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AVAILABILITY ANALYSIS OF A BI-FUEL SI ENGINE MODEL FOR IMPROVEMENT ITS PERFORMANCE

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

Keywords: Exergy, Availability, Modeling, Bi-fuel, SI Engine.

I. INTRODUCTION

The first law of thermodynamics (FLT) is the law of conservation of energy. It explains internal energy as a state function and affords the energy conservation functional statement. It affords no knowledge about the processes direction that it can automatically happen, i.e. the reversibility aspects of thermodynamic processes.

The second law of thermodynamics set up the different forms of energy in the quality and describes that some processes cannot automatically happen others 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 to analyzing energy and other systems and processes. In a system, the exergy is the maximum useful work, which it can be carried out through system's composite and same composite of the environment. Therefore, use of SLT in internal combustion engine analysis has been intensified. Exergy analysis is a method of thermodynamic analysis based on the second law of thermodynamics.

Exergy analysis affords a true measure that actual performance how approaches nearly to the ideal. It recognizes more clearly thermodynamic losses the causes and locations than energy analysis. Therefore, it can support in modifying and optimizing engine performances. For this reason, in recent years increasing recognition and application of the exergy methods usefulness by academia, government, and industry has been noticed. 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].

Early work, for ICEs [9, 10] on the global engine operation assessment using the SLT analysis was complied energy and exergy destroyed determination by detailed [11, 12, 13]. The SLT controversy has been applied to assessment concepts of modern engine [10] to survey the operating parameters influence on efficiency [13 and 14]. The overall exergy and energy balance are considered in the period of engine cycle theoretically [15, 16]. Some review researches about exergy and energy analysis were published and developed [17, 18, 19, 20, 21, 22]. The purpose of this paper is using of the exergy analysis in a bi-fuel SI engine for improvement of its performance.

II. DEVELOP 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 [23]. An engine model has been used for predicting the overall engine performance and emissions with acceptable relative error (average 8% error) [23]. The engine model is developed in a two-zone model, while considering the chemical synthesis of fuel, including 10 chemical species. 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 [23]. However, the model has only been used for the FLT.

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

It has been realized that the FLT is not able of affording an appropriate comprehension into engine operations [17, 18, 19, 20]. Therefore, in this paper concentrates on the bi fuel 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 are the source of the availability destroyed (A_I or A_{dest}) and chemical availability (A_{fch}).

The mentioned 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. Therefore, the terms of availability will be able to be determined.

In thermal systems, an exergy analysis, it is conventionally to divide the system's availability consists in two main parts: the chemical availability and the thermo-mechanical availability. In a system, the thermo-mechanical availability (A_{tm}) denotes the maximum useful mechanical work educe able with the environment when the system reaches in thermal and mechanical equilibrium that its mass not allowed to react chemically or move with the surrounding atmosphere. As well in a system, the chemical availability (A_{fch}) denotes the maximum useful work, which can be yielded because of variations among the system's components partial pressure 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 transfers, work transfers, and experimenting mass from inside control volume boundaries. The rate term of heat transfer availability is stated by Equation (1):

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

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

The rate term of work transfer availability is presented by Equation (2):

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

This term express work done rate of the system minus work done rate of 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):

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

where, 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, 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 that it is determined based on entropy balance in a two zone combustion model. m_u and m_b are the mass, s_u and s_b are 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, 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 the source of the entropy generation, accordingly the 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 contemplated in this research includes of the combustion irreversibility and heat transfer irreversibility that it expressed by Equation (8):

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

The efficiency is determined based on the perspective of the FLT and SLT. The FLT and SLT efficiencies have been determined as Equations (9) and (10), respectively:

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

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

III. 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 geometric characteristics, operation parameters and the fuels specification are given such 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 [23]. In this model, exergetic analysis is executed simultaneously, concerns cylinder content thermodynamic condition. Figure 1 shows the general structure of an exergy based bi-fuel SI engine.

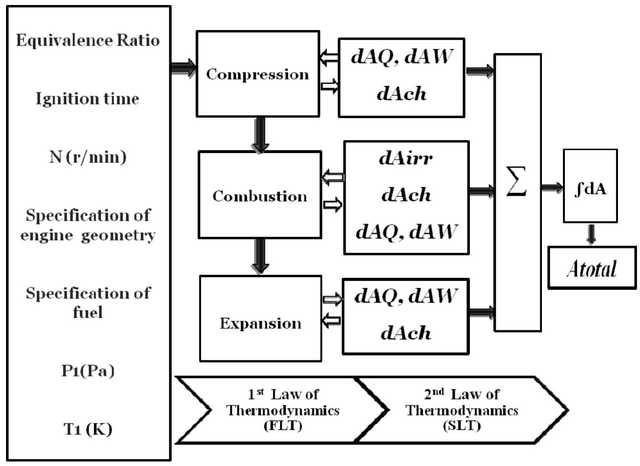

Figure 1. Simplified structure of the exergy based bi fuel SI engine model

IV. RESULTS AND DISCUSSION

Figures 2a and 2b show the main availability (exergy) terms, during the interrogated the engine cycle part for the conditions presented in these Figures for CNG and gasoline fuels. As shown in these Figures, the thermo-mechanical availability (A_{tm}) grows up slowly during the compression stroke and before the combustion starting, so that chemical availability of fuel (A_{fch}) abides constant.

The total availability (A_{total}) variation represents the variation of thermo-mechanical availability's behaviour. With the beginning of the combustion, at 35° bTDC, 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. During this cycle, reduces 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 level that is constant. The results obviously 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 3 shows the cumulative availability terms, during the interrogated the engine cycle's part for the conditions presented in this figure for the CNG mode. The Figure shows thermo-mechanical, chemical, heat transfer, work, total availabilities, and the availability destroyed. In addition, Figure 3 clearly shows that during compression, increased thermo-mechanical availability concerns 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.

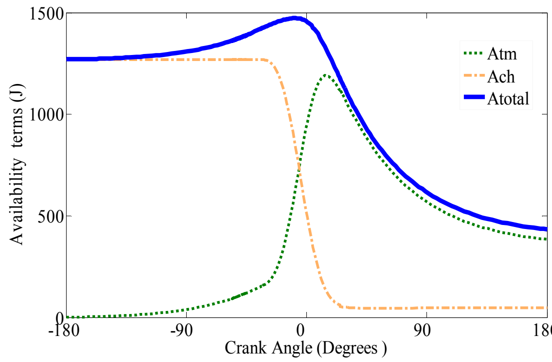

Figure 2a. Main availability terms in CA, ϕ =0.9; r=9.25; θ_s=35° bTDC; N=3000 r/min, $\Delta\theta_b$ =60 CAD, CNG mode

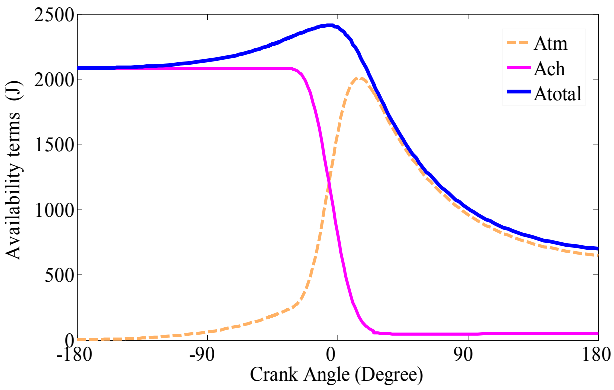

Figure 2b. Main availability terms in CA, ϕ =0.9; r=9.25; θ_s=35° bTDC; N=3000 r/min, $\Delta\theta_b$ =60 CAD, gasoline mode

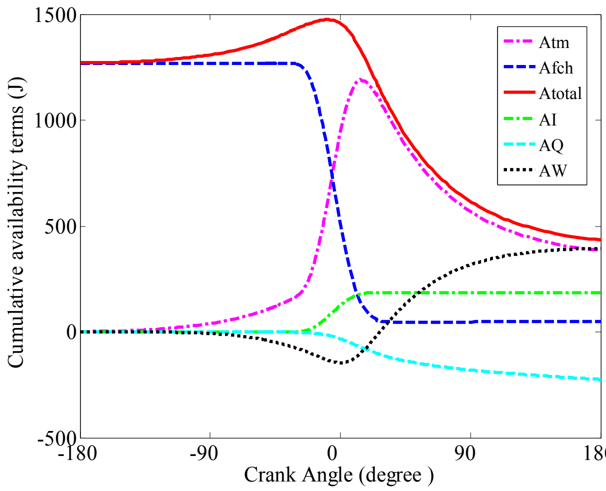

Figure 3. Cumulative availability terms in CA, ϕ =0.9; r=9.25; θ_s=35° bTDC; N=3000 r/min, $\Delta\theta_b$ =60 CAD, (CNG mode)

Figure 4 shows the equivalence ratio's effects (ϕ) on availability terms in the compression, combustion, and expansion periods. In this Figure shows the equivalence ratio effects on the thermo-mechanical availability after the beginning of the combustion.

There are closer differences in Figure 4a 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 4c shows effects of equivalence ratio on total availability (CNG mode) availability contribution for the rich mixture, because of insufficient oxygen values because of deficiency of the fuel and major irreversibility. 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 4b. 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 4c, 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 5 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 5a). The values of the fuel chemical availability in Figure 5b have not changed in the engine speed for the same fuel's value supplied to the cylinder. A sharp deference occurs in chemical availability in the combustion process and the slopes of the lines no change with increasing the engine speed due to the constant of combustion duration. The variations in total availability shows in Figure 4c reveal the combination of thermo-mechanical and fuel availability.

Figure 6 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 6a. 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 that shows in Figure 6b. However, the fuel chemical availability changed in the combustion process. Total availability variations in Figure 6c represent the combination of the chemical availability of the fuel and thermo-mechanical availability that reaches the maximum at 20° bTDC at the end of combustion compared to other values.

Figure 7 shows the deference of the FLT efficiency (η_I) and the SLT efficiency (η_{II}) based on equivalence ratio, ignition time or spark advance (SA) and engine speed. The FLT and the SLT efficiencies reduce with growing up equivalence ratio that shows in Figure 7a. The richness fuel air (FA) ratio mixture results to increases the FLT and the SLT efficiencies. However, the richness of the fuel air mixture has negative effects on the efficiencies. The ignition time effects on the FLT and the SLT efficiencies shows in Figure 7b. In this figure is clear that the FLT and the SLT efficiencies have the maximum value in 25° bTDC. The difference of the FLT and the SLT efficiencies with engine speed are presented in Figure 7c. The efficiencies have a maximum value in the engine speed about 3000 r/min.

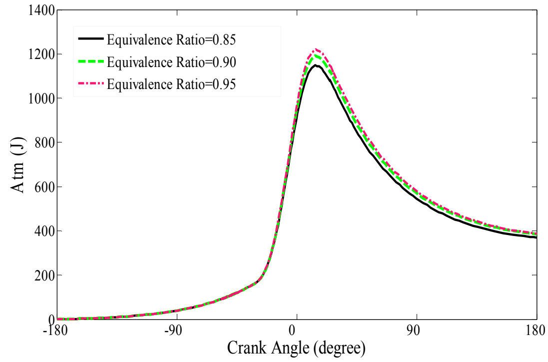

Figure 4a. Effects of equivalence ratio on thermo mechanical availability (CNG mode)

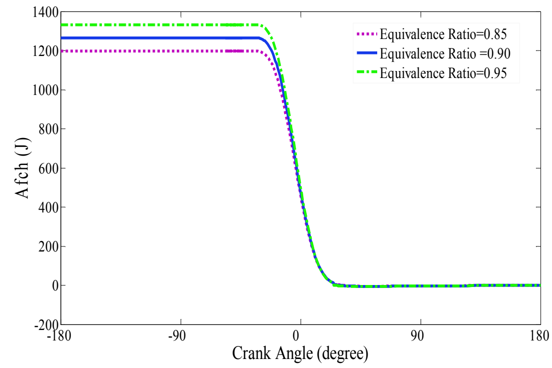

Figure 4b. Effects of equivalence ratio on chemical availability (CNG mode)

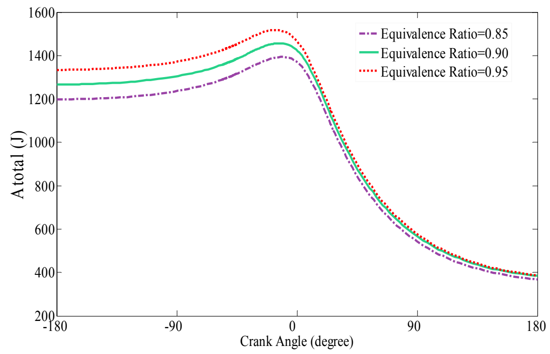

Figure 4c. Effects of equivalence ratio on total availability (CNG mode)

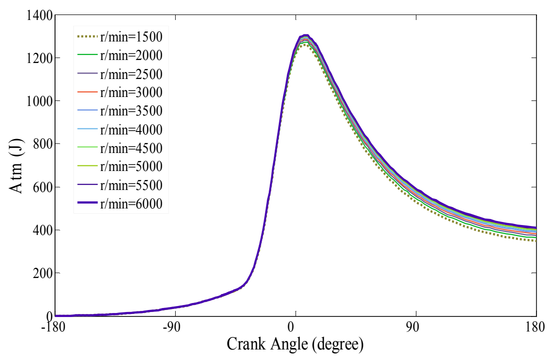

Figure 5a. Effects of speed on thermo mechanical availability (CNG mode)

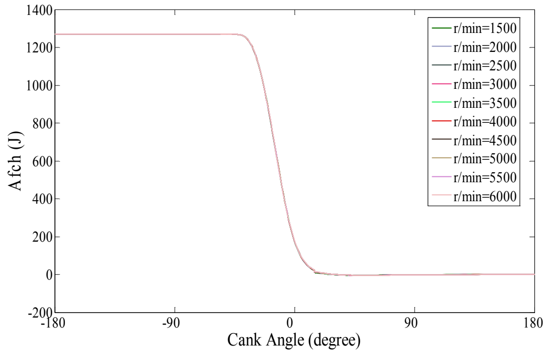

Figure 5b. Effects of speed on chemical availability (CNG mode)

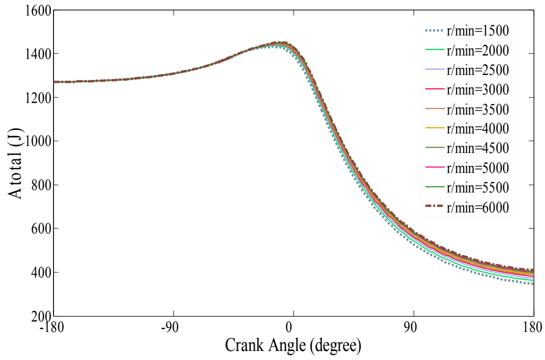

Figure 5c. Effects of speed on total availability (CNG mode)

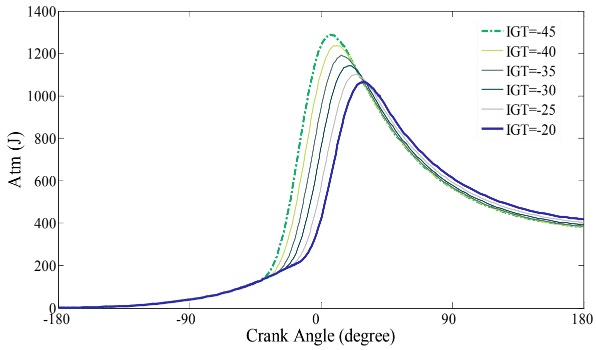

Figure 6a. Effects of ignition time on thermo-mechanical availability (CNG mode)

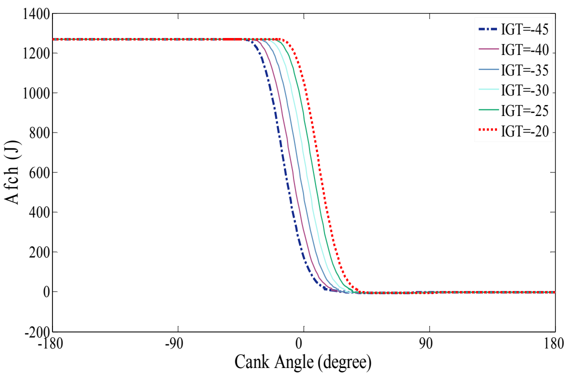

Figure 6b. Effects of ignition time on chemical availability (CNG mode)

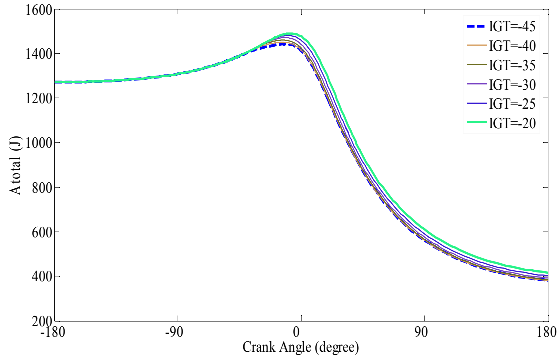

Figure 6c. Effects of ignition time on total availability (CNG mode)

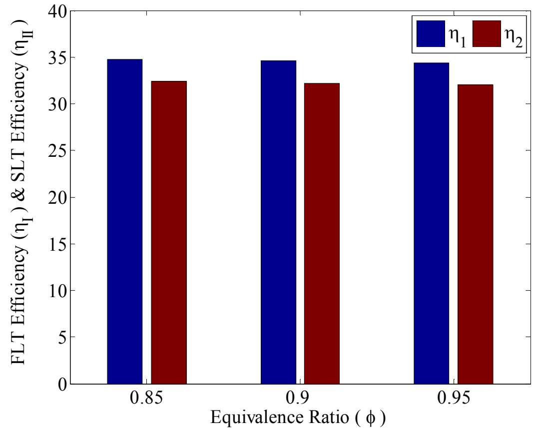

Figure 7a. Effects of equivalence ratio on the FLT and SLT efficiencies

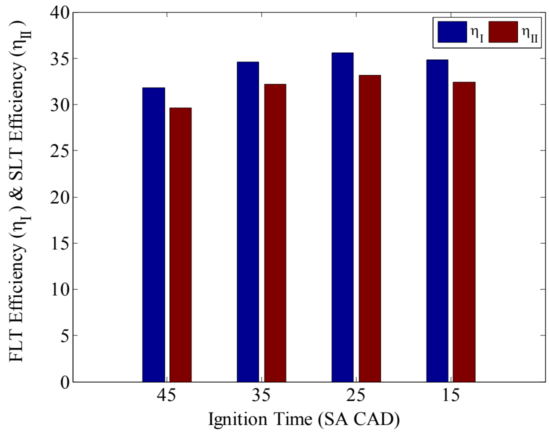

Figure 7b. The effects of ignition (spark) time on the FLT and SLT efficiencies

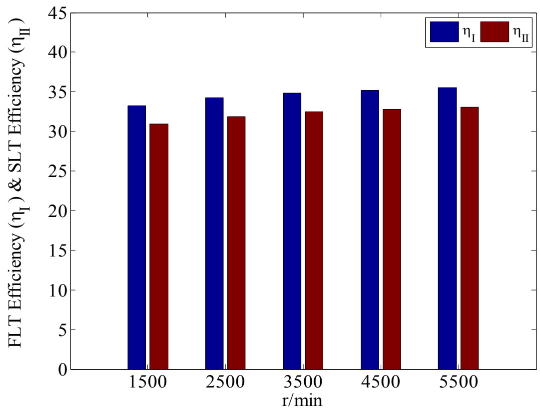

Figure 7c. The effects of engine speed on the FLT and SLT efficiencies

V. CONCLUSIONS

An exergy based SI engine model (EBSIEM) for evaluating of the bi fuel SI engine performance was created in this paper. The ignition time (spark advance) equivalence ratio, and engine speed effects on 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 that differences of operational parameters that had affected the availability transfers, irreversibilities and efficiencies. For example, grow up in equivalence ratio causes and increased in irreversibilities, so that it reduces the FLT and the 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.

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.K)
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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BIOGRAPHY

Kambiz Rezapour was born in Karaj, Iran. He received his B.Sc., M.Sc. and Ph.D. degrees all in Mechanical Engineering. He has graduated in Ph.D. degree at the University of Bradford, UK. He is currently an Assistant Professor of Mechanical Engineering Department, Karaj Branch, Islamic Azad University, Karaj, Iran. He has 18 years experience in energy efficiency, energy management, energy conservation in residential, commercial and industrial sectors, combined heat and power, renewable energy, energy resources, internal combustion engine, Exergy analysis, artificial neural networks and optimization. He fulfilled a number of research projects in these fields and published 25 technical papers in journals, international and national conferences, and four technical books.