23rd ABCM International Congress of Mechanical Engineering
December 6-11, 2015, Rio de Janeiro, RJ, Brazil

THE APPLICATION OF THE CURRENT REVERSAL MODE OF OPERATION IN LAMBDA SENSOR FOR MONITORING INDUSTRIAL COMBUSTION

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Abstract. *The Current Reversal Mode (CRM) is a dynamic measurement technique which presents potential for determining the equilibrium electromotive force of a solid electrolyte sensor while at the same time providing additional information about its characteristics. One of them and the more important is its electrical resistance. Basically the technique consists of applying a potential difference forward into the sensor and to measure the resultant electrical current. The next step is to apply the same potential difference backward into the sensor and to re-measure the electrical current. The relation between forward and reverse electrical currents is linearly proportional to the percentage of oxygen in the medium where the measurements are made if, for example, the interest is the monitoring of industrial combustion. The proposal of this study was to apply the Current Reversal Mode into a commercial lambda sensor and to make measurements of oxygen percentage in the flue gases of an industrial combustion chamber. Results did show that such technique is simple and accurate when the flue gases oxygen percentage in the range of 2 to 16% were measured.*

Keywords: *Industrial combustion, Lambda sensor, Oxygen Monitoring*

1. INTRODUCTION

The monitoring and control of efficiency and pollutants emission in the field of industrial combustion is one of the serious problems society faces due to the increasing fossil fuels use. 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 to the relatively high investment they have to do acquiring or borrowing combustion monitors (Souza Sobrinho et al., 2012).

One way to control combustion is to make 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 (Souza Sobrinho et al., 2012).

For the detection of oxygen, the most common sensor used is a zirconium oxide element, known as zirconia cell or electrochemical sensor which 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 open circuit emf (E) of the lambda sensor is given by the Nernst equation (Gibson et al., 1999):

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

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, $p(O_2)_{test}$ is the oxygen partial pressure in the combustion flue gases and $p(O_2)_{ref}$ is the reference gas (commonly air) oxygen partial pressure.

Equation (1) being logarithmic shows that when oxygen concentration comes to extreme points, as for example, 0% and 20.96%, the voltage signal of the lambda sensor goes to infinite and zero respectively, irrespective of flue gases temperature. Even with this limitation zirconia cell probe such as lambda sensor has been used in many applications and studies published in the literature and most of them based on its logarithmic nature.

In the year 1997, as referenced by the article of Schwandt and Fray (2000), Fray and Kumar applied a patent describing a technique which circumvented such problem. They presented a new approach of using 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. The technique is known as CRM – Current Reversal Mode which is similar to the perturbation method. Gibson et al. (1999), using commercial lambda sensors applied such technique for monitoring oxygen concentrations on the 2-16% range.

Varamban et al. (2005) extended such perturbation method proposing a scheme to measure the emf and short circuit current of a potentiometric oxygen sensor simultaneously. 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 oxygen was obtained using the Nernst equation.

Hills et al. (2006) demonstrated that the Current Reversal Mode when applied correctly yields the same information as given by the open-circuit emf measurements (equation 1), but also furnishes 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, as highlighted by such authors.

Kotzeva et al. (2007), using emf and CRM, studied the thermal transfer in oxygen lambda sensor and they deduced that the temperature gradient across the yttria-stabilized zirconia (YSZ) electrolyte is in the range 30-60 °C. 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. 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.

Souza Sobrinho et al. (2012) applied the CRM for monitoring oxygen concentration in flue gases of a combustion chamber and they concluded that such method is reliable and very cost effective when compared to the conventional way of using equation (1) for controlling industrial combustion.

Differently from the majority of the above mentioned authors that developed studies on CRM using instruments such as high impedance electrometer (Keithley 614), True RMS multimeter, DC power supply, function generator (Rigol Waveform Generator DG 1022), Source Measure Unit (Keithley 236) and oscilloscopes for heating and controlling output signals of such sensors, in the present study, especially designed electronic circuits were mounted in order to substitute such instrumentation. The designed electronic circuits heat a commercial lambda sensor, excite it with a square wave potential and acquire in oscilloscope the signals of the resulting electrical currents for various levels of oxygen concentration in a combustion chamber. Results presented interesting aspects of the CRM way of conditioning electrochemical oxygen sensors.

2. MATERIAL AND METHOD

A commercial lambda sensor (Fig. 1) was installed in the chimney of an industrial combustion chamber. The combustion chamber has a Weishaupt LPG Burner of 50 kW. Close to the lambda sensor was installed a type K thermocouple.

An electronic circuit was developed for heating and conditioning the lambda sensor with a square wave potential as shown in Figure 2. Basically it 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, at a fixed potential difference of 12 V. For the application of the Current Reversal Mode the lambda sensor was maintained at the temperature of 700 °C and the square wave potential difference of 35 mV at the frequency of 2 Hz was applied in the forward and reverse directions. Such values of electrical parameters and temperature were assumed considering indications of researchers of this method in the literature (Gibson et al., 1999, Varamban et al., 2005, Hills et al., 2006).

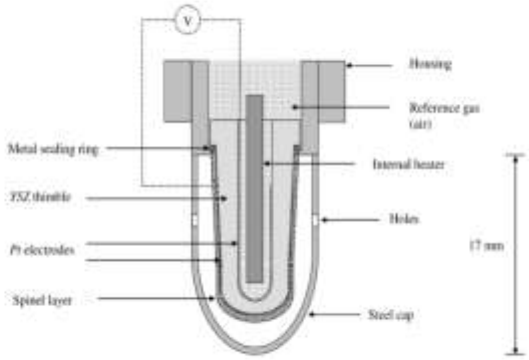


Figure 1. Lambda sensor’s scheme (Adapted from Hills et al., 2006)

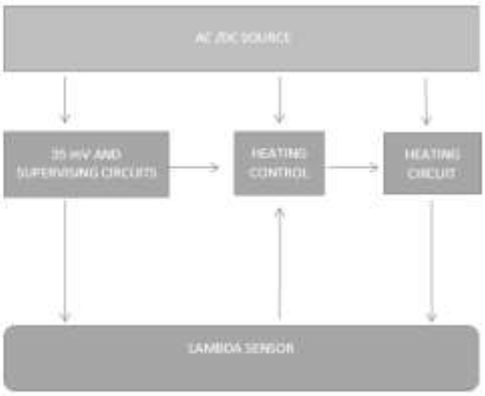


Figure 2. Electronic scheme for conditioning the oxygen sensor

Figure 3 shows the square wave potential applied to the lambda sensor. Electrical currents were acquired in both the forward and the reverse directions, their ratio recorded and compared with oxygen concentration measured by a reference combustion gases analyzer.

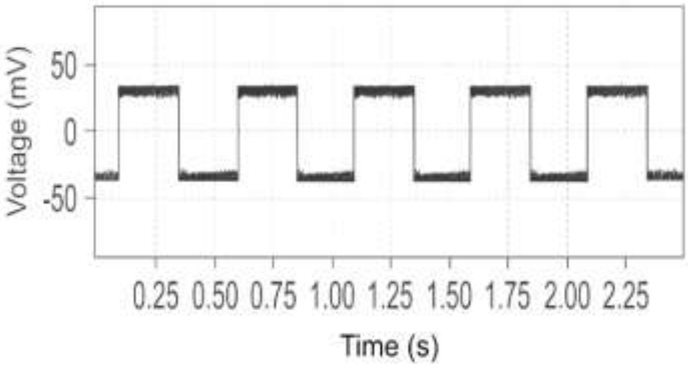


Figure 3. Applied 35 mV square wave potential

The present method basically follows procedure described early by Gibson et al., (1999). Measurements were made in the oxygen concentration range of 2-16%.The current response signals were simultaneously acquired by the FLUKE 189 multimeter with resolution of 0.01 µA and accuracy of 0.25% and the TEKTRONIX TPS 2024 oscilloscope. The thermocouple signal was recorded by a temperature controller showing resolution of 1 °C and accuracy of 0.5%. The oxygen concentration in the flue gases was measured by the TESTO 300 XL combustion gases analyzer with resolution of 0.1% and accuracy of 0.2%.

3. RESULTS AND DISCUSSION

Knowing the electrical resistance of the heating element of a lambda sensor at a certain temperature is important since the electronic circuit developed to heat such sensor will control its electrical resistance in order to maintain the desired temperature as for example, in the present study, 700 °C (973 K). The relationship between the temperature of the heating element of the lambda sensor against its electrical resistance is shown in Figure 4. In this situation the combustion chamber was heated by the LPG burner until approximately 400 °C was reached at the chimney. After that the burner was turn off and simultaneously the resistance of the heating element and the temperature given by the thermocouple installed close to the lambda sensor were monitored. The fitting equation which relates resistance to temperature in this case is $R(\Omega) = 0.017T(°C) + 2.966$. In order to maintain the temperature of heating element at 700 °C the electronic circuit kept the resistance of heating element around 14.87 Ω.

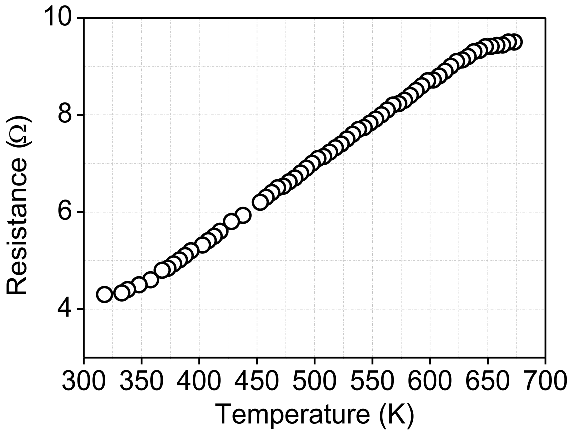
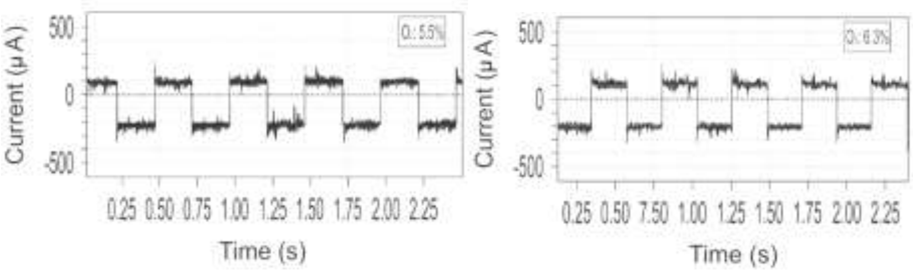


Figure 4. Electrical resistance of the heating element against temperature

The time 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 °C was measured by the present authors in a previous publication (Souza Sobrinho et al., 2012). The heater time response was about 7 seconds and its time constant was about 2 seconds.

The variation of the internal electrical resistance of the lambda sensor when it is submitted to temperature variation from the ambient until 700 °C as consequence of the actuation of the heating element was also measured. At the ambient temperature its resistance is about 20 MΩ falling almost instantaneously to 0 Ω at the working temperature. For the 35 mV applied potential into the lambda sensor, Figure 5 shows electrical current responses at various percentages of oxygen. As expected by the application of the Current Reversal Method of operating electrochemical sensor, the ratio of the forward direction current to the reverse direction current increases with the increase in the percentage of oxygen in the flue gases in chimney of the combustion chamber.



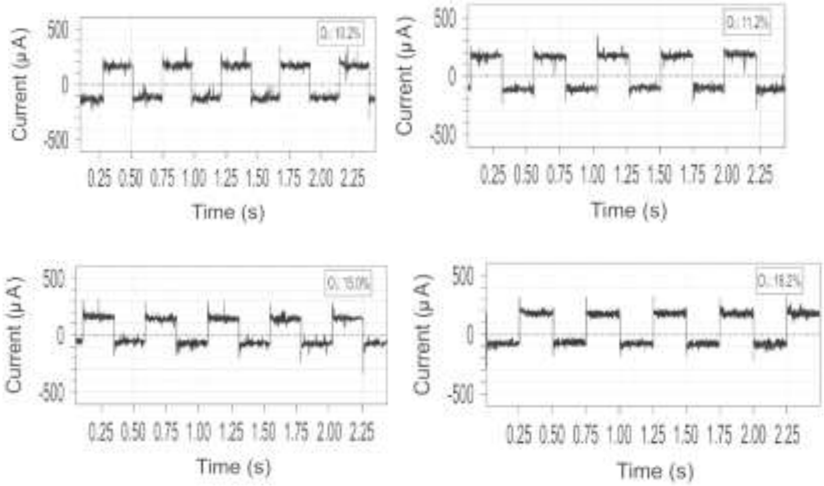


Figure 5. Current-time curves of the lambda sensor operated in CRM for various oxygen concentrations

Figure 6 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 factor is relatively very good and from 15% up another correlation shows itself also very good. There is a transitional behavior of the lambda sensor at the range of 12 to 15%. It is interesting to observe that the same transitional behavior was observed by Gibson et al. (1999) and Varamban et al. (2005). They were the first to apply the Current Reversal Mode to electrochemical sensors in order to control combustion processes.

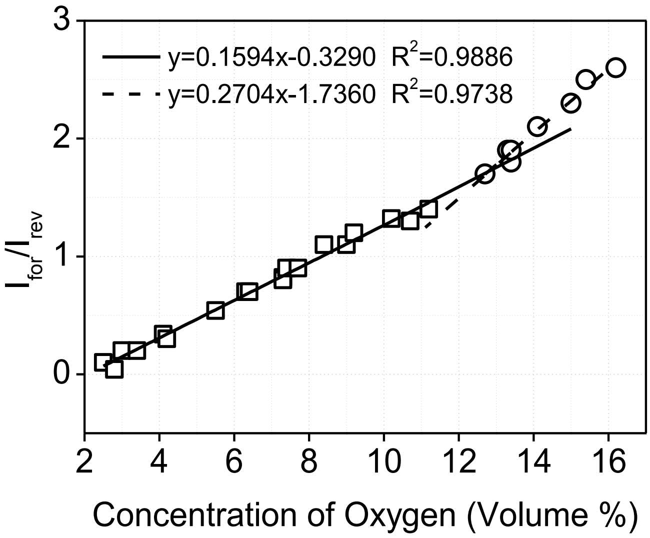


Figure 6. Currents ratio against oxygen percentage at 35 mV

4. CONCLUSION

In this study the relatively new method of operating electrochemical sensors, the Current Reversal Mode (CRM), was applied to an electrochemical oxygen sensor, the commonly known lambda sensor, with the aim of controlling industrial combustion. This new method of stimulating oxygen sensor proved to be effective when compared to the conventional method of operating lambda sensor since results showed very good correlation factors and linearity against results presented by commercial combustion monitor.

5. ACKNOWLEDGEMENTS

The authors thank the Brazilian National Council for Scientific and Technological Development (CNPq) for financial support of all activities and infra-structure related to the present study.

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2. RESPONSIBILITY NOTICE

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