Measurements of the flue gases oxygen concentration by Lambda sensor

Medidas da concentração do teor de oxigênio em gases de combustão através do sensor Lambda

Antonio Serafim de Souza Sobrinho
serafim_fisica@yahoo.com.br

Rigoberto Soares do Nascimento
rigobertosoares@gmail.com

Renato Silva Pinheiro
pinheiro.silva@gmail.com

Lutero Carmo de Lima
lutero@uece.br
Universidade Estadual do Ceará

Resumo

Monitores de combustão industrial atualmente disponíveis no mercado brasileiro são relativamente caros e exigem manutenções periódicas. Já é conhecido que o sinal emitido pelos monitores de combustão baseado em sensor eletroquímico também é proporcional à variação da temperatura do local onde eles são instalados causando erros na determinação do percentual de oxigênio nos gases de combustão. A proposta deste estudo é apresentar um método simples de se determinar o teor de oxigênio usando-se um sensor Lambda automotivo. Os resultados mostram que o método apresentado é confiável e barato no propósito de controlar a combustão industrial em particular.

Palavras-chave: Eficiência De Combustão. Gases De Combustão. Sensor Lambda. Teor De Oxigênio. Controle Térmico.

Abstract

Monitors of industrial combustion presently available at the Brazilian market are relatively expensive and periodically require maintenance. It is well known that the signal of combustion monitor based on electrochemical sensor is proportional to the variation of temperature close to the sensor causing as consequence errors in the determination of the oxygen percent of flue gases. The proposal of this study is to present a simple method of determining the flue gases oxygen concentration based on the automotive Lambda sensor. The method makes use of the Current Reversal Mode of operation of such sensor. Results show that such method is reliable and very cost effective to control combustion specially the industrial combustion.

Keywords: Combustion Efficiency. Flue Gases. Lambda Sensor. Oxygen Concentration. Thermal Control.

1 Introduction

Control of efficiency and reduction of pollutant emissions, especially in the industrial combustion, can be performed before, within or after the combustion region. (WAWRZINEK and TRIMIS, 2001). In the first case, a small quantity of fuel is deviated to instruments where its heat capacity and/or its chemical composition are determined and the most appropriate air fuel ratio is set. In the second approach, parameters inside the combustion environment are monitored by some sensors as for example ionization current or optical sensors and in due time adjustments are made.

The control of the efficiency made after the combustion region is the one in which the air fuel ratio is determined by the measurement of oxygen, carbon monoxide or carbon dioxide concentration in the flue 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. When the optimum excess air setting is approached, the relative change in oxygen is much more accentuated than the relative change in carbon monoxide or carbon dioxide for a given change in excess air. (WULFINGHOFF, 2009).

The Orsat analyzer is the pioneer of combustion efficiency testers. This chemical testing apparatus in which flue gases are mixed with a liquid reagent that changes volume as a result of the reaction, is simple and accurate. However, the apparatus is built of delicate glass tubing and requires a fine touch.

In recent years electronic testers have become available for analyzing flue gases and most of them is based on electrochemical cell as the gas sensing element. 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. The first Lambda sensor designed to measure the oxygen content of exhaust gases in a passenger car was produced by Bosch in 1976. About 30 years later, Bosch has produced almost 500 million Lambda sensors. McDonald et al. (1998) used automotive zirconium oxide oxygen sensors, including unheated two wire Lambda sensors and heated four wire Lambda sensors, for the development of self tuning residential oil burner. They observed that unheated Lambda oxygen sensor could be useful in steady state applications but that relatively long burn times, more than five minutes, would be required for good results. Even though the accuracy of the sensor is relatively good. The heated automotive Lambda sensor resolves the issue of burn duration but the cost factor is almost triple at about US$ 75 per unit.

Unéus et al. (1999, 2001) used Metal Insulator Silicon Carbide sensors, Semiconducting Metal Oxide sensors and a linear Lambda sensor in an electronic nose for the evaluation of on-line flue gases measurements in 500 kW pellets fuelled boiler of apartment blocks. The linear Lambda sensor worked well for prediction of oxygen concentration.

Wiesendorf et al. (1999) investigated experimentally the bottom zone of a Circulating Fluidized Bed (CFB) boiler in Gardanne, France. According to the authors, several flow quantities have been monitored successfully by different measurement techniques as capacitance, pressure, temperature and zirconia-cell probe (Lambda sensor). They used the unheated Lambda sensor to detect the change between oxidizing and reducing conditions before and afterwards in the bottom zone of such boiler and of another in Sweden.

Niklasson et al. (2003) investigated local air ratio in a circulating fluidised bed (CFB) furnace, estimated by fluctuating signals from zirconia cell probes and compared to simultaneous analysis of concentrations of extracted gas samples. The time fraction during which the fluctuating zirconia cell signal shows oxidising gas conditions is strongly correlated to the local air ratio of the gas. They came up with a cheap and robust technique for on-line monitoring of the gas conditions in the furnace when, for example, optimizing the operation of a CFB boiler to reduce nitrous oxide emissions.

Eskilsson et al. (2004) used semi-conducting gallium oxide sensor to monitor the flue gases concentration of unburnt and Lambda sensor to monitor oxygen concentration in a study of optimization of efficiency and emissions in pellet burners. They concluded that those sensors may provide efficient control for optimal performance of such burners.

Johansson et al. (2007), in order to visualize the co-existence of fluid and combustion parameters, studied the dynamics of furnace processes in a CFB boiler. They used a zirconia-cell (Lambda) probe to indicate whether the environment at the probe tip was oxidizing or reducing and observed that peaks in the signal of the zirconia cell represent reducing conditions.

Gibson et al. (1999) developed a novel approach of using an zirconia sensor for monitoring high concentrations of oxygen. The technique consists of applying a potential to an oxygen conducting solid electrolyte in one direction and the current measured, the potential reversed and the current re-measured, to obtain a current ratio which strongly and linearly depends on percentage of oxygen.

Varamban et al. (2005) extended the perturbation method developed by Gibson et al. and proposed a scheme to measure the emf and short circuit current of a potentiometric (zirconia) sensor simultaneously. A small amplitude alternating square voltage pulse was applied across the electrodes and the respective currents were measured. From those currents, the open circuit potential and the short circuit current which are characteristic of the electrochemical cell were calculated. A theory for each scheme was proposed and performance evaluated. From the open circuit potential the concentration of the unknown sample was obtained using the corresponding equation.

Hills et al. (2006) demonstrated that the Current Reversal Mode (CRM) which is a novel and patented technique by Fray and Kumar when applied correctly yields the same information as an open-circuit emf measurements, but also gives further information about the conditions of the electrochemical sensor in the form of the total cell resistance. They also developed a mathematical model for the application of CRM in terms of an equivalent electrical circuit. The predictions of the model agreed well with the experimental data.

Kotzeva et al. (2007) using emf and Current Reversal Mode (CRM) studied the thermal transfer in oxygen Lambda sensors and they deduced that the temperature gradient across the yttria-stabilized zirconia (YSZ) electrolyte is approximately 30-60ºC. They also investigated the behavior of the heater and variation of the temperatures on the surface of the YSZ electrodes as a function of heating potentials quantified. Their heat transfer model suggested that the most significant temperature drop takes place in reference air gap and test gas gaps of the sensor, i.e., places where heat is transferred through a gas phase.

Francioso et al. (2008) presented low-cost electronics and thin film technology for sol-gel titania Lambda probes for combustion monitoring. They observed that probes suffered from fast flow variation and exhaust turbulence that may cause a lack of operative temperature stability; so they designed a specific low-cost interface based on a MicrochipTM 16F819 microcontroller. The aim of the activity was the realization of an electronic board capable to read the output signal of the fabricated sensor, to convert this signal into a digital output, to generate a reference stable voltage for electrical contact polarization and to provide a good proportional-derivative-integrative (PID) temperature control, supplying a pulse with modulation (PWM) wave to the heater and contemporary reading of the effective temperature by means of an embedded thermometer.

For the present work a commercial automotive four wire heated Lambda sensor was used as the sensing element. The Lambda sensor was installed in the chimney of a combustion chamber and the Current Reversal Mode (CRM) was applied for the determination of the oxygen content of flue gases. An electronic circuit was mounted in order to maintain at 700ºC the sensor temperature irrespective of the flue gases temperature.

2 Principle of operation and experimental procedure

A zirconium oxide oxygen sensor, as for example the commercial Lambda sensor (Fig. 1), consists of a pair of porous platinum electrodes separated by a layer of the zirconium oxide. At high temperatures (above 300ºC) 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.

Figure 1: One wire and four wire Lambda sensors

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

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

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,   is the oxygen partial pressure in the combustion flue gases and is the reference gas (air) oxygen partial pressure.

The basic characteristic output curve of voltage as a function of changes in the air/fuel ratio for a typical zirconium oxide sensor is illustrated in Figure 2. Curves are different at different temperatures but will have the same characteristic shape and exhibit the same type of jump in output at stoichiometric conditions. At stoichiometric conditions (air/fuel ratio equal to one, zero percent exhaust gas oxygen) the large change in the output voltage, termed the **lambda jump**, is basically insensitive to sensor temperature. (McDonald et al., 1998).

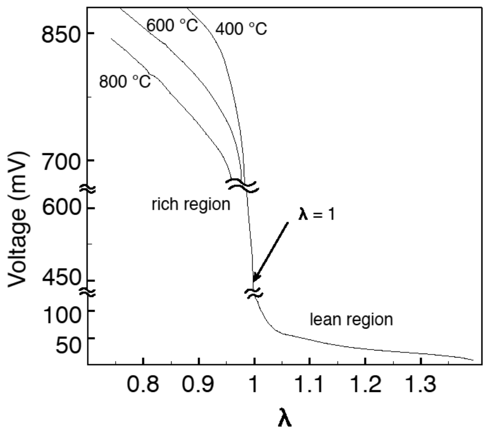

Figure 2: Voltage curve of a Lambda sensor

A commercial heated Lambda sensor was installed in the chimney of the combustion chamber. Close to the Lambda sensor was installed a type K thermocouple. An electronic circuit was developed for heating the Lambda sensor. Basically his 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. The voltage signal of the sensor was monitored by a FLUKE 189 multimeter with resolution of 0.01 mV and accuracy of 0.4% and for the application of the Current Reversal Mode 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 1ºC and accuracy of 0.5%. The oxygen concentration was measured by the Testo 300 XL combustion gases analyser with resolution of 0.1% and accuracy of 0.2%. The oxygen concentration was calculated by the use of equation (1) in its inverse form. 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, as illustrated by Gibson at 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 and the TEKTRONIX TPS 2024 oscilloscope.

3 Results and discussion

The relationship between the temperature of the heating element of the Lambda sensor against its electrical resistance is shown in Fig. 3. In this situation the combustion chamber was heated by the LPG burner until approximately 300ºC. After that the burner was turn off and simultaneously the resistance of the heater element and the temperature given by the thermocouple installed near the Lambda sensor were monitored.

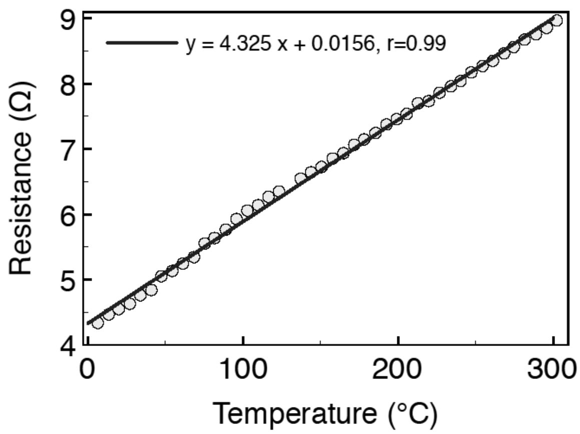

Figure 3: Curve of calibration of resistance of the heating element against temperature

Fig. 4 shows the response of the heater element during the application of a pulse of electrical power aiming to set the working temperature of the Lambda sensor at 700ºC. The heater time response was about 7 seconds and its time constant was about 2 seconds.

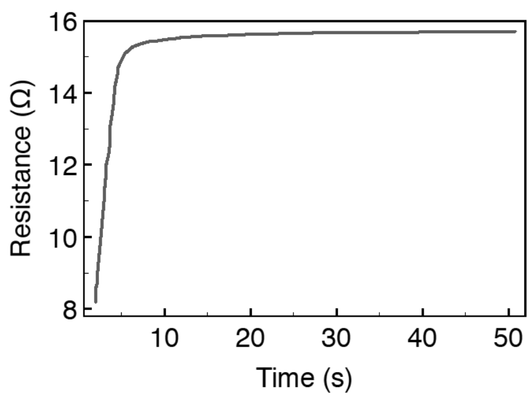

Figure 4: Variation of the electrical resistance of the Lambda sensor during the application of an electrical power pulse in the heating element

Fig. 5 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 700ºC 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.

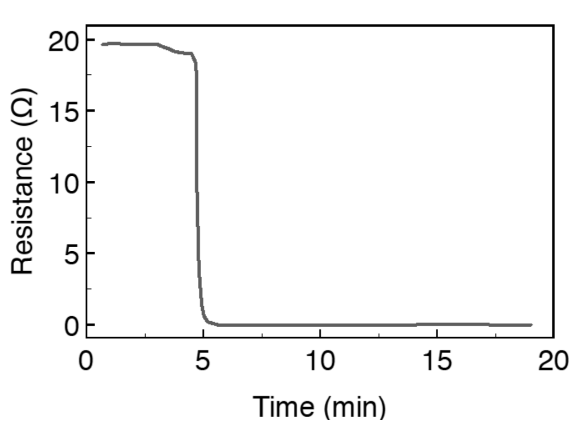

Figure 5: Variation of the internal resistance of the Lambda sensor during heating period

Fig. 6 presents the variation of the electrical resistance of the Lambda sensor at the working temperature of 700ºC 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%.

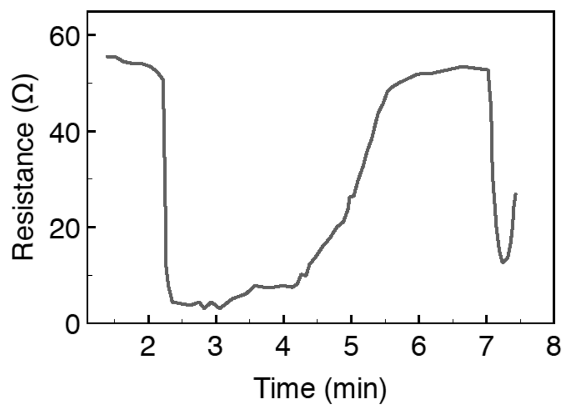

Figure 6: Electrical resistance of the Lambda sensor at 700ºC during variation of the oxygen content from 21 to 2% and back to 21%.

Fig. 7 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 and 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.

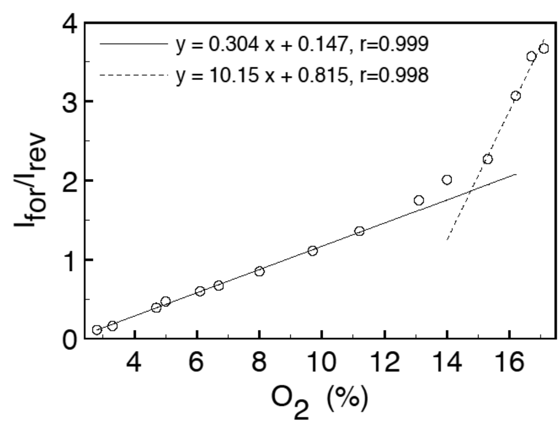

Figure 7: Ratios of electrical currents versus concentration of oxygen at 700ºC

4 Conclusion

In this work it was presented a simple method of determining oxygen concentration in the exhaust gases of combustion particularly the industrial combustion. Results demonstrated the feasibility of the proposed method showing almost perfect correlation factor of 0.97 when the Lambda sensor is operated in an usual combustion chamber. The Current Reversal Mode of operation on the Lambda sensor has proven to be a very successful method of monitoring industrial combustion.

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About the authors

Antonio Serafim de Souza Sobrinho

Rigoberto Soares do Nascimento

Renato Silva Pinheiro

Undergraduate students of Physics by the State University of Ceará.

Lutero Carmo de Lima

Graduated in Physics by the University of Santo Amaro, M.Sc. and Dr. Eng. in Mechanical Engineering by the Federal University of Santa Catarina and University of São Paulo, respectively. He is presently adjunct Professor at the State University of Ceará and basically works in fundamental problems of the thermal science, clean energy and instrumentation. Published more than 90 articles on referenced congresses and journals. He was awarded a Fulbright Fellow and inducted as Vice President of PHI BETA DELTA, Chapter Beta Theta, Honour Society for International Scholars, USA.