

AA25 – A Sustainable and Substitute Energy Resource Model with LPG Utilization in the Alumina Production Process

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Abstract

The final stage of the alumina production is so-called calcination process which have been witnessed to utilization of different kind of fuel sources for decades in the refineries. Type of fuel which is the most important key element of the alumina calcination process has significant impact either on greenhouse gas emissions or specific energy consumption. Beside this, accessibility to the reliable fuel resources has become an important prerequisite to achieve sustainable smooth process conditions and prevention of undesired production curtails. Two different fuel types have been used so far in the calciners of Seydisehir ETİ Aluminium Plant (SEAP) where the new energy resource conversion takes place. When SEAP was privatized by Cengiz Holding in 2005, a huge modernization effort was completed on fuel resource conversion from fuel oil to natural gas (NG) which is easier to use and extremely clean. Nowadays, a requirement to find an alternative fuel resource to NG has become highly outstanding situation at SEAP due to unexpected and overwhelming fluctuations in the energy prices all over the world. As a result of researches and feasibility studies among various fuel resources, it was determined that Liquid Petroleum Gas (LPG) would be the most economical and reliable option to consume in calcination systems. As it was known, the direct use of LPG in the firing systems is not as suitable as NG, it requires further processing steps in terms of vaporizing and calorific value adjustment. At SEAP, once the liquid has been vaporised, it needs to be blended in adequate ratio with compressed air to duplicate the calorific value of NG at a rate equal to the appliance rate of consumption, and at a quality such that calciner operates equally well under either gas. The resulting product, Synthetic Natural Gas (SNG), is ready to feed to calciners. The most critical parameter to follow in this process is Wobbe Index which indicated the appropriate calorific value for the LPG-Air blender system. The mentioned system has been commissioned and fired at one of the calciners in SEAP. The outcome of this trial has been monitored via collecting relevant process data and it will be evaluated with the comparison of specific energy consumption as well as stable operating conditions in the details of this paper.

Keywords: Alumina calcination, Alumina production, LPG usage, SNG, Wobbe index

1. Introduction

The alumina production process is a labour-intensive process that must be continuously kept under control. This process is well-known all over the world as the Bayer Process which is mostly preferable in alumina production with respect to achievable low production costs thanks to its high efficiency and low energy consumption performance. Until the final product, alumina, is obtained from bauxite ore, stages such as bauxite crushing and milling, bauxite digestion, liquor clarification, gibbsite precipitation and evaporation are completed by keeping the required parameters at appropriate values [1]. The next and final stage is calcination. After completion of the decomposition and filtration sections (parts of gibbsite precipitation), Aluminium tri-hydroxide $\text{Al}(\text{OH})_3$ or in other words $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ product is obtained and fed to the calciners in

order to perform the related phase transformation by removing physical and chemical water it contains. After all these processes, Alumina (Al_2O_3) is finally obtained, which will be transferred either to the smelter cells for primary aluminium production process or to the commercial storage silos for domestic and foreign sales.

In energy-hungry industrial applications such as the alumina calcination process, the importance of the type of fuel used becomes more evident. All possible units in SEAP facilities had been converted to NG. For alumina calcination, which is the main subject of this paper, combustion with NG takes place in both stationary fluidized bed furnace and rotary kilns. Although the system is operated regularly with NG gas, necessity of a new alternative fuel resource has been occurred. The reason for the emergence of this need is fluctuations in energy prices and energy supply problems all around the world. That is why, necessary studies were also carried out in SEAP and LPG was determined as the most suitable fuel type to be utilized. Normally, LPG is a mixture that consists of mostly propane and butane compounds, but considering the industrial controllable conditions and its higher heating value to replace NG, SEAP preferred to set up its LPG system with 100 % propane content in its alumina calcination process. SEAP decided to use this fuel resource since LPG prices depend on the petroleum market prices and natural gas has its own pricing, they have to be considered separately. It is important to follow the prices regularly so that an estimation can be done and decision can be made on which fuel is going to be used in the following production period. LPG storage tanks, LPG vaporizer and LPG/Air blender were selected appropriate to utilization of propane.

LPG can directly be used in gas phase in the burner systems as a fuel resource but this does not encounter the purpose of mentioned changes because it would require changes in the burners and flow trains since those two gases belong to different gas families, the interchangeability between NG and LPG is not straightforward. To give an example from a related industry, the Alcoa Company implemented an LPG-Air mixture system due to energy savings and environmental impact, LPG-Air mixture had to replace diesel oil, the fuel used in the anodes baking furnaces in Alumar's facility, the largest refinery of alumina in Brazil [2]. The mixture capacity range is 0–3200 Nm^3/h each unit, mixture outlet pressure is 4.0 bar, mixture average composition is 57 % LPG + 43 % Air, mixture Wobbe Index is 11800 kcal/Nm^3 while mixture HHV is 13 300 kcal/Nm^3 .

NG mostly consists of methane and it has a lower calorific value than propane. While the higher heating value of NG is around 9 200 kcal/Sm^3 , the gross calorific value of propane is around 12 000 kcal/kg since it has a higher carbon content. Since the aim of this study is to acquire an alternative with same properties to NG, propane is not directly fed to the burners. SNG is defined as Synthetic Natural Gas or Substitute Natural Gas. SNG, also known as LPG-Air or Propane-Air mixture, is a gas produced with the use of LPG that has almost exactly the same properties as NG, making it a perfect substitute for NG. The necessary amount of LPG is combined with a fixed proportion of air to obtain targeted properties. With the aid of a vaporizer, liquid LPG must first be transformed into a gaseous phase [2]. Layout and arrangement of the above-mentioned system can be seen on Figure 1.

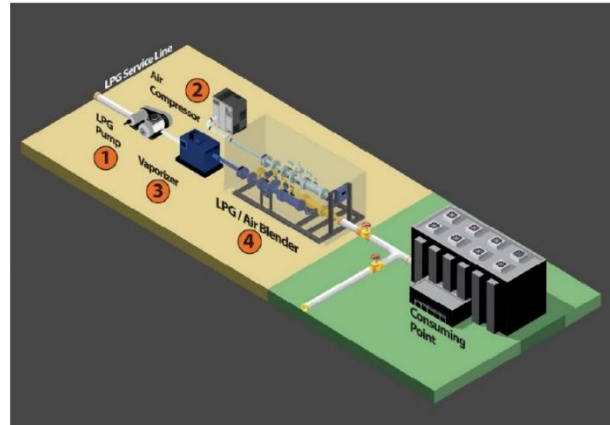


Figure 1. LPG Plant Arrangement and Flowsheet [3].

An Italian physicist named Goffredo Wobbe developed a formula in 1927 which named as Wobbe number, or Wobbe index of a fuel gas is found by dividing the high heating value of the gas in calorific per standard cubic meter by the square root of its specific gravity with respect to air. The Wobbe index is considered to be one of the best indicators of interchangeability. The Wobbe index can generally be defined as "energy flow". The ratio of LPG and diluent (air) will depend on the Wobbe index of the fuel being replaced (NG). Wobbe number matching ensures that two different fuels behave exactly like the same fuel and that the fuel exchange becomes transparent. Two different gases with the same Wobbe number will produce an equal amount of heat with the same amount of combustion air from the same burner. The matched Wobbe index of the two fuels ensures that they will have the same fuel and that the transition will be seamless, with no changes to piping or combustion equipment in case of substituting on rich gas [4].

The aim of this study is to consider the changes in the system as a result of using the SNG instead of NG, which is obtained according to the appropriate Wobbe Index value with the LPG-Air mixture, and to evaluate the results in terms of alumina production cost.

2. Methodology

2.1 Theoretical Wobbe Index Calculations of an LPG-Air Mixing System

The Wobbe index is a factor that determines whether the combustion characteristics of the original gas (NG) and the substitute (LPG/Air) gas are the same. If the Wobbe indexes of two different types of gases are the same, they both give equal heat when burned in the burners. While designing the LPG/Air unit, the Wobbe index is a very important design data [5].

If the gas flow in an orifice section is examined with the help of Bernoulli equation to obtain the Wobbe Index where number "1" represents the wider section of the orifice and "2" is for the narrowed section;

$$P_1/\gamma + C_1^2/2g + Z_1 = P_2/\gamma + C_2^2/2g + Z_2 + \Sigma Hk \quad (1)$$

where:

P	Pressure, Pa
γ	Specific gravity, kg/m ² s ²
C	Velocity, m/s
g	Gravitational acceleration, m/s ²
Z	Elevation, m
ΣHk	Total loss, m

Assuming $Z_1 = Z_2$ and $\Sigma H_k = 0$, thus:

$$P_1/\gamma + C_1^2/2g = P_2/\gamma + C_2^2/2g \quad (2)$$

If organized;

$$(P_1 - P_2)/\rho = (C_1^2 - C_2^2)/2 \quad (3)$$

where:

ρ Density, kg/m^3

Since the flow is same at two sections;

$$\begin{aligned} Q_1 &= Q_2 \\ F_1 \times C_1 &= F_2 \times C_2 \\ C_1/C_2 &= F_2/F_1 \\ C_2 &= C_1 \times (F_1/F_2) \end{aligned} \quad (4)$$

where:

Q Flowrate, m^3/s

F Cross-sectional area of flow, m^2

If Equation (3) is put into (4);

$$(P_1 - P_2)/\rho = C_1^2 \times ((F_1/F_2)^2 - 1) \quad \text{is obtained}$$

$$((F_1/F_2)^2 - 1) = k \quad \text{is named}$$

$$(P_1 - P_2)/\rho = C_1^2 \times k \quad (5)$$

is approached.

Equation (5) is the general equation of any fluid. If this equation is written for two different gases and compared to each other;

$$((P_1 - P_2)/\rho)/((P'_1 - P'_2)/\rho') = (C_1^2 \times k)/C_1'^2 \times k' \quad (6)$$

The pressures of these two gases in the gas line are equal ($P_1 = P_1'$, $P_2 = P_2'$). Also, when the same orifice is considered, the k coefficients are equal to each other ($k=k'$). Accordingly, if simplifications are made, Equation (6) becomes:

$$\rho'/\rho = C_1^2/C_1'^2 \quad (7)$$

In order for the gases flowing through this orifice to be completely substituted for each other, the thermal (heating) power they provide must be equal.

$$\text{Thermal power} = \text{Thermal power}'$$

$$Q \times k = Q' \times k' \quad (8)$$

$$C_1 \times F_1 \times K = C_1' \times F_1' \times K' \quad (\text{For same orifice: } F_1 = F_1') \quad (9)$$

where:

K Calorific value

So;

$$C_1/C_1' = K'/K \quad (10)$$

$$C_1^2/C_1'^2 = K'^2/K^2 \quad (11)$$

These two equations are formed.

If Equation (11) is put into Equation (7);

$$\rho'/\rho = C_1^2/C_1'^2 = K'^2/K^2 \quad (12)$$

is obtained. After the arrangement;

$$K/\sqrt{\rho} = K'/\sqrt{\rho'} \quad (13)$$

Equation (13) has showed up as Wobbe Index (WI). In practice, instead of ρ (density) expression, specific gravity (SG) is used.

Thus, the final equation to determine the appropriate LPG/Air mixture ratio to produce SNG can be expressed as below.

$$WI_{mix} = K_{mix}/\sqrt{SG_{mix}} \quad (14)$$

In detail;

$$WI_{mix} = \frac{x_{LPG} \times K_{LPG}}{\sqrt{(1 - x_{LPG}) \times SG_{Air} + x_{LPG} \times SG_{LPG}}} \quad (15)$$

The LPG/Air mixture ratio that can substitute the NG to be used in the system can be found by trial-and-error method with the help of Equation (15). In this equation, volume fraction of gas needs to be used because calorific value and density of gas mixture are proportional to volume fraction. Thus, x_{LPG} here represents the volume fraction of LPG.

The Wobbe index can also be interpreted as a function of gas quality. It varies according to the LPG/Air ratio and LPG composition. Hydrocarbon gases with the same Wobbe index form the same amount of heat and combustion products. They also require an equal amount of combustion air.

2.2 Practical Wobbe Index Calculations at SEAP

The first parameter that should be known to calculate the Wobbe Index value of LPG/Air blend system is the calorific value of the fuel resource currently being used. In this context, the fuel is NG and standard gross calorific value of it is 9 155 kcal/Sm³. The calculations to be made in the light of this information are as follows;

Specific gravity of NG that SEAP used in the facility was found as 0.61 according to its chemical composition. Thus, by using Equation (14);

$$WI_{NG} = K_{NG}/\sqrt{SG_{NG}} \quad (16)$$

$$WI_{NG} = 9\,155/\sqrt{0.61} \quad (17)$$

$$WI_{NG} = 11\,722 \text{ kcal/Sm}^3 \quad (18)$$

That means LPG/Air blend ratio should be arranged to get the Wobbe Index value of 11 722 in Equation (18).

Since the composition of LPG at SEAP is mainly consist of propane, related values are calculated for propane according to grab sample analysis. Calorific value of it is 23 648 kcal/Sm³ and density of propane at STP (0 °C and 1 atm) 1.986 kg/m³. At the same time, calorific value of air is 0, density of air at STP is 1.292 kg/m³ and specific gravity (SG) is 1. Therefore, the SG of propane is calculated in Equation (19) according to that density.

$$SG_{LPG} = SG_{Propane} = \frac{\rho_{gas}}{\rho_{air}} = \frac{1.986}{1.292} = 1.537 \quad (19)$$

$$11\,722 = \frac{x_{LPG} \times 23,648}{\sqrt{(1 - x_{LPG}) \times 1 + x_{LPG} \times 1.537}} \quad (\text{kcal/Sm}^3) \quad (20)$$

After placing the formula on Excel and by using Solver, required ratios are determined. When the LPG composition in the mixture was adjusted as 0.566, the rest of the mixture remained at 0.434 which is air composition and when these values were inserted into the formula, the sought-after Wobbe Index value of 11 722 was obtained.

As a summary, in order to equal the Wobbe index values both of NG and SNG to be burned in the calciner, LPG and Air compositions with the help of the regulators on the LPG-Air Blender system is adjusted. The theoretical result is shown below.

Table 1. Theoretical LPG/air composition in SEAP SNG system.

Air% in SNG	LPG% in SNG
43.40%	56.60%

This ratio is valid only when the gross calorific value of NG is 9 155 kcal/Sm³. However, NG supplier of SEAP cannot provide exactly same calorific value at every month. For instance, in one month the value is 9 191 kcal/Sm³ and in another month it is 9 389 kcal/Sm³. Hence, Wobbe Index can vary depending on the gas composition and its calorific value.

The NG transportation pipeline, valve train and related accessories at the calcination area of SEAP in the current situation was implemented to operate with 4 barg pressure. In order to utilize LPG easily with the same infrastructure whenever it is required as a backup fuel, and in order not to make any changes in the existing NG supply system of the calciner, the SNG system has also been designed according to 4 barg pressure usage.

In general, SNG systems are designed for 1 barg or 1 atm pressure considering its easy handling and continuous consumption under different ambient air conditions. In addition, 4 barg is a pressure that requires specific precautions while preparing and usage of LPG mixtures and SNG. Thus, SEAP has adopted a new approach that enables supply of SNG at 4 barg without doing any changes or modification on the existing fuel transfer, regulation and combustion system.

In the concept of ideal gases, at 20 °C, the vapor pressure of commercial propane is 7.4 bar, while that of commercial butane is 1.2 bar. In addition, 30 % propane – 70 % butane containing LPG mixture fuel has a vapor pressure value of 3.0 bar at the same temperature. For this reason, it was concluded that bulk LPG with almost 100 % propane content should be used in the system installed at SEAP. Another reason behind the preference of propane is that as the pressure of LPG increases, its tendency to the liquefaction (dew) increases as seen in the graph below (Figure 2) [6].

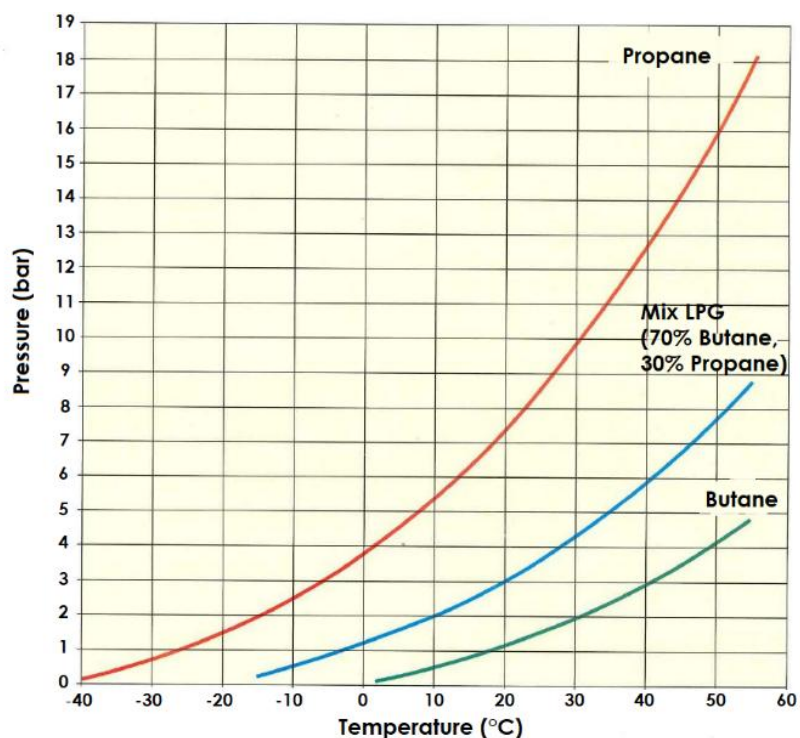


Figure 2. Saturation Vapour Pressure for Components of LPG.

However, the increase in percentage of propane in the LPG mixture provides opportunity to utilize the SNG at low surrounding temperatures corresponding to the similar dew point with the mixture. Considering that LPG temperature will exceed 40 °C in the vaporizer system, the fuel for the system operating at 4 barg pressure should contain almost 100 % propane in order to avoid liquefaction problems as can be seen on Figure 3.

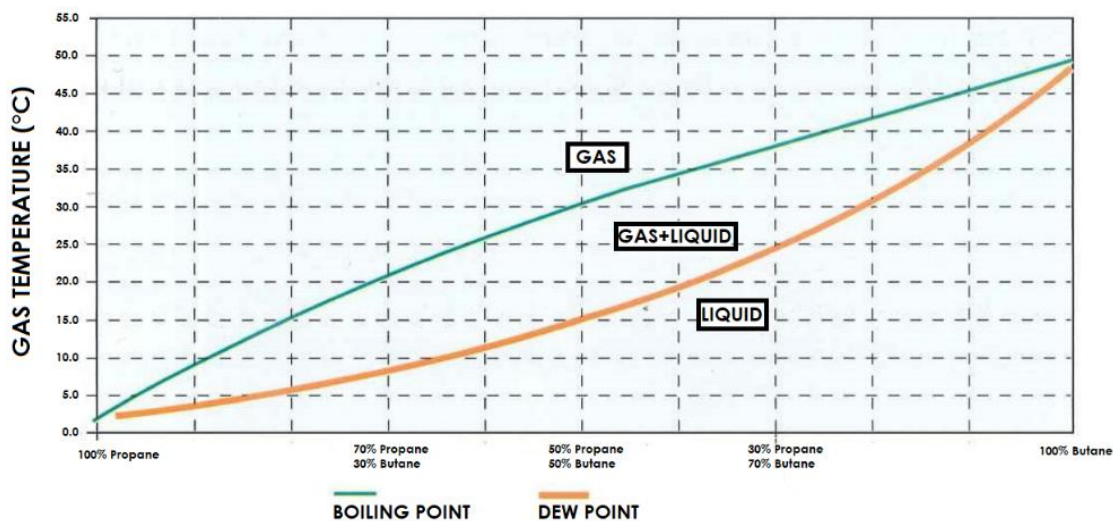


Figure 3. Boiling and Dew Point Temperatures of LPG Mixtures at $P_{\text{gas}} = 4$ barg.

The aforementioned LPG system was implemented and commissioned at one of SEAP's calciners in order to test its practical usage on an industrial scale calcined alumina production. During the operation, after several adjustment and optimization works were done the most appropriate SNG mixture composition was achieved. As it can be seen on Table 2, blended propane LPG ratio in

the mixture that was fed to the burner adjusted day by day for getting the optimum Wobbe Index values. The propane percentage in the mixture has been increased by adjusting the regulators of the LPG/Air mixer system, thus the Wobbe index has also changed. Although the propane-air ratio theoretically determined as 56.6 % and 43.4 %, it was understood that 4 barg operating pressure which is the requirement of existing combustion system was the reason theoretical values could not be obtained. As can be seen from Table 2, the propane ratio increased up to 63 % while SNG having similar volumetric flows comparing with NG utilization.

Table 2. Daily SEAP Wobbe Index measurement and adjustment.

Number of Days	Propane Blending Ratio, %	Air Blending Ratio, %	Wobbe Index
Day 1	57.8	42.2	11 268
Day 2	58.1	41.9	11 194
Day 3	57.8	42.2	11 182
Day 4	59.3	40.7	11 515
Day 5	61.5	38.5	11 901
Day 6	62.7	37.3	12 136
Day 7	63.3	36.7	12 241
Day 8	62.4	37.6	12 069
Day 9	61.5	38.5	11 899
Day 10	60.2	39.8	11 807

When the propane and air ratios that calculated by the SNG system were placed into Equation (15) and made the calculations, it was seen that the Wobbe Index result, which was expected to come out theoretically, could not be reached. For instance, in Day 10;

$$WI_{mix} = \frac{0.602 \times 23,648}{\sqrt{(1 - 0.602) \times 1 + 0.602 \times 1.537}} = 12\,376 \text{ (kcal/Sm}^3\text{)} \quad (21)$$



Figure 4. Inline Propane Ratio Measurement Device at SEAP.

As can be seen, the theoretically expected Wobbe Index value is 12 376, but the value read on the screen is 11 807. This means that some situations have arisen that are not taken into account when making the theoretical calculation. The reason for this difference is the pressure factor, because the pressure throughout the system is assumed to be 4 barg while making the theoretical calculation. However, the pressure in the LPG and air side is always +/- 0.3 barg changing

regarding to fluctuations on the system. Nevertheless, the replacement of the NG by the SNG is not supposed to cause any problem if their Wobbe Indexes do not differ in more than about 5 % [7]. Hence, no extra problems were observed in the operation of the system and during the combustion.

When the calciner system was operated with NG the average gas volumetric flow of the kiln was about 1435 Sm³/h. That is to say, that amount of gas is flowed into the system to achieve a good combustion for calcination process while producing desired product quality. Accordingly, the flow rate was adjusted considering that the produced SNG should be fed to the kiln through the gas valve train at the same amount. However, the required in-furnace temperature could not be achieved with SNG at the same gas flow rate, so the flow increased to 1500 Sm³/h to reach the required temperature. This means that when the LPG system is used, the consumption will be a little higher than the NG, which also confirms the difference between theoretical calculation and actual values of Wobbe Indexes.

3. Results and Discussion

After all preparations were completed, the bulk LPG system was commissioned. With the help of pumps, propane was taken to the storage tanks in kilograms, it was sent to the vaporizer system first and then to the blender, where the appropriate fuel/air mixture will be set and SNG will be obtained.

The produced SNG has been successfully burned instead of NG in SEAP rotary kilns. Before the SNG system was activated, the kiln was operated with NG for 10 days in metallurgical alumina mode. In a 10-day period, the calciner has run in the same mode and this enabled us to compare the two fuel types under the same conditions by correlating with the production-consumption data. Results of these trials has listed in Table 3.

Table 3. Production and consumption values for LPG and NG in 10 days.

Days	Daily LPG Consumption, kg	Daily Alumina Production Amount, tonnes	Specific Consumption, kg LPG/t Alumina	Daily NG Consumption, Sm ³	Daily Alumina Production Amount, tonnes	Specific Consumption, Sm ³ NG/t Alumina
Day 1	28 070	328	85.6	34 500	322	107.1
Day 2	27 555	315	87.5	35 300	336	105.1
Day 3	27 526	317	86.8	35 100	331	106.0
Day 4	28 345	326	86.9	35 100	339	103.5
Day 5	28 758	338	85.1	35 800	342	104.7
Day 6	29 534	351	84.1	35 100	330	106.4
Day 7	28 797	336	85.7	35 300	332	106.3
Day 8	28 393	341	83.3	36 200	335	108.1
Day 9	27 993	332	84.3	36 000	331	108.8
Day 10	28 609	338	84.6	36 100	335	107.8
Total / Average	283 580	3 322	85.4	354 500	3 333	106.4

According to the results obtained, the amount of fuel that needs to be consumed to produce one tonne of alumina can be calculated:

$$\frac{283\,580 \text{ kg LPG}}{3\,322 \text{ tonnes Al}_2\text{O}_3} = 85.4 \text{ kg LPG/t Al}_2\text{O}_3 \quad (22)$$

According to Equation (23) consumed amount of NG to produce one tonne of Al_2O_3 :

$$\frac{354\,500 \text{ Sm}^3 \text{ NG}}{3\,333 \text{ tonnes Al}_2\text{O}_3} = 106.4 \text{ Sm}^3 \text{ NG/t Al}_2\text{O}_3 \quad (23)$$

Considering that the process is carried out under the same conditions, while producing the same amount of alumina, 85.4 kg LPG was consumed which corresponds to 111.9 Sm^3 NG as can be seen in Equation (24).

$$\frac{85.4 \text{ kg LPG}}{1 \text{ t Al}_2\text{O}_3} \times \frac{12000 \text{ kcal}}{1 \text{ kg LPG}} \times \frac{1 \text{ Sm}^3 \text{ NG}}{9155 \text{ kcal}} = 111.9 \text{ Sm}^3 \text{ NG/t Al}_2\text{O}_3 \quad (24)$$

Equation (24) shows that a 5 % specific consumption ratio difference between LPG and corresponding NG which is in the tolerable range for this kind of industrial scale production. This result also demonstrates that there is a necessity of further adjustment, optimization and fine-tunings need to be performed.

4. Conclusions

The aim of this study was to examine the implementation of a sustainable back-up or standby fuel resource on an industrial scale production system which is for the alumina calcination process at SEAP. Stationary fluidized bed furnace and rotary kilns in the facility have been burned with NG. As the daily NG consumption rate is between 30 000 to 50 ,000 Sm^3 at SEAP which can be considered as high fuel consuming facilities, the economic analysis of the fuel resource is also done continuously. Imbalances in worldwide energy prices have led SEAP as well to find a solution, and as a result of researches and calculations, Synthetic Natural Gas (SNG), also known as LPG-Air or Propane-Air mix has come to the fore as the most suitable fuel resource to replace NG.

The most important parameter when using the SNG is the Wobbe Index because it is an accurate representation of the calorific value of the fuel feeding to calciner burners. If two different gases have the same Wobbe number, they will produce an equal amount of heat and combustion products and will require the same amount of combustion air. Although the propane ratio in the SNG mixture was found to be 56.50 % and the air ratio as 43.50 % as a result of theoretical Wobbe index calculations, it was determined that when the action started, the appropriate propane ratio should be above 60 %, and this can be seen in Table 2.

Ultimately, after completing all the relevant preparations, system was commissioned and alumina production was carried out. Before the burner was ignited with SNG, it was first burned and operated with NG to achieve the targeted kiln inside temperature and to do comparison between two fuel types. The kiln was operated with both types of fuel during 10-day periods in order to fully complete required adjustment and optimization works.

According to collected actual process data, the specific consumption rate of LPG per tonne of alumina produced is 85.4 kg while it corresponds to 111.9 Sm^3 for NG. Thus, approximately 5 % specific consumption ratio difference between LPG and corresponding NG was occurred. It was in a tolerable range so; the applicability of substitution concept was proven. That means LPG can exactly be considered as a backup or standby fuel depending on both NG supply problems and sudden cost fluctuations.

As it was clearly indicated in this paper, the resulting production data revealed that the SNG produced with LPG can be used successfully. If the increase in NG prices exceeds LPG, SNG may even be SEAP's main fuel choice since the difference is really low. Finally, this paper demonstrates us, LPG can be used not only in alumina calcination but for various purposes such as standby or backup, base load, peak shaving and commingling systems.

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