thermodynamics is used for analyze of engine performance and pollutant emissions parameters, but it does not consider the quality of energy content of a system. During the last two decades, it has been understood that the first-law theory, often fails to give a good insight into the engine's operation [1]. Therefore, the first and second-law analyses should be applied to the engine process simultaneously. The key concept in second-law analysis is exergy; exergy is a special case of the more fundamental concept, available energy, introduced in ref [2]. Over the years, reports on the detailed use of the exergy analysis in internal combustion engines have been reported by several authors [3–7]. A thorough review of these papers can be found in review paper [8].

Rakopoulos and Kyritsis [9] developed a zero-dimensional code for studying of the effects of cylinder wall temperature profile on the second-law transient performance of an IDI, turbocharged, multi-cylinder diesel engine after a ramp increase in load, with special emphasis to the low heat rejection case. The result of this work shows that the transient first-law properties response remained almost unaffected by the applied wall temperature schedule and also the engine and turbocharger second-law terms were greatly affected especially when a low heat rejection cylinder wall was chosen.

Rakopoulos and Giakoumis [7] carried out a second law analysis in a multi-cylinder turbocharged Diesel engine and all their components by using a single-zone thermodynamic model. In this analysis, all the exergy terms, i.e. work, heat and mass transfer, exergy accumulation in every control volume and fuel flow were calculated in the pre and main chamber and in the all component of engine. Tabulation of all second law analysis terms was given at full load-maximum speed operation and also the differences against first law assessments were discussed. It was showed that the exergy analysis offers a more spherical and comprehensive insight into the processes occurring in a diesel engine that it's traditional first law counterpart.

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Nomenclature

E	internal energy (J)
G	Gibbs function (J)
Ex	exergy (J)
S	entropy (J/K)
T	temperature (K)
kk	number of species
I	irreversibility (J/K)
x	mole fraction of species
y	mass fraction of species

Greek letters

μ	chemical potential (J/kg)
θ	crank angle (degree)
z	number of carbon atom

Abbreviations

BTDC	before top dead center
ATDC	after top dead center
EVO	Exhaust Valve Opening (degree)
IDI	Indirect Injection Engine
CA	crank angle (degree)
SOC	start of combustion
EBU	eddy break up
ID	ignition delay (crank angle)
N	engine revolution (rpm)

Subscripts

ch	relating to chemical exergy
tm	relating to thermo-mechanical exergy
f	relating to fuel
w	associated with work transfer
Q	associated with heat transfer
0	dead state, or environment state
pr	relating to combustion products
ox	relating to oxidants
fuel	relating to fuel

Superscript

0	restricted dead state

Ghazikhani et al. [10] carried out an experimental study about the effect of using Exhaust Gas Recirculation (EGR) on BSFC and various exergy terms of an IDI diesel engine cylinder. Their results show that the applying EGR to engine mainly increases the total in cylinder irreversibility due to extension of the flame region which result higher combustion temperature. Also, the results revealed that the behavior of the total in-cylinder irreversibility and engine BSFC are the same especially at high load conditions.

Jafarmadar [11] carried out a numerical analysis about the combustion of hydrogen with air at constant pressure condition(1 bar) for various air fuel ratios and initial temperatures by using a zero-dimensional single zone model with chemical kinetic mechanism. The predictions show that second law efficiency increases with increasing of φ at constant initial temperature (1000 K). Also, the predictions show that the increase of initial temperature from 1000 to 1100 K at $\varphi = 1.4$ causes the decrease in second law efficiency, while the increase of it from 1100 to 1400 K causes the increase of second law efficiency and the decrease of irreversibility. It was found that the second law efficiency reaches to maximum value at the case of $\varphi = 1.4$ and initial temperature 1400 K.

Rakopoulos and Giakoumis [12] carried out an experimental investigation on a 6-cylinder, IDI (indirect injection), turbocharged and after-cooled, medium–high speed diesel engine of marine duty coupled to a hydraulic brake. The exergy analysis is carried out at the engine and all of its subsystems by using zero-dimensional model. Various exergy terms calculated during a transient event such as work, heat transfer, exhaust gas and irreversibility .In particular, the irreversibility terms for the diesel engine and its subsystems are calculated for every transient cycle. Also, the rate and cumulative terms of all important availability properties are given, in comparison, for the first and last cycle of the transient event. The importance of the combustion irreversibility as well as of the exhaust manifold ones is readily revealed.

Rakopoulos and Michos [13] carried out a numerical studying about the prediction of spark ignition engine performance, nitric oxide emissions by using multi-zone combustion model. They also carried out an exergy analysis of the same engine with syngas fuel at various loads [14]. They showed that when engine load was increased from 40% to 100% of full load, with the relative air–fuel ratio also increasing from 1.56 to 1.83, the exergy destruction due to combustion raised from 14.19% to 15.02% of the fuel injected exergy, while the corresponding percentage of cumulative heat loss decreased from 13.37% to 9.05%.

Abassi et al. [15] investigated the effect of injection system characteristics on the first and second law terms in high-speed DI diesel engines with swirl combustion chamber. The sensitiveness of various injection system parameters on the first and second law terms was studied.

Fathi et al. [16] studied the influence of the initial charge temperature under various injection timings on the second law terms in a direct injection SI engine fuelled with hydrogen by using a three dimensional CFD model and they showed that the indicated work availability is more affected by varying injection timing in comparison with other second law terms. Also with increasing of initial temperature, heat loss and exhaust gas availabilities increase while indicated work availability, combustion irreversibility and entropy generation decrease.

Abassi et al. [17] investigated the effect of inlet charge temperature on the first and second law terms in DI diesel engines by using a three dimensional CFD model. They showed that an increase of inlet charge temperature causes the indicated work exergy, irreversibility and entropy generation be reduced while heat loss and exhaust loss exergies be increased. Also, irreversibility and indicated work exergy more influenced than the other terms when inlet charge temperature is raised.

In recent years, three dimensional modeling has become an important powerful tool for analysis of combustion systems from the second law of thermodynamics point of view. Such computer models have contributed to better understanding and solution of long standing practical combustion problems in diesel engines.

As can be seen in the relevant literature, there is no attempts up to now about the three dimensional studying of the combustion process in pre and main chambers of IDI diesel engines from second law view point .In this present work, first law terms for these chambers are calculated by using the results of a three dimensional CFD code. Also for the second law analysis, an in-house computational code is developed. The second law terms such as burnt fuel exergy, indicated work exegy, exergy loss associated with the heat transfer to walls, combustion irreversibility and exhaust gas exergy per cycle are evaluated for these chambers by this code.