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Research paper

Estimation of combustion air requirement and heating value of fuel gas mixtures from flame spectra

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HIGHLIGHTS

- Flame emission spectroscopy applied to evaluate the fuel quality of gas mixtures.
- Spectra of reference hydrocarbon gas + low calorific gases mixtures presented.
- Air flow at OH peak related to stoichiometric combustion air and heating value.
- Method has potential with industrial waste gas evaluation.

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ABSTRACT

This paper explores an optical method for evaluating the quality of fuel gases with uncertain composition. A spectrometer is used to acquire the radiation from flames generated with different fuel gas mixtures. Natural gas flame spectra are known to have features which vary with air/fuel ratio. In the current study flame spectra were collected from a number of fuel gas mixtures consisting of a reference hydrocarbon gas and varying amounts of a low calorific gas. During these tests the fuel flow rate was kept constant and the air flow rate was varied to generate flames with different air/fuel ratios. Analysis of the spectra showed that as air is decreased from a value greater than the stoichiometric requirement for the reference gas the OH band intensity goes through a maximum and decreases at lower air flow rates. The air flow rate at which the OH maximum occurs is correlated to the stoichiometric or combustion air requirement and the higher heating value, which are fuel quality parameters for that mixture. This observation suggests the basis for a method which has the potential to be designed and applied for estimating the combustion air requirement and heating value of gas mixtures with unknown fuel properties. To the best of our knowledge very little research is reported in literature on the application of flame emission spectroscopy for direct fuel quality evaluation.

1. Introduction

Gaseous fuels play a vital role in the production of energy and in industrial heating. Gaseous combustion is cleaner, more efficient and easier to implement when compared to solid and liquid fuels. Fuel gases may be classified according to their calorific value which is a measure of the heat they generate. Natural gas which is mostly methane is widely used in industrial combustion. Methane and higher hydrocarbons such as propane and butane are high calorific gases. Syngas produced from gasification of fossil fuels and containing high amounts of hydrogen along with carbon monoxide is an example of a medium calorific fuel. Gases which are derived from the steel, gas and chemical industrial streams often contain hydrogen and carbon monoxide diluted with inert gases such as carbon dioxide or nitrogen. Examples of such low calorific product gases are coke oven gas and blast furnace gas which when used as fuel have the potential to reduce the cost of industrial combustion. One of the challenges faced in this task is to adapt an existing combustion system, generally designed for natural gas, for use with fuel gases with varying properties, without affecting the efficiency and other operational criteria. Further, gas flaring is an important component of industries such as the Canadian oil sands development which are being setup to meet the ever increasing requirement for energy around the world. In general waste gas streams from refineries and chemical plants have varying composition and they are often fed to a flare stack to destruct harmful emissions [1].

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Nomenclature

FES	flame emission spectroscopy
HHV	higher heating value
CA	combustion air requirement
Specific gravity (ρ)	density of gas/density of air
CARI index	CA/$\sqrt{}$specific gravity
nm	nanometer (unit for wavelength)
Wobbe index (WI)	HHV/$\sqrt{}$specific gravity

To achieve efficient flaring it is necessary to know the amount of air required. Knowledge about the calorific value of the flared gases will allow one to determine if they can be used as energy saving fuels rather being burned. This paper describes an optical method which has the potential to be applied to develop a cost effective and field deployable technology to evaluate the fuel quality of industry generated waste gases.

Two important parameters which are traditionally used to define fuel quality are the Wobbe index (WI) and the combustion air requirement index (CARI). For a given flow control valve with prescribed area of cross section and pressure drop, WI is defined as the ratio of the higher heating value (HHV) per unit measure of the gas to the square root of the specific gravity ρ of the gas.

$$WI = HHV \Big/ \rho^{(1/2)} \tag{1}$$

In the current document HHV and WI are expressed in (kJ/Nm^3) and specific gravity is defined as density of gas/density of dry air. The Wobbe index (WI) is named after the Italian physicist Geoffredo Wobbe [2] who observed in 1927 that gases with equal values of WI may be exchanged in process heating. Furnaces, turbine or and boilers in refineries and other industries can be exposed to frequent and sudden changes in the fuel gas composition. The flow of a fuel gas mixture through an orifice varies with its specific gravity. Wobbe index is defined to include the effect of specific gravity and it is used to compare the combustion energy output of different fuel gases without knowing their detailed composition. If two fuels have identical Wobbe indices for given pressure and valve settings the energy output will also be identical. The Wobbe index is a critical factor to minimize the impact of fluctuations in the fuel gas supply and to increase the efficiency of the combustion system [3] because equipment designed to operate at a certain WI usually have a tolerance of only ~5%.

Combustion air requirement (CA) is the amount of air required for complete combustion of a unit measure of a gas. As stated earlier the volumetric flow of a gas through an orifice is related to its specific gravity. CARI includes this effect of specific gravity in determining the air flow needed when the fuel composition changes in industrial heating processes and it is defined as the ratio of combustion air requirement (CA) to the square root of specific gravity ρ.

$$CARI = CA/\rho^{(1/2)} \tag{2}$$

Volume units are used to specify the rates of all the flow dependent variables in this paper. CA and CARI are ratios and are dimensionless.

Literature [3] on Wobbe instruments indicates that, for many saturated hydrocarbons, there is a nearly perfect linear relation between the Wobbe index and the CARI index. Therefore, instead of measuring the higher heating value of a fuel directly using a calorimeter, it is possible to determine the air requirement to calculate the CARI index and then correlate it to the Wobbe index. This is stated in industrial reports [4] as the purpose of defining and calculating CARI.

Currently available commercial Wobbe meter devices (e.g. Hobre, COSA, and Siemens) determine the combustion air requirement by burning a small quantity of the test fuel with known amount of air and measuring the excess oxygen with a commercial O_2 sensor. O_2 may be measured with a traditional zirconia sensor [5]. Gas chromatography is another but expensive method for measuring excess oxygen [6]. The principles of these established technologies are described in the references cited. Combustion air requirement is calculated from the measured excess oxygen. Specific gravity and HHV of the gas are measured with separate techniques and the CARI and Wobbe indices are deduced with Equations (1) and (2). Commercial Wobbe instruments routinely measure CARI and correlate it with WI. When natural gas used in industry contains ethane, propane or other saturated hydrocarbon in addition to methane the Wobbe or CARI index may be used to monitor and control the combustion. When gases such as CO and H_2 are present WI and CARI are not strictly proportional and it is useful to measure both WI and CARI to optimize the combustion.

Spectroscopy is a conventional optical [7] method for recording the spectral radiation from a flame. In recent decades the availability of small portable fiber coupled spectrometers has made Flame emission spectroscopy (FES) an attractive technique for studying laboratory as well as large scale flames [8–11]. In this approach a fiber optic probe views the flame, collects and transfers the input light to the spectrometer which disperses the signal and records a spectral profile which is an array of intensities at different wavelengths. Typically the fused silica optical fiber has a 25° view angle and is enclosed in a steel jacket with a fused silica window. The steel jacket allows cooling connections for the fiber if necessary and it is also useful for easy probe handling. Commercially available hand-held spectrometers are equipped with CCD (charged couple device) array detectors and spectral ranges extending from 200 to 800 nm. They can acquire a flame signature in milliseconds and hence FES can be designed to have fast response and online monitoring capabilities. The characteristics of the spectral profiles of natural gas flames are related to changes in the air/fuel ratios, flow rates and heat release. Chemiluminescence in gas flames and the correlation of CH and OH radical emission to the air to fuel ratio is well reviewed by Guyot and Lacarelle [12] and the references cited there in. The purpose of the current research is to explore the applicability of flame emission spectroscopy for designing a tool for estimating the fuel quality of varying gas mixtures as they are fed into a combustion system for industrial heating.

2. Measurement setup

A blast burner, which is a modified version of a Bunsen burner, was used for these bench scale studies. Fig. 1 shows a schematic diagram of the measurement setup. The blast burner with a grid on the top allows better mixing and gives a hotter flame. This burner is enclosed in a chamber connected to a fume hood for proper venting of the exhaust gases. Air holes in the chamber near the top cylindrical tube allow sufficient air infiltration to dilute and cool the post combustion gases. A thermocouple is inserted in the chamber and also in the cylindrical pipe connecting the chamber to a fume hood to monitor the temperature in these regions and keep it below 200 C. The chamber is equipped with a removable door. This door (not shown) was closed during data acquisition and it is fitted with a centrally located glass view port. The closed door blocks external light from entering the probe. It also prevents room air from mixing with the combustion air. The inside walls of the enclosure were painted black to minimize reflected radiation. To ensure further