

# THEORETICAL AND EXPERIMENTAL STUDY ON DIESEL ENGINE PERFORMANCE UNDER SYNTHETIC ATMOSPHERE FOR RECYCLE OPERATION

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## ABSTRACT

The closed cycle diesel engine provides an economic solution to fill the strongly needed energy gap for naval submarine between the low performance conventional diesel electric system and the high performance nuclear reactor plant. The interrelationships between the non-air oxidants with moderate gases for synthetic atmosphere and engine performance, are neither well documented nor understood. A theoretical model based on fuel/synthetic atmosphere cycle approximation for the diesel engine, is developed. Model results show direct reflection of the intake gas mixture constituents effects without the uncertainties associated with the combustion process for actual cycle modeling under synthetic atmosphere. This necessitates the generation of temperature entropy charts for both synthetic atmosphere and corresponding combustion gases. The charts and engine cycles presentation are programmed for PC with sufficient generality to represent any synthetic atmosphere constituents and under different excess synthetic atmosphere factors. An experimental rig, including a single cylinder diesel engine, gas metering apparatus and instruments, is designed, constructed and employed to provide results for comparison. The performance deteriorating effects due to CO<sub>2</sub> % increase by volume and the beneficial effects due to O<sub>2</sub>% increase by volume, in the engine inlet mixture, are analyzed. The theoretical model results, show satisfactory correlation with the experimental results and/or with previous works.

**Keywords:** Diesel engine, Synthetic atmosphere, Theoretical, Experimental

## INTRODUCTION

The energy capacity of conventional electric powered submarine is only sufficient to allow undersea missions of about 48 hours, to be carried out before the storage batteries are to be recharged oversea or under snorkel mode [1-3]. On the other hand, the nuclear submarine can access almost limitless power. However, it is not available for all navies for economical or strategic reasons. It is also too large and noisy for shallow seas [4]. Thus, there is a strong need for a power system that can fill the energy gap between the low performance conventional diesel electric battery system and the high performance nuclear reactor

base plant. The submerged endurance is of fatal importance in submarine effectiveness. Alternative systems have been proposed and the closed cycle diesel engine system provides the economical solution to fill this gap [1,5-7]. The engine, then, has to make use of synthetic atmosphere of oxygen and managed exhaust gases. The size of the exhaust gas management system is a direct reflection of the partial pressure of the CO<sub>2</sub> in the working fluid. The higher the concentration of CO<sub>2</sub>, the greater the possible separation and removal and hence the smaller the management system [8,9]. The non-air breathing diesel may also be used in industrial applications where

contamination of air supply is a practical possibility like in mines, industrial and chemical plants and nuclear power plants...etc. [10]

Karim [10] analyzed experimentally the effect of unconventional atmosphere on diesel engine performance. He created the atmosphere by the addition of contamination gases such as  $\text{CO}_2$ ,  $\text{N}_2$  or  $\text{O}_2$  to the air intake change. The engine tolerated admission of  $\text{CO}_2$  concentration up to 16% by volume. However, the  $\text{CO}_2$  increase means, in effect, a reduction in the actual quantity of  $\text{O}_2$  inhaled by the engine.

Zheng *et al* [11-14] made a theoretical and experimental work to study the effect of synthetic atmosphere on diesel engine performance. An imperial formula for the heat release was used in the actual cycle simulation program. The gravimetric concentration of  $\text{O}_2$  was maintained fixed at 23% while increasing the  $\text{CO}_2$ . The IDI diesel engine with compression ratio of 23, continued running until  $\text{CO}_2\%$  by mass of 45%. At about 50%  $\text{CO}_2$ , there was a sudden loss in performance. It is emphasized that maintaining the  $\text{O}_2\%$  concentration constant by mass in the studies means, in effect, that the  $\text{O}_2$  mass ingestion increases at the same engine speed and fueling rate.

Hawley [15] used a 4-cylinder diesel engine with number one cylinder operating on non-air atmosphere. This provision enabled the extremes of engine performance to be observed. He reported achieving engine operation with up to 70%  $\text{CO}_2$  concentration by charge preheating to  $150^\circ\text{C}$ . He observed severe degradation in performance.

Fowler [16] developed a complete closed cycle diesel engine. He reached only 4%  $\text{CO}_2$  by volume in the synthetic atmosphere with nitro-diesel system. The main restriction was the specific heat ratio of the inlet working fluid with the exhaust management system.

The overall implication of the previous works indicates that the interrelationships

between the non-air oxidants and engine's performance are not well documented nor understood. The complexity of the combustion process under synthetic atmosphere with the uncertainties associated with the mixing, kinetics of reaction, non-equilibrium effects, heat release data as well as heat transfer data, ... etc. would have made using the presently developed actual cycle simulation models, practically impossible to be justified at least until adequate data becomes available. A fuel/synthetic atmosphere cycle approximation is, therefore, developed that directly reflects the effects of synthetic constituents variation.

Hence, the present work was established with the overall objective of delineating, assessing and determining the theoretical and experimental performance of diesel engine when operating in non-air mixtures based on using  $\text{CO}_2$  as moderating gas and  $\text{N}_2$  as top up gas.

#### EXPERIMENTAL SYSTEM

To validate the theoretical model, a fully instrumented test rig, with a precise control system, was designed and constructed. The synthetic atmosphere was produced from mixing of bottled gases in the gas mixing unit, after being metered by choked nozzle meters as shown in Figure 1. The oxygen, the moderating gas and top up gas are fed to the mixing unit via a system of needle control valves; both coarse and fine. The choked nozzles were calibrated for air,  $\text{O}_2$ ,  $\text{N}_2$  and  $\text{CO}_2$  to cover all the envisaged flow combinations. The variation of the combined gas flow rates allows for complete fluid control over the engine intake operational requirements. The system can accurately supply a wide variety of different atmospheres to the engine at preset flow rates, pressures and temperatures which are independent of ambient conditions. Full details of the experimental set up can be obtained from Reference 17.

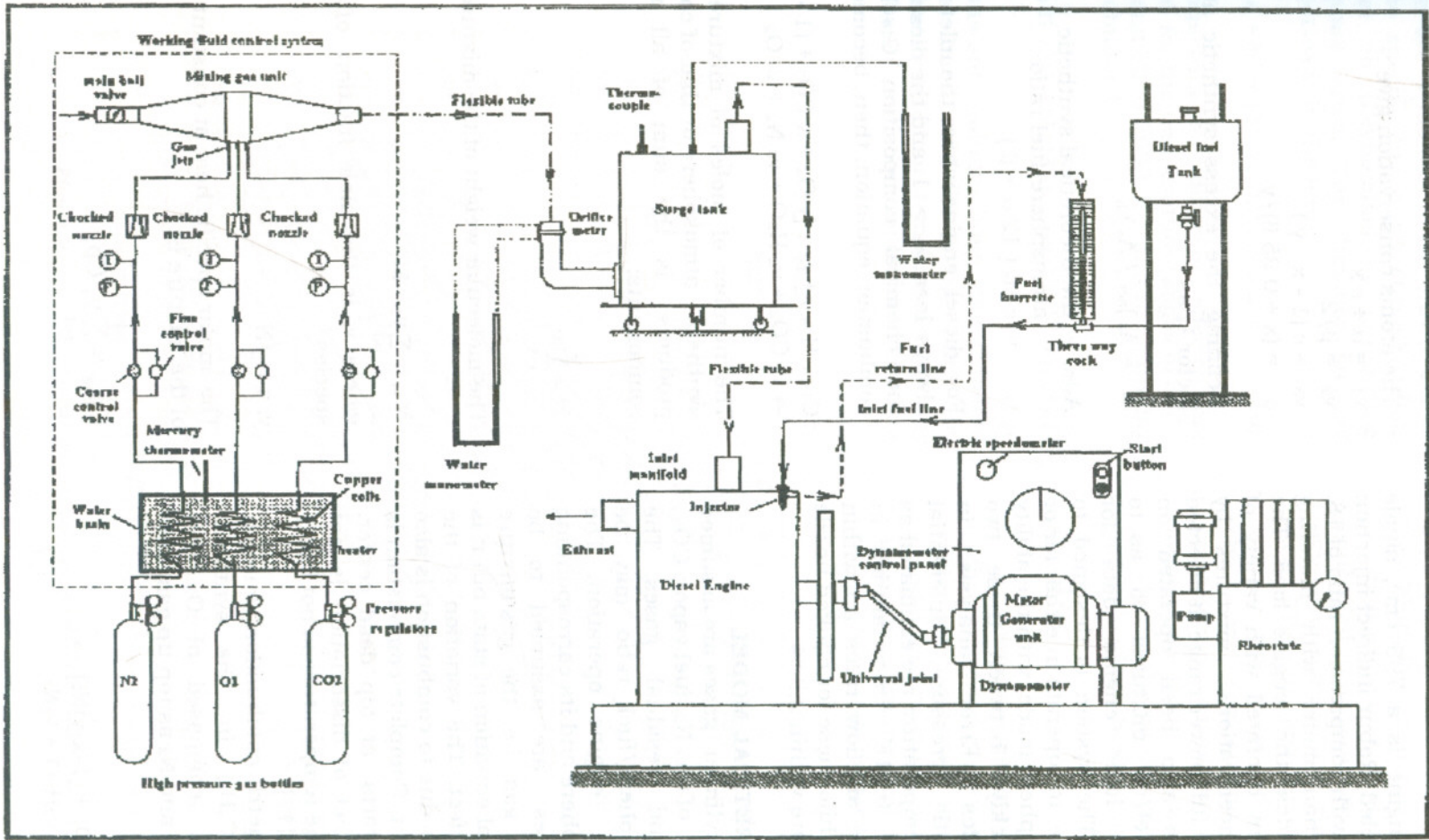


Figure 1

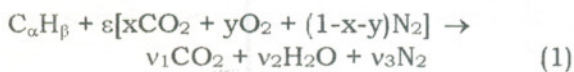
A schematic drawing of the synthetic atmosphere diesel engine test rig.

The test engine is a 795 cm<sup>3</sup>, single cylinder, air cooled, Robur indirect injection diesel engine, with compression ratio of 18. An electric dynamometer with motoring capability provides the engine load. The engine has been operated with variety of CO<sub>2</sub>/O<sub>2</sub>/N<sub>2</sub> concentrations mixtures by volume over its full power range at selected speeds. It has also been operated on conventional fuel/air mixtures so as to produce base line engine data for comparison. The system is designed to allow the engine to operate in either air or synthetic atmosphere mode, with the ability to switch quickly between these two operating modes. Error analysis in measuring static pressure, differential pressure, total temperature are estimated as 0.05 bar and 0.01K. Uncertainties in measuring orifice air flow rates are within 0.8 and 2.7% while these for choked nozzle gases flow rates are within 2.8 %

### THEORETICAL MODEL

The engine cylinder gases are assumed to be a mixture of O<sub>2</sub>, N<sub>2</sub>, fuel vapor, CO<sub>2</sub>, water vapor and residual gases. The synthetic atmosphere/fuel ratio may be changed during engine operation. The synthetic atmosphere and its corresponding combustion gases are assumed to be thermally perfect gas, i.e. the gas mixture obeys the thermal equation of state but it is calorically imperfect. The variation of the number of moles due to combustion is also taken into account. Complete combustion is assumed and starts at top dead center. However, the effect of dissociation is not included since the temperature is not likely to reach that limit [17].

The stoichiometric combustion equation for the fuel (C<sub>α</sub>H<sub>β</sub>) in the synthetic atmosphere that composed of O<sub>2</sub> gas, moderate gas CO<sub>2</sub> and N<sub>2</sub> as top up gas, may be written as:



The atoms conservation give :

$$v_1 = \alpha + \varepsilon x \quad (2a)$$

$$v_2 = \beta/2 \quad (2b)$$

$$v_3 = \varepsilon (1 - x - y) \quad (2c)$$

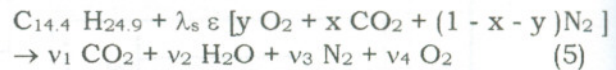
$$\varepsilon = (x + 0.25 \beta)/y \quad (2d)$$

Defining the excess synthetic atmosphere factor  $\lambda_s$  as :

$$\lambda_s = A_s)_{act} / A_s)_{th} \quad (3)$$

$$A_s)_{Th} = \text{the theoretical synthetic atmosphere-fuel ratio} \\ = \varepsilon M_s (12 \alpha + \beta) \quad (4)$$

For diesel engine where the inlet mixture is always lean,  $\lambda_s > 1$  and the diesel fuel with the chemical composition C<sub>14.4</sub>H<sub>24.9</sub>, the combustion equation, then, becomes [18]:



The number of moles of mixture N of the synthetic atmosphere or that of combustion products is the sum of all moles "j" components:

$$N = \sum_{i=1}^j v_i \quad (6)$$

The molecular weight of the mixture M

$$M_m = \sum_{i=1}^j y_i M_i \quad (7)$$

where  $y_i$  is the mole fraction of any given species

$$y_i = v_i / N \quad (8)$$

The molar specific heat at constant pressure of the mixture is:

$$C_{p_m} = \sum_{i=1}^j y_i C_{p_i} \quad (9)$$

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The molar specific heats at constant pressure are available in the JANAF tables [18]. The specific heats are curve fitted for computer to polynomials by minimizing least-square error. The function for any given species is in the form:

$$C_p(T) = a + bT + cT^2 + \dots + kT^{10} \quad (10)$$

The constants for different species are obtained for the temperature ranges of 300 - 1000K and 1000-3000 K, and the enthalpy is then obtained:

$$h = \int_{T_1}^{T_2} C_p dT = [aT + 1/2 bT^2 + \dots + 1/10 jT^{10} + 1/11 kT^{11}]_{T_1}^{T_2} \quad (11)$$

The constant volume lines, the constant pressure lines and the energy lines are, then, constructed on temperature entropy chart based on the following reference

conditions where the entropy is taken as zero [19, 20]:

$$T_o = 300K, P_o = 1.0 \text{ bar}, V_o = 25.41 \text{ m}^3/\text{mole}$$

Figures 2 and 3 show a sample of the generated temperature entropy chart for synthetic atmosphere that consists of 30% CO<sub>2</sub>, 21% O<sub>2</sub> and the remainder is N<sub>2</sub> by volume per mole and the corresponding chart for combustion gases per mole combustion gases at excess synthetic atmosphere factor  $\lambda_s = 1.5$ , respectively.

The total heat liberated from combustion per mole of combustion gases is:

$$Q = H/M_f \quad (12)$$

A computer program is written with sufficient generality to generate the diesel cycle with process iterations for any in cylinder composition, any excess synthetic atmosphere factor and certain compression ratio as shown in Figures 2 and 3.

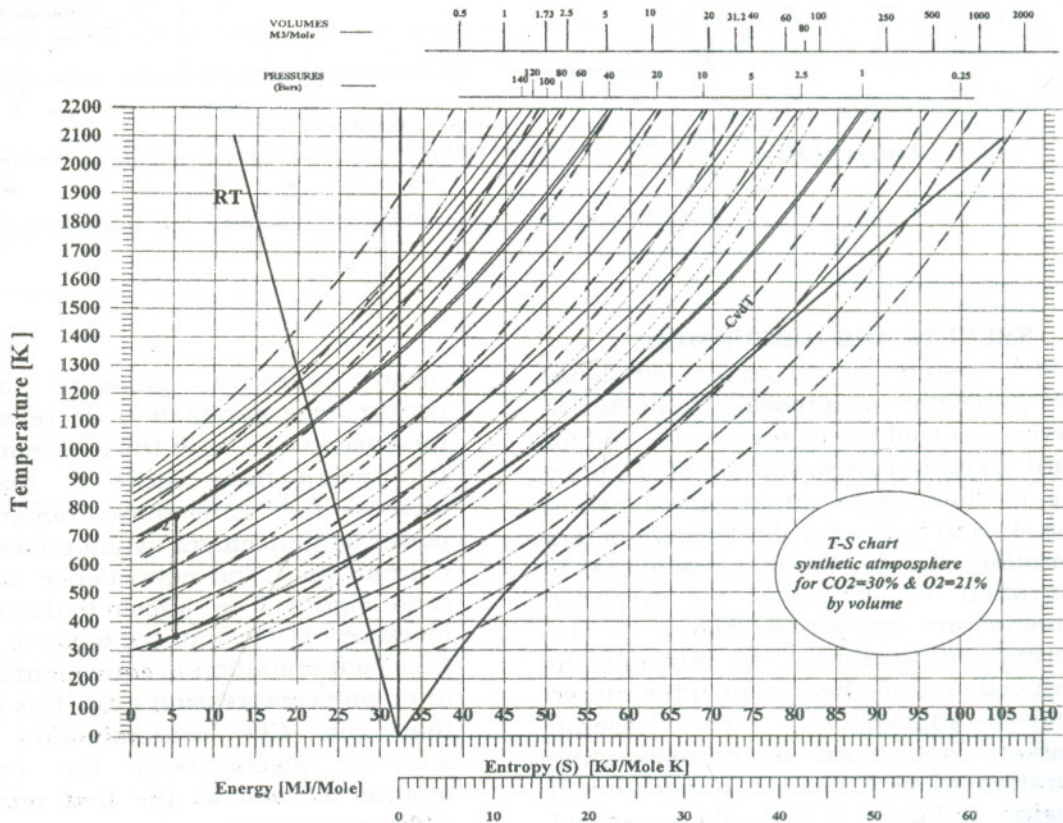
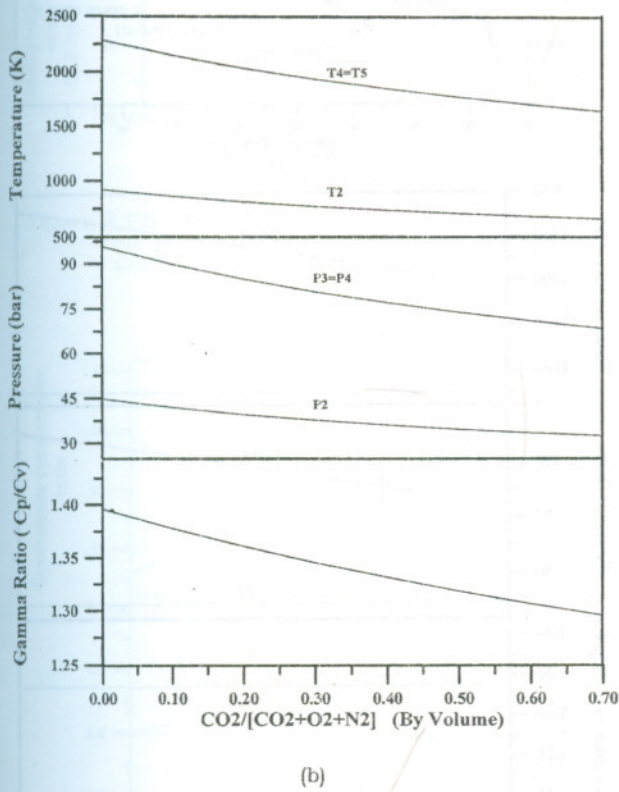
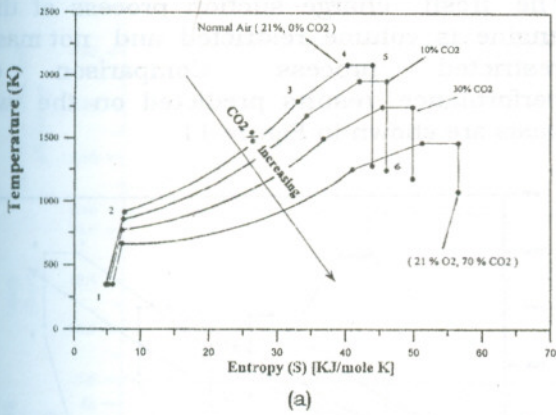
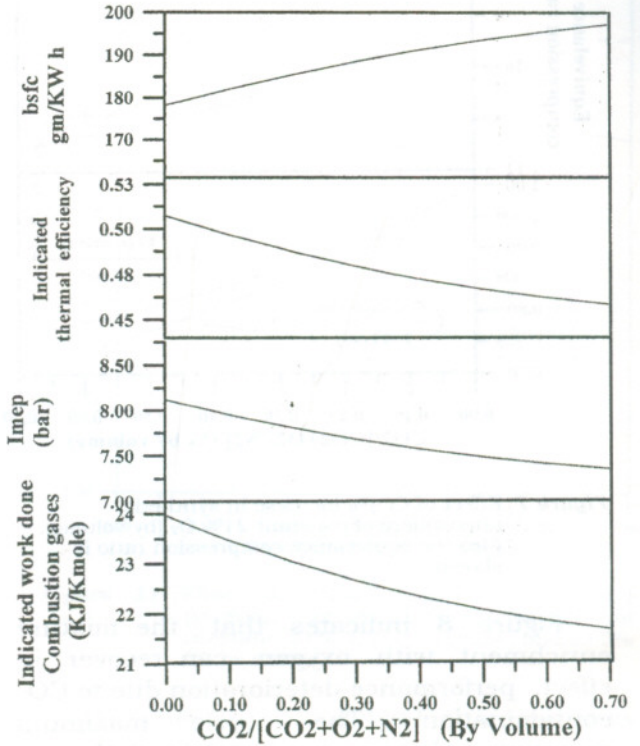


Figure 2 (T-S) chart for synthetic atmosphere, CO=30% by volume.

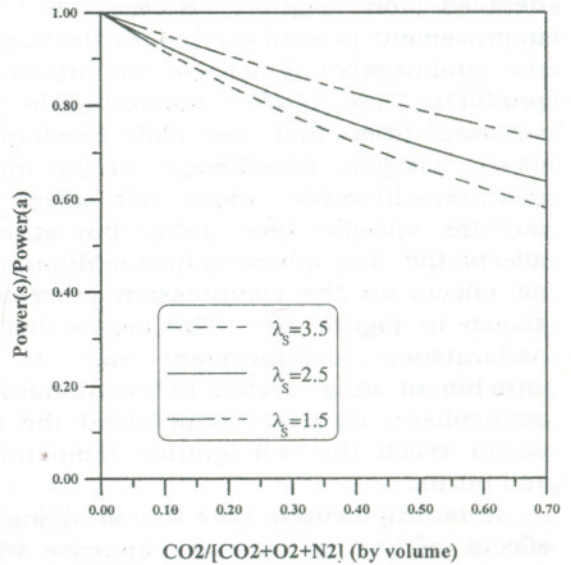
# Theoretical and Experimental Study on Diesel Engine Performance under Synthetic Atmosphere for Recycle Operation



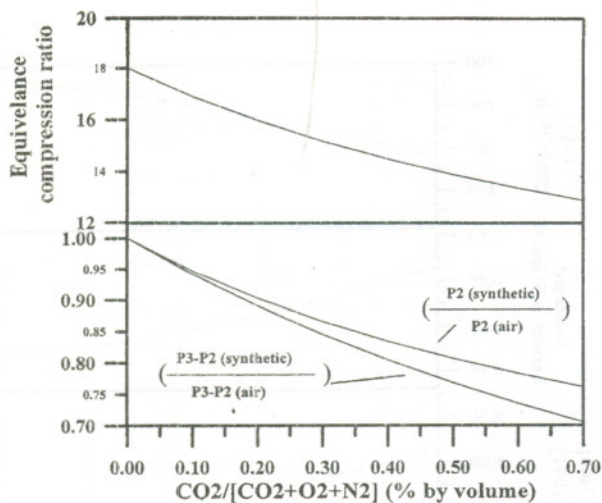
**Figure 4** Effect of CO<sub>2</sub> % increase in synthetic atmosphere for constant 21% O<sub>2</sub> (by Volume) on: (a) Engine T-S cycle; (b) Incylinder parameters(a)



**Figure 5** Effect of CO<sub>2</sub> % increase in synthetic atmosphere, on performance parameters, for constant 21% O<sub>2</sub> (by Volume)



**Figure 6** Effect of CO<sub>2</sub>% increase in synthetic atmosphere of constant 21% O<sub>2</sub> (by volume) on power output

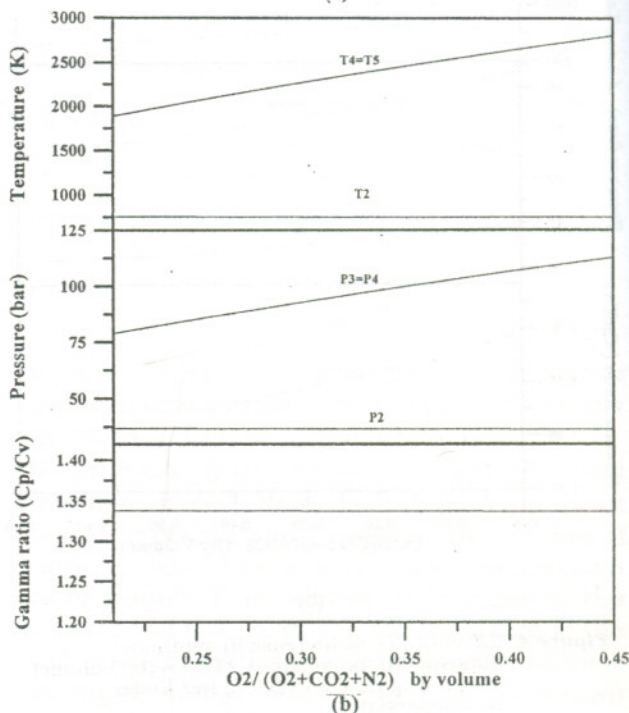
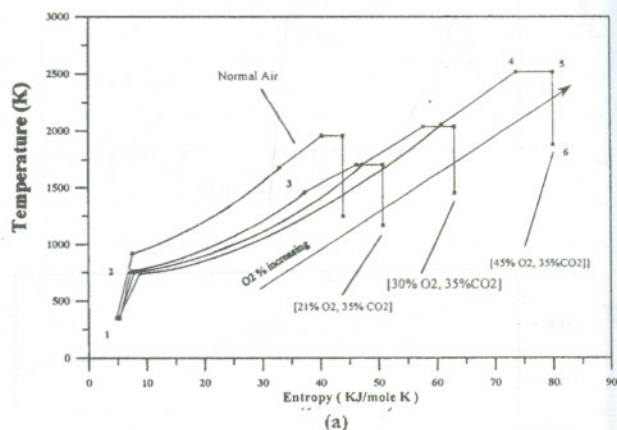


**Figure 7** Effect of CO<sub>2</sub>% increase in synthetic atmosphere of constant 21% O<sub>2</sub> (by volume). Also the equivalence compression ratio is shown.

Figure 8 indicates that the mixture enrichment with oxygen can recover, in effect, performance deterioration due to CO<sub>2</sub> contamination. The cycle maximum pressure and temperature of incylinder gas increase and the corresponding beneficial effects on performance parameters are detailed on Figures 8 and 9. This improvement is attributed to the decrease in the total number of moles of combustion gas products. This implies increase in the heat released from fuel per mole combustion gases. Oxygen enrichment of the intake mixture, however, does not affect the mixture specific heat ratio but strongly affects the first phase of heat addition with no effects on the compression process as shown in Figure 10. This means that the performance enhancement due to O<sub>2</sub> enrichment in a certain CO<sub>2</sub> contaminated atmosphere, is achieved provided the fuel would reach the self ignition temperature and burns.

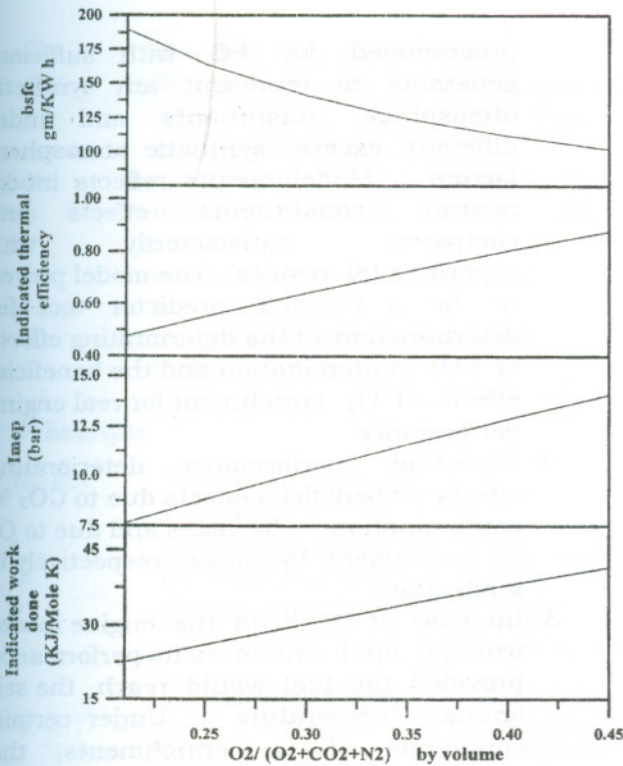
It is emphasized here that studying the effects of CO<sub>2</sub> % by mass increase while maintaining oxygen concentration constant at 23.3 % such as those done by [12,13] and others, leads to an increase of the actual quantity of oxygen admitted to the cylinder. This is because the CO<sub>2</sub> is a weighty gas compared to O<sub>2</sub> or N<sub>2</sub>. Hence, maintaining

O<sub>2</sub> % by mass constant does not represent an adequate way to analyze the effects of CO<sub>2</sub> contamination on engine performance. The fresh charge suction process of the engine is volume restricted and not mass restricted process. Comparison of performance results predicted on the two basis are shown in Figure 11.

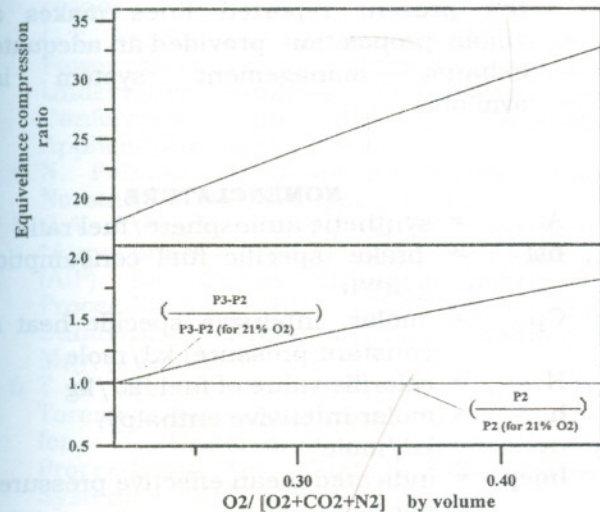


**Figure 8** Effect of O<sub>2</sub>% increase in synthetic atmosphere for constant 35% CO<sub>2</sub> (by volume) on: (a) Engine T-S cycle; (b) in-cylinder parameter

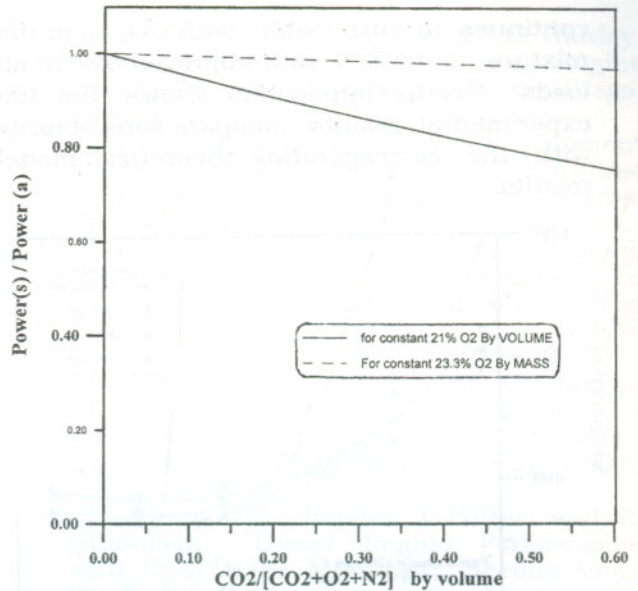
## Theoretical and Experimental Study on Diesel Engine Performance under Synthetic Atmosphere for Recycle Operation



**Figure 9** Effect of O<sub>2</sub>% increase in synthetic atmosphere on performance parameters, for constant 35% CO<sub>2</sub> (by volume)



**Figure 10** Effect of O<sub>2</sub>% increase beyond 21% by volume and predicting the effect of compression ratio on the base of the maximum pressure of the cycle.



**Figure 11** Effect of CO<sub>2</sub>% increase on power (s) 1 power(a), for synthetic atmosphere of constant 21% O<sub>2</sub> by volume, and 23.3% O<sub>2</sub> by mass.

A series of engine load characteristics under constant speed operation, are experimentally carried out with increasing engine intake percentage volume concentration of CO<sub>2</sub>. Figure 12 presents the brake specific fuel consumption against brake power for engine operation under different synthetic atmospheres of different CO<sub>2</sub> % by volume and under constant O<sub>2</sub> of 21% by volume. The figure also shows the results of the base line engine under normal air operation. It appears that at high load, maintaining oxygen concentration by volume constant at 21% and increase of CO<sub>2</sub> % by volume of the engine intake charge to up to 24%, there is only slight increase in bsfc. At idling and low loads, on the other hand, the increase in bsfc is remarkable with CO<sub>2</sub> % increase up to 20 % and the engine runs stable. Reaching 24% CO<sub>2</sub>, it is noticed that the engine runs rough, unstable and the noise level increased. At 25% CO<sub>2</sub>, sudden loss in performance is noticed which may be attributed to ignition failure at this high level of CO<sub>2</sub>% content. Figure 13, on the other hand, presents the effect of O<sub>2</sub> % by volume mixture enrichment of 25%. The engine, then,



continues to run stable with CO<sub>2</sub> % in the mixture up to 28% with improved bsfc at all loads. Overall implication shows that the experimental results compare satisfactorily with the corresponding theoretical model results.

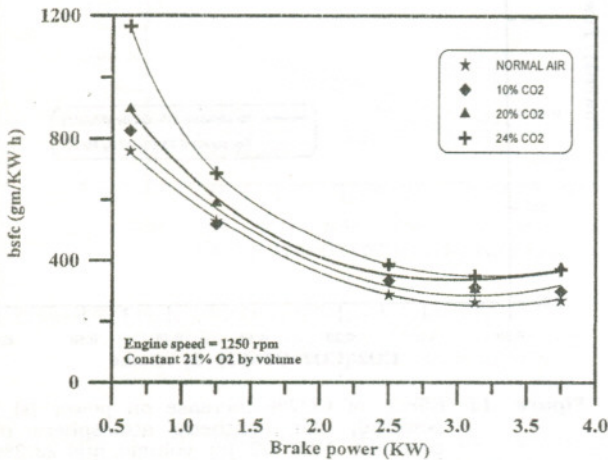


Figure 12 Brake specific fuel consumption against Brake power for synthetic atmosphere of constant 21% O<sub>2</sub> by volume

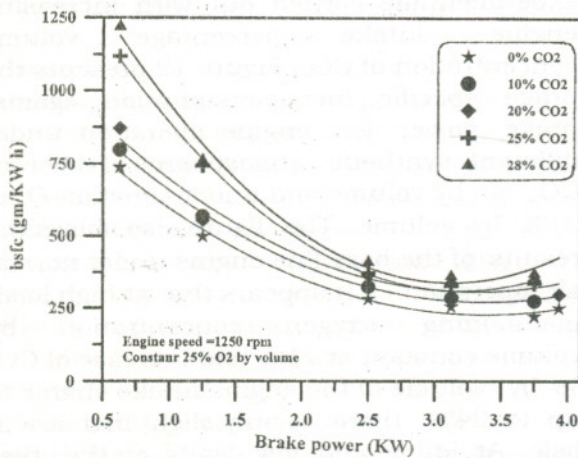


Figure 13 Brake specific fuel consumption against brake power for synthetic atmosphere of constant 25% O<sub>2</sub> by volume

**CONCLUSION**

1. A theoretical model based on the fuel/synthetic atmosphere cycle approximation for diesel engine, is developed. The temperature-entropy charts and engine cycle presentation are

programmed for PC with sufficient generality to represent any synthetic atmosphere constituents and under different excess synthetic atmosphere factors. Model results reflects intake mixture constituents effects and compares satisfactorily with experimental results. The model proved to be a valuable predictor tool for determination of the deteriorating effects of CO<sub>2</sub> contamination and the beneficial effects of O<sub>2</sub> enrichment for real engine performance.

2. Reporting performance deteriorating effects or beneficial effects due to CO<sub>2</sub> % contamination by mass and due to O<sub>2</sub> % enrichment by mass, respectively is inadequate.
3. Increase of O<sub>2</sub> % in the engine intake working fluid enhances its performance provided the fuel would reach the self ignition temperature. Under certain conditions of O<sub>2</sub> enrichments, the performance of engine may, reach higher levels compared to that of using normal air.
4. Development of a complete recycle diesel engine having good performance along the present reported lines makes a viable proposition provided an adequate exhaust management system is available.

**NOMENCLATURE**

- A<sub>s</sub> = synthetic atmosphere/fuel ratio
- bsf = brake specific fuel consumption g/kWh
- C<sub>p</sub> = molar intensive specific heat at constant pressure, kJ/mole
- H = calorific value of fuel kJ/kg
- h = molar intensive enthalpy, kJ/mole
- Imep = indicated mean effective pressure, bar
- M<sub>f</sub> = total number of moles of combustion gases/kg of fuel
- M<sub>s</sub> = molecular weight of the synthetic atmosphere, kmol/kg
- Q = heat liberated / mole combustion gases. kJ/mole

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- T = absolute temperature, K  
 $x, y$  = the percentages in the mixture of  $CO_2$  and  $O_2$  by volume, respectively  
 $y_i$  = mole fraction of any given species  
 $\epsilon$  = molar synthetic atmosphere/fuel ratio  
 $v_i$  = species moles of combustion products  
 $\lambda_s$  = excess synthetic atmosphere factor

**Subscripts**

- th, act theoretical and actual, respectively  
*i* specify any given species 1,2,3,...*j*  
*m* denotes mixture  
*s* denotes synthetic

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# دراسة نظرية وعملية لأداء محركات الديزل التي تعمل بغازات مخلقة لتعمل بمبدأ الدورة المغلقة

السيد محمد مرزوق ، أحمد محمود نور

قسم هندسة القوى الميكانيكية - جامعة الإسكندرية

## ملخص البحث

إن الحاجة الملحة تتطلب استخدام وسيلة دفع جديدة للغواصات البحرية قادرة على ملئ الفجوة بين الأداء المتدني للغواصات التقليدية التي تعمل بنظام الديزل والبطاريات والأداء العالي للغواصات النووية وذلك يرجع أساساً لطول فترة الغطس المتصلة .

وقد تبين أن نظام محرك الديزل ذا الدورة المغلقة ، بالإضافة للتطبيقات الأخرى ، يقدم حلاً إقتصادياً مناسباً للملئ تلك الفجوة . وفي هذا النظام يعتمد محرك الديزل ، بدلاً من الهواء، على مخلوط غازي مخلق مكون من الأكسجين وغازات العادم المعالجة . لذلك أرسى البحث الحالي على أساس دراسة نظرية ومعملية لتحديد أداء محرك الديزل تحت ظروف تشغيله لا هوائياً بالمخلوط الغازي المخلق . قدم البحث نموذج نظري يعتمد على دورة الوقود/ المخلوط الغازي المخلق التقريبية لخرق الديزل . إستلزم ذلك تكوين خرائط درجة الحرارة مع الأنتروبي لكل من المخلوط الغازي المخلق ونواتج الإحتراق المناظرة . وتم تجهيز وتطبيق النموذج باستخدام الحاسوب بقدر من العمومية ليكون قادراً على التعامل مع أى نسبة خلط غازي وأى قيمة لمعامل الزيادة للمخلوط الغازي المخلق . كما تم بناء جهاز معملية لخرق ديزل أحادي الأسطوانة بغرض توفير نتائج معملية للمقارنة بالنتائج النظرية . وقد تم تحديد مدى تدني أداء الخرك مع زيادة نسبة ثاني أكسيد الكربون بالحجم في الخليط عند ثبوت نسبة الأكسجين وكذلك تم تحديد مدى تحسن أداء الخرك مع زيادة نسبة الأكسجين بالحجم في الخليط عند ثبوت نسبة ثاني أكسيد الكربون . وقد أظهرت نتائج النموذج النظرية بطريقة مباشرة تأثير تغيير نسب تكوين الغاز المخلق على أداء الخرك وبين بدرجة مقبولة توافقها مع النتائج المعملية . وكذلك أظهرت تعارض النتائج البحثية السابقة في هذا المجال وإسباب التعارض .