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Numerical energetic and exergetic analysis of CI diesel engine performance for different fuels of hydrogen, dimethyl ether, and diesel under various engine speeds

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ABSTRACT

The current study addresses engine specification and second thermodynamic law analysis of the CI diesel engine fueled with hydrogen, DME, and diesel at six engine speeds. The 3-D simulation was first carried out and then the results were exploited to calculate availability through a developed in-house code. Availability analysis was performed separately for chemical and thermo-mechanical availability to highlight each fuel'0s capacity in chemical and mechanical efficiency delivery. The results indicate that hydrogen fuel prevails in chemical and thermo-mechanical availability, indicated power, and mean effective in-cylinder pressure under all crank angle and engine speeds. Temperature distribution has more extensive and intensified region developed across the cylinder, although hydrogen demonstrated the lowest ISFC (indicated specific fuel consumption) value. With regard to engine speed, 2000 rpm shows overall better IP (indicated power), IMEP (indicated mean effective pressure), chemical and thermo-mechanical availability, irrespective of fuel type. The mean irreversibility rate for PMC (pre-mixed combustion) and MCC (mixing controlled combustion) combustion phase shows a different trend. Furthermore, hydrogen fueled engine demonstrates the highest temperature distribution of 2736 K and the wall heat flux to the amount of 29160 W. The variance of chemical availability for Hydrogen from 1500 to 4000 rpm decreases by crank-angle evolution from 43.3% to 10.1% corresponding to 10−40°CA after top dead center.

Introduction

With ever-increasing rate of energy consumption worldwide, energy quality investigation is in more spotlights in scientific communities. Energy efficiency analyses give the best approximation for energy related devices to be modified in order to avoid fuel waste and accomplish higher desired output simultaneously. The first law survey is usually implemented on ICEs (internal combustion engines) with the aid of

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thermodynamic parameters or spray characteristics to consider engine performance and emissions [1–6]. Second law efficiency for engines was examined in myriads of literature reports [7–10]. More recently, Fathi et al. [11,12] studied numerically the SI engine from the second law standpoint under different charge temperatures and injection timings for the first study. Their results revealed that increasing charge temperature results in higher heat loss availability whereas lower irreversibility and entropy generation can be accomplished. Their second study examined the effect of equivalence ratio along with the injection timing on SI (spark ignition) engine fueled with hydrogen to explore second law efficiency. They found out that combustion irreversibility and exhaust gas availability are more susceptible to the equivalence ratio variation and the amount of fuel availability that transfers to environment with exhaust gases. Several studies have been devoted on exergetic efficiencies of diesel engines such as EGR (exhaust gas recirculation) effects on BSFC and irreversibility [13], therein authors concluded that with increasing EGR ratio, irreversibility increase takes effect due to extension of flame region, which decreases the combustion temperature.

The effect of n-heptane and natural gas blends were surveyed in HCCI (homogenous charge compression ignition) engines from the second thermodynamic law viewpoint [14]. A complete chemical kinetic mechanism was utilized in order to analyze the availability of system for varied EGR and natural gas percentage addition. They proved that the natural gas addition results in lower exergy destruction along with second law efficiency augmentation. Ozkan et al. [15] discussed the effect of pre-injection timing on diesel engine's exergetic and energetic performance elaborately. Their results point out that by applying appropriate pre injection, no perceptible influence can be noticed on thermal and exergetic efficiency, but NOx emissions were reduced significantly by 7.4%. A novel crank-angle resolved exergy analysis methodology was utilized for determination of the optimal operating condition of gasoline fueled HCCI engine [16]. It was observed that the equivalence ratio should be preserved at high values for majority of engine operational conditions while pressure was used to regulate engine load. Moreover, it was indicated that combustion timing has to be such adjusted to be placed just before the sharp increase of unburned species losses. Jafarmadar [17] carried out exergy analysis in combustion chamber of the IDI diesel engine. The results demonstrated 56% and 77% of the total irreversibility stems from main chamber combustion in part and full load mode of engine operations, respectively.

3-D modeling was performed based on CFD (computational fluid mechanics) approach to capture engine performance as well as thermo-chemical data. The data were thereafter used to calculate the availability of each engine fueled with different fuels with the aid of in-house developed code. The numerical method incorporates the results of in-cylinder properties acquired from AVL Fire code and thermo-mechanical in-house code for measuring the availability of produced work and heat. Availability destruction was classified and investigated regarding two combustion periods for each fuel.

Numerical implementation

First law of thermodynamic (energy) analysis

The numerical approach was carried out according to a single-cylinder of Ford Diesel 1.8L engine (the operational condition and engine specifications are gathered in Tables 1 and 2). Energy investigation was carried out with AVL FIRE code, which performs 3-D meshing of geometrical domain and solves conservation equations based on the finite volume method. Due to symmetrical geometry of the cylinder and existence of four nozzles in the experiments, a quarter of computational domain of the cylinder was modeled to both reduce the cost and to correspond with one injector to each section. CFD meshing model of swirl combustion chamber is presented in Fig. 1 for a) TDC and b) 60°ATDC positions.

CFD simulation employs finite volume discretization method, which has the ability to preserve conservation properties. The discretized conservative equations are solved using SIMPLE (Semi-Implicit Method for Pressure Linked Equation) [18] algorithm to update pressure and velocity for each iteration. For solving the linear system, GSTB method was applied [19]. Each computational cell was initialized with swirl/tumble mode. The initial pressure and temperature were set to 0.1 MPa and 330 K, however the calculations were initiated with 2.7 MPa and 600 K corresponding to 30°CA BTDC. The initial turbulent kinetic energy and turbulent length scale are 15 m^2/s^2 and 0.003 m, respectively. The combustion chamber density was prescribed according to the ideal gas law. The calculations of boundary values were performed with the extrapolation whereas the derivatives calculations were handled with the least square fit method. The energy equation was solved by the total enthalpy approach. The under-relaxation factor of 0.6 and 0.5 were adopted for the momentum and pressure correction in the relevant equations. The simulations proceed with MINMOD relaxed scheme for the momentum equation and the central differencing for the continuity. The turbulence and the energy equations were discretized by upwind scheme. The convergence criteria were tuned 10 and 100 as the minimum and maximum number of iterations. The grid consists of 48421 cells that give sufficient resolution for response independency. Turbulence and energy equations were discretized with an upwind scheme whereas momentum equation was discretized with the finite difference method. The powerful yet time-consuming turbulence modeling methodology of LES (large eddy simulation) was selected as to calculate accurately the highly turbulent and instantaneous phenomenon into swirling combustion

Table 1 – Operational condition.

Engine speed (rpm)	Torque (N m)	Ignition delay (°CA)	Nozzle velocity (m/s)
≈1500	160.2	1.6	359
≈2000	190.2	2	395.7
≈2500	203.6	2.9	427
≈3000	199.2	3.2	475.2
≈3500	180.1	3.7	496.1
≈4000	171	4.1	530.6

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