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# Interchangeability of Natural Gas Quality Indicators as Fuel for Gas Turbine Performance of Power Generation


Seham N. Tawfic[1*] and Ibrahim M. Abou El Leil[2]

[1]Chemical Engineering Department, Faculty of Engineering, Tobruk University, Tobruk, Libya

[2]Petroleum Engineering Department, Faculty of Engineering, Tobruk University, Tobruk, Libya


# قابلية تبادل مؤشرات جودة الغاز الطبيعي كوقود لأداء التوربين الغازي في توليد الطاقة


سهام نجيب توفيق[1*] و إبراهيم محمد أبوالليل[2]

[1]قسم الهندسة الكيميائية، كلية الهندسة، جامعة طبرق، طبرق، ليبيا

[2] قسم هندسة البترول كلية الهندسة، جامعة طبرق، طبرق، ليبيا

[*]Corresponding author: seham67@hotmail.com



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**الملخص**

تعتمد التوربينات الغازية عالية الفعالة في الوقت الحاضر على جودة الوقود المستخدم. حيث يسمح الوقود عالي الجودة بتحقيق درجات حرارة احتراق مرتفعة، مما يؤدي إلى تحقيق مستوى مقبول من الطاقة المنتجة. لذلك، يجب إيلاء المزيد من الاهتمام لجودة الوقود من جميع المصادر، والذي يتم استخدامه في التوربين الغازي. وبناءً على ذلك، يجب دراسة خصائص ومعايير جودة مخاليط الغاز الطبيعي لتحديد مواصفاتها ومدى جودتها. وعليه فإن هذه الدراسة تسلط الضوء على الغازات الطبيعية التي تنتج من حقول بعض الحقول الليبية مثل حقل زلطن والراقوبة والحُطيبة التابعة لشركة سرت للنفط والغاز بهدف تقييم مؤشرات الجودة كوقود للتوربينات في توليد الطاقة، وتوفير رؤية وفهم لتركيب الوقود بحيث يمكن اتخاذ التدابير لتقليل تأثير أي مكونات رئيسية للوقود، إلى جانب التأثير المحتمل على مكونات التوربين. حيث تشمل هذه المعايير الوزن الجزيئي للغاز$(M_w)$ ، والكثافة النوعية$(\gamma_g)$ ، وعامل الانضغاط (z)، والضغط الحرج المُزيَفْ $(P_{pc})$، ودرجة الحرارة الكاذبة الحرجة $(T_{pc})$ ، والضغط المُختزل المُزيَفْ $(P_{pr})$ ودرجة الحرارة المُختزلة المُزيَفَةْ $(T_{pr})$ لتقدير مؤشرات الجودة مثل القيمة الحرارية الإجمالية (GHV) ، ومؤشر ووبي (WI) ، ورقم الميثان (MN) وقيم القيمة الحرارية (CV). لقد أظهرت النتائج المتحصل عليها وجود اختلاف بين هذه المعايير لخليط الغاز الطبيعي، والتي يمكن أن يُعزى ذلك إلى التركيب الكيميائي للمكونات وسلوكها. ومن ناحية أخرى يمكن استخدام هذه الخصائص كدليل لفهم سلوك الغازات كوقود لعمليات الاحتراق في التوربينات الغازية. وبشكلٍ عام، تشير معايير الجودة إلى أن المواصفات والخصائص تقع ضمن الحدود المطلوبة لجودة الغازات الطبيعية ويمكن استخدامها كوقود للتوربينات في توليد الطاقة.



**الكلمات المفتاحية**: الغاز الطبيعي، التوربين الغازي، مواصفات الغاز، الجودة، مؤشرات، معايير، توليد الطاقة.



**Abstract**

Today's highly efficient gas turbines relies on the quality of the fuel utilized. Where, high-quality fuel permits achieving high combustion temperatures, thereby achieving an acceptable level of produced energy. Therefore, more attention has to be placed on the quality of the fuel, from all sources, entering the gas turbine. Consequently, the characterizations and quality parameters of natural gas mixtures must be investigated to determine their specifications. This study highlights the natural gases that produced from Zelten, Al Ragoba and Al Hotaiba gas fields of Sirte Oil Company aiming to assess the quality indicators as a fuel for turbines of power generation and provides an insight as well as understanding of fuel composition so that measures can be taken to minimize the impact of any major constituents of the fuel, along with the potential impact on turbine components. These parameters are gas molecular weight ($M_w$), specific gravity ($\gamma$), compressibility factor (z), pseudocritical pressure ($p_{pc}$), pseudocritical temperature ($T_{pc}$), pseudoreduced pressure ($p_{pr}$) and pseudoreduced temperature ($T_{pr}$) to estimate the quality indicators such as gross heating value (GHV), Wobbe index (WI), methane number (MN) and calorific values (CV). The obtained results revealed that there are a variance between these parameters of the natural gas mixtures, which may be attributed to the chemical compositions of components and their behaviors. On the other hand, these characterizations can be used as guide to understand the gases behavior as a fuel for combustion processes in gas turbines. In general, the quality parameters indicate that the specifications and characterizations within the required limits for natural gases quality and can be utilized as a fuel for turbine in power generation.

**Keywords:** Natural gas, gas turbine, gas specifications, quality, indicators, parameters, power generation.

## 1. Introduction

Natural gas is an important fossil fuel that has played an increasingly significant role in worldwide electric power generation since the 1980s. The key driver underlying the importance of natural gas as a vital enabler of modern living has been its relative advantage via other fossil fuels in terms of emissions and pollutants. In comparison to coal, the primary fossil fuel used for electric power generation in the world on a constant consumption basis, natural gas emits nearly 45% less $CO_2$ and 80% less nitrogen oxides ($NO_x$) with negligible amounts of sulfur oxides, particulates, and mercury [1,2].

The environmental advantages of natural gas are further amplified by the significantly higher thermal efficiency of the power plants that burn it for electric power generation in comparison to other variants of oil or coal. Natural gas-burning modern gas turbines can readily reach efficiencies of 56–57% in combined cycle configurations.

An industrial gas turbine can run on a wide variety of fuels to produce power. Depending on the fuel composition and resulting properties, specifically the hydrogen–carbon ratio, the available output power, operability, and emissions of the engine can vary significantly. This study is an examination of how different fuels can affect the output characteristics of Turbines [3].

## 2. Study Objectives

The main purpose of this study was analyzing the influence of different gas compounds interchangeability on the quality of natural gases that will be produced in the three gas fields in Sirte Oil Company, using the various quality as interchangeability parameters.

## 3. Study Methodology

The natural gas samples data of chemical analysis under consideration were obtained from the producing gas field of Sirte Oil company. The gas fields considered in this study are illustrated in Figure 1.

In this study the estimation and calculations of the various parameters and indicators were carried out using the mathematical equations to distinguish the characterizations of natural gases.

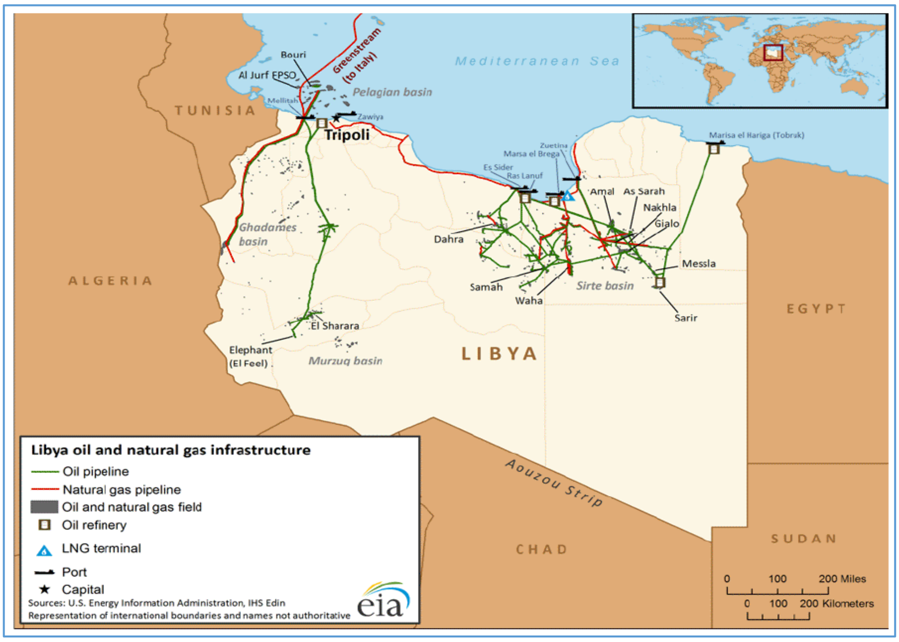


**Figure 1:** Map showing the location of gas fields under consideration.

## 4. Gas Quality Indicator

Gas companies generally define gas quality as the chemical composition of the gas, with all its different species such as the various hydrocarbons, inert gases such as nitrogen and carbon dioxide as well as generally undesirable species such as sulphur, water and mercury. For most gas users, adjustment for the typical combustion characterizing quantities such as the Wobbe Index, the calorific value and the Methane Number is needed to ensure a clean, safe, energy efficient and reproducible performance.

Calculating the delivered energy to the customers is performed on the basis of all the analyses and calculations. The method of calculation takes into consideration regional differences in gas composition as a result of the actual operating conditions [4,5].

The main quality parameters of natural gas are described below:

### 4.1. Specific Gravity

The specific gravity is the density of natural gas divided by the density of air at the same pressure and temperature and is an expression of the amount of heavier hydrocarbons that are in the natural gas. The specific gravity is expressed as following:

$$\textit{Specific gravity of gas mixture} = \frac{Mole\ Wt}{28.85} \quad (1)$$

### 4.2. Calorific Value

This term describes the amount of heat generated during combustion of the natural gas. The customer pays for the delivered amount of energy, and not for the delivered amount of natural gas.

### 4.3. Net Calorific Value

The net calorific value is describing the amount of heat generated, when the temperature of the combustion air and the natural gas prior to combustion is 25°C, when the combustion products (flue gas) are cooled to 25°C, and when the water produced during combustion is present in the form of steam [4].

### 4.4. Gross Calorific Value

A term describing the amount of heat developed by combustion of one cubic meter of gas at constant pressure when the gas and air for the combustion have a temperature of 25°C, the combustion products being brought to that temperature and the water formed by the combustion being present in liquid state. The delivered amount of energy is calculated by multiplying the delivered amount of gas by the calorific value [5].

### 4.5. Wobbe Index

The *Wobbe-Index* (WI) or *Wobbe number* is an indicator of the interchangeability of fuel gases such as natural gas. The Wobbe - Index was defined 1927 by the engineer Goffredo Wobbe. It is used to compare the combustion energy output of different composition fuel gases in an appliance.

The Wobbe Number is sometimes used to specify gas heating value in gas purchasing contracts and is usually expressed in metric units $MJ/Sm^3$.

The Wobbe number of a fuel gas is found by dividing the high heating value of the gas in Btu per standard cubic foot by the square root of its specific gravity with respect to air. The higher a gases Wobbe number, the greater the heating value of the quantity of gas. The Wobbe number can be calculated from Equations (2, 3, and 4) [6,7]:

$$\textit{Wobbe number} = \frac{Gross\ heating\ value}{\sqrt{Specific\ gravity}} = \frac{GHV}{\sqrt{\gamma_g}} \quad (2)$$

$$\text{Imperial unit Wobbe number} = \frac{GHV\ of\ mixture}{\sqrt{Specific\ gravity, \gamma_g}}\ Btu/scf \quad (3)$$

$$\text{Metric unit Wobbe number} = \left(\frac{Btu}{SCF}\right)\left(\frac{MJ}{948\ Btu}\right)\left(\frac{35.315}{Sm^3}\right) \quad (4)$$

### 4.6. Methane Number

The methane number (*MN*) of a gas is a gas quality indicator typical for reciprocating gas engines. Pure methane has a high knock resistance and is therefore given a *MN* of 100 (8). The *MN* number of mixtures of different gases can be determined by using the method described in (9).

Most engines have the best fuel efficiency for a *MN* higher than 80. The *MN* of the bulk of natural gases exceeds 70, which is still acceptable if precautions are taken. Only a very limited number of natural gases have a *MN* lower than 70 (10).

#### 4.6.1. Calculation of Methane Number from Composition

The Methane Number can be calculated by different methods. Many of the calculation methods are proprietary and are not in the public domain. But several technical papers have been presented by standards associations and technical societies. The suggested methods are as follows.

##### 4.6.1.1. Linear Correlation of Methane and Wobbe Numbers

The Methane Number and Wobbe Numbers of various LNG compositions are estimated using the MWM method for Methane Number and the results were plotted showing the relationship between Wobbe Number and Methane Number. The plot suggests intersecting straight lines with a break in the slope occurring at a Wobbe Number of about 54.9 $MJ/Sm^3$ and a Methane Number of about 77 (11).

##### 4.6.1.2. The Hydrogen/Carbon Ratio Method

A method of calculating Methane Number has been suggested in Europe which describes a method of quantitively relating Methane Number to Hydrogen/ Carbon ratio in the natural gas motor fuel.

It possible to relate motor Octane Numbers for natural gas to the composition of the gas based on the Hydrogen/Carbon ratio for the sum of components. If the fuel composition is known, the Hydrogen and carbon atoms in the mixture are counted, and the ratio of Hydrogen atoms to carbon atoms is calculated to calculate the motor Octane Number (11).

$$\text{Octane Number} = -406.14 + 508.04 \times H/C - 173.55 \times (H/C)^2 + 20.17 \times (H/C)^3 \quad (5)$$

If we know the motor Octane Number, the Methane Number is calculated as following

$$\text{Methane Number} = 1.624 \times \text{Octane Number} - 119.1 \quad (6)$$

However, the methane number is evaluated in order to analyse the knock resistance of each stream before the ignition, compared with a reference fuel mixture. The calculation is performed by the method of radii ratio (H/C) presented Equation (7).

$$MN=1.624*(406.14 + 508.04 * RHCR - 173.55 * RHCR^2 + 20.17 * RHCR^3) \quad (7)$$

Where RHCR represents the relations between the radius of hydrogen and carbon to the radius is given by, Equation (8) (12):

RHCR = (%methane*4 + %ethane * 6 + %propane * 8

+ (%isobutene + %n-butane*10 + (%iso-pentane + n-pentane) * 12

+ (%hexane and longer hydrocarbon chains)*14/(%methane *1

+ %ethane * 2 + %propane *3 + (%isobutene + %n-butane*4

+ (%iso-pentane + n-pentane)*5 + %(hexane and longer hydrocarbon chains)*6 (8)

##### *4.6.1.3.* The ISO/TR 22302-2014 Method

The European standard proposes a method to calculate Methane Number based on gas composition. It proposes that natural gas should be marked in two grades (13).

• Grades X: Methane Number no less than 65 to be used as burner fuel.

• Grades Y: Methane Number no less than 80 to be used as motor fuel.

### 4.7. Sulphur Content

The natural gases could be contain non- hydrocarbon gases such as hydrogen sulphide ($H_2S$). The sulphur in a gaseous fuel will be converted to $SO_2$ during the combustion process and as such emitted to the atmosphere.

### 4.8. Results And Discussion

#### 4.8.1. Pseudocritical and Pseudoreduced Properties of Natural Gases

Tables 3, 4 and 5 present the chemical composition of natural gas for three gas fields of Sirte Oil Company namely Zelten, Al Ragoba and Al Hotaiba. On the other hand, the natural gases pseudocritical properties were calculated to estimate gas mixture specific gravity (SG), molecular weight (Mw) and compressibility factor (z) as shown in Tables 1, 2 and 3.

**Table 1:** Chemical composition and pseudocritical properties of Zelten gas field

| Components | *Mol. fraction* | *Critical press.* | *Critical temp.* | *Mol. weight* | $y_i p_{ci}$ | $y_i T_{ci}$ | $y_i M_i$ |
|---|---|---|---|---|---|---|---|
| | $y_i$ | $p_{ci}$ (psi) | $T_{ci}$ (°R) | $M_i$ | | | |
| $CH_4$ | 0.721 | 673.1 | 343.0 | 16.043 | 485.31 | 247.30 | 11.57 |
| $C_2H_6$ | 0.123 | 708.3 | 549.6 | 30.070 | 87.12 | 67.60 | 3.70 |
| $C_3H_8$ | 0.072 | 617.4 | 665.6 | 44.097 | 44.45 | 47.92 | 3.18 |
| $C_4H_{10}$ | 0.014 | 550.7 | 765.3 | 58.123 | 7.71 | 10.71 | 0.82 |
| $C_5H_{12}$ | 0.022 | 489.0 | 845.6 | 72.150 | 10.76 | 18.60 | 1.59 |
| $C_6H_{14}$ | 0.002 | 439.7 | 914.2 | 86.177 | 0.88 | 1.83 | 0.17 |
| $C_7H_{16}^+$ | 0.0011 | - | - | - | - | - | - |
| $CO_2$ | 0.018 | 1071.1 | 547.6 | 44.010 | 19.28 | 9.86 | 0.79 |
| $N_2$ | 0.012 | 187.5 | 227.2 | 28.013 | 2.25 | 2.73 | 0.34 |
| $H_2S$ | 0.011 | 493.1 | 672.4 | 34.08 | 5.42 | 7.40 | 0.37 |
| $\sum$ | 0.996 | | | | $p_{pc}$= 663.18 | $T_{pc}$= 413.95 | $Mw$ = 22.53 |
| Specific gravity | | | $\gamma_g = Mw/29$ = 22.53/29 = 0.77 | | | | |
| Pseudoreduced pressure ($p_{pr}$) | | | $p_{pr} = \frac{p}{p_{pc}} = \frac{430}{663.18} = 0.65$ | | | | |
| Pseudoreduced temp. ($T_{pr}$) | | | $T_{pr} = \frac{T+460}{T_{pc}} = \frac{570}{413.95} = 1.38$ | | | | |
| Compressibility factor (z) | | | 0.85 | | | | |

**Table 2:** Chemical composition and pseudocritical properties of Al Ragoba gas field

| Components | *Mol. fraction* | *Critical press.* | *Critical temp.* | *Mol. weight* | $y_i p_{ci}$ | $y_i T_{ci}$ | $y_i M_i$ |
|---|---|---|---|---|---|---|---|
| | $y_i$ | $p_{ci}$ (psi) | $T_{ci}$ (°R) | $M_i$ | | | |
| $CH_4$ | 0.692 | 673.1 | 343.0 | 16.043 | 465.79 | 237.36 | 11.10 |
| $C_2H_6$ | 0.125 | 708.3 | 549.6 | 30.070 | 88.54 | 68.70 | 3.76 |
| $C_3H_8$ | 0.083 | 617.4 | 665.6 | 44.097 | 51.24 | 55.25 | 3.66 |
| $C_4H_{10}$ | 0.012 | 550.7 | 765.3 | 58.123 | 6.61 | 9.18 | 0.70 |
| $C_5H_{12}$ | 0.006 | 489.0 | 845.6 | 72.150 | 2.93 | 5.07 | 0.43 |
| $C_6H_{14}$ | 0.0005 | 439.7 | 914.2 | 86.177 | 0.22 | 0.46 | 0.043 |
| $C_7H_{16}^+$ | 0.0002 | - | - | - | - | - | - |
| $CO_2$ | 0.045 | 1071.1 | 547.6 | 44.010 | 48.20 | 24.64 | 1.98 |
| $N_2$ | 0.02 | 187.5 | 227.2 | 28.013 | 3.75 | 4.54 | 0.56 |
| $H_2S$ | 0.01 | 493.1 | 672.4 | 34.08 | 4.93 | 6.73 | 0.34 |
| $\sum$ | 0.993 | | | | $p_{pc}$= 672.21 | $T_{pc}$= 411.93 | $Mw$ = 22.57 |
| Specific gravity | | | $\gamma_g = Mw/29$ = 22.57/29 = 0.78 | | | | |
| Pseudoreduced pressure ($p_{pr}$) | | | $p_{pr} = \frac{p}{p_{pc}} = \frac{430}{672.21} = 0.64$ | | | | |
| Pseudoreduced temp. ($T_{pr}$) | | | $T_{pr} = \frac{T+460}{T_{pc}} = \frac{570}{411.93} = 1.38$ | | | | |
| Compressibility factor (z) | | | 0.84 | | | | |

**Table 3:** Chemical composition and pseudocritical properties of Al Hotaiba gas field

| Components | *Mol. fraction* $y_i$ | *Critical press.* $p_{ci}$ (psi) | *Critical temp.* $T_{ci}$ (°R) | *Mol. weight* $M_i$ | $y_i p_{ci}$ | $y_i T_{ci}$ | $y_i M_i$ |
|---|---|---|---|---|---|---|---|
| $CH_4$ | 0.787 | 673.1 | 343.0 | 16.043 | 529.73 | 269.94 | 12.63 |
| $C_2H_6$ | 0.04 | 708.3 | 549.6 | 30.070 | 28.33 | 21.98 | 1.20 |
| $C_3H_8$ | 0.02 | 617.4 | 665.6 | 44.097 | 12.35 | 13.31 | 0.88 |
| $C_4H_{10}$ | 0.01 | 550.7 | 765.3 | 58.123 | 5.51 | 7.65 | 0.58 |
| $C_5H_{12}$ | 0.004 | 489.0 | 845.6 | 72.150 | 1.96 | 3.66 | 0.29 |
| $C_6H_{14}$ | 0.003 | 439.7 | 914.2 | 86.177 | 1.32 | 2.75 | 0.26 |
| $C_7H_{16}^+$ | 0.002 | - | - | - | - | - | - |
| $CO_2$ | 0.104 | 1071.1 | 547.6 | 44.010 | 111.40 | 56.95 | 4.58 |
| $N_2$ | 0.014 | 187.5 | 227.2 | 28.013 | 2.63 | 3.18 | 0.39 |
| $H_2S$ | 0.015 | 493.1 | 672.4 | 34.08 | 7.40 | 10.09 | 0.51 |
| $\sum$ | 0.999 | | | | $p_{pc}=$ 700.63 | $T_{pc}=$ 389.51 | $Mw=$ 21.32 |
| Specific gravity | | | $\gamma_g = Mw/29 = 21.32/29 = 0.73$ | | | | |
| Pseudoreduced pressure ($p_{pr}$) | | | $p_{pr}=\frac{p}{p_{pc}}=\frac{430}{700.63}=0.62$ | | | | |
| Pseudoreduced temp. ($T_{pr}$) | | | $T_{pr}=\frac{T+460}{T_{pc}}=\frac{570}{389.51}=1.46$ | | | | |
| Compressibility factor (z) | | | 0.86 | | | | |

Figure 2 shows the composition analysis of the different gas samples considered in this study. It obviously that there is a variance in chemical constitutes from field to another, but there is no much difference between them. On the other side, the non-hydrocarbon gases e. g. $CO_2$, $H_2S$ and $N_2$ that are regarded an impurities of natural gases are lower contents and these gases can be regarded as sweet ones, and this means that cannot be affecting negatively on the turbine performance and power plant equipment.

### 4.8.2. Gross Heating Value of Natural Gases

The gross heating value of natural gases can be calculated for ideal gas according to Equation (9) [14]:

$$L_{c\ ideal} = \sum_i y_i L_{ci} \qquad (9)$$

The above Equation can be used to calculate the gross heating value, and in many cases the units must be converted from ideal gas to real gas at standard conditions by dividing the ideal value on compressibility factor (z) at standard conditions according to Equation [10]:

$$L_c = \frac{L_{c\ ideal}}{z} \qquad (10)$$

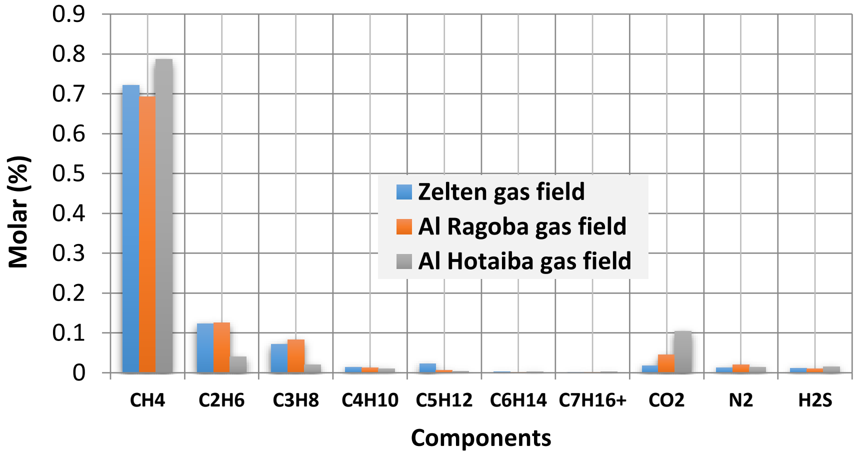


**Figure 2:** Initial compositional analysis for samples gas from gas fields

The compressibility factor (z) can be estimated at standard conditions by applying Equation (11):

$$z = 1- (\sum_i y_i\sqrt{1-z_i}\ )^2 \qquad (11)$$

The gross heating values and Wobbe Indices of natural gases were calculated for the investigated gas fields and presented in Tables 6,7 and 8.

The calculating heating values of natural gases display a variation from field to another, whereas 1287.06 *Btu/scf*, 1202.54 *Btu/scf* and 994.34 *Btu/scf* for Zelten gas field, Al Ragoba gas field and Al Hotaiba gas field respectively, and this attributed to the chemical composition of the natural gas for each field.

**4.8.3. Gross Calorific Value**

The gross calorific values of studied natural gases has been estimated and presented in Tables 6,7 and 8. The calculated values vary from field to another, this naturally attributes to the chemical composition of the gas.

**4.8.4. Wobbe Index of Natural Gases**

The calculated Wobbe Indices for the investigated natural gases has been carried out and presented in Table 6,7 and 8. The Wobbe Indices of a gases with a specific gravities is 0.77, 0.78 and 0.73 of Zelten, Al Ragoba and Al Hotaiba gas fields are 1466.74, 1361.61 and 1163.79 heating values respectively.

However, these gases with this ranges of specific gravities are well within the typical range mentioned in the AGA bulletin.

**4.8.5. Methane Number of Natural Gases**

Methane number has been calculated for the investigated natural gases and presented in Tables 4,5 and 6.High numbers of MN means high efficiency and hence lower $CO_2$ and a good performance of generating turbines.

**Table 4:** Quality indicators for Zelten gas field

| Components | Mole fraction $y_i$ | Gross heating value (Btu/scf) $L_{ci}$ | $y_iL_{ci}$ | Compressibility factor (z) Standard conditions | |
|---|---|---|---|---|---|
| | | | | $z_i$ | $y_i\sqrt{1-z_i}$ |
| $CH_4$ | 0.721 | 1009.7 | 727.99 | 0.9980 | 0.0322 |
| $C_2H_6$ | 0.123 | 1768.8 | 217.56 | 0.9919 | 0.0111 |
| $C_3H_8$ | 0.072 | 2517.5 | 181.26 | 0.9825 | 0.0095 |
| $C_4H_{10}$ | 0.014 | 3262.1 | 45.67 | 0.00354 | 0.01310 |
| $C_5H_{12}$ | 0.022 | 4009.6 | 88.21 | 0.00065 | 0.02199 |
| $C_6H_{14}$ | 0.002 | 4756.2 | 9.51 | 0.00081 | 0.00100 |
| $C_7H_{16}^+$ | 0.0011 | 5502.8 | 6.05 | 0.00012 | 0.00110 |
| $CO_2$ | 0.018 | 0.0 | 00.0 | 0.9943 | 0.00136 |
| $N_2$ | 0.012 | 0.0 | 00.0 | 0.9997 | 0.00021 |
| $H_2S$ | 0.011 | 0.0 | 00.0 | - | |
| $\sum$ | 0.996 | | 1276.25 Btu/scf | | 0.09156 |
| Gross heating value for ideal gas and compressibility factor at standard conditions | | | $z = 1- (\sum_i y_i\sqrt{1-z_i}\ )^2 = 1- (0.09156)^2 = 0.9916$ | | |
| Gross heating value as real gas (GHV) | | | $L_c = \frac{L_{c\,ideal}}{z} = \frac{1276.25\ BTU/scf}{0.9916}$=1287.06 *Btu/scf* | | |
| Wobbe Index | | | $WI = \frac{HHV}{\sqrt{SG}} = \frac{1287.06}{\sqrt{0.77}} = 1466.74$ | | |
| Calorific value | | | CV = 33,105 (KJ/Nm$^3$) | | |
| Methane number | | | MN = 1.624 (3287.29 – 2244.07 +941.05) – 119.1 = 3103.35 | | |

**Table 5:** Quality indicators for Al Ragoba gas field

| Components | Mole fraction $y_i$ | Gross heating value (Btu/scf) $L_{ci}$ | $y_i L_{ci}$ | Compressibility factor (z) Standard conditions | |
|---|---|---|---|---|---|
| | | | | $z_i$ | $y_i\sqrt{1-z_i}$ |
| $CH_4$ | 0.692 | 1009.7 | 698.71 | 0.9980 | 0.0309 |
| $C_2H_6$ | 0.125 | 1768.8 | 221.10 | 0.9919 | 0.01125 |
| $C_3H_8$ | 0.083 | 2517.5 | 208.95 | 0.9825 | 0.01097 |
| $C_4H_{10}$ | 0.012 | 3262.1 | 39.15 | 0.00354 | 0.01198 |
| $C_5H_{12}$ | 0.006 | 4009.6 | 24.06 | 0.00065 | 0.00510 |
| $C_6H_{14}$ | 0.0005 | 4756.2 | 2.38 | 0.00081 | 0.00499 |
| $C_7H_{16}^+$ | 0.0002 | 5502.8 | 1.10 | 0.00012 | 0.00020 |
| $CO_2$ | 0.045 | 0.0 | 00.0 | 0.9943 | 0.00078 |
| $N_2$ | 0.02 | 0.0 | 00.0 | 0.9997 | 0.00035 |
| $H_2S$ | 0.01 | 0.0 | 00.0 | - | |
| $\sum$ | 0.993 | | 1195.45 Btu/scf | | 0.07652 |
| Gross heating value for ideal gas and compressibility factor at standard conditions | | | z = 1- ($\sum_i y_i\sqrt{1-z_i}$ )$^2$ = 1- $(0.07652)^2$ = 0.9941 | | |
| Gross heating value as real gas (GHV) | | | $L_c = \frac{L_{c\,ideal}}{z} = \frac{1195.45\ BTU/scf}{0.9941}$=1202.54 *Btu/scf* | | |
| Wobbe Index | | | $WI = \frac{HHV}{\sqrt{SG}} = \frac{1202.54}{\sqrt{0.78}} = 1361.61$ | | |
| Calorific value | | | CV = 32,355 (KJ/Nm$^3$) | | |
| Methane number | | | MN = 1.624 (3144.78- 2053.72 + 821.07 ) – 119.1 = 2986.20 | | |

**Table 6:** Quality indicators Al Hotaiba gas field

| Components | Mole fraction $y_i$ | Gross heating value (Btu/scf) $L_{ci}$ | $y_i L_{ci}$ | Compressibility factor (z) Standard conditions | |
|---|---|---|---|---|---|
| | | | | $z_i$ | $y_i\sqrt{1-z_i}$ |
| $CH_4$ | 0.787 | 1009.7 | 794.63 | 0.9980 | 0.03519 |
| $C_2H_6$ | 0.04 | 1768.8 | 70.75 | 0.9919 | 0.00360 |
| $C_3H_8$ | 0.02 | 2517.5 | 50.35 | 0.9825 | 0.00265 |
| $C_4H_{10}$ | 0.01 | 3262.1 | 32.62 | 0.00354 | 0.00988 |
| $C_5H_{12}$ | 0.004 | 4009.6 | 16.04 | 0.00065 | 0.00399 |
| $C_6H_{14}$ | 0.003 | 4756.2 | 14.27 | 0.00081 | 0.00299 |
| $C_7H_{16}^+$ | 0.002 | 5502.8 | 11.01 | 0.00012 | 0.00199 |
| $CO_2$ | 0.104 | 0.0 | 00.0 | 0.9943 | 0.00785 |
| $N_2$ | 0.014 | 0.0 | 00.0 | 0.9997 | 0.00024 |
| $H_2S$ | 0.015 | 0.0 | 00.0 | - | |
| $\sum$ | 0.999 | | 989.67 Btu/scf | | 0.06838 |
| Gross heating value for ideal gas and compressibility factor at standard conditions | | | z = 1- ($\sum_i y_i\sqrt{1-z_i}$ )$^2$ = 1- $(0.06838)^2$ = 0.9953 | | |
| Gross heating value as real gas (GHV) | | | $L_c = \frac{L_{c\,ideal}}{z} = \frac{989.67\ BTU/scf}{0.9953}$= 994.34 *Btu/scf* | | |

| | |
|---|---|
| Wobbe Index | $WI = \frac{HHV}{\sqrt{SG}} = \frac{994.34}{\sqrt{0.73}} = 1163.79$ |
| Calorific value | CV= 31,250 (KJ/Nm$^3$) |
| Methane number | MN = 1.624 (3400.20-2400.88+ 1037.99 ) – 119.1= 3189.50 |

Figure 3 gives a comparison between quality parameters for the studied natural gases of three gas fields. It is obviously that Zelten natural gas is the best quality comparing with the other two fields.

On the other side, Table 7 shows a comparison of Wobbe Index for the studied local gases with the published global ones.

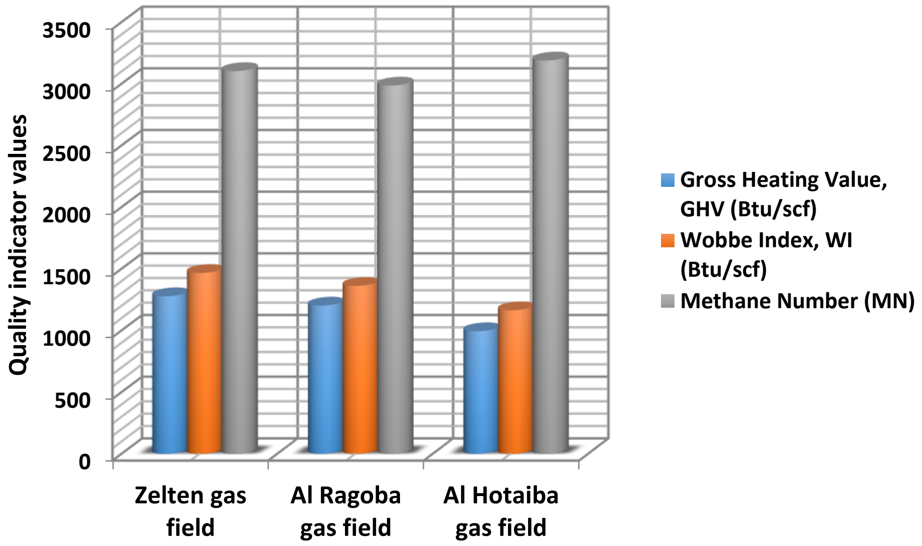


**Figure 3:** A comparison between quality parameters for natural gases.

**Table 7:** Comparison of Wobbe Index for the studied local gases with global ones [15].

| Location | Minimum Wobbe Index (BTU/scf) | Maximum Wobbe Index (BTU/scf) |
|---|---|---|
| United States | 1060.12 | 1400.02 |
| Brazil (North) | 1086.14 | 1207.04 |
| Brazil (Center and South) | 1248.02 | 1435.10 |
| Spain | 1295.44 | 1551.14 |
| Argentina | 1270.25 | 1401.00 |
| Europe | 1246.17 | 1449.20 |
| Venezuela (DPIEP)* | 1196.45 | 1396.14 |
| Venezuela (D&P)* | 1185.02 | 1326.15 |
| Venezuela (D1X)* | 1241.31 | 1535.00 |
| Venezuela (L&M)* | 1204.11 | 1370.44 |
| Venezuela (CIGMA)* | 1210.21 | 1356.71 |
| Zelten gas field | 1212.60 | 1466.74 |
| Al Ragoba gas field | 1154.15 | 1361.61 |
| Al Hotaiba gas field | 1050.22 | 1163.79 |

* Venezuela's Northeastern and different Venezuelan LNG fields and markets

Figure 4 shows the curve of minimum and maximum WI for different countries or regions comparing with those of local natural gas fields. It was selected 1300 BTU/scf as an optimal value for maximum WI. The investigated natural gases WI should be similar to this value.

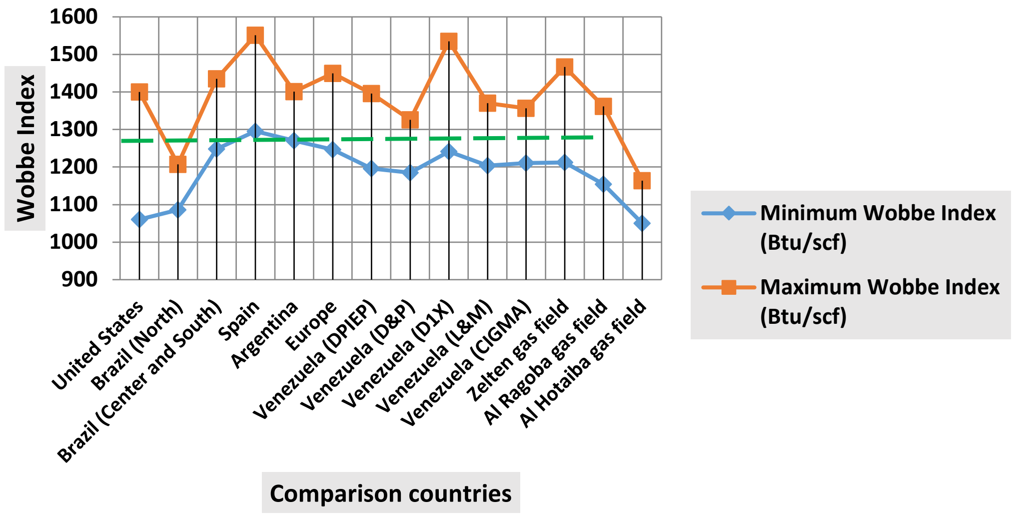


**Figure 4:** Minimum and maximum Wobbe Index ranges for different European and American countries comparing with the studied natural gases

### 4.9. Conclusion

In light of the previous findings of this study the following conclusions can be drawn:

1. The interchangeability of quality parameters are key factors to assure the investigated natural gas quality. These gases could be commercialized in the in International Markets with high quality standards and high economic yield.
2. The results of the studied gas samples gas from the investigated gas fields well presented an indicator of quality similar to the optimal values determined for the global published data.
3. These gases have a lower content of non-hydrocarbon gases and can be regarded as sweet ones, hence they couldn't promote adverse effects on turbine components in addition a good performance of turbine efficiency.
4. In general, it could be say that these gases with this ranges of studied quality indicators are within the typical range mentioned in the concerning literatures.

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