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Monitoring Industrial Combustion Through Automotive Oxygen Sensor

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ABSTRACT

The monitoring of oxygen percentage in flue gases is one of various ways of controlling efficiency and emissions of industrial combustion. In general, flue gases analyzers are expensive and not accessible to small scale industries. The automotive Lambda sensor is an oxygen sensor which controls the electronic injection of the modern internal combustion vehicles. The aim of this study is to present two methods of measuring the oxygen concentration in flue gases of industrial combustion by the use of the automotive Lambda sensor. One method uses the voltage signals of a heated Lambda sensor and the other one uses the Current Reversal Mode (CRM) of operation of such sensor. Results presented in this article show that such methods are effective to control industrial combustion.

1. Introduction

The monitoring and control of efficiency and pollutants emissions in the field of industrial combustion is one of the serious problems society faces due the fossil fuels use and climate change, respectively. The automotive sector and the big scale industries in certain way have conditions to tackle such problems while the small scale industries have limitations to solve it due the relatively high investment they have to do acquiring or renting combustion analyzers or services.

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There are various approaches of controlling combustion. One of them is to determine beforehand the heat capacity and chemical composition of a fuel and pre-set the air-fuel ratio. Other is to monitor the combustion in-situ using optical sensors and in due time make the adjustment of the air fuel ratio. Another approach is to measure the concentration of gases such as oxygen, carbon monoxide or carbon dioxide in the exhaust and to make the adjustments. Among these gases, the measurement of oxygen concentration is better suited for the efficiency test of a combustion process because oxygen and excess air are almost independent of the fuel type.

The method of controlling combustion by the measurement of the concentration of gases in the exhaust is feasible mostly due to the development of the modern solid state sensors. Various types of solid state sensors have been originally developed for the combustion efficiency control in the automotive industry and as highlighted by Shuk *et al*. (2008) more recently these technologies have been adapted to industrial furnaces, boilers and gas turbines.

For the detection of oxygen, the most common sensor used is a zirconium oxide element, known as zirconia cell or electrochemical sensor that develops a voltage difference across two platinum electrodes separated by a porous ceramic layer if there is a difference in oxygen concentration. This process generally in automobile is made by an oxygen sensor known as Lambda sensor. In the commerce there are various types of Lambda sensor. The original type is the one with only one wire. It is heated by the exhaust gases of the vehicle. Other type is of two wires which is basically the type of one wire with an additional ground. There is also Lambda sensor with three and four wires in which two wires work heating the body of the sensor and the other wires acquire the sensor’s voltage signal which is related to the oxygen content of the flue gases. The five wire sensor is the wide band Lambda sensor which has a conception different from the others narrow band Lambda sensors.

In the literature there are many works where researchers used Lambda sensors for investigating different aspects of combustion. For example, MacDonald *et al*. (1998) used heated and unheated Lambda sensors for investigating self tuning of residential oil burners. Wiesendorf *et al*. (1999) used such unheated sensor for the detection of change between oxidizing and reducing conditions of boilers. Gibson *et al*. (1999) created a new method of using Lambda sensors for the measurement of oxygen content in flue gases. Niklasson *et al*.

(2003) used such sensors for investigating local air fuel ratio in a Circulating Fluidised Bed (CFB) furnace and Eskilsson *et al*. (2004) used Lambda sensors to monitor oxygen concentration for control of efficiency and emissions in pellet burners. Varamban *et al*. (2005) extended the method developed by Gibson *et al*. (1999) through the use of Lambda sensor. Johansson *et al*. (2007) studied the dynamics of furnace processes in a CFB boiler through the use of Lambda sensor. Souza Sobrinho *et al*. (2010) used the Lambda sensor for the measurement of oxygen concentration in flue gases of an industrial combustion chamber by the method of Current Reversal Mode created by Gibson *et al*. (1999). Francioso *et al*. (2008) presented low-cost electronics and thin film technology applied to Lambda sensors for the monitoring of combustion. De Lima *et al*. (2011) studied the control of oxygen excess in an industrial combustion chamber through the measurement of voltage signal of a heated Lambda sensor.

The objective of the present article is to make a comparative analysis of the methods of utilization of the Lambda sensor realized by Souza Sobrinho *et al*. (2010) and de Lima *et al*. (2011). For both works the Lambda sensor was installed in the chimney of a combustion chamber where its voltage signal and its working temperature were monitored and applied in the Nernst equation for the determination of the oxygen content of flue gases. An electronic circuit was mounted in order to maintain at 700 °C the sensor temperature irrespective of the flue gases temperature. As complement, the Current Reversal Mode (CRM) was also applied to the Lambda sensor.

2. Material and Methods

Following Souza Sobrinho *et al*. (2010) and de Lima *et al*. (2011), a zirconium oxide oxygen sensor, as for example the commercial Lambda sensor, consists of a pair of porous platinum electrodes separated by a layer of the zirconium oxide. At high temperatures (above 300 ºC) the zirconium ceramic becomes conductive to oxygen ions. When exposed to two different levels of oxygen concentration on either side of the cell (for example, ambient air and combustion exhaust gases) a voltage is produced. The voltage output is dependent on the two partial pressures of oxygen in addition to temperature and can therefore be used to determine air/fuel ratio for an exhaust stream from a combustion system when referenced to the known ambient oxygen concentration in air.

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The open circuit emf (E) of the Lambda sensor is given by the Nernst equation:

$$E = -\frac{RT}{zF}\ln\left[\frac{p(O_2)_{test}}{p(O_2)_{ref.}}\right] \quad (1),$$

where R is the universal gas constant, F is the Faraday constant, T is the absolute temperature of the Lambda sensor, z is the number of electrons migrated from one electrode to another for each molecule of oxygen, $p(O_2)_{test}$ is the oxygen partial pressure in the combustion flue gases and $p(O_2)_{ref.}$ is the reference gas (air) oxygen partial pressure.

A commercial heated Lambda sensor was installed in the chimney of a combustion chamber. Close to the Lambda sensor was installed a type K thermocouple. An electronic circuit was developed for heating the Lambda sensor. Basically this circuit supervises the electrical resistance of the sensor's heater. The heating circuit works with two power sources in a parallel configuration feeding electrical current between 100 mA and 1.1 A. For the application of the Current Reversal Mode the Lambda sensor was maintained at the temperature of 700ºC and the square wave potential difference of 35 mV at the frequency of 2 Hz was applied in the forward and reverse directions. Electrical currents were measured in both the forward and the reverse directions and their ratio recorded and compared with oxygen concentration measured by a reference combustion gases analyzer. This method followed experimental procedure illustrated by Gibson *et al*. (1999). Measurements were made in the oxygen concentration range of 2-16% which is the most usual range of operation in the environment of the industrial combustion. The square wave signals applied to the Lambda sensor were generated by the RIGOL Waveform Generator DG 1022. The current response signals were simultaneously acquired by the FLUKE 189 multimeter. The electrical current signal of the sensor was measured with resolution of 0.01 µA and accuracy of 0.25%. The thermocouple signal was recorded by a temperature controller showing resolution of 1 ºC and accuracy of 0.5%. The oxygen concentration was measured by the Testo 300 XL combustion gases analyzer with resolution of 0.1% and accuracy of 0.2%.

3. Results and Discussion

Results and analysis presented hereafter are based as per se on articles of Souza Sobrinho *et al*. (2010) and de Lima *et al*. (2011). Figure 1 shows the response of the heating element during the application of a pulse of electrical power aiming to set the working temperature of the Lambda sensor at 700 ºC. The heater time response was about 7 seconds and its time constant was about 2 seconds.

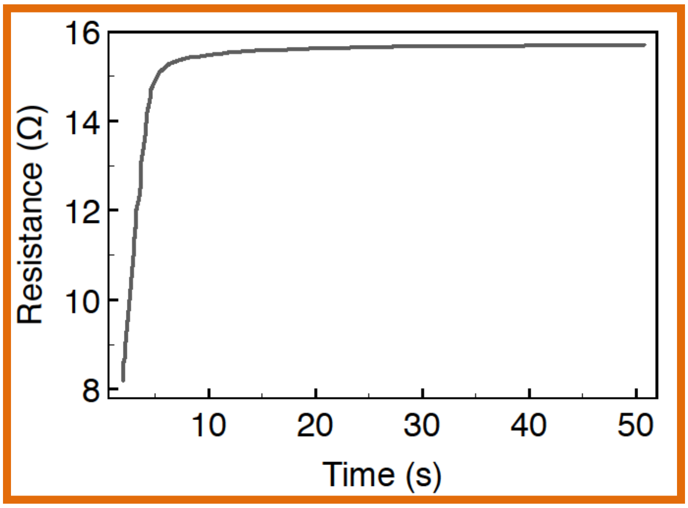

Figure 1: Variation of the resistance of the heating element inside the Lambda sensor during the application of an electrical power pulse.

Figure 2 presents the variation of the internal electrical resistance of the Lambda sensor (not the heating element) when it is exposed to temperature variation from the ambient until 700 ºC as consequence of the actuation of the heating element. At the ambient temperature its resistance is about 20 MOhm falling almost instantaneously to 0 Ohm at the working temperature.

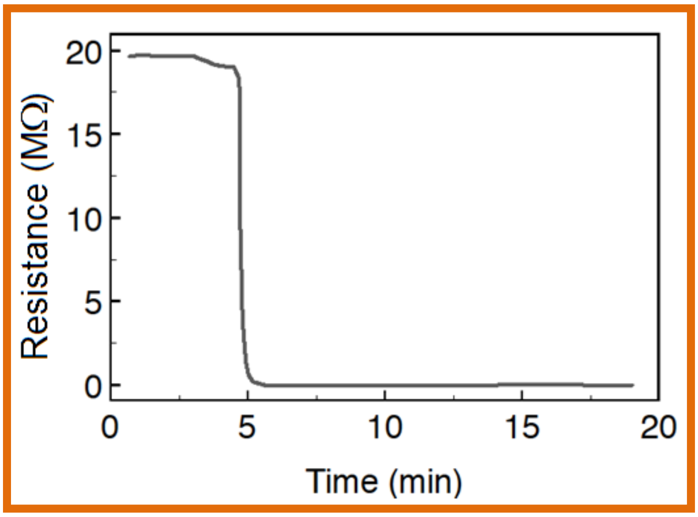

Figure 2: Variation of the internal resistance of the Lambda sensor during heating period.

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Figure 3 presents the variation of the electrical resistance of the Lambda sensor at the working temperature of 700 ºC during the variation in the percentage of oxygen in flue gases from 21 to 2% and returning to 21%. At 55 Ohm the concentration of oxygen is 21% and at 5 Ohm the concentration of oxygen is about 2%.

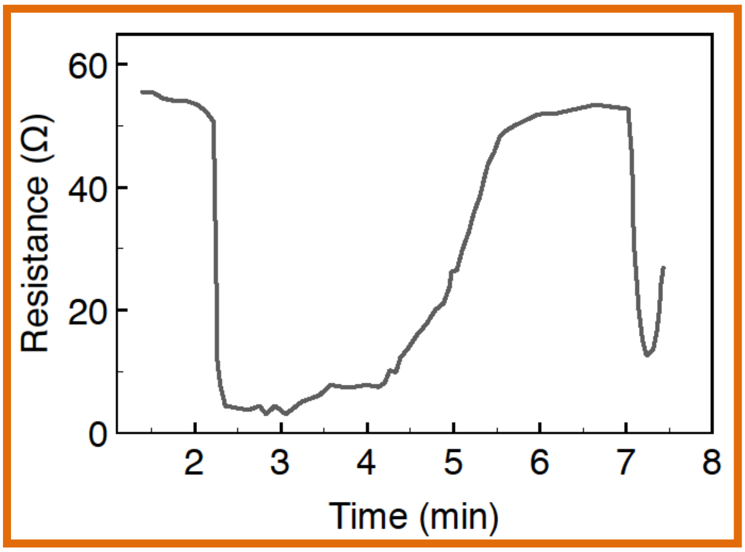

Figure 3: Electrical resistance of the Lambda sensor at 700 ºC during variation of the oxygen content from 21 to 2% and back to 21%.

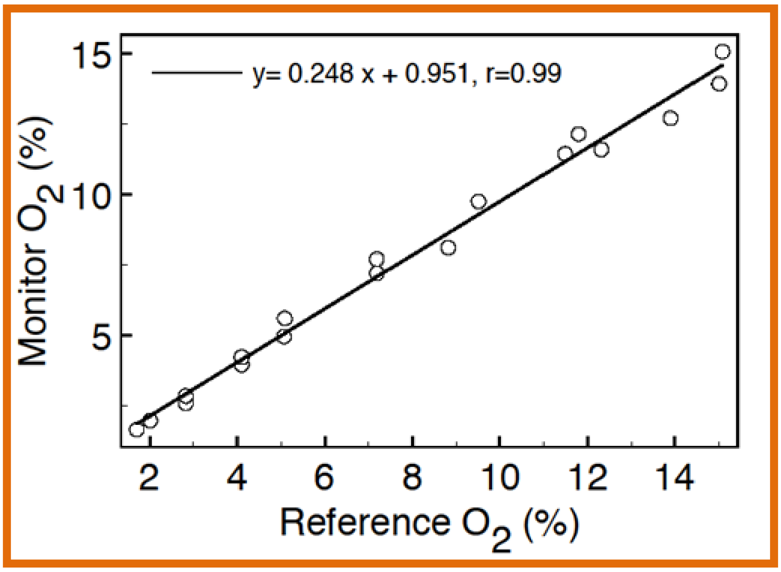

Figure 4: Flue gases oxygen percentage against measurements of the reference monitor.

Figure 4 presents the percentage of oxygen in flue gases determined by equation (1) with input of the emf (E) furnished by the Lambda sensor at the fixed temperature of 700 °C in the heating element for different situations of LPG combustion against measurements taken from the reference combustion analyzer (Testo 300 XL). The average deviation of the set of measurements was of ±5%. The correlation factor was of 0.97 demonstrating good agreement between the measurement of oxygen concentration at the flue gases and the measurements made by the reference monitor.

Figure 5 presents the relation between forward and reverse electrical currents furnished by the Lambda sensor due to the stimulation of the square wave potential difference of 35 mV applied in the forward and reverse directions with the frequency of 2 Hz. Until 12% of oxygen the correlation is perfect and from 15% up another correlation shows itself perfect, characterizing a transitional behavior of the Lambda sensor at the range from 12 to 15%. It is interesting to note that the same behavior was observed by Gibson *et al*. (1999) and Varamban *et al*. (2005). They were the first to apply the Current Reversal Mode to Lambda sensor aiming to improve combustion systems.

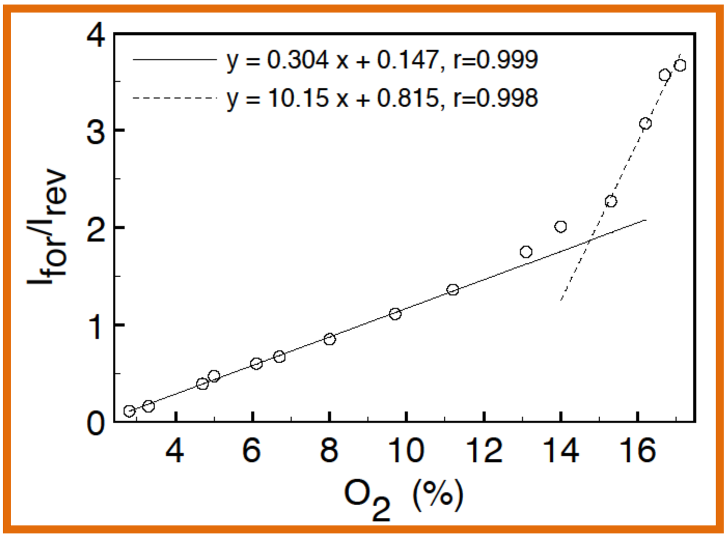

Figure 5: Ratios of electrical currents versus concentration of oxygen at 700 ºC.

4. Conclusion

In this work it was presented two simple methods of measuring oxygen concentration in the exhaust gases of combustion particularly the industrial combustion. Results demonstrated the feasibility of the proposed methods showing average deviation of ± 5% and correlation factor of 0.97 when the Lambda sensor was operated in its traditional method which consists in measuring the logarithmic voltage signal against the oxygen content. The Current Reversal Mode of operation showed better correlation factor although at the range from 12 to 15% it was

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observed a transitional behavior on the signal of the Lambda sensor. The method which makes use of the Nernst Law equation is simple although not accurate when oxygen concentration in flue gases is higher than 12%. On the other hand, the Current Reversal Mode (CRM) of operation of the Lambda sensor presented better precision than the first method applied. However the CRM method requires a more sophisticated and expensive instrumentation.

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