RESEARCH ARTICLE

JENER Journal of Empirical and Non-Empirical Research
Volume 2, Issue 8, Page 344-350 | Article No. 47
DOI: 10.4898/jener.v2i8.a47
ISSN: 7895-9216
Journal homepage: https://jenerjournal.com
Journal email: editor@jenerjournal.com

JENER Journal
JENER Journal of Empirical and Non-Empirical Research

Volumetric Analysis of a Gaseous Fuel Containing Methane, Ethane and Propane

[1,2]Emu, A. O., [1]Madu, K. E., [1]Philip, E. C., [1]Onyenanu, I. U. & [1]Uyaelumuo, A. E.

[1]Mechanical Engineering Department, Chukwuemeka Odumegwu Ojukwu University, Uli, Nigeria
[2]Marine Engineering Department, Southern Delta University, Ozoro, Nigeria

ARTICLE INFORMATION

Article history:
Published: August 2026

Keywords:
Methane Gas
Ethane Gas
Propane Gas
Volumetric Analysis
Stoichiometric Air
Theoretical Air

ABSTRACT

Most gaseous fuels and liquid fuels are mixtures of multiple chemical compounds. In recent years, these mixtures became more complicated when the suppliers started to admix bio-fuels into the petrochemical basic fuels. In the volumetric analysis of methane, ethane and propane in the process of combustion, one takes into cognizance the effects of the presence or absence of each constituent in determining the efficiency of industrial machines. As the properties of such mixtures can vary with composition, there is a need for reliable analytical techniques in order to ensure stable operation of devices such as internal combustion engines and gas turbines. The focus of the paper lies on gaseous and liquid fuels, which are dominant in the transportation sector and in the distributed generation of power. Asides introduction to the physical principles and review of the literature, various techniques are critically discussed and compared with each other. Also, equation can only be solved by iterative trials and error procedure using sensible enthalpy vs temperature components. The knock resistance for a given gaseous fuel mixture is expressed as an equivalent fraction of propane in methane, under identical engine conditions.

1. Introduction

In this paper, we introduce the chemistry and thermodynamics of combustion of methane, ethane and propane as hydrocarbon fuels - (C_xH_y), in which the oxydizer is the oxygen contained in atmospheric air. Note that we will not cover the combustion of solid fuels or the complex blends and mixtures of the hydrocarbons which make up gasolene, kerosene, or diesel fuels. Modern energy conversion technology relies on primary sources based on fossil as well as renewable fuels. Gas analysis is so paramount; and must be made rapidly and accurately to ascertain its pureness. Methane and ethane have low heating capacity compare to propane on a volumetric basis. Propane, on the other hand, has lower anti-knocking property than methane, thus reduces methane number [1-5]. Gaseous and liquid fuels represent the major part of the energy mix. This is illustrated in Figure 1 based on data from the recent EU Energy in Figures Pocketbook 2014 [6-7]. These latest figures from 2011 suggest that ~53% of the overall global fuel consumption is related to fossil oil and gas resources. The third large slice with ~29% represents solid fuels like coal. Coal and other solid fuels are commonly used in large scale power plants for base load coverage. On the other hand, mobile and flexible energy conversion technology, including automotive propulsion and gas turbines for balancing peak electricity demands, are predominantly based on gaseous and liquid fuels. In the following, the term fuel refers to gases and liquids, and solids will not be covered [8-12].

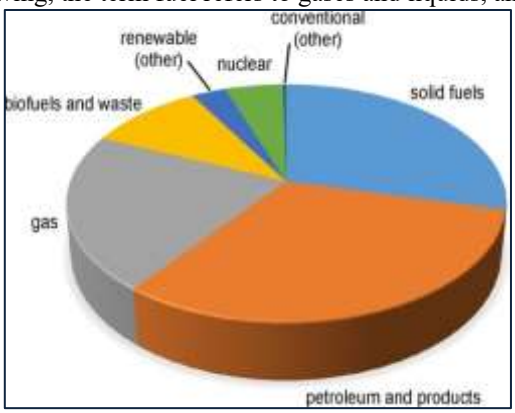
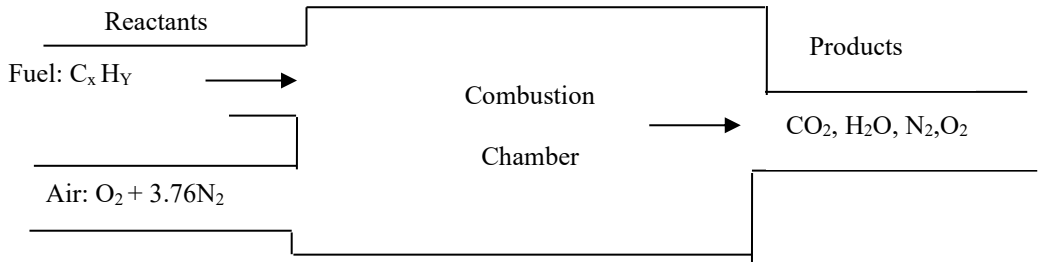


Figure 1: World gross inland consumption by fuel. The “renewable (other)” slice comprises hydro, geothermal, solar, and wind power. The data are taken from the EU Energy in Figures Pocketbook 2014 [6].

Many commercial fuels are, nowadays, blends of a fraction from the petrochemical industry (like natural gas, gasoline, and diesel) and a bio-fuel (like biogas, bio-ethanol or biodiesel). When fuels are blended, the physicochemical properties and hence the performance in an engine may vary substantially [11]. Atmospheric air contains approximately 21% oxygen (O_2) by volume. The other 79% of "other gases" is mostly nitrogen (N_2), so we will assume air to be composed of 21% oxygen and 79% nitrogen by volume. Thus each mole of oxygen needed to oxidize the hydrocarbon is accompanied by 79/21 = 3.76 moles of nitrogen. Using this combination the molecular mass of air becomes 29 [kg/kmol].

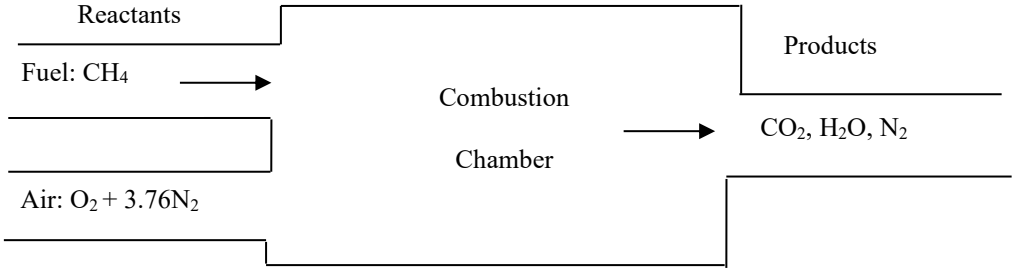
The First Law Analysis of Combustion - The main purpose of combustion is to produce heat through a change of enthalpy from the reactants to the products. From the First Law equation in a control volume, ignoring kinetic and potential energy changes and assuming no work is done, we have:



Where z is known as the stoichiometric coefficient for the oxidizer (air)
Note that this reaction yields five unknowns: z, a, b, c, d, thus we need five equations to solve. Stoichiometric combustion assumes that no excess oxygen exists in the products, thus d = 0. We obtain the other four equations from balancing the number of atoms of each element in the reactants (carbon, hydrogen, oxygen and nitrogen) with the number of atoms of those elements in the products. This means that no atoms are destroyed or lost in a combustion reaction [13-19].
Atoms of those elements in the products, means that no atoms are destroyed or lost in a combustion reaction, see Table 1 below;

Element	Amount in reactants	=	Amount in Products	Reduced equation
Carbon (C)	X		A	a = x
Hydrogen (H)	Y		2b	b = y/2
Oxygen (O)	2z		2a+b	z = a + b/2
Nitrogen (N)	2(3.76)z		2c	c = 3.76z

Note that the water formed could be in the vapor or liquid phase, depending on the temperature and pressure of the combustion products. As an example consider the stoichiometric combustion of methane (CH_4) in atmospheric air. Equating the molar coefficients of the reactants and the products we obtain:



$$CH_4 + 2(O_2 + 3.76N_2) \Rightarrow CO_2 + 2H_2O + 7.52N_2$$

Theoretical Air and Air-Fuel Ratio -The minimum amount of air which will allow the complete combustion of the fuel is called the Theoretical Air (also referred to as Stoichiometric Air). In this case the products do not contain any oxygen. If we supply less than theoretical air then the products could include carbon monoxide (CO), thus it is normal practice to supply more than theoretical air to prevent this occurrence [20]. This Excess Air will result in oxygen appearing in the products.
The standard measure of the amount of air used in a combustion process is the Air-Fuel Ratio (AF), defined as follows:

$$AF = \frac{m_{air}}{m_{fuel}}$$

Thus considering only the reactants of the methane combustion with theoretical air presented above, we obtain:

b) 50% Excess air (150% Theoretical air):

$$C_4H_{10} + (1.5)(6.5)(O_2 + 3.76N_2) \Rightarrow 4(CO_2) + 5(H_2O) + (0.5)(6.5)(O_2) + (1.5)(6.5)(3.76N_2)$$

$$C_4H_{10} + 9.75(O_2 + 3.76N_2) \Rightarrow 4(CO_2) + 5(H_2O) + 3.25(O_2) + 36.7(N_2)$$

$$50\%\ \text{Excess}\ AF = \frac{m_{air}}{m_{fuel}} = \frac{9.75(4.76)\ [\text{kmol}]\ 29\ \left[\frac{\text{kg}}{\text{kmol}}\right]}{1\ [\text{kmol}]\ (4(12)+10)\ \left[\frac{\text{kg}}{\text{kmol}}\right]}$$

$$AF = 23.2\ \frac{\text{kg - air}}{\text{kg - fuel}}$$

$CH_4 + 2(O_2 + 3.76N_2) \leftrightarrow$ Reactants

fuel 2 kmol air

$$AF = \frac{m_{air}}{m_{fuel}} = \frac{2(4.76)\ [kmol]\ \ 29\left[{}^{kg}/_{kmol}\right]}{1\ [kmol]\ \ (12+4)\left[{}^{kg}/_{kmol}\right]}$$

$$AF = 17.3\ \frac{kg\text{-}air}{kg\text{-}fuel}$$

2. Materials and Method

Combustion always occurs at elevated temperatures and we assume that all the products of combustion (including the water vapor) behave as ideal gases. Since they have different gas constants, it is convenient to use the ideal gas equation of state in terms of the universal gas constant, as follows:

$$P.V = m.R.T = \frac{m}{M}R.M.T$$

where: m is mass [kg], V is volume [m^3], P is pressure [kPa] and T is temperature [K]

$R\left[\frac{kJ}{kg.K}\right]$ is the gas constant

$M\left[\frac{kg}{kmol}\right]$ is the molar mass of the substance

thus: $P.V = N.R_u.T$

where: $R_u = R.M = 8.314\left[\frac{kJ}{kmol.K}\right]$ is the Universal Gas Constant

$N = \frac{m}{M}$ is the number of kmols

The mechanism used to compute the auto-ignition delay time is optimized based on RCM measurements performed at engine conditions. After optimization, the knock resistance is measured by the knock-limited spark timing (KLST) and calculated using PKI. These were found to agree within the uncertainty of the measurement (0.75Oca) for all fuels. In the analysis of the products of combustion there are a number of items of interest [21]:

- What is the percentage volume of specific products, in particular carbon dioxide (CO_2) and carbon monoxide (CO)?
- What is the dew point of the water vapor in the combustion products? This requires evaluation of the partial pressure of the water vapor component of the products.
- There are experimental methods of volumetric analysis of the products of combustion, normally done on a **Dry Basis**, yielding the volume percentage of all the components except the water vapor. This allows a simple method of determining the actual air-fuel ratio and excess air used in a combustion process.

For ideal gases we find that the mole fraction y_i of the i'th component in a mixture of gases at a specific pressure P and temperature T is equal to the volume fraction of that component.

Since from the molar ideal gas relation: $P.V = N.R_u.T$, we have [22-30]:

$$y_i = \frac{N_i}{N} = \frac{P.V_i/R_u.T}{P.V/R_u.T} = \frac{V_i}{V}$$

Furthermore, since the sum of the component volumes V_i must equal the total volume V, we have:

$$\sum_{i=1}^{n} y_i = 1$$

Using a similar approach we determine the partial pressure of a component using Dalton's Law of Partial Pressures:

$P = P_1 + P_2 + P_3 + \ldots$

where: $P_i = \frac{N_i.R_u.T}{V}$ is the partial pressure of the i' th component assuming that it occupies the entire volume V

thus: $\frac{P_i}{P} = \frac{N_i.R_u.T/V}{N.R_u.T/V} = \frac{N_i}{N} = y_i$

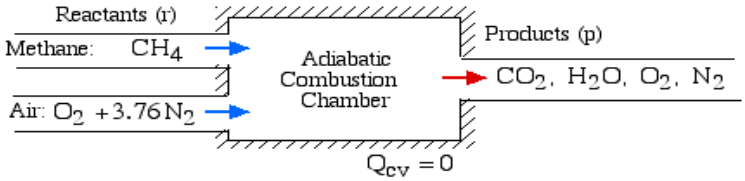
3. Results and Discussion

3.1 Analysis of combustion of Methane

Determine the adiabatic flame temperature for the complete combustion of Methane (CH_4) with 250% theoretical air in an adiabatic control volume.

250% Theoretical air:

$$CH_4 + (2.5)2(O_2 + 3.76N_2) \Rightarrow CO_2 + 2H_2O + 3O_2 + (5)(3.76)N_2$$



$$Q_{cv} = 0 = \sum_p N_p h_p - \sum_r N_r h_r$$

$$0 = \sum_p N_p [h_f^o + h(T)]_p - \sum_r N_r [h_f^o + h(T)]_r$$

where: h(T) is the sensible enthalpy as a function of temperature T

thus since the reactants are assumed to be at 25°C:

$$\underline{1[-393,520 + h(T)]} + \underline{2[-241,820 + h(T)]} + \underline{3[h(T)]} + \underline{18.8[h(T)]} = \underline{1(-74,850)}$$

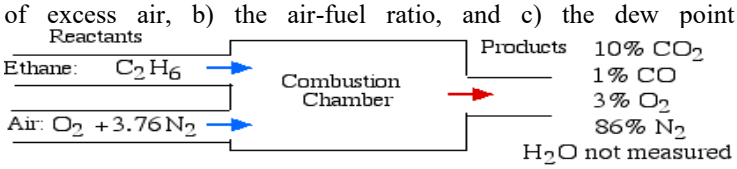
$\Uparrow$ CO_2 $\Uparrow$ H_2O $\Uparrow$ O_2 $\Uparrow$ N_2 $\Uparrow$ CH_4

Simplifying:

$$h(T)_{CO_2} + 2[h(T)_{H_2O}] + 3[h(T)_{O_2}] + 18.8[h(T)_{N_2}] = 802,310 \left[\frac{kJ}{kmol\ fuel}\right]$$

3.2 Analysis of Combustion of Ethane

In this analysis, Ethane (C_2H_6) is burned with atmospheric air, and the volumetric analysis of the dry products of combustion is determined the following: 10% CO_2, 1% CO, 3% O_2, and 86% N_2. Also, the combustion equation, and determine a) the percentage of excess air, b) the air-fuel ratio, and c) the dew point of the combustion products are separately calculated.



Assuming 100 kmoles of dry products:

$$aC_2H_6 + b(O_2 + 3.76N_2) \Rightarrow 10(CO_2) + CO + 3(O_2) + 86(N_2) + c(H_2O)$$

equating coefficients for each component:

$$\text{nitrogen } N_2\text{: } b = \frac{86}{3.76} = 22.87$$

$$\text{carbon C: } 2a = 10 + 1 \Rightarrow a = 5.5$$

$$\text{hydrogen H: } 6a = 2c \Rightarrow c = 3a = 16.5$$

thus:

$$5.5(C_2H_6) + 22.87(O_2 + 3.76N_2) \Rightarrow 10(CO_2) + CO + 3(O_2) + 16.5(H_2O) + 86(N_2)$$

Simplifying for 1 kmol fuel:

$$C_2H_6 + 4.16(O_2 + 3.76N_2) \Rightarrow 1.82(CO_2) + 0.18(CO) + 0.55(O_2) + 3(H_2O) + 15.64(N_2)$$

a) determine % excess air:

Theoretical: $C_2H_6 + z(O_2 + 3.76N_2) \Rightarrow 2CO_2 + 3(H_2O) + 3.76z(N_2)$

equating coefficients, $z = 2 + \frac{3}{2} = 3.5$ (oxygen component balance), thus:

$$C_2H_6 + 3.5(O_2 + 3.76N_2) \Rightarrow 2CO_2 + 3(H_2O) + 13.16(N_2)$$

$$\%\ \text{Theoretical air} = \frac{4.16}{3.5} = 1.19 \Rightarrow 119\%$$

thus % Excess air = 19%

b) Air - fuel ratio: $AF = \dfrac{m_{air}}{m_{fuel}} = \dfrac{4.16(4.76)\ [kmol]\ 29\left[\frac{kg}{kmol}\right]}{1\ [kmol]\ (2(12)+6)\left[\frac{kg}{kmol}\right]}$

$$AF = 19.1 \frac{kg\text{-}air}{kg\text{-}fuel}$$

c) Dew - point: $N_{H_2O} = 3$, $N_{total} = 1.82 + 0.18 + 0.55 + 3 + 15.64 = 21.19$

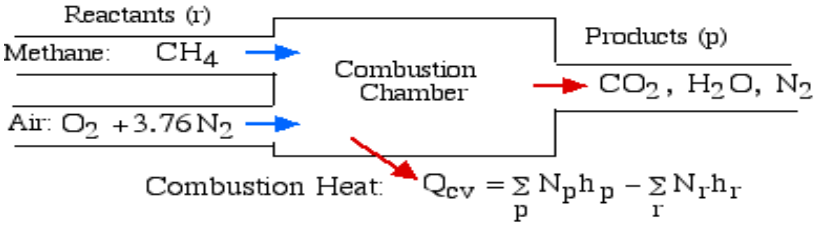
$$\frac{P_{H_2O}}{P} = \frac{N_{H_2O}}{N_{total}} = \frac{3}{21.19} \Rightarrow P_{H_2O} = (101.32\ kPa)\left[\frac{3}{21.19}\right] = 14\ kPa$$

$$T_{dew\text{-}point} = T_{sat@14kPa} \approx 53°C$$

3.2.1 Combustion Molar Enthalpy Tables

As an example, consider again the complete combustion of Methane (CH_4) with theoretical air:

$$CH_4 + 2(O_2 + 3.76N_2) \Rightarrow CO_2 + 2H_2O + 7.52N_2$$



Notice that in the reactants and the products of the above example we have basic elements O_2 and N_2 as well as compounds CH_4, CO_2, and H_2O. When the compound is formed then the enthalpy change is called the Enthalpy of Formation, denoted h_f^o, and for our example:

Substance	Formula	hfo [kJ/kmol]
Carbon dioxide	CO_2(g)	-393,520
Water Vapor	H_2O(g)	-241,820
Water	H_2O(l)	-285,820
Methane	CH_4(g)	-74,850

Where (g) refers to gas and (l) refers to liquid.

The negative sign means that the process is Exothermic, i.e. heat is given off when the compound is formed. Note that the enthalpy of formation of basic elements O_2 and N_2 is zero. Consider first the case in which there is sufficient heat transfer such that both the reactants and the products are at 25°C and 1 atm pressure, and that the water product is liquid. Since there is no sensible enthalpy change the energy equation becomes:

$$Q_{cv} = \sum_p N_p (h_f^o)_p - \sum_r N_r (h_f^o)_r$$

$$= 1(-393,520) + 2(-285,820) - 1(-74,850)$$

$$Q_{cv} = -890,310 \left[kJ/kmol\ fuel \right]$$

on a unit mass basis:

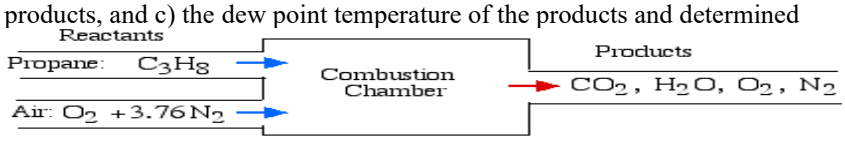
$$q_{cv} = \left[\frac{Q_{cv}}{M_{CH_4}} \right] = \frac{-890,310}{(12+4)} = -55,644 \left[kJ/kg\ fuel \right]$$

This heat (Qcv) is called the Enthalpy of Combustion or the Heating Value of the fuel. If the products contain liquid water then it is the Higher Heating Value (as in our example), however if the product contains water vapor then it is the Lower Heating Value of the fuel. The enthalpy of combustion is the largest amount of heat that can be released by a given fuel.

Adiabatic Flame Temperature - The opposite extreme of the above example in which we evaluated the enthalpy of combustion is the case of an adiabatic process in which no heat is released. This results in a significant temperature increase in the products of combustion (denoted by the Adiabatic Flame Temperature) which can only be reduced by an increase in the air-fuel ratio.

3.3 Analysis of Combustion of Propane

Here, Propane (C_3H_8) is burned with 61% excess air, which enters a combustion chamber at 25°C. Assuming complete combustion and a total pressure of 1 atm (101.32 kPa), the air-fuel ratio [kg-air/kg-fuel], the percentage of carbon dioxide by volume in the products, and c) the dew point temperature of the products and determined



61% Excess air (161% Theoretical air):

$$C_3H_8 + (1.61)z(O_2 + 3.76N_2) \Rightarrow 3(CO_2) + 4(H_2O) + (0.61)z(O_2) + (1.61)(3.76)z(N_2)$$

equating coefficients, $z = 3 + 2 = 5$ (oxygen component balance), thus:

$$C_3H_8 + 8.05(O_2 + 3.76N_2) \Rightarrow 3(CO_2) + 4(H_2O) + 3.05(O_2) + 30.27(N_2)$$

$$a)\ AF = \frac{m_{air}}{m_{fuel}} = \frac{8.05(4.76)\ [kmol]\ 29 \left[kg/kmol \right]}{1\ [kmol]\ (3(12)+8) \left[kg/kmol \right]}$$

$$AF = 25.3 \frac{kg\text{-}air}{kg\text{-}fuel}$$

$$b)\ N_{CO_2} = 3,\ N_{total} = 3 + 4 + 3.05 + 30.27 = 40.32$$

$$\frac{V_{CO_2}}{V_{total}} = \frac{N_{CO_2}}{N_{total}} = \frac{3}{40.32} = 0.074 \Rightarrow \%CO_2 = 7.4\%$$

$$c)\ N_{H_2O} = 4,\ \frac{P_{H_2O}}{P} = \frac{N_{H_2O}}{N_{total}} = \frac{4}{40.32} \Rightarrow P_{H_2O} = (101.32\ kPa)\left[\frac{4}{40.32} \right] = 10.05\ kPa$$

$$T_{dew\text{-}point} = T_{sat@10kPa} = 45.8°C$$

This equation can only be solved by an iterative trial and error procedure using the tables of Sensible Enthalpy vs Temperature for all four components of the products - CO_2, H_2O, O_2, and N_2. A quick approximation to the adiabatic flame temperature can be obtained by assuming that the products consist entirely of air. This approach was introduced to us by Potter and Somerton in their Schaum's Outline of Thermodynamics for Engineers, in which they assumed all the products to be N_2. We find it more convenient to use air assuming a representative value of the Specific Heat Capacity of Air: $C_{p,1000K} = 1.142$ [kJ/kg.K].
Thus summing all the moles of the products we have:

$$N_{total} = 1 + 2 + 3 + 18.8 = 24.8 \text{ kmols products.}$$

$$24.8[h(T) - h^{o}]_{air} = 24.8(M_{air})(C_{p,1000K})(T_{adiabatic} - 298K) = 802,310 \left[\frac{kJ}{kmol\ fuel}\right]$$

where: $M_{air} = 29 \left[\frac{kg}{kmol}\right]$ is the molecular mass of air

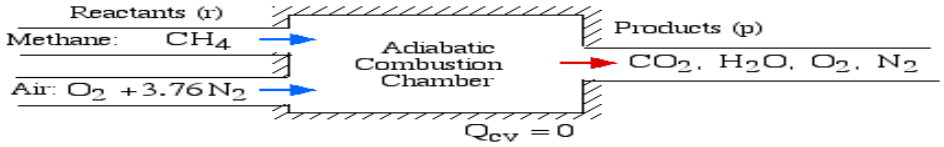
$C_{p,1000K} = 1.142 \left[\frac{kJ}{kg.K}\right]$ is the specific heat capacity of air

thus solving: $T_{adiabatic} = 1275K$ (assuming that all the products are air)

Using the tables of Sensible Enthalpy vs Temperature we evaluated the enthalpy of all four products at a temperature of 1280K. This resulted in a total enthalpy of 802,410 [kJ/kmol fuel], which is extremely close to the required value, thus justifying this approach.

250% Theoretical air:

$$CH_4 + (2.5)2(O_2 + 3.76N_2) \Rightarrow CO_2 + 2H_2O + 3O_2 + (5)(3.76)N_2$$



$$Q_{cv} = 0 = \sum_{p} N_p h_p - \sum_{r} N_r h_r$$

$$0 = \sum_{p} N_p [h_f^o + h(T)]_p - \sum_{r} N_r [h_f^o + h(T)]_r$$

where: $h(T)$ is the sensible enthalpy as a function of temperature T
thus since the reactants are assumed to be at 25°C:

$$1[-393,520 + h(T)] + 2[-241,820 + h(T)] + 3[h(T)] + 18.8[h(T)] = 1(-74,850)$$

$\Uparrow$ CO_2 $\Uparrow$ H_2O $\Uparrow$ O_2 $\Uparrow$ N_2 $\Uparrow$ CH_4

Simplifying:

$$h(T)_{CO_2} + 2[h(T)_{H_2O}] + 3[h(T)_{O_2}] + 18.8[h(T)_{N_2}] = 802,310 \left[\frac{kJ}{kmol\ fuel}\right]$$

In determination on the adiabatic flame temperature for the complete combustion of Propane (C_3H_8) with 250% theoretical air in an adiabatic control volume [T = 1300K]. This equation can only be solved by an iterative trial and error procedure using the tables of Sensible Enthalpy vs Temperature for all four components of the products - CO_2, H_2O, O_2, and N_2. A quick approximation to the adiabatic flame temperature can be obtained by assuming that the products consist entirely of air. This approach was introduced to us by Potter and Somerton in their Schaum's Outline of Thermodynamics for Engineers, in which they assumed all the products to be N_2. We find it more convenient to use air assuming a representative value of the Specific Heat Capacity of Air: $C_{p,1000K} = 1.142$ [kJ/kg.K].
Thus summing all the moles of the products we have:

$$N_{total} = 1 + 2 + 3 + 18.8 = 24.8 \text{ kmols products.}$$

$$24.8[h(T) - h^{o}]_{air} = 24.8(M_{air})(C_{p,1000K})(T_{adiabatic} - 298K) = 802,310 \left[\frac{kJ}{kmol\ fuel}\right]$$

where: $M_{air} = 29 \left[\frac{kg}{kmol}\right]$ is the molecular mass of air

$C_{p,1000K} = 1.142 \left[\frac{kJ}{kg.K}\right]$ is the specific heat capacity of air

thus solving: $T_{adiabatic} = 1275K$ (assuming that all the products are air)

Using the tables of Sensible Enthalpy vs Temperature we evaluated the enthalpy of all four products at a temperature of 1280K. This resulted in a total enthalpy of 802,410 [kJ/kmol fuel], which is extremely close to the required value, thus justifying this approach.
The above presentation gives an overview of the analysis of gaseous fuels – specifically the analysis of natural gas, biogas and other alternatives (such as syngas). The definition of the Wobbe index establishes a comparability and exchangeability of gaseous fuels. In other words, for a given burner system, one fuel can be replaced by another when they exhibit the same Wobbe index, without the need for modifying the burner settings and configuration.

4. Conclusion

Most gaseous fuels are not in the purest forms. There is often, a blend of two or more hydrocarbons in any designated fuel mixture. That is why it becomes expedient to undertake a volumetric analysis of fuel, just as we have done. From the foregoing, it could be adduced that given the conditions in the above analysis, a fuel mixture of Methane, Ethane and Propane does not produce a homogenous combustion. The whole gamut of the characteristics and/or behaviors of the component fuel that make up the mixture must be factored in, in order to arrive at a plausible and intelligible conclusion. Hence, the need for volumetric analysis of this kind, to ascertain the behaviors of fuel-mixtures; and make possible projections. Also, Volumetric analysis of gaseous fuel helps to

promote knock resistance of gaseous fuels and undertake knock measurements in the engine. It also described the characteristics to the effects of changes in the composition of gaseous fuels on engine knock by computing auto-ignition process during the compression and burn periods of the engine cycle.

References

[1] World Energy Outlook 2014; International Energy Agency: Paris, France, 2014.
[2] Madu, K. E. & Atah, C. M. (2024a). Analysis of Thermodynamic Properties of an Isolated System. International Journal of Progressive Research in Engineering Management and Sciences (IJPREMS), Vol. 10, Issue 2, pp86-92
[3] Madu, K. E. & Atah, C. M. (2024b). Effect of Sudden Pressure Drop in a Nozzle Flow. International Journal of Scientific Research and Engineering Trends (IJSRET), Vol. 10, Issue 2, pp93-98
[4] Madu, K. E. & Atah, C. M. (2024c). Effects of Variation of Ambient Temperature in Energy Interactions in a Closed System. International Journal of Progressive Research in Engineering Management and Sciences (IJPREMS), Vol. 4, Issue 2, pp393-401
[5] Nosegbe, U. & Madu, K. E. (2025). Energy Analysis of 3 x 2.5 MW Centaur 40 Terminal Gas Turbine Generators. European Journal of Sustainable Development Research, Vol. 9, Issue 3
[6] *EU Energy in Figures Pocketbook*; Publications Office of the European Union: Luxembourg,2014.
[7] Okafor, A. M. & Madu, K. E. (2025). Thermal Properties of Composite Materials: A Systematic Review of Experimental and Theoretical Models. International Journal of Research Publication and Reviews (IJRPR), 6(4), pp11018-11038
[8] Davis, S. C., Diegel, S. W. & Boundy, R. G. (2014). *Transportation Energy Data Book*, 33rd ed., Oak Ridge National Laboratory: Oak Ridge, TN, USA
[9] Madu, K. E. (2026). Combustion Analysis and Thermodynamic Determination of the Heating Values of Fuels. JENER Journal of Empirical and Non-Empirical Research, 2(07), 476-480
[10] Madu, K. E. (2026). Analysis of the Saturated and Supercritical Stirling Cycle Thermodynamic Heat Engine Cycle. JENER Journal of Empirical and Non-Empirical Research, 2(07), 70-82
[11] Lehmann, S.; Lorenz, S.; Rivard, E.; Brüggemann, D. Experimental analysis and semicontinuous simulation of low-temperature droplet evaporation of multicomponent fuels. *Exp. Fluids* 2015, *56*, 1–12.
[12] Madu, K. E. (2026). Impact of friction on the velocity of flow of African oil bean seed oil biodiesel. JENER Journal of Empirical and Non-Empirical Research, 2(07) 52-56
[13] Lichty, L.C.; Phelps, C.W. Gasoline-alcohol blends in internal combustion engines. *Ind. Eng. Chem.* **1938**, *30*, 222–230.
[14] Madu, K. E. (2026). Heat Analysis under Local Thermal Non-Equilibrium Conditions. JENER Journal of Empirical and Non-Empirical Research, 2(07), 481-484
[15] Madu, K. E. (2018). Performance analysis of a steam power plant operating under superheated and isentropic conditions. *Equatorial Journal of Engineering*, 22-28
[16] Madu, K. E. (2018) Thermodynamic properties and heat generation potential of octane fuel under stoichiometric condition. *Equatorial Journal of Chemical Sciences*, 2(2), 14-19
[17] Madu, K. E. (2018a). Evaluation of the Behaviour of Steam Expanded in a Set of Nozzles, in a Given Temperature. Equatorial Journal of Engineering, 9-13, ISSN: 0184-7937
[18] Madu, K. E. (2018b). Estimation of the Power Capacity of a Belt in a Fan-Motor Assemblage, Under a Given Allowable Stress. Equatorial Journal of Computational and Theoretical Science, Volume 02, Issue 02, 16-20
[19] Madu, K. E. (2018c). Evaluation of the Performance of a Spark-Ignition Four Cycle Engine, in Tropical Environment. Equatorial Journal of Engineering, 43-50, ISSN: 0184-7937
[20] Turner, D., Xu, H., Cracknell, R. F., Natarajan, V. & Chen, X. (2011). Combustion performance of bio-ethanol at various blend ratios in a gasoline direct injection engine. *Fuel*, *90*, 1999–2006
[21] Sielghem, L., Alekseev, V. A., Vancoillie, J., Nilsson, E. J. K., Verhelst, S. & Konnov, A. A. (2014). Laminar burning velocities of primary reference fuels and simple alcohols. *Fuel*, *115*, 32–40.
[22] Nwaeze, G. I., Emu, A. O., Ani, E. A., Moh, K. D. & Madu, K. E. (2025). Exergetic Analysis of Human Metabolism During Athletic Activities. International Journal of Science, Architecture, Technology, and Environment, 2(06), 347-358
[23] Nwanze, N. E., Madu, K. E., Emu, A. O. & Igbagbon, E. J. (2025b). Examining the Thermodynamic Effect of Incorporating Wetted Media Evaporative System Gas Turbine Power Plant. International Journal of Progressive Research in Engineering Management and Sciences, 5(01), 756-763
[24] Kiefer, J., Noack, K. & Kirchner, B. (2011). Hydrogen bonding in mixtures of dimethyl sulfoxide and cosolvents. *Curr. Phys. Chem.*, *1*, 340–351.
[25] Noack, K., Kiefer, J. & Leipertz, A. (2010). Concentration dependent hydrogen bonding effects on the dimethyl sulfoxide vibrational structure in the presence of water, methanol and ethanol. *ChemPhysChem*, *11*, 630–637.
[26] Ulbig, P. & Hoburg, D. (2002). Determination of the calorific value of natural gas by different methods. *Thermochim. Acta*, *382*, 27–35.
[27] Madu, K. E., Nwankwo, E. I., Orji, M. U. & Aneke, A. C. (2020). Investigation of the Conditions that Trigger Cavitation in a Pump. International Journal of Mechanical and Industrial technology, 7(2), 1-7
[28] Madu, K. E. & Uyaelumuo, A. E. (2018). Factorial Analysis of Surface Condenser for Thermal Power Plant. Equatorial Journal of Engineering, 37-42, ISSN: 0184-7937
[29] Philp, R. P. (1994). High-temperature gas-chromatography for the analysis of fossil fuels: A review. *J. High Resolut. Chromatogr. 17*, 398–406.
[30] Cross, R.A. Analysis of major constituents of fuel gases by gas chromatography. *Nature* 1966, 211,409