COBEM 2021 26th International Congress of Mechanical Engineering
ABCM Associação Brasileira de Engenharia e Ciências Mecânicas
November 22-26, 2021, Virtual Congress, Brazil

COB-2021-0125
IMPLEMENTATION OF A SUPERVISORY SYSTEM WITH LAMBDA WIDEBAND SENSOR FOR ANALYSIS OF OXYGEN CONCENTRATION IN INDUSTRIAL COMBUSTION PROCESSES

João Vitor Marchi Pedro de Azevedo Silva
Fernando Henrique Mayworm de Araujo
São Paulo State University, School of Engineering, Campus Guaratinguetá
333 Ariberto Pereira da Cunha Ave., Guaratinguetá, SP, 12516-410, Brazil
Department of Chemistry and Energy
joao.marchi@unesp.br
fernando.araujo@unesp.br

Daniel Julien Barros da Silva Sampaio
São Paulo State University, School of Engineering, Campus Guaratinguetá
333 Ariberto Pereira da Cunha Ave., Guaratinguetá, SP, 12516-410, Brazil
Department of Electrical Engineering
daniel.sampaio@unesp.br

João Andrade de Carvalho Junior
São Paulo State University, School of Engineering, Campus Guaratinguetá
333 Ariberto Pereira da Cunha Ave., Guaratinguetá, SP, 12516-410, Brazil
Department of Chemistry and Energy
ja.carvalho@unesp.br

Abstract. *The high quality standards imposed in the current industry, and the need to maintain competitiveness in markets increasingly saturated of participants, have been forcing companies to seek innovative solutions that ensure a better benefit-cost ratio. In addition, there is a demand to meet strict rules elaborated to reduce the environmental impact caused by emissions from industrial processes. Thus, a movement in industries aiming for solutions to optimize industrial combustion processes has recently begun. In this sense, the excess air control is able to increase thermal efficiency and also promote a considerable reduction in the emission of pollutants. The Industry 4.0 advent has enabled the development of systems, both accurate and reliable, which allow the analysis of the concentration of components present in combustion products emitted by industrial processes. Currently, most flue gas analyzers are expensive and require periodic maintenance. In this context, this project aims to develop a system for the acquisition and processing of data from a low-cost automotive lambda sensor, in order to analyze the oxygen concentration in industrial combustion processes. Initially, a test bench is proposed, composed of a wideband automotive lambda sensor, which allows operation with high air-fuel ratios, installed in a liquefied petroleum gas (LPG) combustion chamber. A microcontroller (Arduino) will also be installed, which in turn is responsible for obtaining the data provided by the lambda sensor and its integration with MATLAB. The oxygen concentration and lambda factor will be presented to the user in a graphical interface. Given a certain fuel, whose composition is known, the oxygen concentration makes it possible to analyze the adiabatic flame temperature and combustion efficiency. The results will be validated through a comparative analysis with the data found in the literature and also with the values provided by a calibrated flue gas analyzer (Lancom III), which performs oxygen measurements with an accuracy of ±1%. Finally, a statistical study will be conducted in order to verify the susceptibility and accuracy of the proposed combustion bench. Studies conducted in several scientific researches have proved the feasibility of using automotive lambda sensors to analyze the oxygen concentration in combustion processes. Nevertheless, few have used wideband sensors associated with microcontrollers and a graphical interface. That is, this project innovates by integrating a Smart manufacturing (Industry 4.0) concept, through the association between the Arduino platform and computational resources.*

Keywords: *Energy efficiency, Industrial combustion, Lambda sensor, Oxygen concentration, Industry 4.0.*

1. INTRODUCTION

Since immemorial times, combustion has been used for power generation. The technological achievements obtained to date are closely linked to the understanding of the phenomena that occur during the combustion process (Carvalho *et al.*, 2018). Combustion and its control are of utmost importance to the survival of our planet. Basically, about 80% of all human activities depend on some kind of combustion process, such as electricity generation, transportation, industries, trade and services. In contrast to the beneficial aspects of combustion, there is the major problem associated with environmental pollution. Most of the pollutants produced by combustion consist of partially burned and/or unburned hydrocarbons, nitrogen oxides, carbon monoxide, sulfur oxides and particulates found in various forms (Pimenta *et al.*, 2002).

In the vast majority of developing countries, power generation is strongly dependent on burning relatively low-quality fossil fuels. In other cases, fuels of high calorific value are used; however, with large amounts of sulfur and nitrogen in their compositions, resulting in the formation of harmful pollutants in combustion systems.

Both situations cause considerable environmental impacts due to the pollutants contained in the flue gases, which are emitted by boilers of various power plants and industrial sectors. Often, many companies experience a shortage of financial resources destined to the treatment of fuels, as well as to the installation of gas cleaning systems which, in addition to the high cost, cause an increase in costs regarding the generation of electricity and thermal power. Therefore, the implementation of low-cost methods aiming at optimizing the thermal efficiency is the most attractive alternative concerning energy conservation, especially in the industrial combustion and energy generation sectors (Kuprianov, 2005).

It is also worth mentioning the increased concern regarding the environment in recent decades, which has led to the development of strict standards and regulations aimed at reducing the emission of polluting gases. In this context, the search for new alternatives to optimize the thermal efficiency of combustion processes began, while ensuring compliance with environmental legislation. By controlling excess combustion air, it is possible not only to increase the thermal efficiency of combustion ovens, but also to drastically reduce the emission levels of pollutants. In most of the cases, thermal efficiency and pollutant emissions are treated separately, causing the influence of excess air on these two factors to be poorly understood and not optimized (Pinheiro and Valle, 2010).

Thus, the purpose of this paper is to present the development of a low-cost supervisory system aimed at analyzing the oxygen concentration in the flue gases generated by industrial combustion processes. The system basis revolves around a wideband lambda sensor. By integrating it with Smart manufacturing resources, this project represents an affordable prototype which enables the monitoring of a combustion process, in order to maximize its overall quality, both in relation to thermal efficiency and emission of pollutants.

2. LITERATURE REVIEW

2.1 Analysis of Oxygen Concentration in Combustion Processes

In order to achieve the maximum combustion efficiency, so that it is possible to increase productivity, reduce costs and also mitigate environmental impacts, the fuel burning must be complete. Thus, certain amounts of air and fuel need to be mixed under appropriate turbulence, temperature and pressure conditions (Queiroz, 2017). Theoretically, stoichiometry produces a perfect combustion, extracting the maximum energy from the fuel. Nevertheless, this situation is almost impossible to be achieved in practice, since heat losses are inevitable (Biarnes, 2016).

Many operators of industrial furnaces tend to lose significant amounts of energy because of too much air entering the furnace, resulting in heat loss through flue gases. The excess air results in oxygen that is not consumed during combustion, and this oxygen absorbs otherwise usable heat and carries it out of the stack. The chemically ideal amount of air entering a furnace is just enough for all the oxygen in the air to be consumed. However, this ideal (known as the stoichiometric air-fuel ratio) is extremely difficult to reach due to the fact that fuel and air (oxidant) do not completely mix, meaning that a certain amount of excess air will always be necessary for complete combustion (Chapman, 2019). In fact, too little excess air results in inefficient burning of fuel, soot buildup and unnecessary greenhouse gases emissions.

The optimum level of excess air will vary between furnaces and applications, but generally, excess air of 10 – 15% is an attainable goal while maintaining either the current input temperature or production output level, whichever is desired. Considering a furnace with higher excess air than 10 – 15%, there is a clear opportunity to lower the energy costs by reducing air input at the burner and by closing any leaks in the furnace. When the air-fuel ratio is optimized, the resulting energy savings usually range from 5% to 25%.

The amount of excess air within the system can be determined by analyzing the amount of oxygen in the flue gas. Too much excess air leads to lower flame temperatures. That means less heat gets into the system. Also, excess air must heat up to flue gas temperature, which consumes an extra amount of energy, thus decreasing the thermal efficiency. This occurs due to the fact that air brings with it a large amount of nitrogen, when only oxygen is needed in combustion. The nitrogen contained in the air acts as a ballast which must be heated, transporting the energy of the combustion process out of the chimney through the flue gas, causing the efficiency to be reduced (Belohradsky *et al.*, 2014).

On the other hand, low excess air values may result in an incomplete combustion, promoting the formation of carbon monoxide, soot and smoke, besides allowing the accumulation of unburned fuel, increasing the risk of explosion. Yet, lowering the excess air is also responsible for reducing the mass of combustion gases and increasing the heat transfer for steam generation, improving the thermal efficiency (Procel and Eletrobras, 2005).

In light of the above, it can be affirmed that the optimum value of excess air is the one where both influences (low and high excess air) are well balanced, i.e., reasonably low to reduce heat loss without producing an incomplete combustion. For gaseous fuels, around 1 to 2% of excess air is provided, while for liquid fuels, this value varies between 5 to 10%. In the case of solid fuels, excess air can reach 25% (Carvalho *et al.*, 2018). The comparison between heat losses due to excess air and losses resulting from incomplete fuel burning is shown in Figure 1.

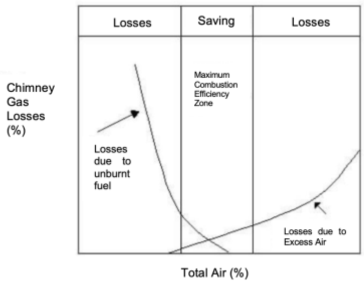

Figure 1. Heat losses due to excess air versus heat losses due to incomplete combustion (Queiroz, 2017).

It can be observed that heat losses due to excess air increase in a much lower proportion than the losses resulting from unburned fuel. Nonetheless, even causing losses at lower rates, the excess combustion air must be controlled in order to maintain the efficiency of the combustion process (Bega, 2003). Another important variable regarding the analysis of oxygen concentration in combustion processes is the lambda coefficient (λ), which can be calculated through Eq. (1):

$$\lambda = \frac{admissible\ mixture}{stoichiometric\ mixture} \tag{1}$$

This variable is used to determine the state of the air-fuel mixture consumed. If it is lower than 1, the mixture is called rich, meaning that the admissible mixture contains more fuel than the ideal amount for oxygen to consume it, and the unconsumed portion will be lost. Still, when the λ-value is higher than 1, the mixture is known as lean, i.e., the admissible mixture has a greater amount of oxygen than the ideal for consuming the present fuel. Finally, in a situation where the λ-value equals 1, it is said to be operating at the stoichiometric point, when the admissible mixture is exactly the same as the ideal (Pereira, 2015).

In addition to thermal efficiency, the emission of pollutants is also strongly linked to excess air, evidencing once again how important it is to control the air-fuel mixture. In Figure 2, the relationship between the λ-value and the emission of the main polluting gases formed in industrial combustion processes is shown.

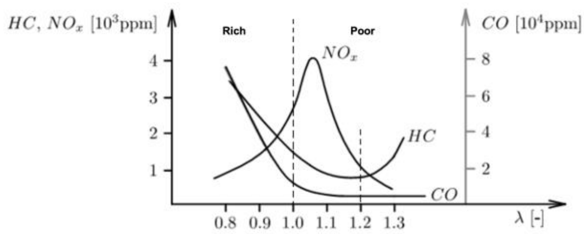

Figure 2. Lambda coefficient versus pollutant emissions in parts per million (Guzzella and Onder, 2010).

When the mixture is rich, part of the fuel is not consumed. This unburned fuel is composed of hydrocarbons that may join the atmosphere, producing a visible and thick smoke (Guzzella and Onder, 2010). Another pollutant formed when operating at rich mixtures is carbon monoxide. In turn, the nitrogen present in atmospheric air is responsible for forming nitrogen oxides. From Figure 2, it is observed that these oxides are formed more intensely when the mixture is lean, with lambda ranging from 1.0 to 1.1. In this range, the temperature in the combustion chamber rises, allowing oxygen to react with nitrogen, giving rise to NO_x (Pulkrabek, 2003). It is also important to note that for lambda values higher than 1.1, the thermal efficiency is minimized due to excess combustion air. Additionally, the flame temperature decreases and, as a result, NO_x emissions are reduced. As there is little fuel burning, HC emissions increase as the mixture becomes leaner ($\lambda > 1.2$), due to combustion failures.

So far, it is already clear that the oxygen concentration in combustion gases plays a vital role in terms of increasing thermal efficiency (which translates into cost savings for companies) and also mitigating the environmental impacts triggered by greenhouse gas emissions. It is known that the vast majority of industrial processes involving combustion reactions require substantial amounts of energy, which is commonly obtained by burning fossil fuels (Baukal, 2004). Moreover, most industrial combustion processes use atmospheric air as an oxidant and, in view that it brings in its composition an excessively high amount of nitrogen, lately, many high-temperature processes contain an oxidant with a higher proportion of oxygen compared to the atmospheric air. This combustion technique is known as “oxygen-enhanced combustion" (OEC) and proves how important it is for the industrial sector to optimize its combustion processes (Santos *et al.*, 2011).

2.2 Automotive Lambda Sensors

Environmental laws and regulations aiming at the control of air pollution are becoming increasingly stringent, especially where there is combustion of fossil fuels or biomass (Lima *et al.*, 2011). The control of both the efficiency and emission of pollutants in the industrial combustion of any energetic can be carried out before, during or after the combustion itself (Wawrzinek and Trimis, 2001). The control of industrial combustion efficiency made after the process is the one in which the air-fuel ratio can be determined from the measurement of oxygen concentration in combustion gases (Lima, 2009). In automobiles, this process is carried out by an oxygen sensor popularly known as lambda sensor.

These sensors were first manufactured on a large scale in 1976 by the German company Robert Bosch GmbH and used in Swedish Volvo cars. Nowadays, it is estimated that Bosch produces about 33 million sensors per year (Robert Bosch GmbH, 2001). The vast majority of lambda sensors currently manufactured consist essentially of a pair of porous platinum electrodes separated by a zirconium dioxide (ZrO_2) thin film. In Figure 3, the cross-section of Bosch LSU wideband lambda sensors is shown.

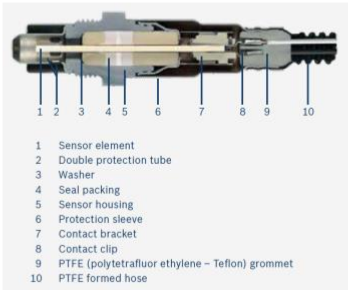

Figure 3. Cross-section through the LSU wideband lambda sensor (Robert Bosch GmbH, 2001).

At high temperatures, the solid zirconium ceramic begins to conduct oxygen ions. When this ceramic is exposed to two different oxygen concentrations on both sides of the cell, an electric potential difference is generated. This voltage is dependent on the temperature and the two partial oxygen pressures. Accordingly, it can be used to determine the air-fuel ratio of combustion systems (Sobrinho *et al.*, 2010). A lambda sensor's typical curve is seen in Figure 4, where the output voltage is a function of λ-value.

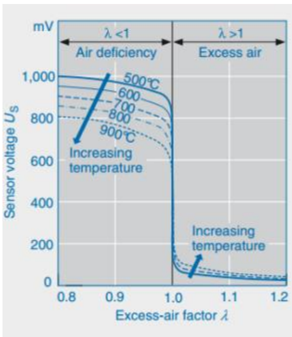

Figure 4. Typical voltage curve of a lambda sensor (ETAS GmbH, 2011).

It is important to verify that the characteristic voltage curve of a lambda sensor is different in each temperature value; however, in any of them it will present the same sudden drop when approaching the stoichiometric condition. The Nernst equation relates the sensor voltage to the oxygen content in the flue gas, the oxygen content in the reference gas (atmospheric air) and also the temperature, as seen in Eq. (2):

$$E = -\frac{RT}{zF} \times \ln\left[\frac{p(O_2)_{test}}{p(O_2)_{ref.}}\right], \tag{2}$$

where E is the voltage developed in the sensor, R is the universal gas constant, T is the absolute temperature inside the lambda sensor, F is the Faraday constant and z corresponds to the number of electrons migrating from an electrode to another inside the sensor.

Lima *et al.* (2011), Sobrinho *et al.* (2010) and Manzoti (2007) proved the feasibility of methods to analyze oxygen concentrations in industrial combustion processes by using commercial automotive lambda sensors. The results obtained by Lima *et al.* (2011), when compared with a reference oxygen analyzer (Testo 300 XL, with resolution of 0.1% and accuracy of $\pm$ 0.2%), presented a maximum deviation lower than 10% in relation to the values presented by the reference analyzer, considering the range of interest for industrial combustion, i.e., oxygen concentrations in combustion products lower than 7%. The average deviation of all measurements was around 4.7%.

In light of the foregoing, the relevance of this project is justified as an affordable and low-cost alternative to the industrial combustion monitors and analyzers available in the Brazilian market, which are considerably expensive and require periodic maintenance. In the current industrial context, innovative solutions are sought with some urgency, capable of not only comply with the environmental standards, but also ensure a favorable cost-benefit ratio. Hence, the analysis of oxygen concentration to control excess combustion air appears as a very promising option, adding simplicity with a high capacity to match the industrial sector's current demands. Recently, other studies have proven the feasibility of using automotive lambda sensors to analyze the oxygen concentration in combustion processes. Nonetheless, few have made use of wideband sensors associated with microcontrollers and graphical interfaces, an aspect in which this project innovates, by integrating contemporary concepts of Industry 4.0, such as the use of electronic prototyping platforms for the supervision of industrial processes.

3. METHODOLOGY

After the fulfillment of preliminary stages regarding a state-of-the-art literature review and also the acquisition of all the required knowledge for the proper accomplishment of the project, it was proposed the construction of a portable combustion bench, with its operating scheme presented in Figure 5.

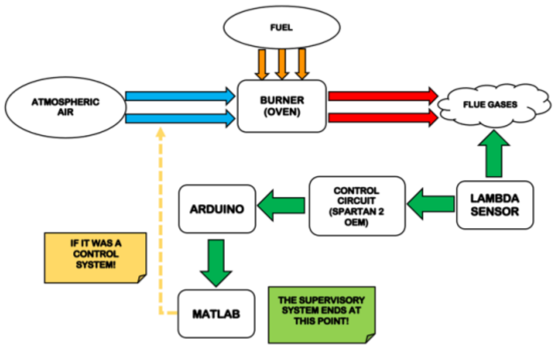

Figure 5. Schematic diagram of the operation of the proposed combustion bench.

Regarding the oven, it has a premixed flame, where it is possible to vary the primary air injection (proportion of oxidant) manually through a valve present in the gas burner (Bunsen burner). Furthermore, this kind of burner requires secondary air in order to promote the complete burning of the fuel. To this end, the lower section of the oven is partially leaked to allow atmospheric air (excess air) to enter the combustion chamber. The Bunsen burner is positioned at the base of the oven, which in turn is welded in the upper section to a vertical carbon steel pipe that acts as a kind of chimney. In it, the lambda sensor is positioned perpendicularly in order to perform measurements as the flue gases are expelled. The diagram of the oven built to integrate the proposed combustion bench is shown in Figure 6.

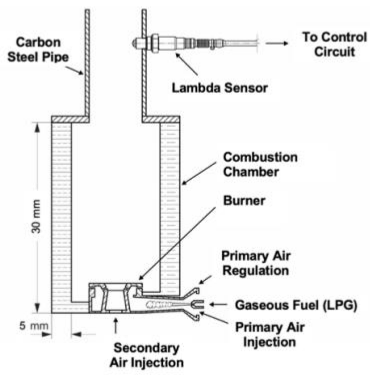

Figure 6. Schematic diagram of the oven used in the combustion bench.

Liquefied petroleum gas (LPG) was used as fuel. In addition to the fact that its composition is known, this gaseous fuel was chosen due to its easy access, since it is commonly used in gas stoves, complying with the idea of assembling an affordable and low-cost system. Moreover, it is important to note that the regulation of the air-fuel mixture (excess air) by the oxygen concentration measured in the exhaust gases is independent of the fuel used, as long as its composition is known.

The lambda sensor used in the combustion bench is the LSU 4.9 model, manufactured by Bosch Engineering GmbH©. Basically, it is a planar zirconia dioxide (ZrO_2) dual cell limiting current sensor with an integrated heater. Essentially designed for automotive applications, this sensor's function is to measure the oxygen content and the λ-value of exhaust gases in automotive engines. Because this lambda sensor is a wideband type, it has a very wide output signal (in the range of λ = 0.65 to air), making it capable of being used as a universal sensor for measurements both in the stoichiometric range (λ = 1.0) and other intervals. The schematic diagram of the sensor cell is seen in presented in Figure 7. In it, it is possible to check how the terminals (wires) are connected.

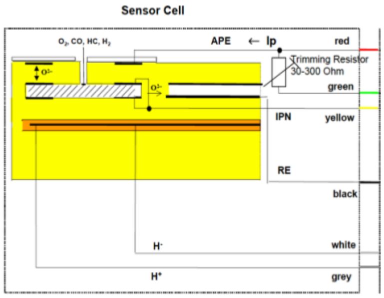

Figure 7. Schematic diagram of Bosch LSU 4.9 sensor cell (Robert Bosch GmbH, 2005).

In order to obtain the signal (potential difference) emitted by the lambda sensor's readings, it is necessary to assemble an electronic support circuit which basically consists of a Spartan 2 OEM microcontroller board manufactured by 14point7©, aimed at controlling wideband lambda sensors such as the one used in this project. Basically, this microcontroller board is responsible for interpreting the electrical signal emitted by the lambda sensor and converting it into a linear analog voltage output ranging from 0 to 5 V (λ-values from 0.68 to 1.36) to the Arduino prototyping platform. This is required due to a sensor's peculiarity, which correlates the reading of oxygen concentration with an electrical current value known as pump current (I_p). The board is powered by a 12V DC voltage supply, while the electrical current is limited by a 5A fuse. The Spartan 2 OEM pinout is shown in Figure 8. In turn, the connection of the LSU 4.9 sensor's terminals on the board was done as indicated in Table 1.

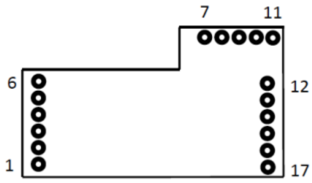

Figure 8. Spartan 2 OEM pinout (14point7, 2016).

Table 1. Connection of LSU 4.9 sensor's terminals on the Spartan 2 OEM microcontroller board.

Pin	Name	Connection
1	LSU IA	Terminal #5 (green wire)
2	LSU H+	Terminal #4 (gray wire)
3	LSU IP	Terminal #1 (red wire)
4	LSU UN	Terminal #6 (black wire)
5	LSU H-	Terminal #3 (white wire)
6	LSU VM	Terminal #2 (yellow wire)
12	12V	Input voltage (with 5A fuse)
13	E Ground	Electronic ground
14	H Ground	LSU Heater ground
16	Lin Out	Linear output (connected to Arduino)

* The pins not indicated in Table 1 were not used.

Finally, the linear output of Spartan 2 OEM is connected to one of the Arduino Mega 2560's analog inputs (in this case, the input designated as "A0" was used). The assembly of the control circuit is seen in Figure 9.

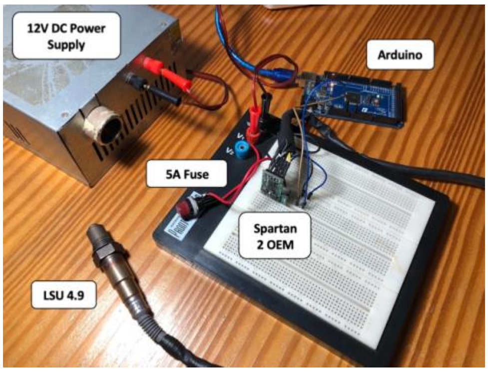

Figure 9. Assembly of the LSU 4.9 lambda sensor's control circuit.

Given the output voltage of Spartan 2 OEM, the lambda coefficient is obtained according to Eq. (3):

$$\lambda = (0.136 * V) + 0.68, \tag{3}$$

where V is the output voltage provided by Spartan 2 OEM, ranging from 0 [V] @ 0.68 [λ] to 5 [V] @ 1.36 [λ]. Next, after collecting the data measured by both the combustion bench and a reference analyzer, the correlation between the output voltage of Spartan 2 OEM and the oxygen concentrations measured by the analyzer will be obtained. Hence, a linear relation between these variables will be identified, making it possible to calculate the oxygen concentrations based on the measurements carried out by the combustion bench, which is seen in Figure 10.

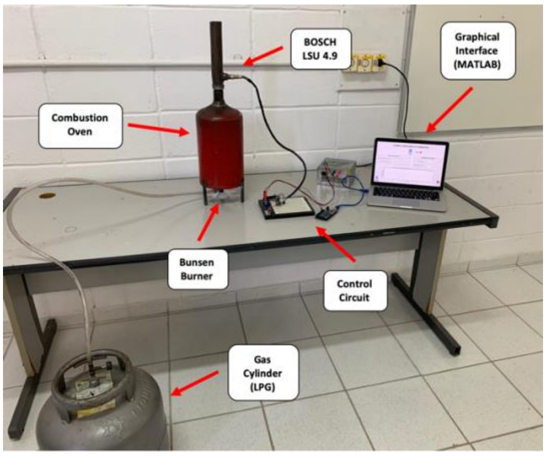

Figure 10. Assembly of the combustion bench.

Next, it is presented the algorithm containing the task specification of the source code developed in Matlab for the supervisory system, as well as its respective flowchart (Figure 11).

1. Initialize the program after user stimulus.

2. Definition and initialization of variables and pins to be used in Arduino.

3. Check the lambda sensor's input voltage. If the measured value is less than a voltage value previously stipulated in the program, this may indicate a malfunction of the sensor. Thus, an error message must be displayed so that the user checks the electrical connections and wiring. Otherwise, proceed to step 4.

4. Get the analog output voltage (0 – 5V) from Spartan 2 OEM.

5. Calculate λ-value and oxygen concentration.

6. Display the real-time results to the user through a GUI (Graphical User Interface).

7. Return to step 3 and run the commands again (loop) until the user decides to abort the execution of the program. Once this occurs, proceed to step 8.

8. Clear the Arduino memory and shut down the program.

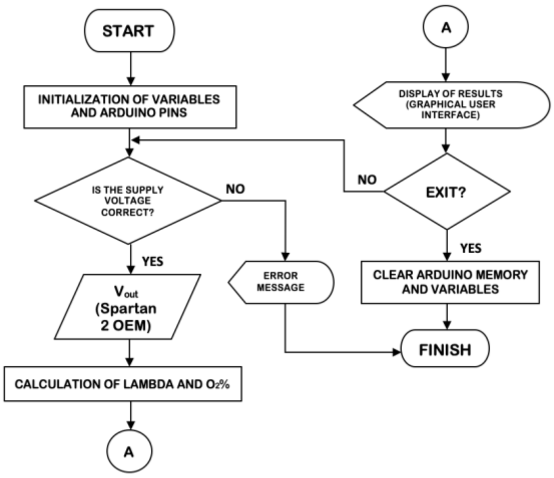

Figure 11. Flowchart of the source code.

In Figure 12, the graphical interface developed in Matlab's App Designer environment is shown, in which the results are presented to the user.

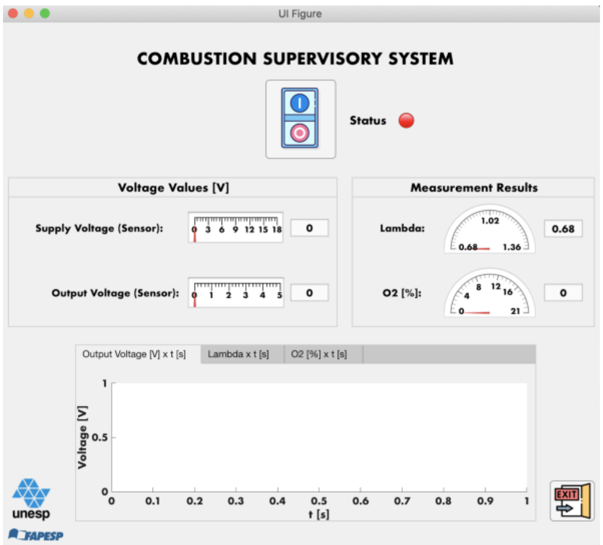

Figure 12. Graphical interface developed in App Designer (Matlab).

Lastly, after taking measurements in different air-fuel proportions, in order to verify the data collected by the assembled combustion bench, a LAND© Lancom III flue gas analyzer was used as reference. This analyzer is capable of performing direct measurements of oxygen concentrations in the range of 0 to 25.0% Vol., with an accuracy of $\pm$ 1% and a resolution of $\pm$ 0.1% Vol. Therefore, it is possible to verify the accuracy and susceptibility of the supervisory system. Subsequently, a statistical analysis was conducted in order to reproduce in numbers how feasible the assembled combustion bench is, taking into account aspects such as cost-benefit and ease in the acquisition and assembly of components. The results obtained are presented and discussed in the following topic.

4. RESULTS AND DISCUSSION

For the data collection stage, eight measurements were performed simultaneously in the reference analyzer (Lancom III) and the combustion bench, each one with different air-fuel mixtures. This was done by regulating the Bunsen burner's primary air intake valve, thus varying the oxidant proportion. In turn, the amount of fuel was kept constant during all measuring points. Initially, a mixture with little oxygen was analyzed, i.e., with the valve closed almost completely, producing a rich mixture. As more measurements were performed, the intake valve was gradually opened, allowing the formation of mixtures with more oxygen in their composition (lean mixtures).

After collecting all the data, it was established a linear correlation between the oxygen concentration measured by Lancom III and the voltage read by the supervisory system developed in Matlab, which is seen in Figure 13. Therefore, it was possible to calibrate the system and calculate the oxygen concentration measured by it. The comparison of these values is presented in Table 2. It is worth mentioning that the values presented are average values, once for each measuring point, the supervisory system collected a sample of approximately 200 values, whereas the reference flue gas analyzer collected 6 values for each measuring point.

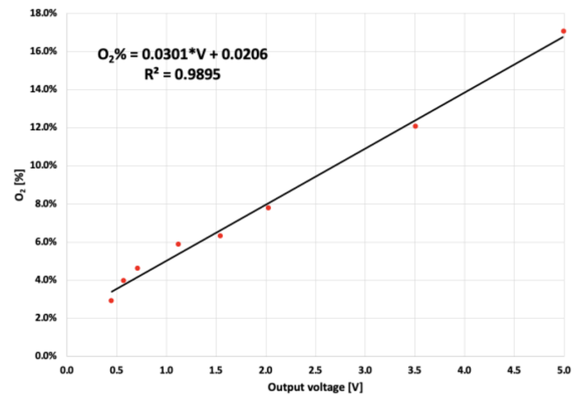

Figure 13. Output voltage versus oxygen concentration (Lancom III) graph.

Table 2. Oxygen concentrations measured by the combustion bench and the Lancom III flue gas analyzer.

Measuring Point	O_2% (Combustion Bench)	O_2% (Lancom III)	Percentage Difference (%)
1 (− Primary Air)	3.41%	2.92%	15.48%
2	3.78%	3.99%	5.40%
3	4.19%	4.62%	9.76%
4	5.44%	5.87%	7.60%
5	6.71%	6.31%	6.14%
6	8.16%	7.80%	4.51%
7	12.62%	12.08%	4.37%
8 (+ Primary Air)	17.10%	17.07%	0.17%
Average Percentage Difference (%)			**6.68%**

The data presented attest to the high susceptibility of the combustion bench. Among the measuring points analyzed, an average percentage difference of 6.68% was obtained, a relatively low and acceptable value. Therefore, it can be said that the results demonstrate how feasible the proposed combustion bench is, which emerges as a highly viable low-cost alternative to the flue gas analyzers currently available in the market, especially when taking into account the main aspects that guided its development, such as cost-benefit and accessibility.

5. CONCLUSION

Currently, the high competitiveness exercised in the industrial sector forces companies to search for innovative and profitable solutions. Regarding industrial combustion, the compliance with the several environmental regulations, aimed at mitigating the harmful impacts already caused by global warming, must also be ensured. Accordingly, controlling the excess combustion air by analyzing the oxygen concentration emerges as an effective and easy-to-implement alternative, in order not only to increase the overall thermal efficiency but also to reduce the emissions of pollutants responsible for worsening the greenhouse effect. In this context, the flue gas analyzers used nowadays are too expensive and require periodic maintenance. Alternatively, this paper proposed the development of a low-cost system, based on an automotive component known as lambda sensor, to analyze the oxygen concentration in combustion gases. This system, which innovates by integrating a wideband lambda sensor to Industry 4.0 resources, showed very promising results when compared to a reference gas analyzer, with an average percentage difference of 6.68%. These results not only attest to the high accuracy and feasibility of the developed system, but also demonstrates that it is fully possible to develop affordable systems with significant results. Later, a control system can be incorporated into this project, in which it would be possible to monitor the combustion chamber and act directly on it, by adjusting the mixture's air-fuel ratio from a command sent by the graphical user interface.

6. ACKNOWLEDGEMENTS

To FAPESP, for financing the development of this research project (Process No. 2020/08358-5).

7. REFERENCES

14point7., 2016. "Spartan 2 OEM Lambda Controller Manual". No. 1, pp. 1–3.
Baukal, C. E., 2004. "Industrial burners handbook". CRC Press: New York.
Bega, E. A., 2003. *Instrumentation applied to boiler control* (in Portuguese). Interciência: Rio de Janeiro, Vol. 3a.
Belohradsky, P., Skryja, P., and Hudák, I., 2014. "Experimental study on the influence of oxygen content in the combustion air on the combustion characteristics". Energy, Vol. 75, pp. 116–126.
Biarnes, M. E., 2016. "Combustion Training". www.e-inst.com/combustion. Accessed 13 January 2021.
Carvalho, J. A., Mendiburu, A. A. Z., Coronado, C. J. R., and McQuay, M. Q., 2018. *Applied Combustion* (in Portuguese). UFSC: Florianópolis.
Chapman, R., 2019. "Understanding the Impact of Excess Air". <https://www.firebridgeinc.com/blog/understanding-the-impact-of-excess-air/>. Accessed 31 August 2021.
ETAS GmbH., 2011. "Lambda Training". No. 1, pp. 1–19.
Guzzella, L., and Onder, C. H., 2010. "Introduction to Modeling and Control of Internal Combustion Engine Systems". Vol. 2, Springer-Verlag: Zurique.
Kuprianov, V. I., 2004. "Applications of a cost-based method of excess air optimization for the improvement of thermal efficiency and environmental performance of steam boilers". Renewable & Sustainable Energy Reviews.
Lima, L. C., 2009. *Construction and evaluation of an industrial combustion monitor* (in Portuguese). Revista Tecnologia, Vol. 28, No. 1, pp. 77-84.
Lima, L. C., Carmona, H. A., Silva, C. V. M., and Francisco, S., 2011. "Oxygen Excess Control of Industrial Combustion through the use of Automotive Lambda Sensor". International Transaction Journal of Engineering, Management, Applied Sciences & Technologies, Vol. 2, No. 3, pp. 365-373.
Manzoti, D. T. C., 2007. *Parametrization of an Automotive Lambda Sensor* (in Portuguese).
Pereira, B. S., 2015. *Air/Fuel Mixture Control in an Internal Combustion Engine: Closed-Loop System* (in Portuguese). Master's Thesis, Graduate Program in Mechanical Engineering, Polytechnic School of the University of São Paulo, Brazil.
Pimenta, J. Lima, L. C., Duarte, J. B. F., and Macedo, R. M., 2002. "Industrial Burners Testing and Combustion Efficiency Analysis". Thermal Engineering: Special Edition, Vol. 2, pp. 3–8.
Pinheiro, P. C. C., and Valle, R. M., 2010. "Combustion Control: Excess Air Optimization". No. 2, pp. 157-162.
Procel, and Eletrobras, 2005. *Energy Efficiency in the use of steam* (in Portuguese). Rio de Janeiro, Brazil.
Pulkrabek, W. W., 2003. "Engineering Fundamentals of the Internal Combustion Engine". Vol. 2, No. 1, Prentice Hall: Platteville.
Queiroz, T. L., 2017. *Implementation of an Automation, Control and Supervision of Combustion System in a Boiler* (in Portuguese). Undergraduate's thesis, Bachelor's degree in Electrical Engineering, Federal Center of Technological Education of Minas Gerais.
Robert Bosch GmbH., 2001. "Oxygen Sensors". No. 1, pp. 13–15.
Robert Bosch GmbH., 2005. "Bosch LSU 4.9 Technical Product Information". No. 1, pp. 1–13.
Santos, A. A. B., Torres, E. A., and Pereira, P. A. P., 2011. "Critical evaluation of the oxygen-enhanced combustion in gas burners for industrial applications and heating systems". Journal of the Brazilian Chemical Society, Vol. 22, No. 10, pp. 1841–1849.
Sobrinho, A. S. S., Nascimento, R. S., Pinheiro, R. S., and Lima. L. C., 2010. "Measurements of the flue gases oxygen concentration by Lambda sensor". Revista Tecnologia, Vol. 31, No. 1, pp. 91–98, Fortaleza, Brazil.
Wawrzinek, K., and Trimis, D., 2001. "Development of a Wobbe number sensor for controlled combustion of gaseous fuels with varying quality". In International Conference on Technologies and Combustion for a Clean Environment (Clean Air VI), Vol. 6, pp. 1–7.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.