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EXERGY ANALYSIS OF A BI FUEL SI ENGINE

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ABSTRACT

This paper characterizes the exergy (availability) analysis in the bi-fuel (CNG and gasoline) spark ignition engines. The engine is modeled using a quasi-dimensional (QD) two-zone thermodynamic analysis. The differential equations relating to the compression, combustion and the expansion are solved by an approximation method. The model includes the intake, exhaust processes and a turbulent combustion model. The engine model is capable of simulating the burn rate, and compared to the computational fluid dynamic (CFD) models is it considerably faster. The developed model is based upon the second law of thermodynamics, and exergy analysis terms. These terms includes thermo-mechanical availability, chemical availability, heat transfer availability, work availability, and the irreversible processes that are the source of destroyed availability. Finally, the effect of the availability, the first law of thermodynamics (FLT) and the second law of thermodynamics (SLT) efficiency of equivalence ratio, ignition time and engine speed are presented and discussed.

INTRODUCTION

The second law of thermodynamics (SLT) sets up the different forms of energy and describes those processes that cannot automatically happen and those that can. The maximum useful work can be defined and produced using the second law of thermodynamics. Exergy is a useful quantity that stems from the SLT, and it helps in analyzing energy and other systems and processes.

In a system, the exergy is the maximum useful work, which it can be carried out through a system’s composite and the same composite of the environment. Therefore, the use of the SLT in internal combustion engine analysis has been increased. Exergy analysis is a method of thermodynamic analysis based on the second law of thermodynamics. Exergy analysis affords a true measure of how actual performance approaches the ideal. It recognises more clearly thermodynamic losses and their causes and locations than energy analysis. Therefore, exergy can support in modifying and optimizing engine performance. For this reason, in recent years, increasing recognition and application of exergy methods by academia, government, and industry has been observed. For instance, research has been carried out in industrial systems [1, 2, 3, 4], thermal energy storage, and environmental impact assessments [5, 6, 7, 8].

The early works on the internal combustion engine assessments [9] and the global engine evaluation using the SLT analysis [10] considers the energy and exergy destroyed in detail [11, 12, 13] and gives the fundamental knowledge about the process.

The SLT has been applied in evaluating combustions engines [10] to review the effect of the operating parameters on the output efficiency [13, 14] and energy and entropy balance in a combustion chamber by mathematical analysis. In all these cases the overall exergy and energy balance are considered in the period of engine cycle theoretically [15, 16].

The purpose of this paper is to show how the exergy analysis can be used to improve the performance of the bi-fuel SI engines.

ENGINE MODEL FOR EXERGY ANALYSIS

The engine specification is defined in Table 1 and it operates at 1500-6000 rpm. Emissions and performance parameters of the bi-fuel engine are measured in full load (WOT) conditions over a wide range of engine speeds according to testing procedures [18]. An engine model has been used for predicting the overall engine performance and emissions with acceptable relative error. The engine model is developed in a two-zone model, while considering the chemical synthesis of fuel, including 10 chemical species. In this model, CNG and gasoline have been considered with a composition of CH_4 and C_7H_{14}, respectively according to the composition and properties of CNG and gasoline in the research [18]. A computer code is developed in MATLAB software to solve the equations for the prediction of temperature and pressure of the mixture in each stage. In addition, it has the ability to simulate turbulent combustion and compared to computational fluid dynamic (CFD) models it is computationally faster and efficient. The model has only been used for the FLT. It is realized that the FLT is not able to afford an appropriate understanding of engine operations [17]. This paper concentrates on SI engine operation investigation using the developed engine model by the SLT outlook (exergy based SI engine model, EBSIEM). Moreover, the engine cycle analysis with the SLT is termed availability (exergy); for example, heat transfer availability (A_Q), work availability (A_W), irreversible processes that is source of the availability destroyed (A_I or A_{dest}), and chemical availability (A_{fch}).

The model is based on the first law of thermodynamics or energy analysis. This simulated bi-fuel SI engine model is developed based on the second law of thermodynamics or exergy (availability) analysis. The terms of availability need to be determined.

In thermal systems, an exergy analysis conventionally divides a system's availability into two main parts: chemical availability and thermo-mechanical availability. In a system, the thermo-mechanical availability (A_{tm}) denotes the maximum useful mechanical work within the environment when the system reaches thermal and mechanical equilibrium, assuming that its mass is not allowed to react chemically, or move within, the surrounding atmosphere. In a system, the chemical availability (A_{fch}) denotes the maximum useful work, which can be yielded because of variation among the system's components partial pressures at the restricted dead state and the same components partial pressures in the surrounding atmosphere.

For the open system type, the equation of availability balance for a customary control volume is explained based on heat transfer, work transfer, and mass from inside control volume boundaries.

The rate term of heat transfer availability is given by equation (1):

$$\frac{dA_Q}{d\theta} = \left(1 - \frac{T_0}{T}\right)\frac{dQ}{d\theta} \tag{1}$$

This term describes the heat-transferred from inside the system's boundaries that has the temperature, which is available for production of the work.

The rate term of work transfer availability is given by equation (2):

$$\frac{dA_w}{d\theta} = \left(\frac{dW}{d\theta} - p_0\frac{dV}{d\theta}\right) \tag{2}$$

This term expresses the work-done rate of the system minus the work-done rate of the surroundings (that is not available for production of work).

The rate term of availability for exergy burned of the fuel is presented by equation (3):

$$\frac{dA_{fch}}{d\theta} = \frac{m_f}{m}\frac{dx_b}{d\theta}a_{fch} \tag{3}$$

m_f and m are the fuel and total masses in the cylinder, respectively.

The rate term of availability destroyed is stated by equations (4) and (5) [17 and 18]:

$$\frac{dI_{comb}}{d\theta} = T_0\frac{dS_{comb}}{d\theta} \tag{4}$$

$$\frac{dI_{comb}}{d\theta} = T_0\left(\left(\frac{d(m_b s_b)}{d\theta}\right) + \left(\frac{d(m_u s_u)}{d\theta}\right)\right) \tag{5}$$

S_{comb} is the entropy rate generation during combustion irreversibility, determined based upon entropy balance in a two zone combustion model. m_u and m_b are the mass, s_u and s_b is the specific entropy of unburned and burned gases in the cylinder, respectively.

Therefore, the following equation of availability balance is expressed a crank angle (CA) basis [17 and 18]:

$$\frac{dA}{d\theta} = \left(1 - \frac{T_0}{T}\right)\frac{dQ}{d\theta} - \left(\frac{dW}{d\theta} - P_0\frac{dV}{d\theta}\right) + \frac{m_f}{m}\frac{dx_b}{d\theta}a_{fch} - \frac{dI_{comb}}{d\theta} \tag{6}$$

Moreover, the heat transfer process is a source of the entropy generation, and accordingly equation (7) $\dot{Q}_u$ and $\dot{Q}_b$ are the heat loss rates from the unburned and burned zones:

$$\dot{S}_Q = \frac{\dot{Q}_b}{T_b} + \frac{\dot{Q}_u}{T_u} \tag{7}$$

Therefore, the total destruction of availability considered in this research includes the combustion irreversibility and the heat transfer irreversibility, expressed by equation (8):

$$\dot{I}_{total} = \dot{I}_{comb} + \dot{I}_Q \tag{8}$$

The efficiency is determined based on the FLT and SLT. The FLT and SLT efficiencies are determined as equations (9) and (10), respectively:

$$\eta_I = \frac{Energy_{out}(work)}{Energy_{in}} = \frac{W}{m_f Q_{LHV}} \tag{9}$$

$$\eta_{II} = \frac{Exergy_{out}(work)}{Exergy_{in}} = \frac{A_W}{m_f a_{fch}} \tag{10}$$

NUMERICAL APPLICATION

The various differential equations of the engine model using the FLT analysis are solved simultaneously during compression, combustion and expansion phases. The engine's geometric characteristics, operation parameters and fuel specifications are given as the input data to the QD dimensional model. The thermodynamic properties and composition in the cylinder are computed during the simulation i.e., equilibrium combustion products and fuel air residual gas [21]. In this model, exergetic analysis is executed simultaneously, concerns the cylinder content's thermodynamic condition.

RESULTS

Figures 1a and 1b show the main availability (exergy) terms, during the interrogated engine cycle for the conditions presented in these figures, for CNG and gasoline fuels. As shown in these figures, the thermo-mechanical availability (A_{tm}) grows slowly during the compression stroke and before the combustion starts, so that the chemical availability of the fuel (A_{fch}) remains constant.

The total availability (A_{total}) variation represents the variation of thermo-mechanical availability behaviour. With the start of combustion at 35° b_{TDC}, the fuel chemical availability reduces instantaneously because of heat conversion. With the end of the combustion, at 25° a_{TDC}, the expansion stroke proceeds while the piston attains BDC.

Table 1 Engine specifications

Engine type	Four stroke, bi-fuel spark ignition
Induction	Naturally aspirated
Number of cylinders	4 cylinder – In line
Bore (mm)	83
Stroke (mm)	81.4
Connecting rod (mm)	150.2
Displacement Volume (cm^3)	1761
Compression ratio	9.25
Maximum power	68.65 kW @ 6000 rpm
Maximum torque	143 Nm @ 2500 rpm
Inlet valve opening (IVO)	32° bTDC
Inlet valve closing (IVC)	64° aBDC
Exhaust valve opening (EVO)	59° bTDC
Exhaust valve closing (EVC)	17° aBDC

During this cycle, reduction in A_{tm} and A_{total} proceeds because of heat and work from the system or the availability transfers, so that irreversibility remains at nearly constant level.

The results show that the value of availability terms in CNG fuelled engines are less than gasoline fuelled. The main reason is occupied large volume in the inlet mixture when the engine is CNG fuelled, although heating value of CNG fuel is higher than gasoline.

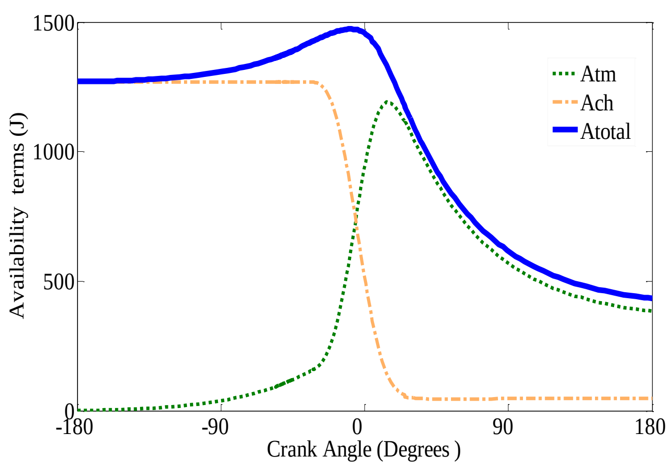

Figure 1a Main availability terms in CA, ϕ=0.9; r=9.25; θ_s=35° bTDC; N=3000 r/min, $\Delta\theta_b$ =60 CAD, CNG mode.

Figure 2 shows the cumulative availability terms, during the the engine cycle's part for the conditions presented in this figure for the CNG mode.

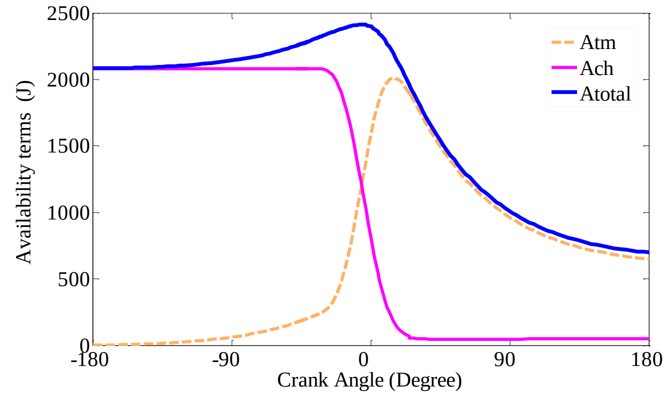

Figure 1b Main availability terms in CA, ϕ=0.9; r=9.25; θ_s=35° bTDC; N=3000 r/min, $\Delta\theta_b$ =60 CAD, gasoline mode.

The Figure shows thermo-mechanical, chemical, heat transfer, work, total availabilities, and the availability destroyed. In addition, Figure 2 clearly shows that during compression, increased thermo-mechanical availability with the work's availability (A_W) and it shows an isochronous difference compare with thermo-mechanical availability with a negative mark. There is insignificant difference in irreversibility (A_I) because of a meaningless the heat transfer availability (A_Q) during the compression stroke before the combustion starting.

Figure 3 shows the equivalence ratio's effects (ϕ) on availability terms in the compression, combustion, and expansion periods. This Figure shows the equivalence ratio effects on the thermo-mechanical availability after the beginning of the combustion.

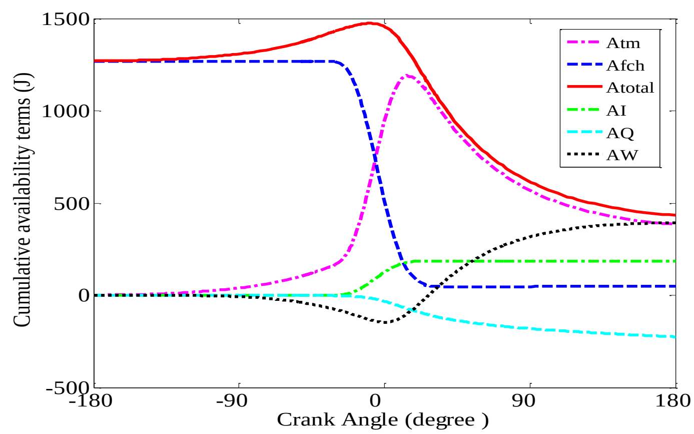

Figure 2 Cumulative availability terms in CA, ϕ=0.9; r=9.25; θ_s=35 bTDC; N=3000 r/min, $\Delta\theta_b$ =60 CAD, CNG mode.

There are closer differences in Figure 3a among the curves of thermo-mechanical availability for ϕ=0.85, 0.9 and 0.95, so that a lean mixture gives significantly minor value, specifically in expansion period. The differences can be described that the excess fuel cannot be converted to work by increased fuel

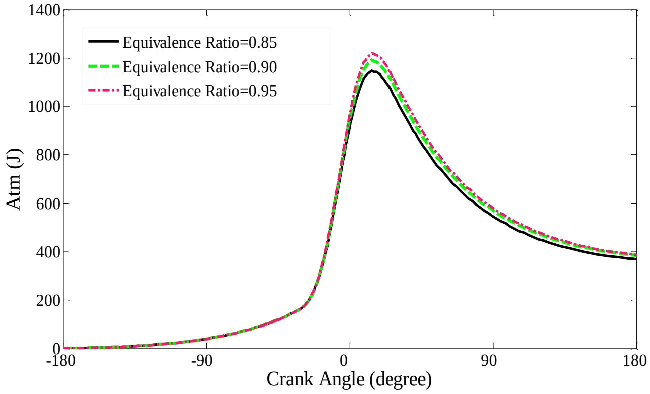

Figure 3a Effects of equivalence ratio on thermo mechanical availability (CNG mode).

Figure 3c shows Effect of equivalence ratio on total availability (in CNG mode) contribution in the richer mixture, that its reason is insufficient oxygen. Moreover, the decreased pressure and temperature of cylinder apparent for the lean mixture gives the minimum thermo-mechanical availability values because of deficiency of the fuel and major irreversibility. The fuel air mixtures richness grows up chemical availability that shows in Figure 3b. However, if excess fuel were more than requirement, it cannot be transformed to useful work efficiently. The main supplying to differences in total availability, presented in Figure 3c, which it is contributed using the chemical availability of the fuel in compression periods, so that the chemical availability of the fuel and thermo-mechanical availabilities denote to it in the cycle's rest.

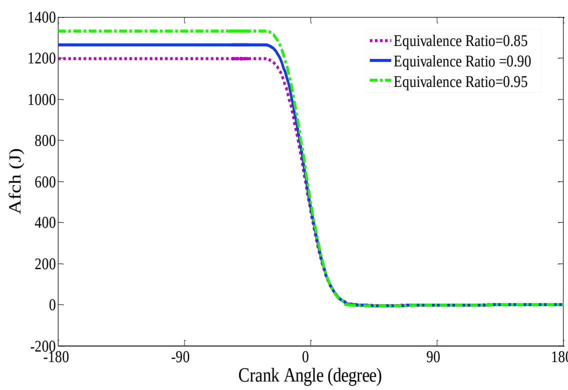

Figure 3b Effects of equivalence ratio on chemical availability (CNG mode).

Figure 4 shows the engine speed effects on availability terms in the cycle's part period. The speed engine grow up has not affected the thermo-mechanical availability peak values (Figure 4a). The values of the fuel chemical availability in Figure 4b have not changed in the engine speed for the same fuel's value supplied to the cylinder.

A sharp difference occurs in chemical availability in the combustion process and the slopes of the lines show no change with increasing the engine speed due to the constant combustion duration.

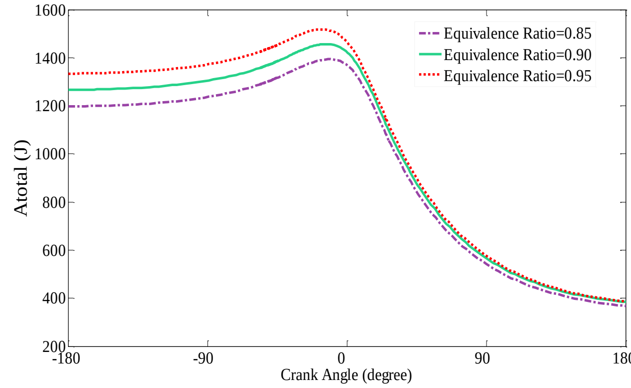

Figure 3c Effects of equivalence ratio on total availability (CNG mode)

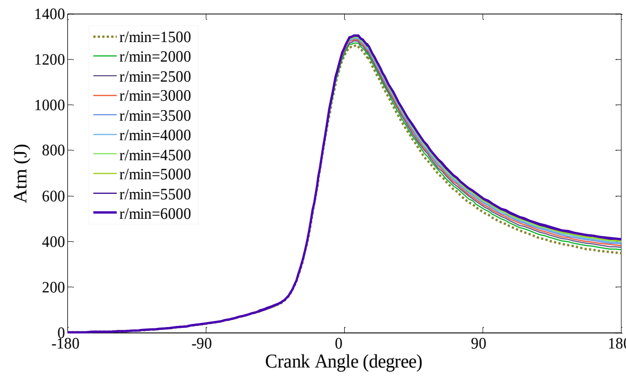

Figure 4a Effects of speed on thermo mechanical availability (CNG mode).

The variations in total availability shows in Figure 4c reveal the combination of thermo-mechanical and fuel availability. Figure 5 shows the effects of the ignition or spark advance (θ_s) on availability terms in the compression, combustion and expansion periods. Thermo-mechanical availability grows up in spark advance that shows in Figure 5a.

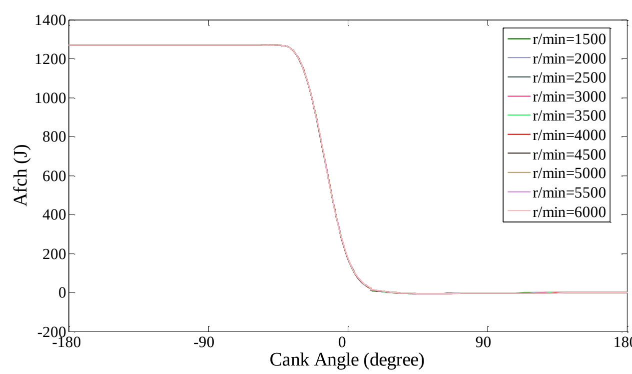

Figure 4b Effects of speed on chemical availability (CNG mode).

When ignition time is decreased (spark advance), thermo-mechanical availability reduces because of the decrease in temperature and pressure. There is no effect on the fuel chemical availability in compression and expansion period, shown in Figure 5b. However, the fuel chemical availability changed during the combustion process.

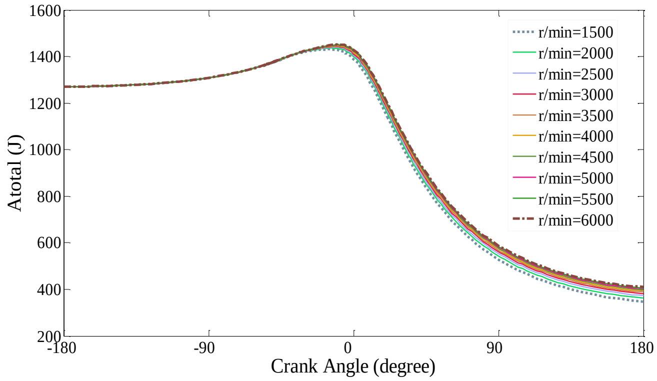

Figure 4c Effects of speed on total availability (CNG mode).

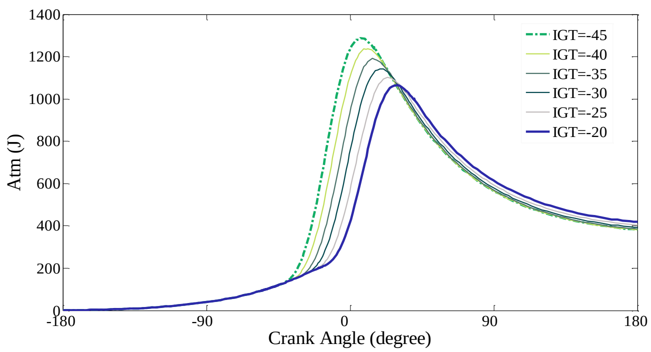

Figure 5a Effects of ignition time on thermo-mechanical availability (CNG mode).

Total availability variations in Figure 5c represent the combination of the chemical availability of the fuel and thermo-mechanical availability that reaches a maximum at 20° bTDC at the end of combustion.

Figure 6 shows the difference of FLT efficiency (η_I) and SLT efficiency (η_{II}) based on equivalence ratio, ignition time or spark advance (SA), and engine speed.

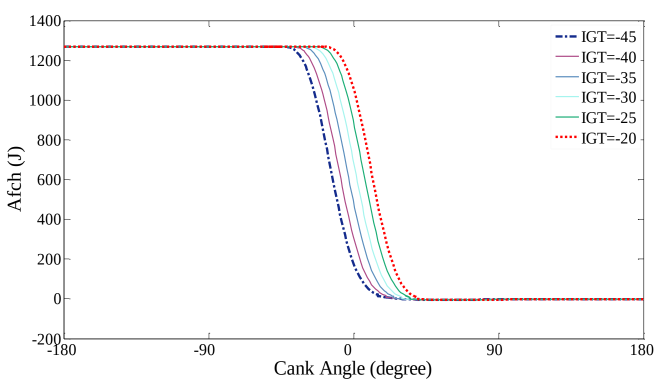

Figure 5b Effects of ignition time on chemical availability (CNG mode).

The FLT and SLT efficiencies reduce with growing equivalence ratio, shown in Figure 6a. The richness fuel air (FA) ratio mixture results in increased FLT and SLT efficiencies. However, the richness of the fuel air mixture has a negative effect upon the efficiencies.

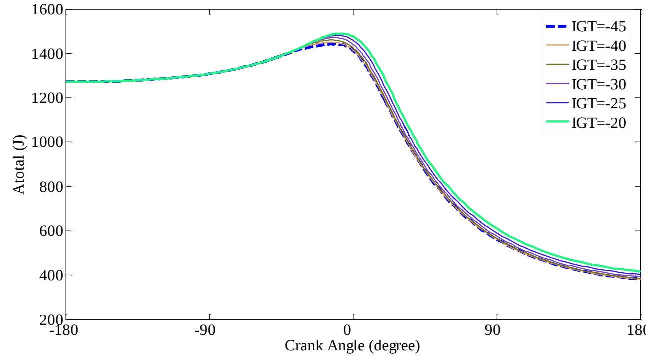

Figure 5c Effects of ignition time on total availability (CNG mode).

The ignition time effects on FLT and SLT efficiencies, shown in Figure 6b. In this figure is clear that the FLT and the SLT efficiencies have a maximum value at 25° bTDC.
The difference of the FLT and the SLT efficiencies with engine speed are presented in Figure 6c. The efficiencies have maximum value in the engine speed about 3000 r/min.

Conclusion

An exergy based SI engine model (EBSIEM) for evaluating of the bi fuel SI engine performance was described in this paper. The ignition time (spark advance) equivalence ratio, and engine speed effects upon availability terms such as the thermo-mechanical availability, the chemical availability of the fuel and the total availability have been surveyed analytically.

The results of exergy (availability) analysis showed the differences of operational parameters that affected the availability transfers, irreversibilities and efficiencies. For example, growth in equivalence ratio causes increased irreversibilities, so that it reduces FLT and SLT efficiencies. The irreversibilities had minimum values for the specified engine speed; equivalence ratio and optimal ignition time (spark advance), when the total availability in the engine cycle reached a maximum.

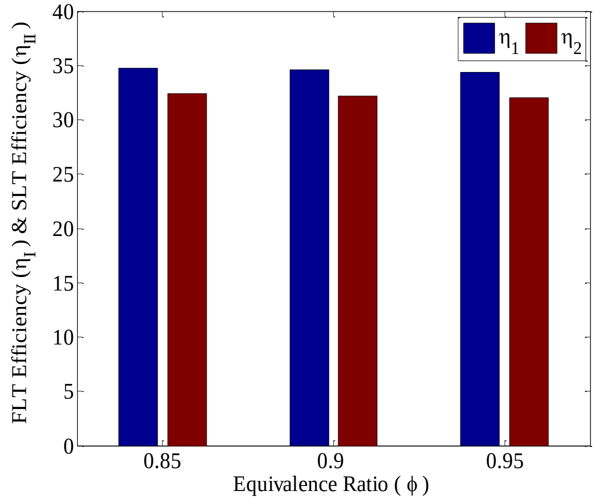

Figure 6a Effects of equivalence ratio on the FLT and SLT efficiencies.

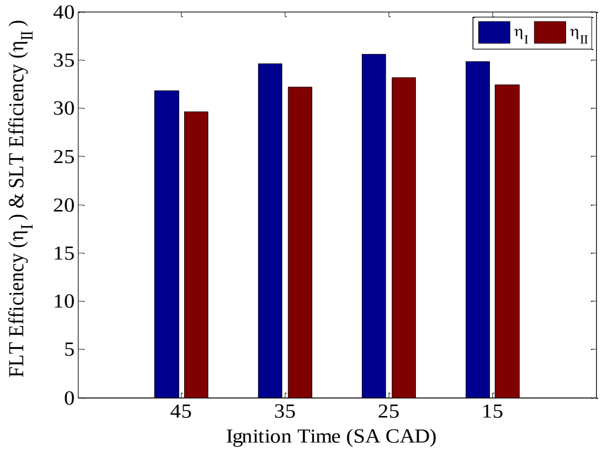

Figure 6b The effects of ignition (spark) time on the FLT and SLT efficiencies.

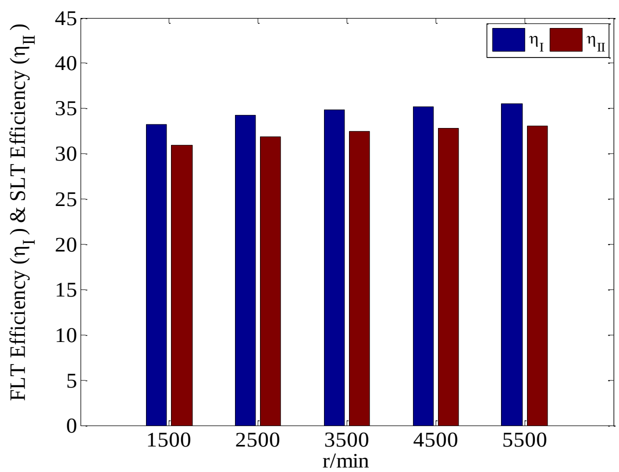

Figure 6c The effects of engine speed on the FLT and SLT efficiencies.

NOMENCLATURES

A	Availability or exergy	(J)
A_{fch}	Fuel chemical availability	(J)
A_Q	Availability transfer with heat	(J)
A_{tm}	Thermo-mechanical availability	(J)
A_w	Availability transfer with work	(J)
A_{tot}	Total availability	(J)
aBDC	After BDC	___
aTDC	After TDC	___
bBDC	Before BDC	___
bTDC	Before TDC	___
EVO	Exhaust valve opening	___
EBSIEM	Exergy based SI engine model	___
FLT	First law of thermodynamics	___
IGT	Ignition (spark) time	___
IVC	Inlet valve closing	___
m	Mass	(kg)
P	Pressure	(Pa)
Q	Heat transfer	(kJ)
s	Specific entropy	($kJ.kg^{-1}.K^{-1}$)
SLT	Second law of thermodynamics	___
T	Temperature	(K)
V	Volume	(m^3)
W	Work done	(kJ)
WOT	Wide open throttle	___
x	mass fraction	___
ϕ	Equivalence ratio	___
η_I	The FLT efficiency	%
η_{II}	The SLT efficiency	%
ω	Angular velocity	($rad.s^{-1}$)
θ	Crank angle	(°CA)
θ_0	Start of combustion	(°CA)
$\Delta\theta$	Total combustion duration	(°CA)

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