Modeling of Properties and SI Engine Pollution of Associated Petroleum Gas in Iraq

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Abstract:

Modeling and simulation of process performance has been conducted around the use of the Iraqi associated petroleum gas as fuel for the spark-ignition engine. The study included a statistical evaluation of the effect of each component on the total properties of the gas. Finally, the gas was tested as a possible fuel for the spark-ignition engine from the emission point of view. This was done numerically using commercial software well established and verified for modeling the operation and performance of spark-ignition engines.

The study was conducted on Ricardo E6/T variable compression ratio engine. The range of the speed studied was 1000-3000 rpm and was limited to a lean range 0.8-0.95. It was also found that the presence of Methane in higher quantity helped in improving the calorific value (on a mass basis) but at the cost of gas density. The presence of higher carbon value gasses did not help improve the fuel heating value.

The highest negative impact on the heating value is CO, H_2S, and C_2H_6 respectively. The study also showed that the associated gas can be used as a fuel after removing sulfur from it.

Keywords: Associated petroleum gas, SI engine, Methane gas, Engine emissions, Natural gas, ANOVA.

نمذجة خواص وتلوث محرك SI للغاز النفطي المصاحب في العراق

الخلاصة:

تم إجراء نمذجة ومحاكاة للأداء حول استخدام غاز البترول العراقي المرتبط كوقود لمحركات SI. اشتملت الدراسة على تقييم إحصائي لتأثير كل مكون على الخصائص الكلية للغاز. تم الحصول على نموذج رياضي للتنبؤ بالخصائص المطلوبة. أخيرًا ، تم فحص انبعاثات العادم عند استخدامها كوقود لمحرك SI بمساعدة كود محاكاة تم التحقق منه. وقد أجريت الدراسة على محرك ضغط متغير Ricardo E6 / T, كان نطاق السرعة التي تمت دراستها يتراوح بين 1000 و 3000 دورة في الدقيقة ، وكانت الدراسة مقصورة على المدى 0,95-0,8. وقد وجد أيضًا أن وجود الميثان بكميات أعلى ساعد في تحسين القيمة الحرارية (على أساس الكتلة) ولكن على حساب كثافة الغاز. لم يساعد وجود الغازات ذات القيمة الكربونية العالية في تحسين قيمة تسخين الوقود. أعلى تأثير سلبي على قيمة التسخين هو CO و H_2S و C_2H_6 على التوالي. كما أظهرت الدراسة أنه يمكن استخدام الغاز المصاحب كوقود بعد إزالة الكبريت منه.

Introduction:

Petroleum deposits often have a gaseous component, commonly called Associated Petroleum Gas (APG) consisting mainly of methane and other short-chain hydrocarbons. Usually, APG can be collected from the oil sites from flared up in the special chimney or vented to the atmosphere. In some cases, it is re-injected inside the oil well to equalize the pressure inside the well and to recover its productivity. Recently, a number of scholars has paid more attention to do some works on APG as a potential source of clean energy [1].

In recent developments, Iraq is planning to cease APG flaring completely by 2021. This will take place in phases to drive investment to utilize APG in a proper manner [2].

Flaring is preferable to venting from a global warming point of view. Flaring oxidizes carbon and creates Carbon Dioxide (CO_2), but reduces the overall global warming potential of the emissions by destroying methane and other hydrocarbons [3]. It reduces emissions of flammable global warming gases, but also creates other pollutants such as Oxides of Nitrogen (NOx), Carbon Monoxide (CO), and Black Carbon (BC). Some studies [4, and 5] reported a serious negative impact on the environmental, socio-economic environment and heavy degradation of host communities and wildlife.

APG is subject to several treatment processes for the purification of non-hydrocarbon substances, and the separation of unwanted liquid components and isolate secondary products of economic value in order to reach Marketed Gas (MG) for commercial purposes and in accordance with standard specifications and conditions both for utilization in thermal and chemical systems as well as for transportation.

Among the properties required by the Iraqi treatment plants for economically profitable MG are [6]: 29.33 to 32.4 kJ/m^3calorific values, low H_2S and CO_2 contents to avoid corrosion of the pipes, free from solid particles and moisture content, free from He and N_2 gasses, and, mercury concentration should not exceed 0.1 PPB as it causes Aluminum embrittlement. As far as its utilization as fuel [7] showed that due to the heavy presence of C_{5+} hydrocarbon contents, the fuel is prone to heavy detonation and tar and soot formation. Hence, specialized pretreatments must be applied before using it in gas turbine power generation.

Another attempt to utilize APG as fuel for the Aircraft Gas Turbine engine was conducted by Gur'yanov [8]. They concluded that for successful utilization of the fuel, pretreatment, as well as engine modification and introduction of specific inert gas must be used.

Rajović et al. [9] tested the impact of using APG as fuel in a cogeneration cycle using the life-cycle approach. The results obtained were promising in that the greenhouse gasses were reportedly reduced. Further, they reported a marginal reduction in resource depletion due to the use of APG instead of conventional fuel. A more interesting study by Nithyanandam et al. [10] showed that Benzene can be produced from APG and then used for several other applications.

Three major terms in identifying some challenges by using APG as fuel for power generation defined [11]. Cost, Hydrogen Sulfide and low Wobbe Index. In their study, they developed an optimization technique for the best concentration between wet, natural and AP gases.

In this work, a statistical analysis of the constituents of the gas is considered to investigate their effects on the key properties needed by the market. Then the study will come up with an equation relating the concentrations to those properties. Finally, the performance of this gas compared with other fuels will be tested from an environmental point of view.

The Study:

Several samples of APG from different Iraqi wells are taken, sampled and their concentrations are determined as shown in Table (1). Only the best result sample (i.e. the one containing the highest percentage of Methane) is used for modeling the engine performance.

First, a test of significance on the effect of fuel constituents on its properties is conducted using the ANOVA test. Then the correlation matrix is established to study the relative effect of each constituent on the fuel properties.

Table (1) Iraqi APG properties.

	Best Achieved After Treatment	Gasoline
C1	81.67%	
C2	9.2%	
C3	5.28%	
nC4	1.7%	
iC4	0.75%	
nC5	0.47%	
iC5	0.45%	
C6	0.34%	
H_2O	0%	
CO_2	0.14%	
N_2	0%	
O_2	0%	
H_2	0%	
H_2S	0%	
Chemical Formula	$C_{1.325}H_{4.277}O_{0.0028}$	C_8H_{18}
Calorific Value (MJ/kg)	48.1	44
Density kg/ m^3 at 28 ^oC	0.88	720-780

Finally, to study the effect of using APG as fuel for the SI engine, a well-verified simulation model is used. The engine used for the study is the Ricardo E6/T variable compression ratio engine. Table (2) below shows the general properties of the engine used.

Table (2) Engine design parameters.

Type	4-stroke, Water-cooled
Number of cylinders	single
Diameter x Stroke x Connecting Rod Length	76.2 x 111.1 x 231.7 mm
Speed range	1000-3000 rpm
Compression ratio	Variable (in this study = 9)
Ignition timing	Variable

The ignition timing is set at 15^o bTDC which is nearly best for both fuels. The mixture strength used is the lean mixtures (equivalence ratio is varied 0.8 to 0.95) while engine speed was varied from 1000 rpm to 3000 rpm at an increment of 500 rpm.

The model used is basically an extension of that developed by Ferguson and Benson [12, 13] and their relative modifications and improvements. The model is used to simulate engine operation. The main features of the model are stated below:

The instantaneous variation in the cylinder volume 'V' it's derivative '$\frac{dV}{d\theta}$' with crank angle rotation 'θ' taking the bottom dead center (BDC) as a reference as well as are calculated using equations (1) and (2) as below :

$$V(\theta) = V_s * \left[\left(\frac{CR}{CR-1}\right) - \left(\frac{1-\cos(\theta)}{2}\right) + \left(\frac{CRL}{S}\right) - \frac{1}{2}\sqrt{\left[\left(\frac{2*CRL}{S}\right)^2 - sin^2(\theta)\right]}\right] \quad \text{……(1)}$$

$$\frac{dV}{d\theta} = \frac{1}{2}V_s \sin\theta \left(\frac{\cos\theta}{\sqrt{\left(\frac{2\,CRL}{S}\right)^2 - sin^2\,\theta}} - 1\right) \quad \text{……..(2)}$$

The gas temperature 'T' and pressure 'P' variation with crank angle inside the cylinder during compression stroke are calculated using the following equations (3) and (4):

$$\frac{dP}{d\theta} = \frac{\left[-\left(1+\frac{R}{C_v}\right).P.\frac{dV}{d\theta} - \frac{R}{C_v}\frac{dQ_{cr}}{d\theta} + \frac{R}{C_v}\frac{dQ_{ht}}{d\theta}\right]}{V} \quad \text{………..(3)}$$

$$\frac{dT}{d\theta} = T.\left(\frac{1}{P}\frac{dP}{d\theta} + \frac{1}{V}\frac{dV}{d\theta}\right) \quad \text{……..(4)}$$

Where "P" is the cylinder pressure (kPa), "θ" is the crank angle (deg), "R" is the constant of gas (kJ/kg-K), "V" is the volume of cylinder (m^3) between the cylinder head and top of piston, "T" is the temperature of cylinder (K), "Q" is heat transfer (kJ), suffix "ht" means lost to coolant and "cr" means lost to crevice, "CRL" means connecting rod length (m), "S" is stroke length (m), "CR" is compression ratio, "u" is internal energy (kJ/kg-K), "Vs" is the swept volume (m^3).

For in-cylinder work and heat transfer, the following equations (5) and (6) are used:

$$\frac{dW}{d\theta} = P\,\frac{dV}{d\theta} \quad \text{………(5)}$$

and

$$\frac{dQ_{ht}}{d\theta} = \frac{h_w}{\omega} A_w(\theta)[(T(\theta) - T_w)] \qquad \text{........(6)}$$

Where "W" is the work (kJ), "Tw" is the temperature of cylinder wall (K), "Aw" is the surface area of the cylinder (m^2), "hw" is the heat transfer coefficient and "ω" is the angular velocity.

The amount of energy lost through crevice volume $\frac{dQ_{cr}}{d\theta}$, in SI engines is calculated using the semi-empirical expression found in Gatowski et al. [14] as shown below:

$$\frac{dQ_{cr}}{d\theta} = (u + R * T).\frac{dm_{cr}}{d\theta} \qquad \text{.........(7)}$$

The sign convention followed in applying this equation is that when $\frac{dm_{cr}}{d\theta}$ is positive, this means that the flow is into the crevice volume and the term in bracket is evaluated at the crevice conditions and Vice Versa.

The Heat Transfer Coefficient (h_w) from gas to walls is calculated by Woschni's (1968) formula [15]:

$$h_w = \frac{P^{0.8} v^{0.8}}{T^{0.53} D^{0.2}} \qquad \text{...........(8)}$$

where;

v = 6.18 C_m is a gas velocity during scavenging and intake stroke; v = 2.28 C_m is a gas velocity during compression stroke; $v = 2.28\,C_m + 0.00324\,\frac{V_s T_a}{P_a V_a}(P - P_{motored})$ is the gas velocity during the other strokes P_a, T_a, V_a is pressure, temperature, and volume of the cylinder at the beginning of compression (IVC) respectively.

The rate of formation of NO '$\frac{d[NO]}{dt}$' was calculated using the theory developed by Lavoie et.al. and its modifications using equation (9):

$$\frac{1}{V}\frac{d}{dt}([NO]\,V) = 2(1-\alpha^2)\left\{\left(\frac{R_1}{1+\alpha\frac{R_1}{R_2+R_3}}\right) + \left(\frac{R_6}{1+\frac{R_6}{R_4+R_5+R_7}}\right)\right\} \qquad \text{........(9)}$$

The detailed method is given in Winterbone [16].

The formation of carbon monoxide is calculated using the theory developed by [17]. The following relation is used to calculate the concentration of CO:

$$[CO] = [CO]_{eq} + COFAC\left([CO]_{max} - [CO]_{eq}\right) \qquad \text{........(10)}$$

Where:

$[CO]$= Corrected concentration of CO

$[CO]_{eq}$= Concentration of CO at equilibrium

$[CO]_{max}$= Maximum value of CO concentration at equilibrium condition, and

COFAC = Scale factor for CO formation.

Results and Discussion

APG characteristics: The averages Iraqi APG properties before and after treatment compared with regular gasoline fuel taken from Hussein HM [18] are shown in Table (1). It is evident that, on a mass basis, APG has around 10% more energy content compared with regular gasoline. This is important from the thermal systems' performance point of view.

To understand the above trend, a statistical correlation study is conducted on the data and the results are presented in Tables (3 and 4). Before starting the statistical analysis, a test of significance for the data is conducted by using the ANOVA test to see whether the results are significant or not.

As shown in Table (4), the mean square within treatments (MSB), 3.244, is much smaller than the mean square (MSA) between treatments, 1061.55. That ratiobetween-groups mean square over within-groups mean square, is called an F statistic (F = MSA/MSB = 327.21) in this example. It tells how much more variability between variables than within variables. The larger ratio is more confident the researcher can be in rejecting the null hypothesis (Ho), which is that all means are equal and there is no treatment effect.

Table (3): Correlation between components and calorific value.

	C1	C2	C3	nC4	iC4	nC5	iC5	C6	CO_2	H_2S	LHV	Density
C1	1.000											
C2	-0.985	1.000										
C3	-0.976	0.998	1.000									
nC4	-0.966	0.985	0.991	1.000								
iC4	-0.971	0.993	0.997	0.998	1.000							
nC5	-0.803	0.840	0.865	0.921	0.899	1.000						
iC5	-0.833	0.881	0.904	0.946	0.931	0.993	1.000					
C6	-0.201	0.263	0.311	0.422	0.378	0.742	0.688	1.000				
CO2	-0.868	0.775	0.742	0.718	0.724	0.470	0.483	-0.165	1.000			
H2S	-0.994	0.965	0.951	0.932	0.939	0.737	0.768	0.104	0.913	1.000		
LHV	0.904	-0.820	-0.791	-0.772	-0.776	-0.541	-0.555	0.091	-0.997	-0.941	1.000	
Density	-0.998	0.989	0.984	0.979	0.982	0.837	0.864	0.258	0.842	0.986	-0.882	1.000

However, P-value is the key factor in the significance test. For significant samples, this should be less than 0.05. In the ANOVA test conducted on the data, the result showed that P is < 0.05. Hence the data is significant and can be used for further statistical and modeling analysis.

Table (4): ANOVA test summary

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	12738.61883	12	1061.551569	327.2108833	3.28E-35	2.010183
Within Groups	126.5254712	39	3.244242852			
Total	12865.1443	51				

From density point of view, the higher percentage of methane in gas is the lower density of the fuel since it is lighter than other gases. Further, on volume basis, higher percentage of methane is lower energy density of the gas. The equation for this gas relating all variables to the gas density is given by:

$$Density = 0.5114 + (-0.2771 * (0.1524) + 0.5655 * \Psi) + (0.3485 * (-1.2518) + 0.2552 * \Psi) + (-0.2115 * (0.1507) + (-0.3202) * \Psi) \quad \ldots\ldots\ldots(11)$$

Where;

$$\Psi = (-6.583) + 0.1204 * C_1 - 0.05206 * C_2 - 0.4758 * C_3 - 0.2956 * nC_4 + 0.0745 * iC_4 - 3.3865 * nC_5 + 4.5253 * iC_5 + 0.2792 * C_6 + 0.32503 * H_2S - 0.05277 * CO_2 - 0.2941 * H_2O - 0.7718 * N_2 + 0.24638 * O_2 + 0.05035 * H_2$$

And that for the calorific value the formula obtained as:

$$LHV = 49.1556 - 2.2237 * (2.1121 - 0.04705 * C_1 + 0.18586 * C_2 - 0.31351 * C_3 + 0.27788 * nC_4 + 1.55856 * iC_4 - 0.4692 * nC_5 - 0.6121 * iC_5 + 0.32818 * C_6 - 0.12814 * H_2S - 0.11353 * CO_2 + 0.7052 * H_2O - 1.3002 * N_2 + 0.9374 * O_2 + 0.7783 * H_2) + 0.48016 * (2.8879 + -0.0647 * C_1 + 0.0658 * C_2 - 0.2615 * C_3 + 0.2225 * nC_4 + 2.8765 * iC_4 + -2.0842 * nC_5 - 3.8783 * iC_5 + 1.2785 * C_6 + 0.05377 * H_2S + 0.2686 * CO_2 - 0.0138 * H_2O + 0.1432 * N_2 + 0.5693 * O_2 + 0.7827 * H_2) - 2.8754 * (6.5366 - 0.05657 * C_1 - 0.01881 * C_2 + 0.1306 * C_3$$

$-0.840098 * nC_4 \; -0.8963 * iC_4 + 2.1773 * nC_5 \; -2.6509 * iC_5 \; -0.0161 * C_6 + 0.0973 * H_2S + 0.4602 * CO_2 \; -1.3845 * H_2O + 1.2078 * N_2 + 0.1177 * O_2 + 1.2416 * H_2)$ …….. (12)

The density equation has $R^2 = 0.995$ (testing) and 0.991 (validation) with RMSE = 9.443e-11 (testing) and 1.3113e-5 (validation). The equation was validated for different types of fuels e.g. Methane (0.656 (Actual)/0.63(Model)), Propane (0.493/0.45) and other natural gas mixtures as in the literature and gave (0.725/0.7213) with the upper value for the exact and the lower for the model.

LHV equation has $R^2 = 0.998$ (testing) and 0.981 (validation) with RMSE = 0.12 (testing) and 0.6 (validation). The equation was validated for different types of fuels e.g. Methane (50/50.6), Propane (45.9/46.45) and other natural gas mixtures as in the literature and gave (45/47) with the upper value for the exact and the lower for the model.

With reference to correlation results, C_2, H_2S, and CO_2 gases are the worst negatively affecting the LHV of the gas. On the other hand, C_1 is the major positively affecting gases. H_2S and CO_2 have no share in the overall calorific value of the fuel; hence, their presence is a major disadvantage in this regard. From a density point of view, the higher the percentage of methane gas, the lower the density of the fuel, since it is lighter than other gases. Further, on a volume basis, the higher the percentage of methane, the lower the energy density of the gas.

Engine Emissions: The emissions studied are the oxides of nitrogen (NOx), carbon monoxide (CO), and unburned hydrocarbon (HC).

First, let us point out the following important points [19]:

1. Using a complex fuel (with different types of hydrocarbons) instead of a simple fuel (with one type of hydrocarbon), complicates the combustion process.
2. Using a complex combustion process (involving the discontinuous burning of combustible air/fuel mixtures in an enclosed chamber) instead of a simple process (involving the continuous open-flame burning), complicates the effective utilization of the fuel.

In this study, the fuel used e.g. Iraqi APG is a mixture of components that are various in nature and properties. For example, the ignition temperature in air (^{o}C) for methane is 595, ethane 510, propane is 470, butane is 460, while gasoline has 220. Therefore, the engine needs to be modified for the new gas. Further, Octane Number (ON) of methane, propane, and butane are greater than 100, while n-butane is 91, n-pentane 62 and n-hexane 25. This causes the overall mixture to behave differently during the combustion process compared with methane and other natural gas fuels.

The variation of carbon monoxide level in the exhaust with engine speed and air-fuel equivalence ratios is shown in Figure (1) below. It is well known that CO results from the incomplete combustion of the carbon materials of the fuel. The largest share among industrial applications that produce this type of emissions is the automotive sector.

As shown in Figure (1), CO emissions increase with an engine speed for all fuels as a result of the reduction in the amount of air induced as the engine speed increases. It also increases with equivalence ratio as a result of an incomplete combustion process in which liberated carbon atoms are only partially oxidized as a consequence of the operation of the engine under oxygen-deficient "rich mixture" conditions which result from the addition of excessive fuel.

Further, the performance of the Iraqi APG is better than Gasoline for low equivalence ratios (0.8 and 0.9) for all speeds. There was a maximum reduction of 20% at low speed and the least reduction was 1.6% at 2000 rpm. At higher speeds and equivalence ratios, the performance was worsened compared with all other fuels. The increment in CO reached 13% at 3000 rpm. This is due to the highest C/H ratio compared to other gaseous fuels. Hence, a higher number of carbon atoms is burned. Further, the amount of air admitted at higher is reduced with engine speed. Hence, the performance worsened with higher equivalence ratios and engine speeds. Another reason was the dissociation of carbon dioxide with cylinder temperature based on Figure (2) that shows higher or nearly equal exhaust temperature for Iraqi NG compared with other fuels.

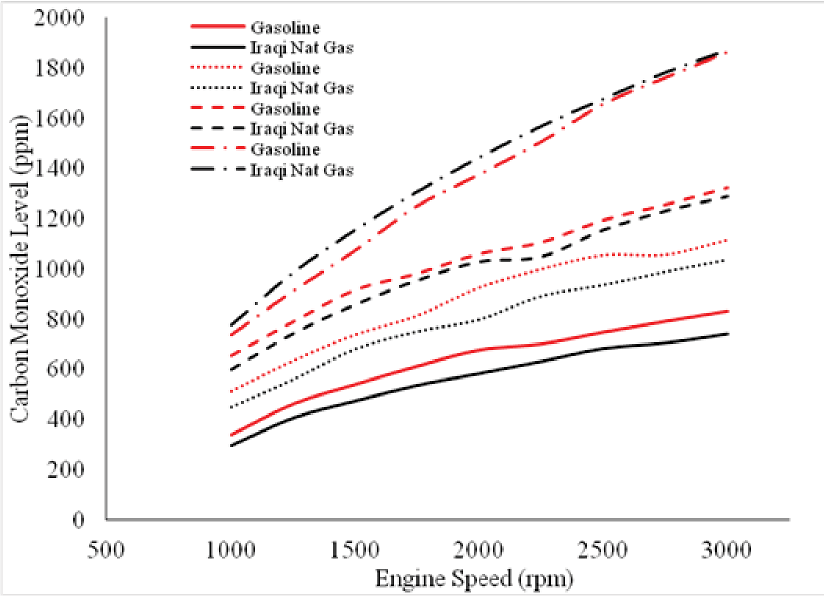

Fig. (1) Carbon monoxide variation with engine speeds at different equivalence ratios

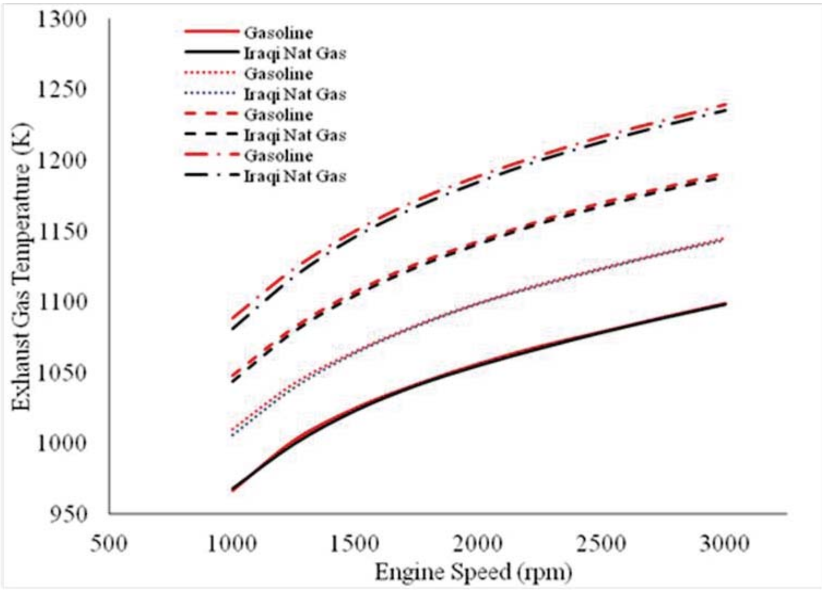

Fig. (2) Exhaust temperature variation with an engine speed for different equivalence ratios

The variation of HC level in the exhaust for both fuels at different engine speeds and air-fuel equivalence ratios is shown in Figure (3). First one should keep in his mind that the values shown in the figure are equivalent to C1 components i.e. Methane gas. So the curve is for the exhaust gas unburned hydrocarbon (C1 equivalent). This helps explain the greater values for the Iraqi associated gas compared with gasoline.

Several theories were proposed to explain the presence of HC in the exhaust. On such theory stated that the presence of HC in the exhaust is due to the quenching of the flame inside the cylinder at the cold wall surfaces instead of the combustion process itself. Another strong and widely accepted theory [20] is called the crevice theory. It states that some amount of the fuel and air gets trapped inside certain places inside the cylinder e.g. between piston and cylinder, where the flame cannot reach. This portion gets released as the cylinder pressure reduces and is emitted to the atmosphere with the exhaust.

As shown in Figure (3), the amount of HC emissions emitted decreases with engine speed. This is expected to be as a result of the insufficient time for the HC molecules to be absorbed and then desorbed by oil inside the cylinder. Further, the reduction in the cycle time also reduced the amount entrained by the crevices inside the cylinder, hence, reduces the amount released with exhaust during the exhaust stroke.

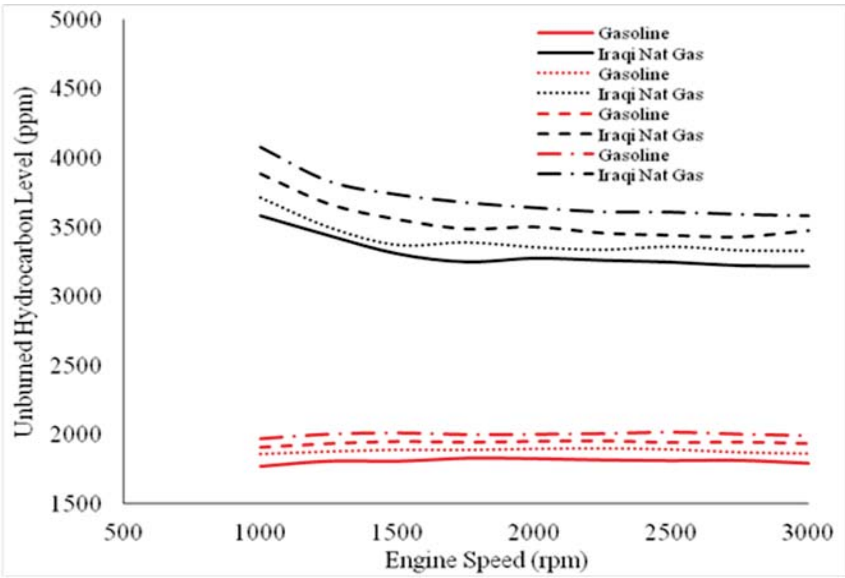

Fig. (3) Hydrocarbon variation with an engine speed for different equivalence ratios

Another factor that may help reduce HC emissions is the higher cylinder wall temperatures at higher speeds. This helps prevent flame quenching and causes the thickness of the oil film on the cylinder wall to be reduced (due to a decrease in oil viscosity with temperature) and hence if adsorbed by the oil, the amount of HC adsorbed and consequently desorbed with exhaust products will be less.

This reduction in lubricating oil thickness at the cylinder wall results in the increase in Henry's constant (which is defined as the ratio of partial pressure of the fuel vapor (P_{fs}) in the gas phase adjacent to the interface S state to the mole fraction of the fuel dissolved in the oil film (n_{fL})) [21] and thus, reduces the fuel vapor absorbed.

Higher exhaust temperature is shown in Figure (2) can also be the reason for the reduction in HC as it may help decrease desorption of HC molecules and also improve the oxidation of HC present in the exhaust products at higher engine speeds.

Several researchers [21] attributed this behavior of HC emissions to the existence of cylinder quench layers. They showed that the observed quench distances were of the right order of magnitude to account for HC emissions. Others found that the quenched mass gets mixed and oxidized inside the cylinder due to fuel-burning during expansion and exhaust processes.

Equivalence ratio Φ also promoted the existence and adsorption and desorption of fuel vapor in the oil and inside the crevices if increased to explain the increase of HC levels with equivalence ratio.

Figure (4) shows the variation of NOx emissions (Mainly NO) with engine speeds for different equivalence ratios. NOx formation depends on several factors including cylinder temperature, oxygen availability, residence time (combustion duration) and A/F ratio.

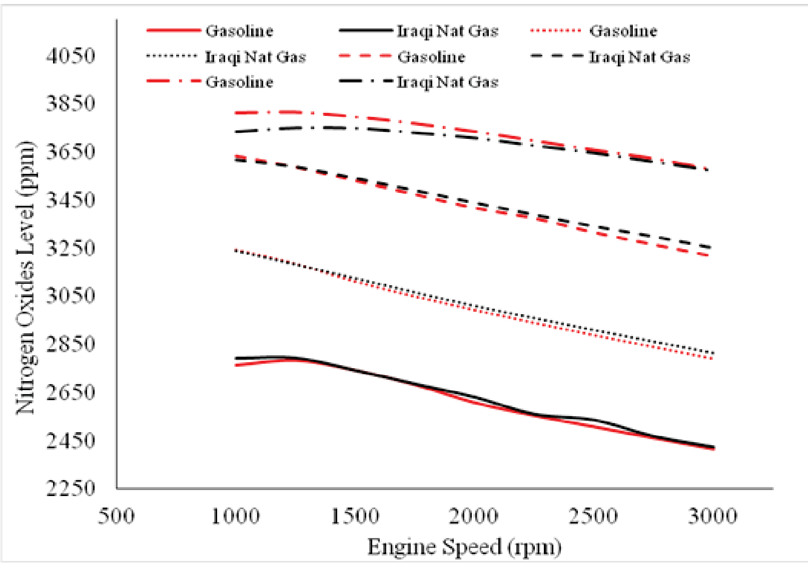

Fig. (4) Oxides of nitrogen variation with an engine speed for different equivalence ratios

NOx molecules in the exhaust are not directly products of the combustion process but, rather, are products of a high-temperature side reaction which involves the disassociation of some of the atmospheric nitrogen molecules, the oxidation of the liberated nitrogen atoms to nitric oxide (NO), and the subsequent conversion of the NO to other nitrogen oxides, such as nitrogen dioxide (NO_2).

NOx emissions decrease with engine speed. This is clear for all fuels, the reduction in oxygen concentration and combustion duration are the prime reasons for this behavior. It is also noticed that NOx emissions are maximum for an equivalence ratio of 0.9. As for the associated gas of Iraq, NOx emissions are higher than others, due to a higher calorific value which results in higher cylinder temperature as shown in Figure (2).

Conclusion:

Modeling of Iraqi APG is made which is able to predict the properties to a good degree of accuracy. Statistical analysis shows that the C1 component has a great positive influence on APG calorific value and a negative effect on gas density. CO_2 and H_2S are the major components that negatively affecting heating value. The study shows that the Iraqi association gas cannot be used without the removal of sulfur from it to reduce the sulfurous-related exhaust emissions.

The main advantage shown by the associated gas is the reduction in CO emissions in the exhaust, comparable levels of NOx as that for gasoline and the lower cylinder pressure and temperature. This means lower levels of thermal and mechanical stresses.

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