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

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ABSTRACT

Basically the technique of Current Reversal Mode (CRM) consists of applying a potential difference forward into the sensor and measuring the resultant electrical current. The next step is to apply the same potential difference backward into the sensor and re-measure the electrical current. The ratio between forward and reverse electrical currents is linearly proportional to the percentage of oxygen in the medium where the measurements are made. The proposal of this study was to apply the Current Reversal Mode into an automotive lambda sensor and to make measurements of oxygen percentage in the flue gases of aindustrial combustion chamber. Results did show that such technique is simple and accurate when the flue gases oxygen percentage were measured. This is an economic alternative for the monitoring industrial combustion for small farmers.

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INTRODUCTION

The monitoring and control of efficiency and pollutants emission in combustion processes are one of the serious problems society faces mainly due to the fossil fuels use. The automotive sector and the big scale industries have means to tackle such problems while the small-scale industries, such as small farmers, have limitations to solve it due to the relatively high investment they have to do acquiring or borrowing combustion monitors. There are several ways to control combustion, monitoring the concentration of oxygen in the exhaust is the most appropriate way to check the efficiency of a combustion process, because the excess or lack of oxygen is virtually independent of the type of fuel (Wulfinghoff DR, 2000). 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 porous platinum electrodes separated by a ceramic layer if there is a difference in oxygen concentration. This process generally in automobile is made by the oxygen sensor known as lambda sensor as seen schematically in Fig. 1. The lambda sensor is an electrochemical sensor installed in motor vehicles widely used in the automotive industry, having high reliability (Fischer *et al.,* 2014). According to Fischer *et al.* (2010), lambda sensors consists of a thimble-type zirconia element and are embedded in a steel housing for protection against thermal and mechanical stresses. A rod-like ceramic heater with a positive temperature coefficient of resistance is inserted in the thimble. The sensor temperature can be controlled by the heater voltage. Usually lambda sensor presents signal output of logarithmic nature, i.e. when oxygen concentration comes to extreme points, as for example, 0% and 20.96%, the voltage signal of the sensor goes to infinite and zero respectively, irrespective of the flue gases temperature. Even with this limitation, zirconia cell probe has been used in many application and most of them based on its logarithmic output. In the year 1997, as cited by Schwandt and Fray (2000), Fray and Kumar applied a patent describing a technique which circumvented such limitation. They presented a new operating technique for a zirconia sensor in order to monitor relatively higher oxygen concentrations. The technique consists of applying a positive voltage pulse to an oxygen conducting solid electrolyte and measuring the resulting electric current, just after applying an inverted voltage pulse and measuring the electric current again, the relationship between the currents strongly depends and of

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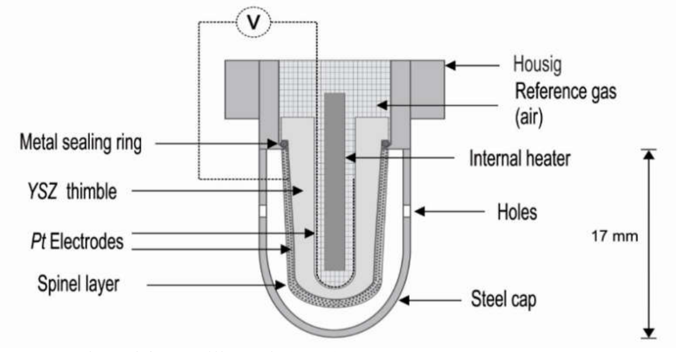
linear way of the percentage of oxygen in the medium where the oxygen conducting solid electrolyte lies. The technique is known as CRM - Current Reversal Mode which is similar to the perturbation method.



Source: Adapted from Hills et al. (2006)

Fig. 1. Scheme of a lambda sensor

Gibson *et al.* (1999), using commercial lambda sensors applied such technique for monitoring oxygen concentrations on the 2-16% range. Varamban *et al.* (2005), extending such perturbation method, 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 when applied correctly yields the same information as given by the open-circuit *emf* measurements, 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 to the monitoring of industrial combustion and they concluded that such method is reliable and very cost effective to the control of such kind of combustion. They also made comparison between two methods of operating lambda sensors: the potentiometric and the CRM. When compared to a conventional combustion monitor, CRM presented better results than the first one. As an extension to the study of Souza Sobrinho *et al.* (2012), in the present study the above mentioned technique (CRM - Current Reversal Mode) was also used for the monitoring of combustion of the same industrial furnace used by those authors. However, especially designed electronic circuits were mounted in order to heat a commercial lambda sensor, to excite it with a square wave potential, and to acquire in oscilloscope the signals of the resulting electrical currents. Results presented further interesting aspects of such method of conditioning electrochemical oxygen sensors.

Theory

The open circuit *emf* of the lambda sensor is given by the Nernst equation:

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

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.

Figure 2 presents output signal of a lambda sensor in mV calculated by the Nernst equation (1) as a function of oxygen concentration for different levels of temperature.

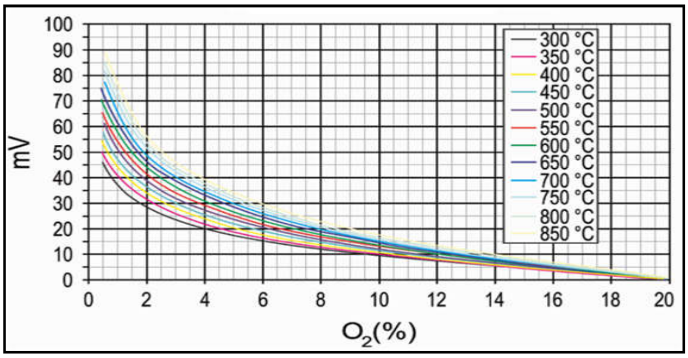


Fig. 2. Theoretical mV output of lambda sensor at different levels of temperature

According to Hills *et al.* (2006) in CRM a low-frequency square wave voltage, V_{appl}, is applied between the sensor electrodes and the forward and reverse currents, I_{for} and I_{rev}, are measured. The forward and reverse currents are:

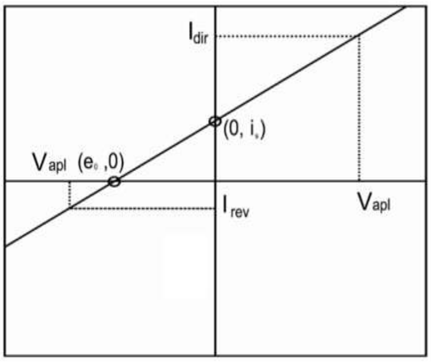
$$I_{for} = \frac{V_{appl} - emf}{R_{for}} \tag{2}$$

$$I_{rev} = \frac{-(V_{appl} + emf)}{R_{rev}} \tag{3}$$

Where $R_{for}$and R_{rev} are total cell resistances in the forward and reverse directions which are assumed to be equal since the CRM does not require diffusion controlled conditions and the sensor output is independent of sensor geometry and this is valid only for small value of currents when the activation and concentrations over-potentials due to polarization of the electrodes can be neglected (Schwandt and Fray, 2000). In other words, the ionic resistance of the electrolyte is identical for both forward and reverse currents. Combining equations (2) and (3), the currents ratio will be where *emf* is given by the Nernst equation (1).

$$\frac{I_{for}}{I_{rev}} = \frac{(V_{appl} + emf)}{(V_{appl} - emf)} \tag{4}$$

Equation (4) shows that for identical applied potential in both forward and reverse directions, the resulting currents are asymmetrical as can be seen in Fig.3 (Schwandt and Fray, 2000). By carefully choosing the magnitude of the applied potential, the current ratio dependence on oxygen concentration is virtually linear at high concentration (Gibson *et al.,* 1999). The relationship between the cell *emf*, its resistance, the bias voltage, and the forward and reverse currents can be visualized using the V-I curve in such figure (Varamban *et al.,* 2005).



Source: Schwandt and Fray (2000)

Fig. 3. Voltage-current for a lambda sensor at constant temperature

MATERIALS AND METHODS

A commercial lambda sensor was installed in the chimney of the 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 depicted in Figure 4, 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 indication of Gibson *et al.* (1999) who applied square wave potentials in the forward and reverse directions in the 5-50 mV range with frequency in the 0.25-2 Hz range and observed that the current ratio was almost linearly upon oxygen concentration when the potential of 35 mV and 2 Hz were used.

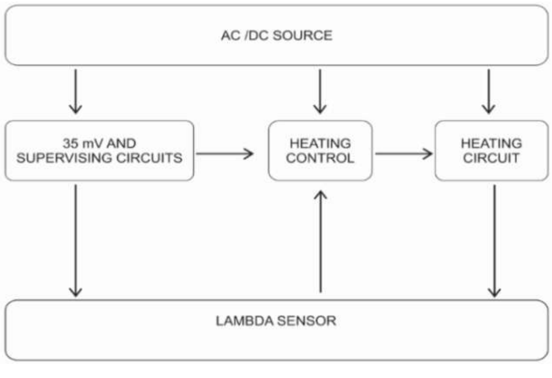


Fig. 4. Block diagram of the supervising electronic circuit

Figure 5 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.

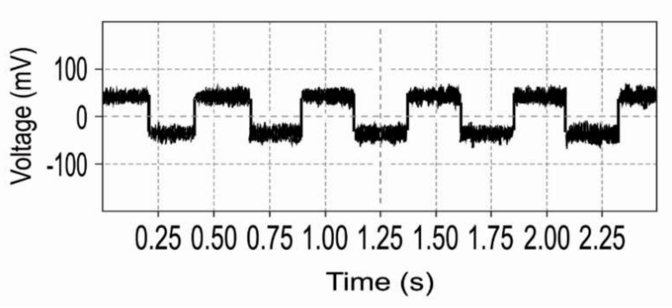


Fig. 5. Applied 35 mV square wave potential

Measurements were made in the oxygen concentration range of 2-21%. 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%.

RESULTS AND DISCUSSION

Since one of the objectives of the present study was the conception of an instrument which relates linearly the signal of the lambda sensor to the percentage of oxygen in the flue gases of an industrial combustion chamber, the potential applied into the lambda sensor will determine if the current ratio is linear or not to the oxygen concentration. According to Gibson *et al.* (1999), for lower applied potentials (e.g. 5 mV) it will result in greater sensitivity, while higher values (e.g. 50 mV) will produce a linear response. That is the basic reason why in this work 35 mV was the chosen applied potential which seems to be appropriate value where sensitivity and linearity are well balanced. 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. In this situation, the lambda sensor was placed inside a furnace containing air which was electrically heated until approximately 700°C was reached.

The temperature on the ambient close to the lambda sensor was monitored by a type K thermocouple. After that, the furnace was turn off and simultaneously the resistance of the heating element and the temperature given by the thermocouple were monitored. The relationship between the temperature of the heating element of the lambda sensor against its electrical resistance is shown in Figure 6. The fitting equation which relates the heater electrical resistance to temperature in this case is $R(\Omega) = 0.017T(°C)+2.966$. Inside the combustion chamber when in operation with the application of the 35 mV potential, in order to maintain the temperature of heating element around 700 °C, the electronic circuit had the function of keeping the resistance of heating element around 14.87 Ω.

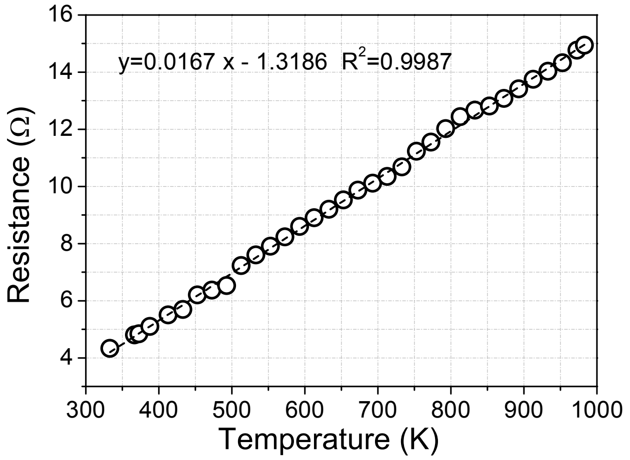


Fig. 6. Electrical resistance of the heating element against temperature

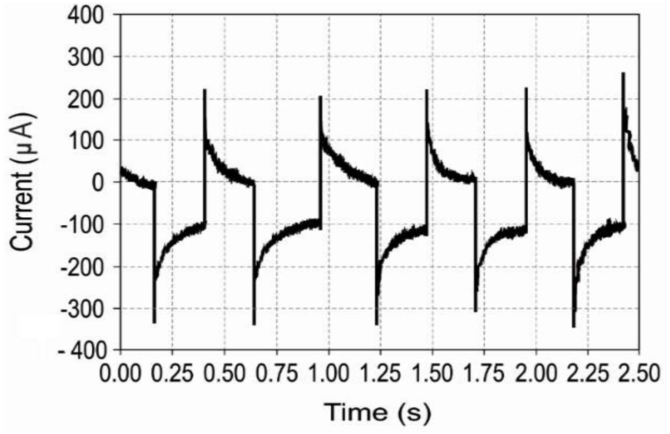


Fig. 7. Current-time curves of the lambda sensor operated in CRM for oxygen concentration of 2.8%

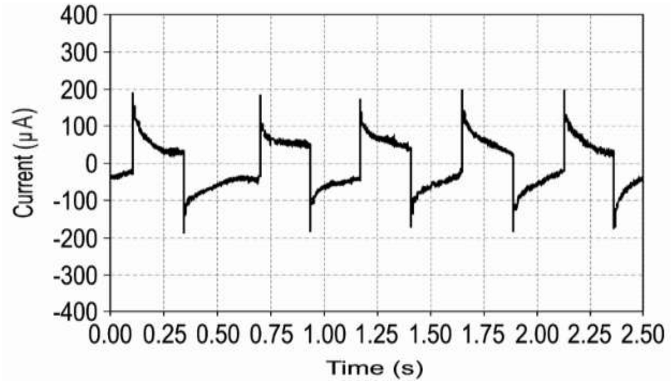


Fig. 8. Current-time curves of the lambda sensor operated in CRM for oxygen concentration of 15.4%

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 used 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 by such authors. 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, Figures 7-9 shows electrical current responses at three different 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.

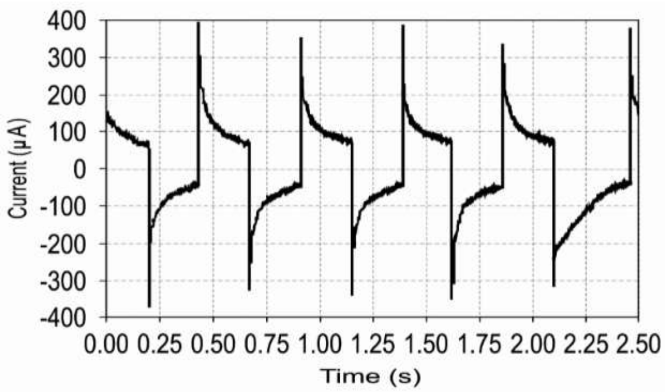


Fig. 9. Current-time curves of the lambda sensor operated in CRM for oxygen concentration of 21%

Figure 10 presents the relation between forward and reverse electrical currents furnished by 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 very good and from 15% up another correlation shows itself perfect, characterizing a transitional behavior of the lambda sensor at the range of 12 to 15%. It is interesting to observe 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 in order to control combustion process.

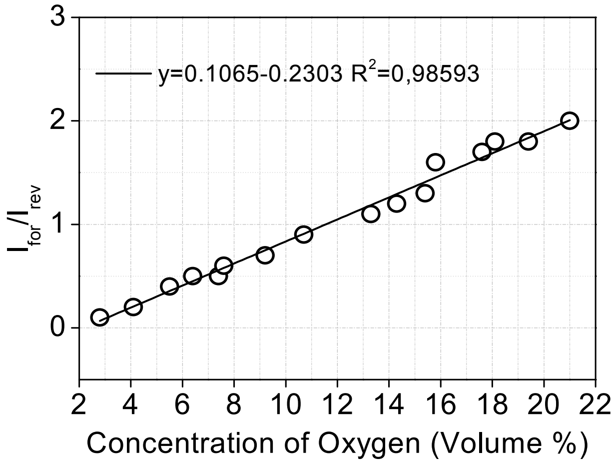


Fig. 10. Currents ratio against oxygen percentage at 35 mV

Conclusion

In this study a method of operating electrochemical sensors, the Current Reversal Mode (CRM), was applied to an automotive 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 excellent correlation factor and linearity against results presented by a commercial combustion monitor. It can be considered as an economical alternative for the monitoring industrial combustion when compared to the cost of commercial combustion monitor.

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