

Performance Analysis of SI Engine Fueled by Ethanol Steam Reforming Products

L. Tartakovsky, V. Baibikov, M. Gutman, A. Mosyak, M. Veinblat
Technion – Israel Institute of Technology, Haifa 32000, Israel

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ABSTRACT

The goal of the present work was to analyze the performance of a spark ignition engine fueled by ethanol steam reforming products. The highest reformer-ICE system efficiency and the lowest CO emissions were achieved with the ethanol steam reforming products obtained at reaction temperature of 1000K and water/ethanol ratio of 1.8. Fueling the SI engine with reformat gas made it possible to achieve the reformer-ICE system efficiency of 40% for the engine fed by SRE products compared with 34% for gasoline and 36% for ethanol. CO emissions were reduced by 3.5 and 10 times compared with ethanol and gasoline, respectively. NO_x emissions were decreased by about 4 times compared with the gasoline fed engine.

INTRODUCTION

Internal combustion engine (ICE) is the main power plant in most of modern transportation systems. As such, it is responsible for a substantial part of petroleum fuel consumption as well as environmental pollution. This fact provides a powerful incentive to design more fuel-efficient engines, in order to reduce petroleum use. The risk of economic dependence on expensive oil has strengthened the support for the development of renewable fuels technologies. Bio-fuels, for example, represented 49% of the growth in non- OPEC oil supply in 2007 and are expected to rise in the future [1].

Bio-ethanol is widely recognized as a promising renewable energy source. A significant advantage of this alcohol over fossil fuels is that it is CO₂ neutral. Thus, ethanol appears as one of the best candidates that can be used for hydrogen generation onboard a vehicle. However, most of the previous studies are focused on hydrogen generation for fuel cells [2-7]. Fuel cells today are much more expensive than an equivalently sized ICE. Economic and environmental comparison of conventional (ICE powered) hybrid and fuel cell vehicles was performed in [8]. The following criteria were taken to be key economic characteristics of vehicles: price (including the price for changing batteries for hybrid and electric vehicles), fuel costs

(which are related to vehicle lifetime), and driving range (which defines the number of refueling stations required). According to this comparison, the hydrogen fuel cell vehicles are not beneficial over conventional and hybrid vehicles. ICE powered vehicles offer low initial cost, easy start-up, proven reliability, good part-load characteristics and recovery potential. The emissions of ICE can be controlled by exhaust catalysts and better control of the combustion process. ICE, in contrary to fuel cell, does not require hydrogen of high purity for its operation. It is much more flexible and can effectively burn different mixtures of hydrogen, carbon monoxide and other gases. In case of ICE, the basic concept involves the use of the engine's exhaust heat to promote on-board reforming of ethanol or other hydrocarbon fuel into a mixture of hydrogen and carbon monoxide with small amounts of carbon dioxide, methane, soot etc. (frequently called syngas) [9-10]. The latter has, as a rule, greater heating value than primary liquid fuel and may be more efficiently burned in the engine in comparison to the original fuel. Because the reforming reactions are endothermic, they provide an opportunity for recycling exhaust gas energy in a thermochemical form that otherwise would have been wasted. This approach, called thermo chemical recuperation (TCR) [9], has been receiving renewed interest as one of the possible methods of increasing efficiency and reducing emissions of ICE.

It is known that an onboard reformer can not work efficiently in a wide range of engine operation regimes typical for a conventional road vehicle, especially at transient modes and cold-start conditions [10]. In case of a hybrid propulsion system, which always has an additional energy source, these shortcomings can be successfully overcome.

Most of the published studies on TCR are focused on gas turbine applications [11-16]. In [17] only partial fuel reformation for ICE was studied. Computational analysis has been performed by Galloni and Minutillo [18] for the case of partial gasoline replacement by a reformat gas in a spark ignition (SI) engine. In this work reformat gas was produced by exothermic partial oxidation of gasoline. The results have pointed out that for the considered case the mean overall efficiency of the integrated reformer-ICE system was close to that of the gasoline fueled SI engine. In

summary it should be noted that ethanol can be converted into hydrogen through steam reforming (SRE) [2, 19], partial oxidation (PO) [20], and auto-thermal reforming (ATR) [21]. PO and ATR processes have the merit of fast start-up time because of the exothermic nature of the oxidation reaction. However, the SRE provides highest hydrogen production. Leung et al [22] studied different methods of on-board ethanol reforming and found that the SRE method makes it possible to generate reformat gas of maximal heating value – by 20% greater than primary liquid ethanol. Fubing et al [23] report on experimental work, where ICE fueling was performed by gasoline, gasoline-ethanol, SRE products (reformat) and gasoline-SRE mixture. The study was carried out on a spark ignition engine with a carburetor. The specifications of the engine were: compression ratio 7.5, max power 63 kW, max speed 3800 rpm. The liquid mixture of ethanol and water was turned to steam after being passed through an evaporator and this steam was reformed in the reactor. However, operating parameters and the performance of steam reactor were not reported in this paper.

Previous studies were focused on thermodynamic analysis of ethanol steam reforming with comparison to other ethanol decomposition methods, and hydrogen production from ethanol with respect to fuel cell applications. The effect of operating parameters on hydrogen yield has been assessed. In the present study effect of operating parameters on the enthalpy of combustion of SRE products was examined with relation to using them as fuel for ICE.

The goal of the present work was to analyze the performance of an SI engine fueled by ethanol steam reforming products. The engine was part of a series hybrid propulsion system and worked at a steady-state single operation regime. A methodology of SRE efficiency assessment was suggested. The possibility of using it for analysis and optimization of reforming parameters was demonstrated. The effect of SRE products composition on engine performance was shown. The predicted performance of the engine fueled by SRE products was compared to that of the same engine fueled by gasoline or liquid ethanol.

REFORMER - ICE SYSTEM MODELING

Figure 1 shows the schematical layout of the considered reformer-ICE system. Heat that should be supplied to the reformer in order to realize the SRE process can be provided by two possible modes.

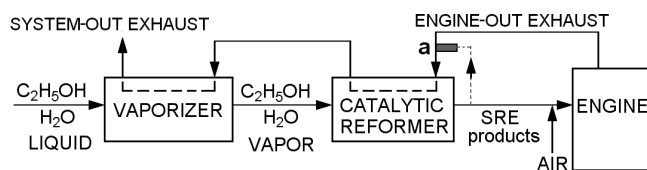


Figure 1. Scheme of the integrated reformer-SI engine system.

a – optional SRE products burner

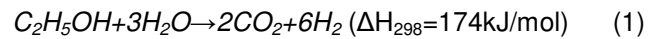
In the first case all of the required heat is supplied from the energy of the exhaust gas. In the second case, an additional fuel should be added and burned to ensure that the required heat for reforming is supplied [2]. The latter may be realized in the lean burn engine (see Table 3) where the required oxygen is available in the exhaust gas. Comparative analysis of the effectiveness of the mentioned above cases will be performed in the future.

To assess the efficiency of the reformer-ICE system, numerical study of both catalytic reformer and the SI engine has been carried out.

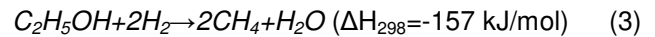
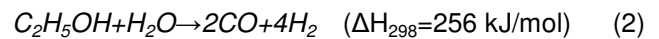
REFORMER MODELING

Ethanol can be converted into gas containing hydrogen through steam reforming, SRE. The thermodynamics of ethanol SRE has been widely discussed in the literature [5, 6, 24, 25]. Possible reaction pathways of SRE can be described by twenty equations [6]. The most important of them are presented below.

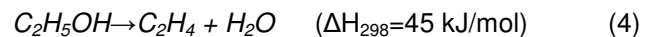
The sufficient steam supply reaction, Eq. (1) is strongly endothermic and produces only hydrogen and carbon dioxide, if ethanol reacts in the most desirable way. It is an ideal pathway by which the highest hydrogen yield may be achieved.



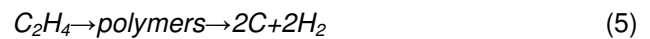
Hydrogen in lower amounts, CO and undesirable products are formed during insufficient steam supply reactions, Eq. (2-5):



Ethanol can be dehydrated to ethylene according to Eq. (4):



A possible route of carbon formation is ethylene polymerization, Eq. (5):



Eq. (1) and Eq. (2) are dominant at temperatures above 800 K. This result is very important, because according to Eq. (5) C_2H_4 presence in steam reforming products leads to carbon formation. It was shown in the study [6] that the carbon (graphite) is absent at the temperature range 600-2000 K and the W/E range of 3-20.

According to results reported in [6], the complete conversion of ethanol was achieved in the temperature range of 400-2000 K and the W/E ratio range of 0-20.

Some of the simulation assumptions are listed below.

- Due to lack of detailed reaction kinetics data, the equilibrium calculations employing the minimization of total Gibbs free energy were done by using the Equilibrium Reactor and Gibbs Reactor models of the CHEMCAD software package. This approach is usually recommended for the fuel reforming simulation and found to be successfully predicting the experimental data [18, 26].
- Species that are involved in the reactions are: CO, CO₂, CH₄, H₂O, C₂H₅OH and H₂.

The steam reforming of ethanol for hydrogen and CO production involves a complex of multiple reactions. Composition and a total enthalpy of combustion (heating value) of the reformat gas (H_{comb}) are affected by the reformer operation conditions. Therefore, added enthalpy of combustion of SRE fuel in comparison to that of the primary ethanol (H_{in}) depends on the process variables. To analyze efficiency of the steam reforming process, it is necessary to know the effect of these variables on added enthalpy of combustion values and heat duty. The latter is the sum of the SRE reactions heat, latent heat of vaporization and sensible heat. The SRE efficiency was defined as the ratio of the added enthalpy of combustion $H_{comb} - H_{in}$ to the heat duty, H_d :

$$\eta = (H_{comb} - H_{in}) / H_d \quad (6)$$

Reformer modeling was carried out for various molar water/ethanol ratios W/E=0–3.8 and reaction temperatures $T_r=500-1200K$.

The proposed system opens new possibilities to achieve great advantages of the known idea of onboard ethanol decomposition, by combining it with the hybrid vehicle concept. The benefits follow from the availability of an additional energy source and operation of the ICE at optimal steady-state regime, and may lead to the elimination of current shortcomings of multi-regime fuel systems with ethanol decomposition.

SI ENGINE MODELING

Modeling of ICE performance has been carried out by using GT-Power software of the GT-SUITE package. The simulated engine size and main parameters were selected while taking into consideration that the engine is a part of a series hybrid propulsion system and the prevention of too high in-cylinder maximal pressure under moderate engine speed. Optimization of engine size and operation regime has not been performed at this stage of the work. Main parameters of the ICE used in the engine modeling are shown in Table 1. The ICE simulated was a naturally aspirated, direct injection (DI), SI engine.

ICE performance was modeled and analyzed for the engine fueling by gasoline, liquid dehydrated ethanol and SRE products. Five cases of different SRE product compositions relevant for various reformer operation conditions have been considered and

presented in Table 2. Variants of SRE gas composition, that have been selected based on the results of reformer modeling, allowed keeping SRE efficiency as close as possible to the optimal value.

Table 1. Main parameters of the simulated engine

Cylinder bore, mm	90
Piston stroke, mm	90
Number of cylinders	4
Compression ratio	10
Engine speed, rpm	4000
Brake power, kW	75

Table 2. SRE product compositions

Reformer operation conditions	Gas composition, molar fraction (%)				
	H ₂ O	CO ₂	CH ₄	CO	H ₂
Mixture 1 (W/E=1.2, $T_r=1100K$)	2.9	1.3	1.0	30.6	64.2
Mixture 2 (W/E=1.2, $T_r=1000K$)	5.0	3.2	4.7	27.3	59.8
Mixture 3 (W/E=1.2, $T_r=950K$)	7.3	5.4	9.0	23.6	54.7
Mixture 4 (W/E=1.8, $T_r=1000K$)	9.4	5.1	2.2	23.4	59.9
Mixture 5 (W/E=1.8, $T_r=950K$)	11.3	7.1	5.4	20.1	56.1

Some of the engine simulation assumptions are listed below.

- Due to negligible amounts of non-reformed C₂H₅OH found in the SRE products at the simulated reforming conditions, ethanol content in the reformat fuels considered in the ICE modeling was assumed to be zero.
- Valves timing remained the same for all types of fuels.
- The engine geometry remained the same with a change in the fuel type.
- The energy that is required to cool, compress gaseous SRE products and inject them into the engine's combustion chamber during the compression stroke was not assessed.
- There are no leaks in the reformer-ICE system and no fuel accumulation between the reformer and the engine. Therefore, the mass flow-rate of the primary water/ethanol mixture entering the reformer is equal to the mass fuel consumption of ICE operating on SRE products.
- Actual burning velocities of the considered fuels inside a cylinder were assumed to be proportional

to the appropriate laminar burning velocities (taking into account that the engine geometry remained the same with change of the fuel type). Laminar burning velocity for each of the considered gaseous fuels (mixtures 1-5) has been estimated based on the published experimental data [27-29]. Laminar burning velocities of gasoline and ethanol were taken from [30]. Fig. 2 shows laminar burning velocity of the considered fuels for different excess air factors (λ).

- Based on the previous assumption, ratio of actual combustion duration of each SRE mixture to that of gasoline was assumed to be inversely proportional to the ratio of the laminar burning velocities of these fuels.

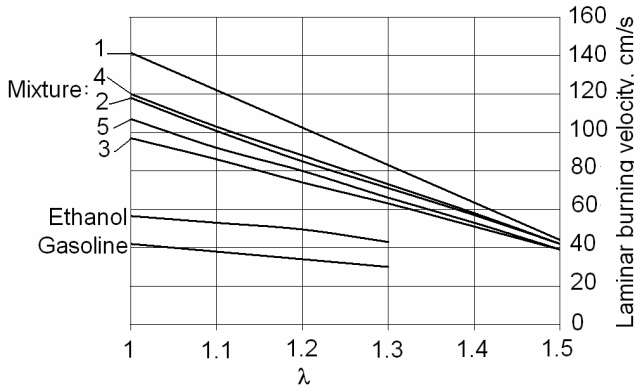


Figure 2. Laminar burning velocity of the considered fuels

Engine performance calculations have been carried out for each of the considered fuel types at various air/fuel mixture compositions and spark timing values. An optimal engine tuning (air/fuel ratio and ignition timing) for each fuel was selected and based on the following criteria: keeping the same power of 75 kW together with maximal possible brake efficiency and lowest NO_x and CO emission level. Keeping the maximal pressure value on the reasonable level was an additional consideration. To avoid knock risk and reduce mechanical stresses, spark timing and excess air factor providing maximal pressure gradient $(dP/dCA)_{\max}$ of less than 0.2 MPa/deg have been selected, [18].

NO_x and CO emissions were predicted by using the extended Zeldovich mechanism and a kinetic model, respectively, [31].

When the engine was fueled by SRE products, the efficiency η_{sys} of the reformer-ICE system was calculated, using primary (liquid) ethanol consumption as a basis:

$$\eta_{\text{sys}} = \frac{1}{bsfc_{et} \cdot Q_{HV}^{et}} \quad (7)$$

Where: $bsfc_{et}$ is brake specific fuel consumption of primary ethanol; Q_{HV}^{et} is ethanol heating value.

$$bsfc_{et} = \frac{bsfc_{mix}}{m_{mix}} \quad (8)$$

Here: $bsfc_{mix}$ is brake specific consumption of SRE products; m_{mix} is a mass of SRE products per 1 kg of primary ethanol. The value of m_{mix} was calculated as follows:

$$m_{mix} = (M_{wat} \cdot W + M_{et} \cdot E) / M_{et} \cdot E \quad (9)$$

Here M_{wat} and M_{et} are the molecular weights of water and ethanol, respectively. W and E are the number of moles of water and ethanol, respectively, in the primary mixture. $(M_{wat} \cdot W + M_{et} \cdot E)$ is the mass of primary mixture. It is equal to the mass of SRE products following the mass conservation law.

Values of η_{sys} enabled a comparison of the reformer-ICE system efficiency with the brake efficiency of the engine fueled by gasoline or liquid ethanol.

RESULTS AND DISCUSSION

REFORMER PERFORMANCE

Mol fractions, M_i , (moles of given product, i , to total moles of SRE products), as were calculated at atmospheric pressure, various water/ethanol ratios and different reaction temperatures are shown in Fig.3. At given W/E, the yield of hydrogen first increases sharply with a rise in temperature and then in the range of $T_r=1000-1200\text{K}$ it practically stabilizes. These results agree with those reported in [5, 6 and 19]. Carbon monoxide yield approaches 0 % when the temperature is 500K. It increases with increasing temperature depending on W/E. For example, in the range $T_r=1100-1200\text{K}$ at $W/E=1.2$ $M_{CO} \approx 30\%$, and at $W/E=3.0$ CO yield drops down to $M_{CO} \approx 20\%$. Decrease in equilibrium yield of carbon monoxide from SRE with increase of W/E was reported also in [6].

In the range of $T_r=1000-1200\text{K}$ M_{CO_2} can be kept low and changes from about 0 % to 5 % with a rise of W/E from 0.6 to 3.0. In the range $T_r=1000-1200\text{K}$ M_{CH_4} drops down from about 12 % to 0 % with an increase of W/E from 0.6 to 3.0. The same trend was observed by Wang [6].

As can be seen from the calculations of SRE product composition for different temperatures and W/E (Fig. 3), the mol fractions of CH_4 and CO_2 at $T_r=1100\text{K}$ and $W/E=1.2$ reach their minimum and increase with further rise of W/E.

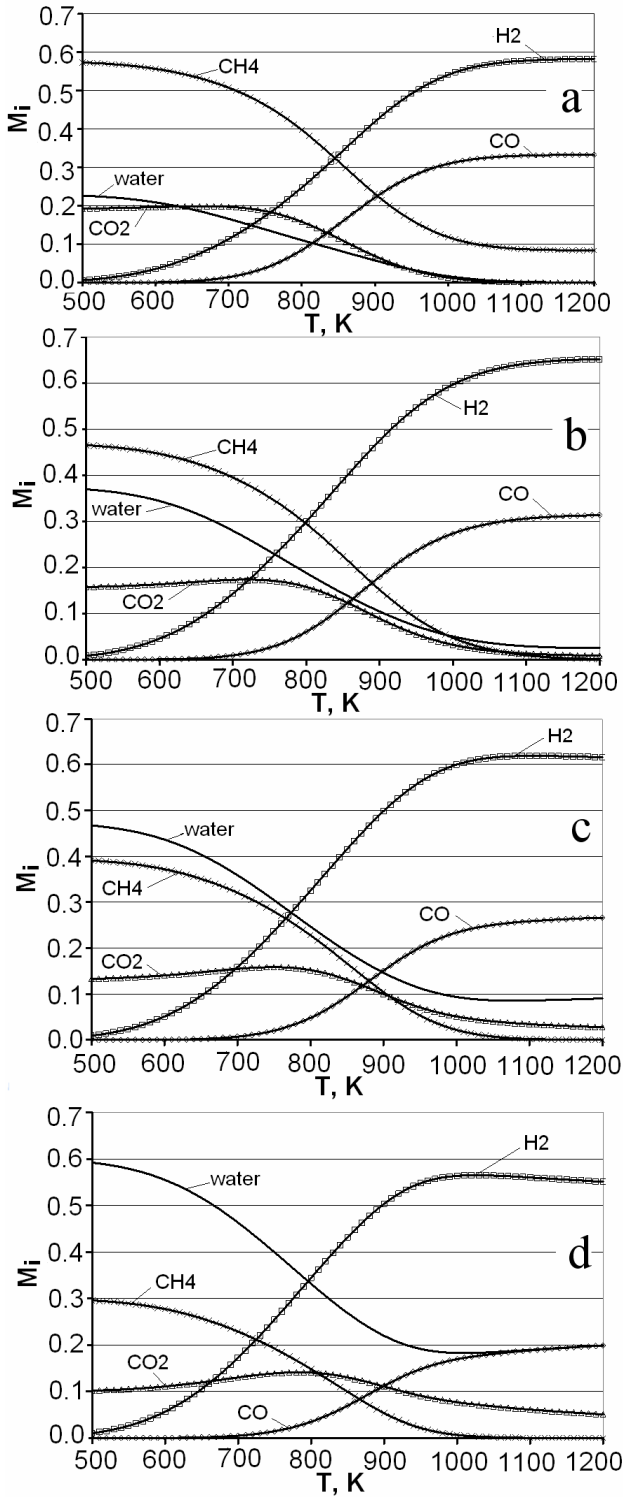


Figure 3. Composition of SRE products at various W/E depending on temperature
 a- W/E= 0.6; b- W/E= 1.2; c- W/E= 1.8; d- W/E= 3

Fig.4 shows the energy efficiency of SRE, calculated according to equation 6, as a function of the W/E in the reformer at the temperature range of 800 -1200K. It was found that η reaches the maximum value of about 0.59 at temperature $T_r=1100K$ and $W/E= 1.2$.

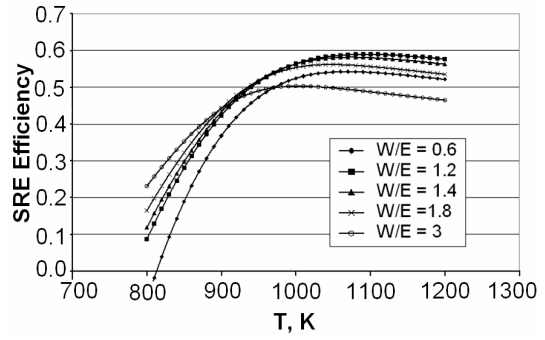


Figure 4. SRE efficiency as a function of temperature and W/E

SI ENGINE PERFORMANCE

The results of ICE performance calculation for the cases of engine fueling by gasoline and ethanol are shown in Fig. 5 and 6, respectively.

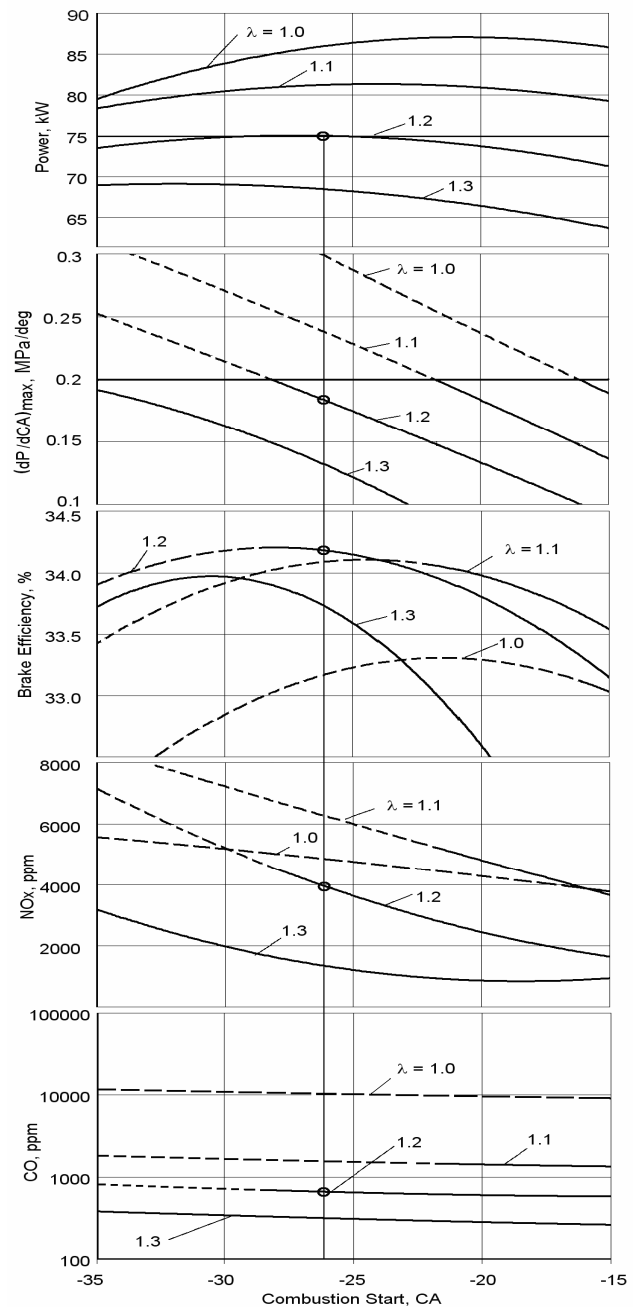


Figure 5. Performance of ICE fueled by gasoline

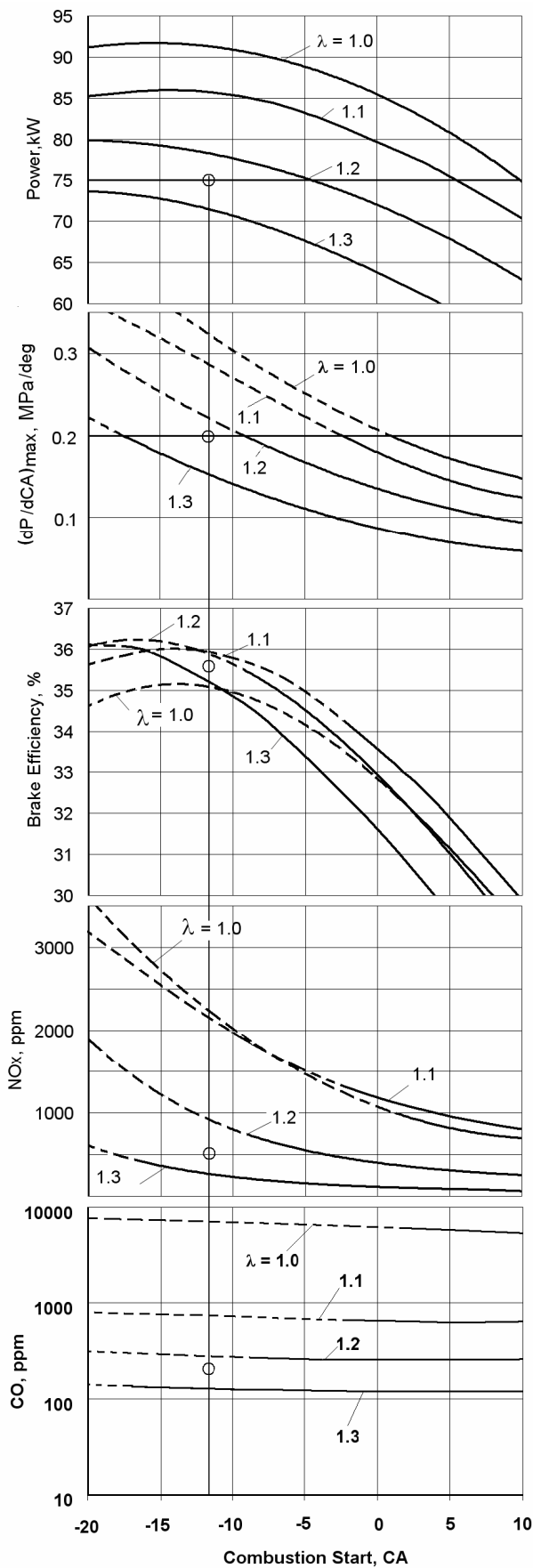


Figure 6. Performance of ICE fueled by ethanol

As can be seen from Fig. 5, the leanest air/gasoline mixture that still allows achievement of the required engine power of 75 kW together with the lowest NO_x emissions is at $\lambda = 1.2$. The appropriate λ value for ethanol fuel was found to be 1.25 – see Fig. 6. As anticipated, maximal pressure values and NO_x production decrease with retarding the combustion start.

Reformate gas compositions that correspond to the selected reformer operation conditions have been derived from Fig. 3 and listed in Table 2. ICE performance has been calculated for all five considered reformate fuel types. An example of calculation results for the Mixture 2 (W/E=1.2, $T_r=1000K$) is shown in Fig. 7, 8.

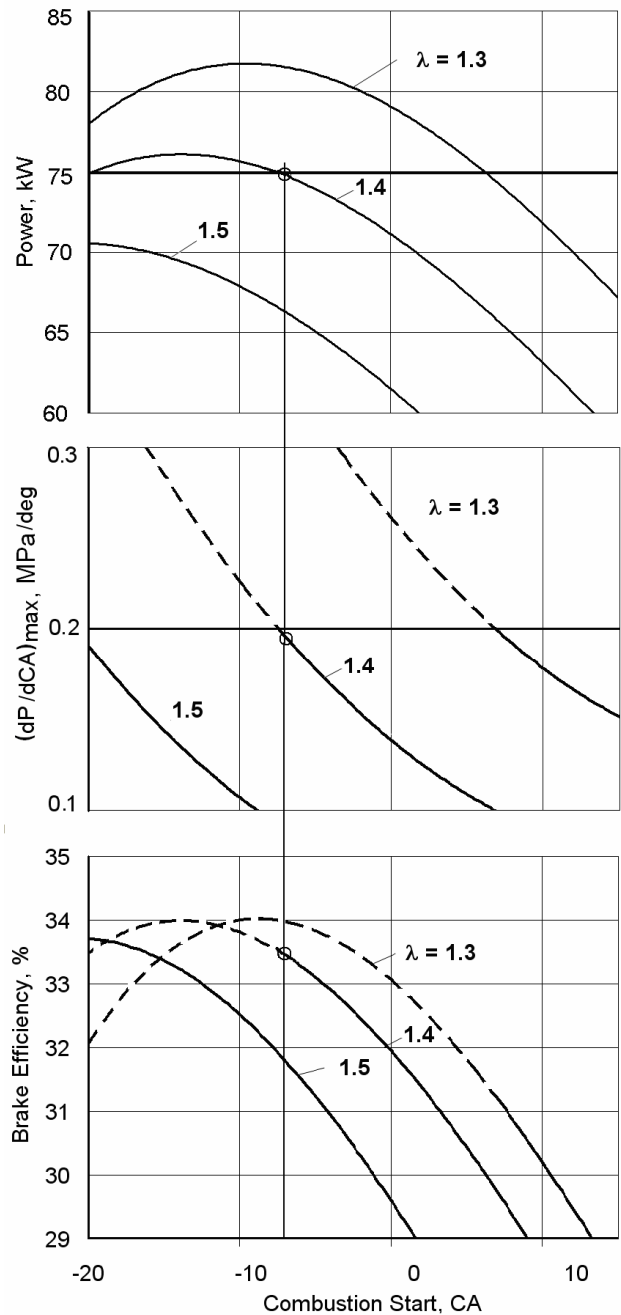


Figure 7. Power, maximal pressure gradient and efficiency of ICE fueled by the SRE products – Mixture 2

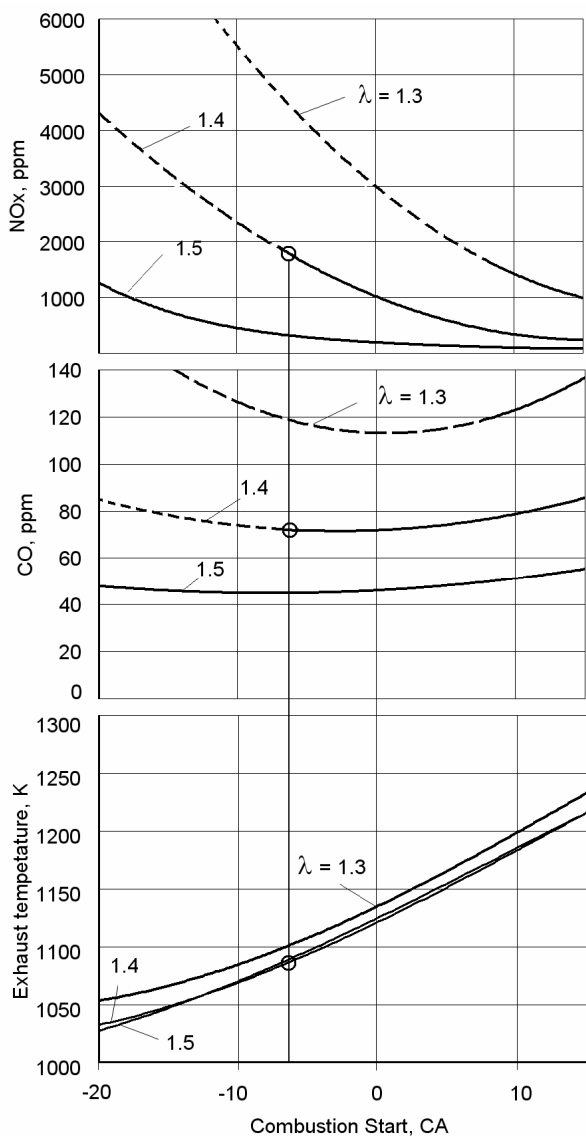


Figure 8. Emissions and exhaust temperature of ICE fueled by the SRE products – Mixture 2

ENGINE PERFORMANCE ANALYSIS

For each type of fuel that was considered, results of the engine performance prediction have been analyzed according to the methodology described in the previous section. The engine's optimal operation regime was chosen for each fuel type. It is marked by a vertical line and points in Figures 5 - 7. The results are summarized in Table 3.

In general, an improvement in fuel consumption and a reduction in engine emissions are possible by operating under "leaner conditions" with the joining of hydrogen. Performed simulations have showed that the engine fueling by SRE products enables operating under λ values of about 1.4 compared with $\lambda=1.2$ and 1.25 for gasoline and ethanol fuels. Precisely the same trend was observed in experimental study [19].

As can be seen from Table 3, ICE operation with Mixture 1, which exactly corresponds to the optimal reformer energy efficiency, is impossible without an additional SRE products burner, because at this operation regime engine's exhaust gas temperature

($T_{\text{exh}}=1075\text{K}$) is not high enough to ensure the required reaction temperature in the reformer $T_r=1100\text{K}$.

Due to very wide flammability limits of hydrogen, the SRE products allowed engine operation with higher λ values: 1.35 – 1.4 compared with 1.2 and 1.25 for gasoline and ethanol, respectively. However, higher burning velocity of Mixtures 1- 5 (Fig. 2) led to an increase in maximal cycle temperatures and an appropriate NO_x formation.

Fig. 9 shows comparison of in-cylinder pressure vs. crank angle, as were predicted for the cases of ICE feeding by gasoline, ethanol and Mixture 4 fuels.

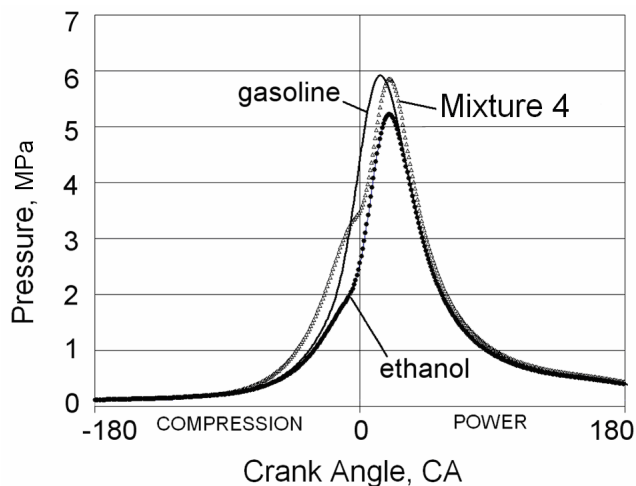


Figure 9. In-cylinder pressure vs. crank angle for different fuels (4000rpm; 75kW; operating conditions are listed in Table 3)

The lowest values of in-cylinder pressure during the compression stroke were obtained in case of engine feeding by ethanol fuel. This is due to the very high heat of vaporization of alcohol compared to gasoline – 904 kJ/kg and 305 kJ/kg, respectively, [32]. The lower compression pressure results in appropriate reduction of pumping work and therefore causes an increase of the engine's efficiency. Actually, the highest values of the engine's brake efficiency have been received with ICE feeding by the liquid ethanol fuel, Table 3. Feeding the engine with the gaseous reformat fuel leads to the highest compression pressures, compared with gasoline and ethanol, because of the absence of the mixture cooling due to the fuel evaporation. This resulted in slightly lower engine brake efficiency, despite the beneficial higher combustion rate of hydrogen rich SRE mixtures. Significant cooling of air/fuel mixture due to the liquid ethanol evaporation along with lower flame temperature of ethanol [32] result also in the lowest NO_x emissions that were achieved with $\text{C}_2\text{H}_5\text{OH}$ compared to gasoline and SRE mixtures – Fig. 10. Predicted NO_x emissions with ethanol (500 ppm) are about 1.5 to three times lower compared to SRE mixtures (750 – 1600 ppm) and almost eight times lower compared to gasoline (about 4000 ppm).

Table 3. Optimized ICE performance for different fuel types

Performance parameter	gasoline	ethanol	Mixture 1 (W/E=1.2 $T_r=1100K$)	Mixture 2 (W/E=1.2 $T_r=1000K$)	Mixture 3 (W/E=1.2 $T_r=950K$)	Mixture 4 (W/E=1.8 $T_r=1000K$)	Mixture 5 (W/E=1.8 $T_r=950K$)
Comb. Start, CA	-26.2	-11.8	5.7	-7.5	-6.2	-5.3	-2
λ	1.2	1.25	1.35	1.4	1.35	1.4	1.35
P_{max} , MPa	5.92	5.22	5.1	6.08	5.9	5.86	5.47
$(dP/dCA)_{max}$, MPa/deg	0.185	0.185	0.195	0.198	0.191	0.176	0.171
Brake Efficiency, %	34.2	35.6	31.4	33.5	33.5	33.3	33.0
NO_x , ppm	3972	510	2467	1666	1290	998	750
CO, ppm	657	193	94.3	75.4	89.4	55	66
T_{exh} , K	1102	1043	1075	1078	1081	1085	1094
Fuel Flow, kg/h	18.1	28.3	38	37.1	38.5	42.9	44.6
$bsfc$, g/kWh	242	378	507	495	513	572	594
$bsfc_{eth}$, g/kWh	-	378	345	337	349	336	349
η_{sys} , %	34.2	35.6	39.0	39.9	38.6	40.0	38.6

Comparison of the total efficiency of the reformer-ICE system in cases of engine feeding by SRE mixtures with the achieved values of the engine brake efficiency for gasoline and ethanol is shown in Fig. 11.

As can be seen, the total system efficiency increased from about 34% for gasoline and 36% for ethanol to 40% for the engine fueled by SRE products. This closely corresponds to assessments made in [22, 33]. The improvement was achieved due to the effect of raising the heating value of the reformat gas, higher flame speed and better completeness of gas combustion in comparison to liquid fuels [22].

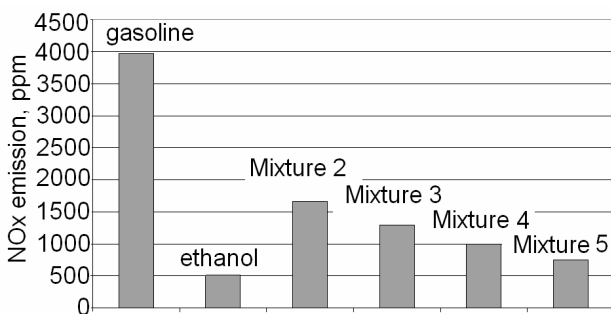


Figure 10. NOx emissions for different fuels_ (4000rpm; 75kW; operating conditions are listed in Table 3)

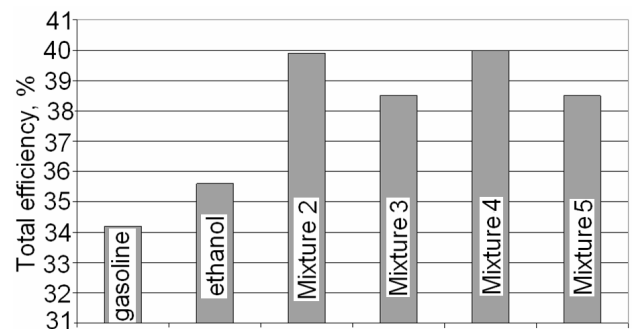


Figure 11. Total efficiency of the reformer-ICE system for different fuels (4000rpm; 75kW; operating conditions are listed in Table 3)

The highest reformer-ICE system efficiency (40%) has been achieved with the Mixture 2 (W/E=1.2, $T_r=1000K$) and Mixture 4 (W/E=1.8, $T_r=1000K$). With Mixture 4 also the lowest for SRE fuels CO emissions (55 ppm) have been observed. NO_x production level that was achieved with this fuel is about 1000 ppm – two times higher compared with ethanol, but about four times lower in comparison with gasoline. The lowest for SRE products NO_x emissions (750 ppm) have been received with the Mixture 5 (W/E=1.8, $T_r=950K$), but total efficiency of the reformer-ICE system with this fuel was lower

than with Mixture 4 and also CO emissions were higher.

Figure 12 shows that TCR made it possible to significantly reduce CO emissions: by 3.5 times compared with ethanol and by more than order of magnitude – compared with gasoline. This can be explained by higher λ values compared with ethanol and also reduced carbon content in the fuel compared with gasoline.

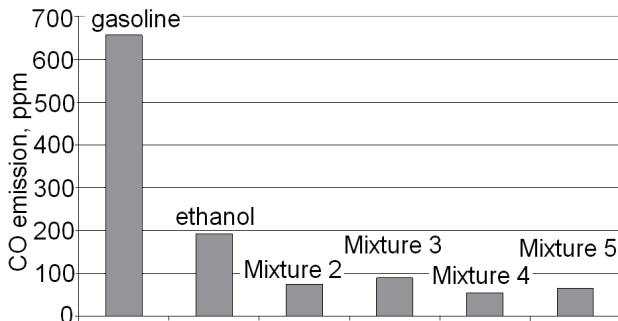


Figure 12. CO emissions for different fuels_ (4000rpm; 75kW; operating conditions are listed in Table 3)

CONCLUSION

Results of the reformer modeling show that energy efficiency of SRE reaches the maximum value of about 0.59 at temperature $T_r=1100\text{K}$ and $W/E=1.2$.

The highest reformer-ICE system efficiency of 40% has been achieved with the Mixture 2 ($W/E=1.2$, $T_r=1000\text{K}$) and Mixture 4 ($W/E=1.8$, $T_r=1000\text{K}$). With the latter also the lowest CO emissions (55 ppm) have been obtained.

Total system efficiency increased from about 34% for gasoline and 36% for ethanol to 40% for the engine fueled by SRE products.

Operation of the SI engine with SRE products resulted in a significant reduction of CO emissions: by 3.5 times compared with ethanol and by more than order of magnitude – compared with gasoline.

NO_x emissions of the SI engine fueled by Mixture 4 ($W/E=1.8$, $T_r=1000\text{K}$) were decreased by about 4 times compared with engine feeding by gasoline.

The results obtained in this work make a comprehensive thermodynamic analysis of the integrated reformer-ICE system possible. In this analysis the effectiveness of the mentioned above modes of heat supply to the reformer, as well as energy required to compress gaseous SRE products and inject them into the engine's combustion chamber will be taken into account.

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CONTACT

Leonid M. Tartakovsky
 +972-4-8292077
tartak@technion.ac.il

DEFINITIONS, ABBREVIATIONS

ATR: Auto-thermal reforming

C: Carbon

CH₄: Methane

C₂H₄: Ethylene

C₂H₅OH: Ethanol

CO: Carbon monoxide

CO₂: Carbon dioxide

DI: Direct injection

H₂: Hydrogen

H₂O: Water

ICE: Internal combustion engine

NO_x: Nitrogen oxides

OPEC: Organization of the petroleum exporting countries

PO: Partial oxidation

SI: Spark ignition

SRE: Steam reforming of ethanol

TCR: Thermo chemical recuperation

W/E: Molar water/ethanol ratio

λ : Excess air factor