

Original Research Article

Monitoring the Air-Fuel Ratio (AFR) of a biomass gasification process with an Arduino Uno 3 and a narrow band Lambda oxygen sensor

Abstract

The Air-Fuel Ratio is one of the key parameters for driving the gasification process. Monitoring of oxygen percentage in flue gas is one of various ways of controlling efficiency and emissions of industrial combustion. Biomass gasification is a thermochemical degradation of the biomass that is accomplished with the Air-Fuel Ratio less than the stoichiometric one that is used in the combustion.

Unfortunately, flue gas analyzers in combustion processes are expensive and not accessible to small-scale industries. This is particularly true in developing countries. The Lambda sensor used in the automotive industry is an oxygen sensor which controls the electronic injection of the modern internal combustion vehicles.

The aim of this study is to present one simple method of measuring the oxygen concentration and calculate the Air-Fuel Ratio in synthesis gas produced by a downdraft biomass gasifier by the use of an Arduino Uno 3 microcontroller and an automotive Lambda sensor. This method uses the voltage signals developed by a heated 4-wire Lambda sensor and the Nerst Equation to calculate oxygen concentration in the producer gas and derive the Air-Fuel Ratio.

Results presented in this article show that this method is a simple and cost-effective way to monitor Air-Fuel Ratio in a biomass gasifier.

Keywords: Air-Fuel Ratio, Biomass, Gasification, Lambda sensor, Arduino

1. Introduction

Biomass gasification is used very little in Burkina Faso, although it has proven to be one of the most efficient methods for converting biomass into thermal and electrical energy. Despite the abundance of waste of agricultural, plant and household origin, the large-scale recovery of this conversion process is very little developed in Burkina Faso [1], [2]. In a bibliographic review made in 2014, it was established that gasification of waste may be an interesting alternative for waste valorisation in Burkina Faso [3]. Other studies on the development of biomass energy in Africa agree with the main conclusions of that review [4], [5], [6].

The equivalence ratio (ER) of a system is defined as the ratio of the hydrocarbon-to-oxidizer ratio to the stoichiometric hydrocarbon-to-oxidizer ratio which can be expressed with equation (1) below:

$$ER = \frac{(\text{fuel to oxidizer ratio})_{act}}{(\text{fuel to oxidizer ratio})_{sto}} = \frac{[m_{fuel}/(m_{oxy})]_{act}}{[m_{fuel}/(m_{oxy})]_{sto}} = \frac{[n_{fuel}/(n_{oxy})]_{act}}{[n_{fuel}/(n_{oxy})]_{sto}} \quad (1)$$

In equation (1), m represents the mass, n represents number of moles. Subscripts act and sto refer to actual and stoichiometric ratios respectively for the corresponding mass or mole fractions.

According to Vaclav et al. [7]: if air is used as the oxidizer, equation (1) can be rewritten as follows:

$$ER = \frac{(\text{fuel to oxidizer ratio})_{act}}{(\text{fuel to oxidizer ratio})_{sto}} = \frac{[m_{fuel}/(m_{air})]_{act}}{[m_{fuel}/(m_{air})]_{sto}} = \frac{[n_{fuel}/(n_{air})]_{act}}{[n_{fuel}/(n_{air})]_{sto}} \quad (2)$$

Air Fuel Ratio is given by equation 3 below:

$$AFR = \frac{m_{air}}{m_{fuel}} = \frac{\rho_{air} \cdot V_{air}}{\rho_{fuel} \cdot V_{fuel}} = \frac{1}{d} \frac{V_{air}}{V_{fuel}} \quad (3)$$

Where ρ is the density, V is the volume, d is the density of the fuel against air.

Comparing equations 3 and 2, we see that ER is the ratio of the stoichiometric AFR to the actual AFR.

Commercial Lambda sensors give the excess oxygen in the flue gas. Therefore we can compute the AFR from the output of the Lambda sensor.

In an experimental study on air gasification of polypropylene, Xiao et al. [8] studied the effect of the ER and found that the equivalence ratio appeared to have a significant effect on the reactor temperature and other gasification results. The increase of the equivalence ratio favored the formation of the fuel gas and decreased the formation of the tars and char. Other authors obtained similar results [9], [10], [11]. Coming out as a summary, the work done by Vaezi et al. [12] used the thermochemical equilibrium modeling to predict the performance of a heavy fuel oil gasifier. Their model combined both the chemical and thermodynamic equilibria of the global gasification reaction in order to predict the final syngas species distribution. They compared the results of their simulations with reported experimental measurements through which their numerical model was validated. They found that the ER exhibits an optimum value respective to producer gas yield as depicted on figure 1 below :

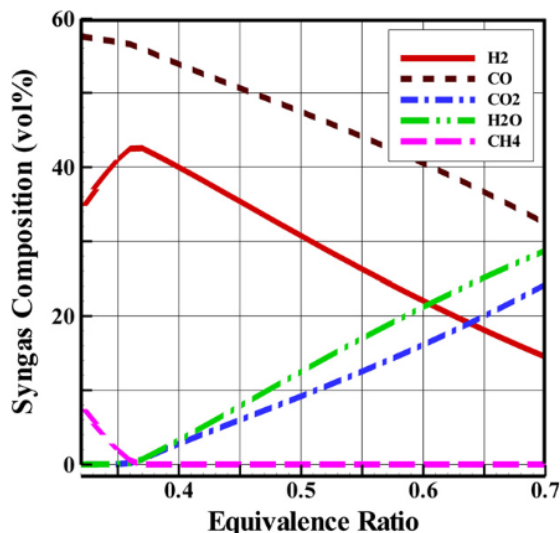


Figure 1 : Effect of the ER on the producer gas composition (from Vaezi et al. [12])

Therefore, monitoring of the ER, i.e. the AFR, appears of the utmost importance in the gasification process. We have designed and tested two wood-fired down-draft biomass gasifiers in Burkina Faso [13], [14]. Unfortunately, we were limited by the failure of the five flue gas analysers we have on hand and even the replacement of the oxygen or carbon monoxide sensors appeared out of reach, because these are relatively costly and not suited for long run usage (maximum 5 minutes recommended by the manufacturers). Therefore, we looked around and found that several authors used Lambda sensors to monitor the excess air and other gases in industrial applications [15], [16], [17], [18]. We also found that the Arduino microcontroller can be used to acquire data from numerous sensors, compute several mathematical functions and display or log these values in a USB drive [19], [20], [21], [22], [23].

Using Lambda sensors and the Arduino microcontroller emerged as a very interesting and cost-effective replacement solution for monitoring the ER in our biomass gasifiers.

2. Materials and methods

2.1 Experimental setup

Overview of the experimental setup is given on figure 2 below :

Figure 2 : Experimental setup

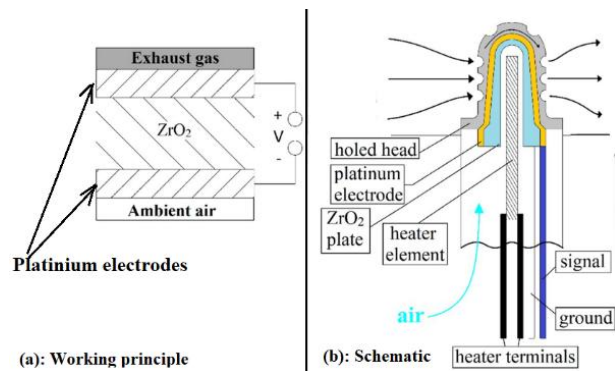
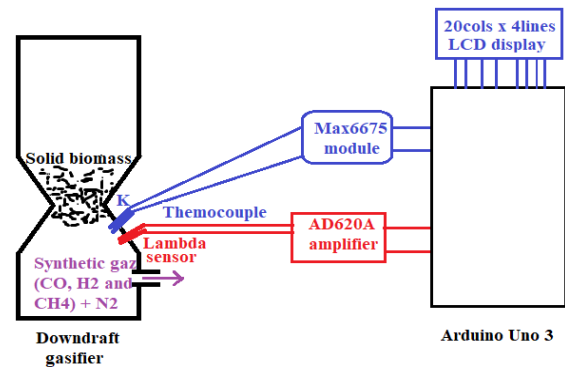


Figure 3 : Working principle and schematic diagram of a Lambda oxygen sensor, from Najjar et al. [24]

Technical specifications of the Arduino Uno 3 development board are given in table 1 below :

Table 1 : Arduino Uno 3 technical specifications

Microcontroller	ATmega328P
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limit)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
PWM Digital I/O Pins	6
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328P) of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328P)

EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz
LED_BUILTIN	13
Length	68.6 mm
Width	53.4 mm
Weight	25 g

2.2 Methods

2.2.1 Determination of the temperature

A K type thermocouple is used along with its amplification and analog to digital converter referenced as Max6675 to acquire the working temperature of the gasifier in °C where the Lambda sensor is plugged in. Conversion in Kis made in the Arduino Integrated Development Environment (IDE).

2.2.2 Determination of the oxygen concentration :

A zirconium oxide oxygen sensor, as for example the commercial narrowband Lambda sensor found in automobiles, consists of a pair of porous platinum electrodes separated by a layer of the zirconium oxide as illustrated by Najjar et al. [24] on figure 3. below.

At high temperatures (above 573K) the zirconium ceramic becomes conductive to oxygen ions. The Lambda sensor is made in the way that the sensing side is plugged into the monitored device, while exposition to air is internally assured through the unplugged part of the sensor (figure 3.b above). When exposed to two different levels of oxygen concentration on either side of the cell, for example : one side to gaz exhaust and another to the ambient air, an electro-motive force (emf) voltage is produced. Partial pressures of oxygen in addition to temperature and the emf 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.

The analog signal output from the Lambda sensor computed by Lutero C. de Lima et al. [25] varies from 0 to 80mV around 800°C. At 500°C they found 28mV at 4% and 7.5mV at 15%. Our Arduino board use a 12 bits analog to digital conversion from 0 to 5V. Taking in account that gasification is conducted under sub-stoichiometric conditions, we limit ourself to oxygen content from 3% to 15% at 850°C. Therefore, we need a maximal analog signal amplification gain of $5000\text{mV}/80\text{mV}=62.5$.

Figure 4 below depicts the AD620 low power μV and mV signal amplifier we used to amplify the emf supplied by the Lambda sensor.

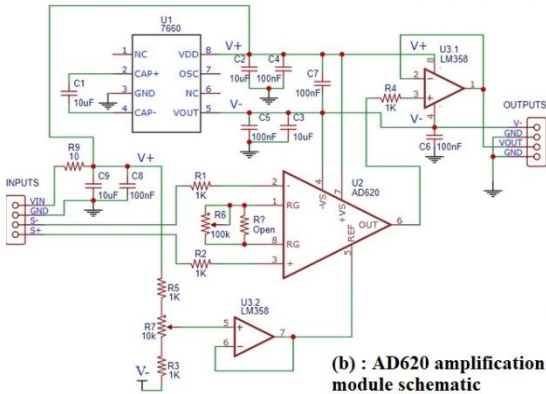
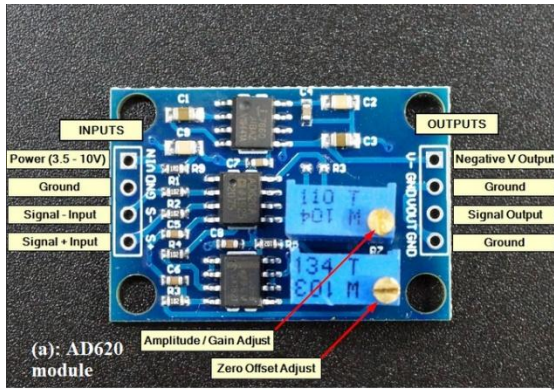


Figure 4 : The AD620 module and schematic

Amplified analog signal from the Lambdasensor was directed to an analog input pin of the Arduino Uno 3 board as illustrated on figure 5 below :

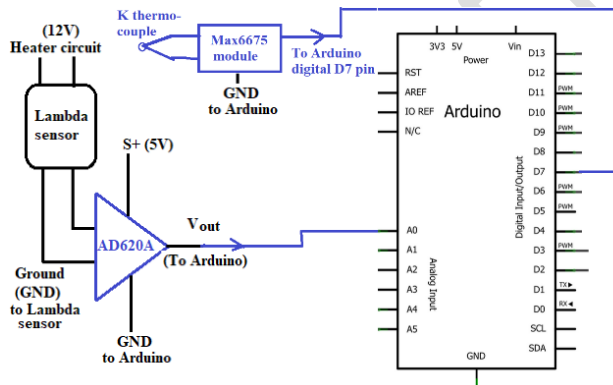


Figure 5: Electrical diagram of the monitoring system

Oxygen concentration is determined through the Nerst Law :

$$O_2(\%) = 20.96 \exp\left(-\frac{zF}{RT} E\right) \quad (4)$$

20.96 is the volumic concentration of oxygen in clean air,

z is the number of electrons migrating between the sensor electrodes,

F is the Faraday constant,

E is the amplified voltage developed across the sensor terminals,

R is the universal constant of ideal gases,

T is the absolute temperature in the Lambda sensor.

A commercial heated 4 wires Lambda sensor was installed in the reduction zone of a downdraft gasifier. Close to the Lambda sensor was installed a type K thermocouple. A simple, electrical circuit comprising a 5V DC power source in series with an ammeter and the heating element of the Lambda sensor was used. An electronic voltmeter was attached in parallel to the heating element. An oscilloscope was also attached to the signal wires of the Lambda sensor as shown in figure 5 below.

Basically the heating element is driven with an electronic circuit to supervise the electrical resistance of the sensor's heater. That electronic control was not used in this paper and will be implemented through the use of the Pulse Wide Modulation (PWM) technique in another upcoming paper.

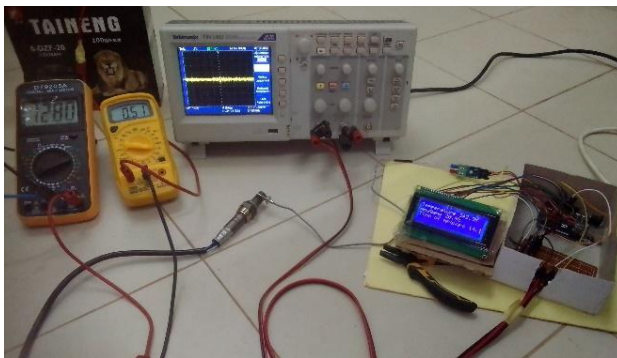


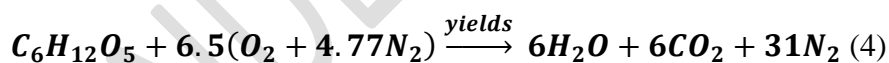
Figure 6 : Heater circuit resistance determination setup

The heater element resistance variation across the time is represented on figure 7 below.

2.2.3 Determination of the AFR

AFR is calculated using equation (3). We must first find the stoichiometric AFR of wood in clean air. Wood composition slightly varies between species, but can be in first approximation represented as $C_6H_{12}O_5$, when wood is supposed not to contain nitrogen or minerals.

The stoichiometric combustion of wood in air containing 21% of oxygen and 79% of nitrogen is the following :



Stoichiometric AFR correspond to 21% of oxygen. Actual AFR, $(AFR)_{act}$ correspond to percent of oxygen given by the lambda sensor according to equation (3). We derive equation below :

$$(AFR)_{act} = \frac{\text{oxygen}(\%)}{20.96} (AFR)_{sto} \quad (5)$$

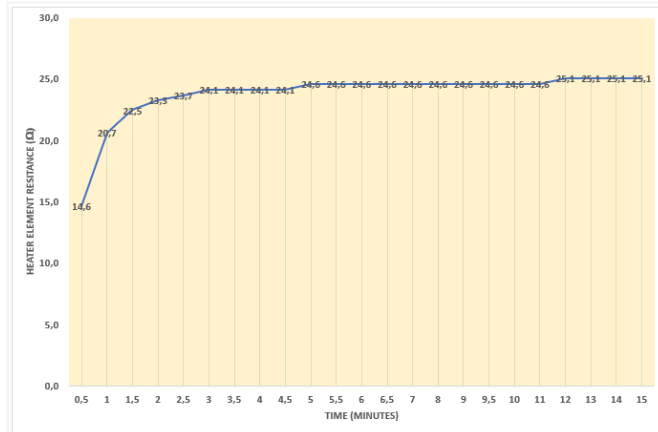
3. Results and discussion

3.1 Calibration of the Lambda sensor

The Lambda sensor does not require a complicated or costly calibration but the heater resistance of a Lambda sensor widely varies from a supplier to another. We thus first checked the response of the heating element during the application of a continuous electrical power aiming to set the required working temperature of the Lambda sensor to more than 600 °C and to check the Lambda sensor is working as intended. Figure 5 above shows the setup for that setup.

The response of the Lambda sensor to a DC power supply is shown on figure 7 below:

Figure 7: Variation of the resistance of the heating element inside the Lambda sensor during the application of an 5V DC power supply.



We can see in figure 7 above that the resistance of our Lambda sensor varies from 14.5Ω to 25.1Ω and is stabilized after 5 minutes of heating.

Table 2 : the heater element resistance varies with the temperature over the time as we can see on below

Time(s)	0,5	2	4	6	8	10	12	14	16
R(Ω)	14,6	23,3	24,1	24,6	24,6	24,6	25,1	25,1	25,1
Temperature(°C)	33	35,6	45	55	62	66	69	70	70,1

This is because the final temperature of the heater element depends on the power energy it receives and heat radiation in the flue gas. Therefore, temperature of the flue gas also impacts the heater resistance. This is why, the heater elements should be managed with an appropriate electronic circuit that aims to maintain the heating element at the correct working temperature.

Gibson *et al.* [26] and Varambanet *al.* [27], using the Current Reversal Mode aimed at improving the accuracy of the measured oxygen content combustion system reported that until 12% of oxygen the correlation is imperfect and from 15% up another correlation showed itself perfect, characterizing a transitional behavior of the Lambda sensor at the range from 12 to 15%.

Using the same method and comparing against measurements taken from the reference combustion analyzer (Testo 300 XL) Luterio C. de Lima *et al.* [25], found that the average deviation of the set of measurements was of $\pm 5\%$ and 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.

In the case of gasification process, we work in sub-stoichiometric conditions. Therefore we are under 14.7% of stoichiometric combustion of gasoline.

First generation of Lambda sensors are 4-wire sensors, whereas the second generation have 5 wires and are called wideband, because these can measure a wider range of oxygen concentration in flue gas. We conclude that a narrowband Lambda sensor for measuring oxygen

content when monitoring biomass gasification is largely sufficient and accuracy have been supposed based on results in references [15], [25], [26] and [27].

3.2 Computing and displaying AFR

Detailed code is given in appendice. Results obtained are displayed on a 20 columns with 4 lines LCD display as see in figure below 8 :

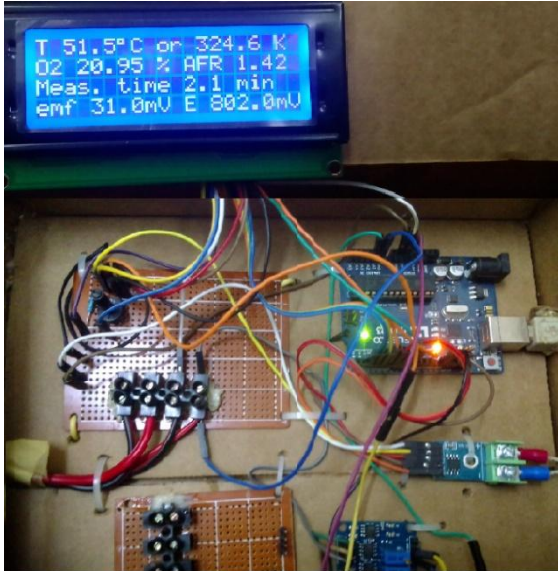


Figure 8 : Finishes prototype with LCD display

In equation 4 above, mass of wood is $m_{\text{wood}} = 164\text{g}$.

Required mass of air for stoichiometric combustion is $m_{\text{air}} = 642.07\text{g}$.

Hence the stoichiometric AFR is :

$$(\text{AFR})_{\text{sto}} = 642.07/164 = 3.91, \text{ and also}$$

$(\text{AFR})_{\text{act}} = (3.91/20.97) \text{ O}_2(\%)$, which give :

$$\text{AFR} = 0.1865 \times \text{O}_2(\%)$$

Reciprocally :

$$\text{O}_2(\%) = \text{AFR}/0.1865$$

According to work of Sahar Safiran et al. [28], optimum AFR for wood and woody biomass gasification was comprised between 1.8 and 2.

We computed oxygen excess against AFR and obtained figure 9 below :

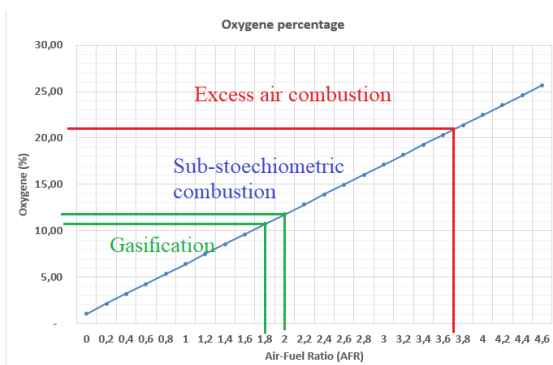


Figure 9 : Oxygene excess as function of AFR

With these results, we can see that monitoring the AFR give us an idea on how well the gasification process is running. As a perspective, we see the possibility of automatically controlling the AFR through a control loop which could give a correction signal through the PWM in order to control the primary air flow of the gasifier thus adjust the AFR.

4. Conclusion

Though a preliminary heating time of 5 minutes was required before the resistance of the heating element was stabilised; this work presents simple methods for acquiring temperature and oxygen concentration with sensors and an Arduino board. Using the Arduino Integrated Development Environment (IDE), we successfully programmed the Arduino Uno 3 board in C++, measured both the lambda sensor temperature with a K type thermocouple, the emf developed by the lambda sensor and the amplified signal E. We calculated O₂ concentration, derived the AFR and displayed temperature T (°C and K), O₂ (%), AFR, Time of Measure (minutes), emf (mV) and E (mV) on an user friendly 20x4 LCD display. An upcoming paper will address the stabilisation of the heating element resistance at a given temperature, when working temperature fluctuates through the use of Pulse Wide Modulation (PWM).

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Appendix A : Arduino code

```
#include<LiquidCrystal.h>
#include"max6675.h"
#include<Wire.h>
#include<U8g2lib.h>
LiquidCrystal lcd(12,8,5,4,3,2);
int OxyPin = A0; //Oxygen pin is A0
int thermoDO = 7; //Digital pin D7
int thermoCS = 13; //CS pin is 13
int thermoCLK = 6; //Ok
float temperature = 0.0; //Define temperature
char disp;
MAX6675 thermocouple(thermoCLK, thermoCS, thermoDO);
int vccPin = 3;
int gndPin = 2;
float oxyPercent; //Oxygen
float eO2=0.0; //Analog voltage developed by the lambda sensor
float To2=600.0; //Working temperature of the lambda sensor
#define F96485.34 //Define the Faraday constant
#define R8.314 // Define the constant gases
#define O2Air20.96 //Define Oxygen concentration in clean air
#define T0273.2 // Define temperature in K
#define z1.6*pow(10,-19) //Electronic charge
float Tom = 0.0; //Time of measure
void setup(){
    Serial.begin(9600);
    // Max 6675 setup
    pinMode(vccPin, OUTPUT); digitalWrite(vccPin, HIGH);
    pinMode(gndPin, OUTPUT); digitalWrite(gndPin, LOW);
    //End setup for Max 6675
    //Setup LCD display
    lcd.begin(20,4); //LCD's number of columns and rows:
    lcd.clear();
    lcd.print("Powering on. Please wait...");
    delay(1500); //Give 1s to read
```

```

lcd.clear();
lcd.print("Lambda sensor calibration in progress");
delay(1500); //Give reader 1.5 second to read the display
}
void loop()
{
temperature = thermocouple.readCelsius()+273.15; //Temperature is converted in K
//Oxygen with Lambda sensor
eO2 = analogRead(OxyPin);
    To2=temperature;
        oxyPercent = 205*(O2Air*(exp((-z*F*eO2)/(R*To2)))/1023.0*5.0));
//Temperature is converted in K
// Calculate Oxygen concentration according to equation derived from the Nerst
Law
//We now display T and O2
lcd.clear(); // Clear LCD to avoid weird characters display
lcd.setCursor(0,0);
lcd.print("Temperature ");
lcd.print(temperature,1); //Display Reactor temperature with 1 decimal
lcd.print("K ");
//Display O2 in %
        lcd.setCursor(0,1);
        lcd.print("Oxygen ");
        lcd.print(oxyPercent, 1); // Print Oxygen content on LCD
        lcd.print("%");
//Display what is the time elapsed?
lcd.setCursor(0,2);
lcd.print("Time of measure ");
unsigned long currentMillis = millis();
Tom = ((currentMillis/1000)/60.0);
lcd.print(Tom,1);
lcd.print("mn");
// End calculating and displaying other parameters
delay(intervalHigh);
}; // End loop

```

UNDER