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Influence of Fuel Mixtures and Biomass on Efficiency and Safety in Combustion Process

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Combustion equipments use fuel mixtures with variable composition according to available products. In order to analyze the characteristics of these blends a set of particular cases were simulated using SimSci Pro II ® software. Simulation was applied to find the correlation between process safety problems, combustion efficiency, equipment reliability and service life as a function of fuel composition.

It was evident that combustion mode failures are related with High Heating Value (HHV) and fuel density. The impact of changes in the composition mixtures over thermal consumption may be significant and may exceed the limits of specified flame conditions in design standards for boilers and furnaces. In turn, these situations may cause both operational problems and integrity issues for the equipment.

The main effects of the variation of calorific value and Wobbe index in the furnaces are evident in the high temperatures of tubes surfaces. There is a direct relationship between the increasing of heating power and the increase of surface temperature at the tubes. This effect causes also overheating in equipments, specially on radiation area; likewise, these conditions affect the burner, which is not designed for these blends, and lead to inefficient combustion, increased gas emissions and higher cost for maintenance due to damage in the structure of the furnace and its associated systems.

Different biomass and mixtures of natural and refinery gas used as fuel in furnaces and boilers were compared in scenarios of operational upset, all of them generating combustion inefficiencies, and negative impact on the integrity of equipment.

1. Introduction

The combustion reaction study includes chemistry kinetics and gas theory. In this regard, in the area immediately after the flame, the combustion products are in chemical equilibrium or very close to equilibrium, so it is possible to develop methods for calculating the adiabatic flame temperature, energy efficiency and the composition of the combustion products.

There are various types of fuel; wood biomass has been used as fuel at industrial and domestic scale during centuries (Mayumi, 2010). Recently, there has been an increasing interest for mixtures with fossil fuel for combustion or co-combustion due to the possibility of decreasing environmental impacts (European Commission, 2010). Biomass fuel is an alternative for non interconnected or distant zones.

From an environmental point of view, there exists concern for emissions, but factors like resources and technology available, cost for operation and maintenance and ability to adapt (Villeneuve, 2012) must be considered.

Fuel gas is the main source of energy used by furnaces and boilers for process heating of streams at industrial scale, also for the thermal decomposition of the intermediate streams and steam production, used directly on plants or power generation. In several cases, biomass gasification can be used in

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industrial processes. In petroleum refining case, fuel gas is generally a blend of natural and multiple gas streams, which are generated in the refining process. These mixtures are usually not homogeneous, so they generate perturbations that modify the degree of desired conversion, thus affecting equipment efficiency, operational safety and pollution emissions, resulting in an increase of maintenance costs, and other related problems.

In order to explore this issue, a case study regarding description and fuel streams characterization was done, facing operational problems due to the presence of High Heating Value (HHV) gas streams to the fuel gas header (Saavedra, 2013).

In the first stage of this study, a simulation of the cases with enriched fuel gas into the furnaces and boilers feed, including streams such as propane, ethane, ethylene and propylene was developed. Obtained results were compared with plant historical data where the effects of the deviations of these gases could be checked and compared with efficiency in industrial process using biomass.

2. Method

2.1 Approach

This paper analyses the properties of fuel (solid and gas) and its impact on thermal efficiency at industrial process, taking a petroleum refining and agro-industrial process using biomass like study cases .

To identify and characterize the multiple gas streams present in the process, it was necessary to extract and analyze characteristics, properties and flows from the stream components, and also study those components utilizing data extracted from the refinery information systems.

After this step, a group of simulation cases was built with SimSci Pro II ® software.

Figure 1 shows simulation scheme submitting the mixture of the natural gas stream (gas Guajira) and refinery gas from the absorber for ethane - ethylene. High Heating Value (HHV) and the relative density of the fuel blend were used to calculate the Wobbe index for fuel gas.

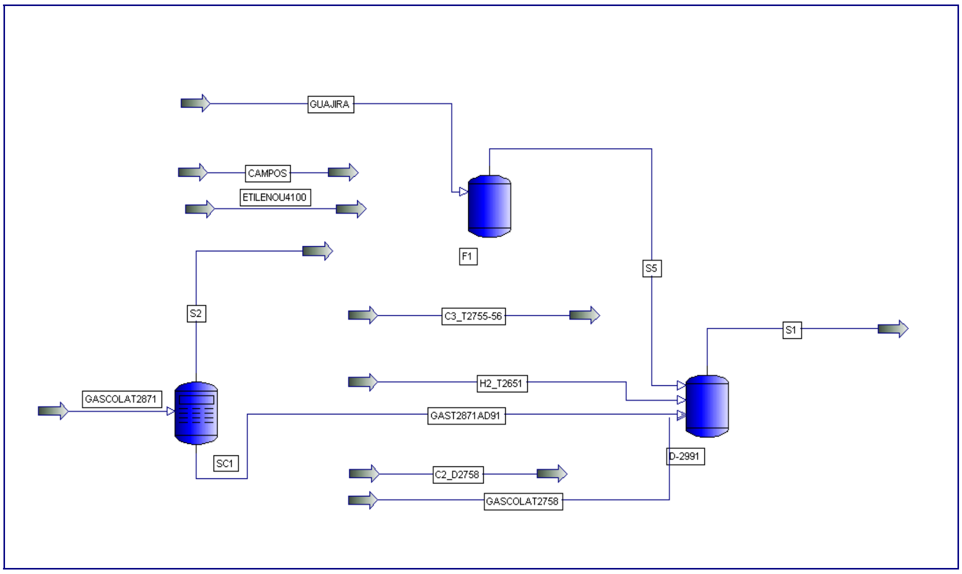

Figure 1.Simulation scheme

- ➢ Methods to calculate gas interchangeability.

Currently there are multiple methods developed to find fuel gases interchangeability, based on the calculus of magnitudes called “Interchangeability indices” which combine physicochemical properties of the gas with combustion phenomena, allowing a better characterization and thus a tighter and more precise interchangeability range. Likewise these methods may help to determine the behaviour of a substitute gas in a combustion process. In this case, interchangeability was evaluated using Wobbe index, which is useful to group gases on the basis of their energetic contents. Based on this calculus, it is possible to point out that two or more gases are interchangeable if they have the same Wobbe number (Cortés, 2003).

Equation 1, was used to evaluate Wobbe index.

$$W_m = \frac{PCS_m}{\sqrt{d_m}} = \frac{\sum X_i PCS_i}{\sqrt{\left(\sum X_i d_i\right)}} \qquad (1)$$

Where, PCS= High Heating Value (HHV) and *d*= density

The resulting Wobbe indices are evaluated considering the classification presented in table 1 (Amell, 1999).

Table 1: Classification of fuel gas by Wobbe Index

Family	**Denomination**		**W[kWh/m3]**
FIRST	Manufactured Gas		6.5-9.0
	GROUP A	City Gas (CH_4-H_2)	6.5-8.0
	GROUP B	Coke Gas	7.0-9.0
	GROUP C	Hydrocarbon gas mixture - Air	6.5-8.0
SECOND		Natural gas	11.0-17.0
	GROUP H	High W	13.5-17.0
	GROUP L	Low W	11.0-13.5
THIRD	Liquefied Petroleum Gas (LPG)		21.5-26.0

Variables that were taken into account to develop this study were: temperature, pressure, molar composition, gas flow, and HHV, which were calculated for each studied stream.
The utilized components were: methane, ethane, ethylene, propane, propylene, n-butane, i-butane, n-pentane, i-pentane, carbon monoxide, carbon dioxide, hydrogen, oxygen, nitrogen, and hydrogen sulfide.
Peng-Robinson's equation was selected to model the thermodynamic behavior of the system, since the blends included hydrocarbons and slightly polar components such as carbon dioxide and hydrogen (Twu, 2007).

Agro-industrial materials furnaces use the energy obtained in solid biomass combustion for heating the air that is used to dry and cook materials. In this case, the heat flow entering the furnace is given by heat entering with the fuel (Qc) and with air (Qa). So, the heat available can be expressed as (Fernandez, 2004):

$$Q_D = Q_C + Q_a$$

Where: Q_D is 17890 kJ/Kg, humidity content 8.9% and ash content 17.8%.

3. Results and analysis

The first simulation was done including a base case, built with the following streams:

- Natural gas (Guajira's gas)
- Refinery gas (hydrogen amine treated gas and gas from the top of the recovered ethylene ethane).

Simulation results show that there are two types of streams derived from the refining process that may be involved with the fuel gas system; the first stream, with high observed values of HHV (Ethane, Propane, and Butane), and the second with obtained a lower value of HHV (Hydrogen and Methane).

Results were analyzed taking into account the characteristics of the compounds present in the simulated streams.

The analysis of these results shows that participation of gas streams with low HHV depends on several factors like:

- Availability of natural gas;
- Operational stability of the process units that generate the streams;
- Operational stability of the process units that receive the streams;

The thermal consumption in the burner is expressed as Wobbe number. In a scenario of adjusted volumetric performance, this consumption will change proportionally with values of Wobbe number of the supply gas. At this point, interchangeability problems are associated with the change of fuel and the absence of any modification in volumetric flow speed or in the burner holes.
Wobbe number provides information about the impact of fuel composition on flame characteristics. Impact of changes in the composition of the fuel mixtures can be significant and may exceed the technical limits for boilers and furnaces design standards. These situations can in due time can lead to performance and integrity emergencies.

Based on simulation results, it has been suggested that composition changes in the gas can affect the efficiency of the application. In most cases this should be only a secondary impact, because changes in useful heat tend to be proportional to the flow entrance of gas, and reasonable changes in commercial gases will not drive to failures, rendering a relatively constant thermal efficiency.

Second order effects over efficiency might be associated with flames inefficiently interacting with heat exchangers and other change influences such as length and shape of the flame. A reduced entry due to the mixture of the stream with a gas with a low Wobbe number may cause a short flame and an inefficient heat transfer. Otherwise, cold flames, from a low Wobbe number fuel gas, may help to increase the production of CO, as a result of insufficient temperature that cannot produce a complete oxidation on reaction area (Muller, 2011). However, this reduced efficiency should be the less important problem for the consumer. A group of researchers from DTI (Williams, 2005) did not found a strong relationship problem between the efficiency of associated applications of gas tested and a wide range of Wobbe number (Rahmounia, 2003).
Wobbe number for the base case can be found on L group of the second family, and for the simulated cases it moves from L to H group at the same family. Table 2 shows simulation results for seven cases, where concentrations of compounds was changed.

Table 2.Simulation results.

Compound	**CONCENTRATION, (molar fraction)**						
	Base Case	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Methane	0,75	0,67	0,69	0,62	0,70	0,58	0,71
Ethylene	0	0	0,05	0,05	0,07	0,05	0,01
Ethane	0,02	0,01	0,06	0,05	0,01	0,10	0,02
Propylene	0,01	0,09	0,01	0,08	0,01	0,08	0,01
Propane	0,01	0,03	0,01	0,03	0,01	0,03	0,01
i-Butane	0	0	0	0	0	0	0.0
n-Butane	0	0	0	0	0	0	0
i-Pentane	0	0	0	0	0	0	0
CarbionDioxide	0	0	0	0	0	0	0
Oxygen	0	0	0	0	0	0	0
Hydrogen	0,16	0,14	0,14	0,13	0,15	0,12	0,20
Carbonmonoxide	0,01	0,01	0,01	0,01	0,01	0,01	0,01
Nitrogen	0,03	0,03	0,03	0,03	0,03	0,12	0,12
Hydrogensulfide	0	0	0	0	0	0	0
			Properties				
Relativedensity	0.539	0.641	0.582	0.670	0.568	0.687	0.542
HHV, Wh/m$_3$	9.64	11.27	10.35	11.75	10.11	12.04	9.40
WOBBE INDEX, kWh/m$_3$	13.13	14.08	13.57	14.38	13.41	14.53	12.76

Fluctuations on fuel gas blends properties cause overheating, due to over or under energy loads, producing an uneven distribution of heat transfer and turbulence in the flame that causes direct impingement in the coil or the burner. This is the appropriate condition for the development of internal coke deposits, high skin temperature and severe environmental and mechanical challenges and damages, as shown on figure 2.

The presence of coke on the inner surface of the coil tubes causes an irregular reduction of the internal diameter of the pipes that increases the pressure drop inside the tubes, also generating a heating transfer resistance that increases metal temperatures, affecting tube material mechanical properties and furnace's operation overall efficiency.

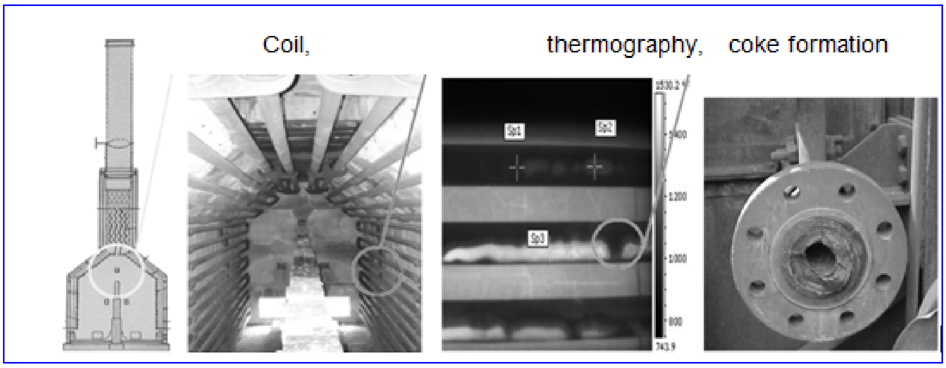

Figure 2. Furnaces inspection images

Problems related with the studied issue of gases interchangeability are concordant with those found in literature (AGA, 1946).
It was possible to find a few common problems related to the combustion process and to gas interchangeability (Williams, 2006):

- Safety: Safety issues in combustion include the control of apparatus and equipments pollution generation (CO), overheating of apparatus surfaces, and clearances maintaining for combustible materials, fire hazards due to flame spread and overpressure due to delayed ignition.

- Performance reliability: Performance problems include flame instability, which generates operational stops due to the activation of safety devices from overheating or depletion of the flame, exhaust or flashback flames from the burner header. They also include reduced efficiency due to changes in input speed, height and shape of the flames, changes related to the exchange of heat at the surface, that alters equipment capacity

- Service life of appliances and equipment: The impact over the service life depends on the thermal degradation, fatigue and deformation of the equipment components, including heat exchange, and fouling due to soot production. These problems can lead to progressive deterioration of performance reliability and security of the processes.

Comparatively, a wide portion of the scientific research in biomass combustion is destined to wood gasification, woody fuels, while research in agricultural biomass is less intensive (Villeneuve et al., 2012).
The problems associated with biomass combustion take into account the contents of chlorine and nitrogen, which are responsible for the formation of HCl and NOx (van Loo and Koppejan, 2008). Problems associated to corrosion and fouling with consequences in equipment integrity and safety process, comparable with the use of fuel gas is also reported.
The results from the combustion of solid biomass showed the following problems:

- Low efficiency (about 49%)
- Increased heat loss in furnaces (5,6% in zones of convection and radiation)
- Unburned mechanical contributed by the high carbon content of ash (10%)
- Increasing environmental concerns.

Although the combustion and co-combustion of solid biomass furnaces are a good solution to the problems of heat and electricity generation in agroindustry, because it avoids costs due to the purchase of power and expensive fuels, energy efficiency is low. These results concur with those reported by Valverde

(2007) for the case of the combustion of rice husk and by Zuorro and Lavecchia for the combustion of spent coffee ground (2011, 2012) and of spent tea leaves (2013).

4. Conclusions

Blends of natural and refinery gas used as fuel in furnaces and boilers, in scenarios of operational abnormality in refineries, are not generally interchangeable, and they generate combustion inefficiencies, and negative impact on the integrity of equipment.
The main effect of the variation of calorific value and Wobbe index in the furnaces is higher temperatures of tube surfaces. In fact there is a direct relationship between the increasing of heating power and the increase of surface (skin) temperature on the surface of the tubes. This effect causes also overheating in equipment, particularly on radiation area. Likewise, these conditions affect the burner, which is not designed for these blends and brings about inefficient combustion, increased gas emissions in the environment and higher maintenance costs due to damage in the structure of the furnace and its associated systems.
Therefore, it is necessary to have an accurate knowledge and control of the amount of energy related to the usage of gas mixtures, since these values can increase furnace operational efficiency, reduce fuel gas consumption and increase the profit margin of the process as a result of the reduction of related costs to the number of unscheduled downtime, maintenance costs and degradation of furnaces materials.
Special attention must be paid to the use of biomass as fuel due to the problems associated with energy efficiency and environmental impact.

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