Significance Of Oxygen Analyzer For Steam Boiler

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Abstract- *The proposed project introduces an innovative idea to engineer low cost in-situ oxygen analyser which is an ideal alternative for very expensive currently prevailing oxygen analysers available in the market. The project proposes an efficient use of easily available sensors which are manufactured in bulk, are compact & ready to use. With the help of these sensors, we can make Steam Boiler more robust, more energy efficient and more economical. We can achieve the next level of reliability/performance in Steam Boiler operation through proposed low cost in-situ oxygen analyser.*

Keywords- Lambda sensor; Low cost; Boiler Indirect Efficiency; SCADA.

I. INTRODUCTION

Coal, oil and natural gas are fossil fuels. They have been in existence for millions of years. Many of us use these fuels as an energy source. However, fossil fuels are non-renewable; if these resources are depleted, they will never be available again. It is therefore important to conserve fossil fuels, using alternative sources of energy when possible or utilizing fossil fuel in an efficient way.

Combustion

Combustion occurs when fossil fuels, such as natural gas, fuel oil, coal or gasoline, react with oxygen in the air to produce heat. The heat from burning fossil fuels is used for industrial processes, environmental heating or to expand gases in a cylinder and push a piston. Boilers, furnaces and engines are important users of fossil fuels. Fossil fuels are hydrocarbons, meaning they are composed primarily of carbon and hydrogen. When fossil fuels are burned, carbon dioxide (CO2) and water (H2O) are the principle chemical products, formed from the reactants carbon and hydrogen in the fuel and oxygen (O2) in the air. The simplest example of hydrocarbon fuel combustion is the reaction of methane (CH4), the largest component of natural gas, with O2 in the air. When this reaction is balanced, or stoichiometric, each molecule of methane reacts with two molecules of O2 producing one molecule of CO2 and two molecules of H2O. When this occurs, energy is released as heat.

$$CH4 + 2O2 \Rightarrow CO2 + 2H2O$$
$$\text{Reactants} \Rightarrow \text{Products} + \text{Heat}$$

In actual combustion processes, other products are often formed. A typical example of an actual combustion process is shown in Figure 1. Fuel has reacted with air to produce the products shown on the right.

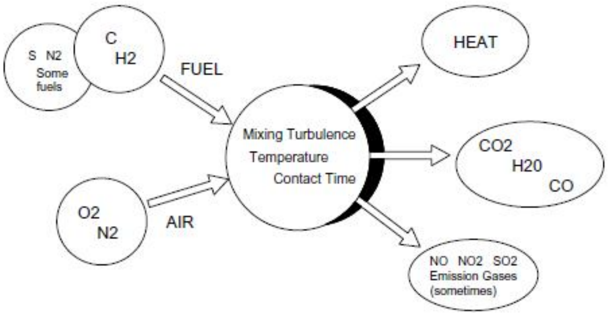


Fig 1. Combustion Diagram

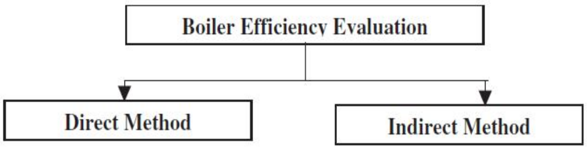
The combining of oxygen in the air and carbon in the fuel to form carbon dioxide and generate heat is a complex process, requiring the right mixing *turbulence*, sufficient activation *temperature* and enough *time* for the reactants to come into contact and combine. Unless combustion is properly controlled, high concentrations of undesirable products can form. Carbon monoxide (CO) and soot, for example, result from poor fuel and air mixing or too little air. Other undesirable products, such as nitrogen oxides (NO, NO2), form in excessive amounts when the burner flame temperature is too high. If a fuel contains sulphur, sulphur dioxide (SO2) gas is formed. For solid fuels such as coal and wood, ash forms from incombustible materials in the fuel.

Boiler Efficiency

Thermal efficiency of boiler is defined as the percentage of heat input that is effectively utilised to generate steam. There are two methods of assessing boiler efficiency.

1) **The Direct Method:** Where the energy gain of the working fluid (water and steam) is compared with the energy content of the boiler fuel.

2) **The Indirect Method:** Where the efficiency is the difference between the losses and the energy input.



Direct Method

This is also known as 'input-output method' due to the fact that it needs only the useful output (steam) and the heat input (i.e. fuel) for evaluating the efficiency. This efficiency can be evaluated using the formula.

$$Boiler\ Efficiency = \frac{Heat\ Output}{Heat\ Input} \times 100$$

Parameters to be monitored for the calculation of boiler efficiency by direct method are :

- Quantity of steam generated per hour (Q) in kg/hr.
- Quantity of fuel used per hour (q) in kg/hr.
- The working pressure (in kg/cm2(g)) and superheat temperature (°C), if any
- The temperature of feed water (°C)
- Type of fuel and gross calorific value of the fuel (GCV) in kCal/kg of fuel

$$Boiler\ Efficiency\ (\eta) = \frac{Q\, x\, (h_g - h_f)}{q \times GCV} \times 100$$

Where, h_g – Enthalpy of saturated steam in kCal/kg of steam
h_f – Enthalpy of feed water in kCal/kg of water

Indirect Method

There are reference standards for Boiler Testing at Site using indirect method namely British Standard, BS 845: 1987 and USA Standard is ASME PTC-4-1 Power Test Code Steam Generating Units'.

Indirect method is also called as heat loss method. The efficiency can be arrived at, by subtracting the heat loss fractions from 100. The standards do not include blow down loss in the efficiency determination process. A detailed procedure for calculating boiler efficiency by indirect method is given below. However, it may be noted that the practicing energy mangers in industries prefer simpler calculation procedures.

The principle losses that occur in a boiler are:

- Loss of heat due to dry flue gas
- Loss of heat due to moisture in fuel and combustion air
- Loss of heat due to combustion of hydrogen
- Loss of heat due to radiation
- Loss of heat due to unburnt

In the above, loss due to moisture in fuel and the loss due to combustion of hydrogen are dependent on the fuel, and cannot be controlled by design.

The data required for calculation of boiler efficiency using indirect method are:

- Ultimate analysis of fuel (H2, O2, S, C, moisture content, ash content)
- Percentage of Oxygen or CO2 in the flue gas
- Flue gas temperature in °C (Tf)
- Ambient temperature in °C (Ta) & humidity of air in kg/kg of dry air
- GCV of fuel in kCal/kg
- Percentage combustible in ash (in case of solid fuels)
- GCV of ash in kCal/kg (in case of solid fuels)

Energy Conservation Opportunities:

The various energy efficiency opportunities in boiler system can be related to combustion, heat transfer, avoidable losses, high auxiliary power consumption, water quality and blowdown. Examining the following factors can indicate if a boiler is being run to maximize its efficiency:

Stack Temperature

The stack temperature should be as low as possible. However, it should not be so low that water vapour in the exhaust condenses on the stack walls. This is important in fuels containing significant sulphur as low temperature can lead to sulphur dew point corrosion. Stack temperatures greater than 200°C indicates potential for recovery of waste heat. It also indicate the scaling of heat transfer/recovery equipment and hence the urgency of taking an early shut down for water / flue side cleaning.

Feed Water Preheating using Economiser

Typically, the flue gases leaving a modern 3-pass shell boiler are at temperatures of 200 to 300 °C. Thus, there is a potential to recover heat from these gases. The flue gas exit temperature from a boiler is usually maintained at a minimum of 200 °C, so that the sulphur oxides in the flue gas do not condense and cause corrosion in heat transfer surfaces. When a clean fuel such as natural gas, LPG or gas oil is used, the economy of heat recovery must be worked out, as the flue gas temperature may be well below 200 °C. The potential for energy saving depends on the type of boiler installed and the fuel used. For a typically older model shell boiler, with a flue gas exit temperature of 260 °C, an economizer could be used to reduce it to 200 °C, increasing the feed water temperature by 15 °C. Increase in overall thermal efficiency would be in the order of 3%. For a modern 3-pass shell boiler firing natural gas with a flue gas exit temperature of 140 °C a condensing economizer would reduce the exit temperature to 65 °C increasing thermal efficiency by 5%.

Combustion Air Preheat

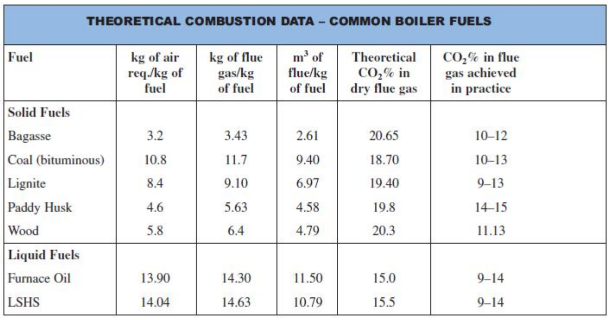
Combustion air preheating is an alternative to feedwater heating. In order to improve thermal efficiency by 1%, the combustion air temperature must be raised by 20 °C. Most gas and oil burners used in a boiler plant are not designed for high air preheat temperatures. Modern burners can withstand much higher combustion air preheat, so it is possible to consider such units as heat exchangers in the exit flue as an alternative to an economizer, when either space or a high feed water return temperature make it viable.

Incomplete Combustion

Incomplete combustion can arise from a shortage of air or surplus of fuel or poor distribution of fuel. It is usually obvious from the colour or smoke, and must be corrected immediately. In the case of oil and gas fired systems, CO or smoke (for oil fired systems only) with normal or high excess air indicates burner system problems. A more frequent cause of incomplete combustion is the poor mixing of fuel and air at the burner. Poor oil fires can result from improper viscosity, worn tips, carbonization on tips and deterioration of diffusers or spinner plates. With coal firing, unburned carbon can comprise a big loss. It occurs as grit carry-over or carbon-in-ash and may amount to more than 2% of the heat supplied to the boiler. Non uniform fuel size could be one of the reasons for incomplete combustion. In chain grate stokers, large lumps will not burn out completely, while small pieces and fines may block the air passage, thus causing poor air distribution. In sprinkler stokers, stoker grate condition, fuel distributors, wind box air regulation and over-fire systems can affect carbon loss. Increase in the fines in pulverized coal also increases carbon loss.

Excess Air Control

The Table gives the theoretical amount of air required for combustion of various types of fuel. Excess air is required in all practical cases to ensure complete combustion, to allow for the normal variations in combustion and to ensure satisfactory stack conditions for some fuels. The optimum excess air level for maximum boiler efficiency occurs when the sum of the losses due to incomplete combustion and loss due to heat in flue gases is minimum. This level varies with furnace design, type of burner, fuel and process variables. It can be determined by conducting tests with different air fuel ratios.

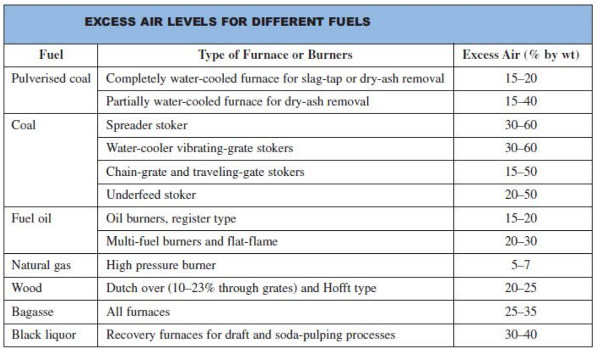


THEORETICAL COMBUSTION DATA – COMMON BOILER FUELS

Fuel	kg of air req./kg of fuel	kg of flue gas/kg of fuel	m^3 of flue/kg of fuel	Theoretical CO$_2$% in dry flue gas	CO$_2$% in flue gas achieved in practice
Solid Fuels					
Bagasse	3.2	3.43	2.61	20.65	10–12
Coal (bituminous)	10.8	11.7	9.40	18.70	10–13
Lignite	8.4	9.10	6.97	19.40	9–13
Paddy Husk	4.6	5.63	4.58	19.8	14–15
Wood	5.8	6.4	4.79	20.3	11.13
Liquid Fuels					
Furnace Oil	13.90	14.30	11.50	15.0	9–14
LSHS	14.04	14.63	10.79	15.5	9–14

Table 1. Theoretical Combustion Data

Typical values of excess air supplied for various fuels are given in below Table



EXCESS AIR LEVELS FOR DIFFERENT FUELS

Fuel	Type of Furnace or Burners	Excess Air (% by wt)
Pulverised coal	Completely water-cooled furnace for slag-tap or dry-ash removal	15–20
	Partially water-cooled furnace for dry-ash removal	15–40
Coal	Spreader stoker	30–60
	Water-cooler vibrating-grate stokers	30–60
	Chain-grate and traveling-gate stokers	15–50
	Underfeed stoker	20–50
Fuel oil	Oil burners, register type	15–20
	Multi-fuel burners and flat-flame	20–30
Natural gas	High pressure burner	5–7
Wood	Dutch over (10–23% through grates) and Hofft type	20–25
Bagasse	All furnaces	25–35
Black liquor	Recovery furnaces for draft and soda-pulping processes	30–40

Table 2. Excess Air for various fuel

Controlling excess air to an optimum level always results in reduction in flue gas losses; for every 1% reduction in excess air there is approximately 0.6% rise in efficiency.

Various methods are available to control the excess air:

Portable oxygen analyzer with a local readout mounted draft gauge, by which the operator can adjust air flow. A further reduction of 10–15% can be achieved over the previous system.

• The same continuous oxygen analyzer can have a remote controlled pneumatic damper positioner, by which the readouts are available in a control room. This enables an operator to remotely control a number of firing systems simultaneously. The most sophisticated system is the automatic stack damper control, whose cost is really justified only for large systems.

Radiation and Convection Heat Loss

The external surfaces of a shell boiler are hotter than the surroundings. The surfaces thus lose heat to the surroundings depending on the surface area and the difference in temperature between the surface and the surroundings. The heat loss from the boiler shell is normally a fixed energy loss, irrespective of the boiler output. With modern boiler designs, this may represent only 1.5% on the gross calorific value at full rating, but will increase to around 6%, if the boiler operates at only 25 percent output. Repairing or augmenting insulation can reduce heat loss through boiler walls and piping.

Automatic Blowdown Control

Uncontrolled continuous blowdown is very wasteful. Automatic blowdown controls can be installed that sense and respond to boiler water conductivity and pH. A 10% blow down in a 15 kg/cm2 boiler results in 3% efficiency loss.

Reduction of Scaling and Soot Losses

In oil and coal-fired boilers, soot build up on tubes acts as an insulator against heat transfer. Any such deposits should be removed on a regular basis. Elevated stack temperatures may indicate excessive soot build up. Also same result will occur due to scaling on the water side. High exit gas temperatures at normal excess air indicate poor heat transfer performance. This condition can result from a gradual build-up of gas-side or waterside deposits. Waterside deposits require a review of water treatment procedures and tube cleaning to remove deposits. An estimated 1% efficiency loss occurs with every 22 °C increase in stack temperature. Stack temperature should be checked and recorded regularly as an indicator of soot deposits. When the flue gas temperature rises about 20 °C above the temperature for a newly cleaned boiler, it is time to remove the soot deposits. It is, therefore, recommended to install a dial type thermometer at the base of the stack to monitor the exhaust flue gas temperature.

It is estimated that 3 mm of soot can cause an increase in fuel consumption by 2.5% due to increased flue gas temperatures. Periodic off-line cleaning of radiant furnace surfaces, boiler tube banks, economizers and air heaters may be necessary to remove stubborn deposits.

Reduction of Boiler Steam Pressure

This is an effective means of reducing fuel consumption, if permissible, by as much as 1 to 2%. Lower steam pressure gives a lower saturated steam temperature and without stack heat recovery, a similar reduction in the temperature of the flue gas temperature results. Steam is generated at pressures normally dictated by the highest pressure / temperature requirements for a particular process. In some cases, the process does not operate all the time, and there are periods when the boiler pressure could be reduced. The energy manager should consider pressure reduction carefully, before recommending it. Adverse effects, such as an increase in water carryover from the boiler owing to pressure reduction, may negate any potential saving. Pressure should be reduced in stages, and no more than a 20 percent reduction should be considered.

Variable Speed Control for Fans, Blowers and Pumps

Variable speed control is an important means of achieving energy savings. Generally, combustion air control is effected by throttling dampers fitted at forced and induced draft fans. Though dampers are simple means of control, they lack accuracy, giving poor control characteristics at the top and bottom of the operating range. In general, if the load characteristic of the boiler is variable, the possibility of replacing the dampers by a VSD should be evaluated.

Effect of Boiler Loading on Efficiency

The maximum efficiency of the boiler does not occur at full load, but at about two-thirds of the full load. If the load on the boiler decreases further, efficiency also tends to decrease. At zero output, the efficiency of the boiler is zero, and any fuel fired is used only to supply the losses.

The factors affecting boiler efficiency are:

- As the load falls, so does the value of the mass flow rate of the flue gases through the tubes. This reduction in flow rate for the same heat transfer area, reduced the exit flue gas temperatures by a small extent, reducing the sensible heat loss.
- Below half load, most combustion appliances need more excess air to burn the fuel completely. This increases the sensible heat loss In general, efficiency of the boiler reduces significantly below 25% of the rated load and as far as possible, and operation of boilers below this level should be avoided.

Proper Boiler Scheduling

Since, the optimum efficiency of boilers occurs at 65–85% of full load, it is usually more efficient, on the whole, to operate a fewer number of boilers at higher loads, than to operate a large number at low loads.

Boiler Replacement

The potential savings from replacing a boiler depend on the anticipated change in overall efficiency. A change in a boiler can be financially attractive if the existing boiler is:

- old and inefficient
- not capable of firing cheaper substitution fuel
- over or under-sized for present requirements
- not designed for ideal loading conditions

The feasibility study should examine all implications of long-term fuel availability and company growth plans. All financial and engineering factors should be considered. Since boiler plants traditionally have a useful life of well over 25 years, replacement must be carefully studied.

System Overview

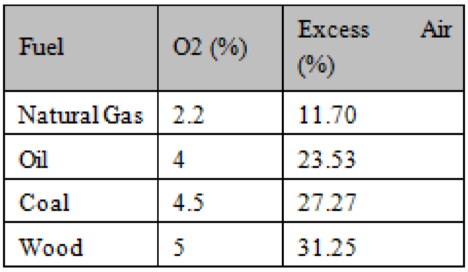
The system is a true embedded system design with a combination of latest analog circuits & microcontroller with embedded software finding its application in mechanical or instrumentation areas.

The system consists of an Oxygen probe with Lambda sensor mounted on the tip of the probe. There is signal conditioning circuit used for amplifying & converting sensor signals in a usable form. The microcontroller based control unit is used for accepting inputs & computing it to display Oxygen content in the flue gas of a steam boiler.

Measuring flue gas stack Oxygen is very much important because of following reasons.

- To ensure efficient combustion of fuel.
- To minimize Stack loss.
- To minimize emissions and enable accurate emissions monitoring.

Table 3. O2 & Excess Air for Various Fuel



Fuel	O2 (%)	Excess Air (%)
Natural Gas	2.2	11.70
Oil	4	23.53
Coal	4.5	27.27
Wood	5	31.25

Optimal Flue Gas Composition

Efficient combustion shall happen when the air fuel ratio is adjusted to the recommended optimum values; however, a boiler with a wide

Operating range requires a control system to constantly adjust the air-fuel ratio with the help of flue gas Oxygen feedback.

Excess Air % = (Flue gas Oxygen / (21 - Flue gas Oxygen)) X 100

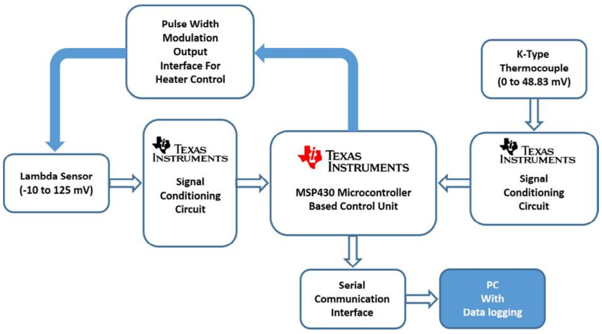


Fig 2. Block Diagram Representation

The proposed system is modular and broadly classified into three modules called as

a) Sensors
b) Signal Conditioning & Computation unit
c) Communication Interface with Data Logging.

The system is deliberately kept modular such that it is easy to debug & easy to replace.

A. Sensors.

The sensors used are Lambda Sensor & K-type thermocouple.

Lambda Sensor

An **oxygen sensor** (or ***lambda sensor***) is an electronic device that measures the proportion of oxygen (O_2) in the gas or liquid being analysed.

It was developed by Robert Bosch GmbH during the late 1960s under the supervision of Dr. Günter Bauman. The original sensing element is made with a thimble-shaped zirconia ceramic coated on both the exhaust and reference sides with a thin layer of platinum and comes in both heated and unheated forms. The planar-style sensor entered the market in 1990, and significantly reduced the mass of the ceramic sensing element as well as incorporating the heater within the ceramic structure. This resulted in a sensor that started sooner and responded faster.

Fig 3. Lambda Sensor

The most common application is to measure the exhaust gas concentration of oxygen for internal combustion engines in automobiles and other vehicles in order to calculate and, if required, dynamically adjust the air fuel ratio so that catalytic converters can work optimally, and also determine whether a catalytic converter is performing properly or not. Divers also use a similar device to measure the partial pressure of oxygen in their breathing gas.

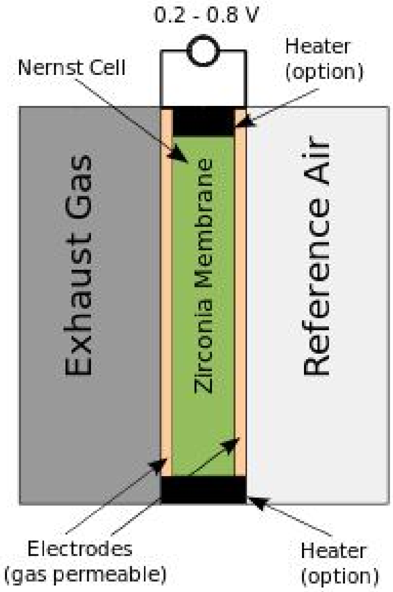


Fig 4. Zirconia cell

Scientists use oxygen sensors to measure respiration or production of oxygen and use a different approach. Oxygen sensors are used in oxygen analyzers which find a lot of use in medical applications such as anaesthesia monitors, respirators and oxygen concentrators.

Oxygen sensors are also used in hypoxic air fire prevention systems to monitor continuously the oxygen concentration inside the protected volumes.

There are many different ways of measuring oxygen and these include technologies such as zirconia, electrochemical (also known as Galvanic), infrared, ultrasonic and very recently laser methods. Each method has its own advantages and disadvantages.

The zirconium dioxide, or zirconia, lambda sensor is based on a solid-state electrochemical fuel cell called the Nernst cell. Its two electrodes provide an output voltage corresponding to the quantity of oxygen in the exhaust relative to that in the atmosphere.

An output voltage of 0.2 V (200 mV) DC represents a "lean mixture" of fuel and oxygen, where the amount of oxygen entering the cylinder is sufficient to fully oxidize the carbon monoxide (CO), produced in burning the air and fuel, into carbon dioxide (CO_2). An output voltage of 0.8 V (800 mV) DC represents a "rich mixture", one which is high in unburned fuel and low in remaining oxygen. The ideal set point is approximately 0.45 V (450 mV) DC. This is where the quantities of air and fuel are in the optimum ratio, which is ~0.5% lean of the stoichiometric point, such that the exhaust output contains minimal carbon monoxide.

The voltage produced by the sensor is nonlinear with respect to oxygen concentration. The sensor is most sensitive near the stoichiometric point (where λ = 1) and less sensitive when either very lean or very rich.

The ECU is a control system that uses feedback from the sensor to adjust the fuel/air mixture. As in all control systems, the time constant of the sensor is important; the ability of the ECU to control the fuel-air-ratio depends upon the response time of the sensor. An aging or fouled sensor tends to have a slower response time, which can degrade system performance. The shorter the time period, the higher the so-called "cross count" and the more responsive the system.

The sensor has a rugged stainless steel construction internally and externally. Due to this the sensor has a high resistance to corrosion allowing it to be used effectively in aggressive environments with high temperature/pressure

K-Type Thermocouple

A **thermocouple** is an electrical device consisting of two dissimilar electrical conductors forming electrical junctions at differing temperatures. A thermocouple produces a temperature-dependent voltage as a result of the thermoelectric effect, and this voltage can be interpreted to measure temperature. Thermocouples are a widely used type of temperature sensor.

Commercial thermocouples are inexpensive, interchangeable, are supplied with standard connectors, and can measure a wide range of temperatures. In contrast to most other methods of temperature measurement, thermocouples are self-powered and require no external form of excitation. The main limitation with thermocouples is accuracy; system errors of less than one degree Celsius (°C) can be difficult to achieve. Thermocouples are widely used in science and industry. Applications include temperature measurement for kilns, gas turbine exhaust, diesel engines, and other industrial processes. Thermocouples are also used in homes, offices and businesses as the temperature sensors in thermostats, and also as flame sensors in safety devices for gas-powered major appliances.

Type K (chromel–alumel) is the most common general-purpose thermocouple with a sensitivity of approximately 41 µV/°C. It is inexpensive, and a wide variety of probes are available in its −200 °C to +1350 °C (−330 °F to +2460 °F) range.

Signal Conditioning & Computation Unit.

Signal conditioning basically forms a signal convertor from sensor in a usable format to microcontroller based computation & control unit.

We shall need signal conditioning for Lambda sensor output (-10 to +125 mV) and thermocouple (0 to 48.83 mV) interface with MSP430 microcontroller series.

There is heater embedded with lambda sensor for heating the sensor till 750 deg C as required by zirconia to get actuated.
Principle of operation of Lambda Sensor – Nernst equation

B. Communication Interface with SCADA.

The computed data shall be transmitted PC for data logging through serial interface.

Trending, reports etc. can be obtained from SCADA.

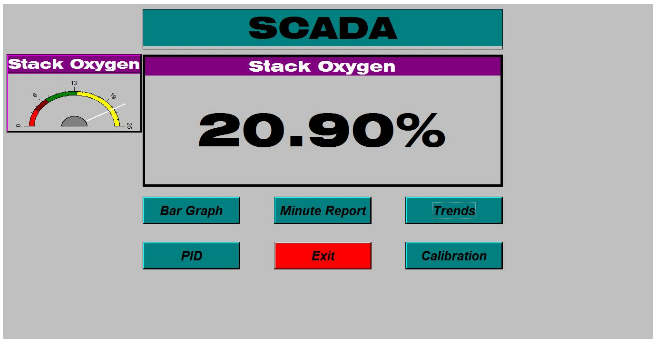


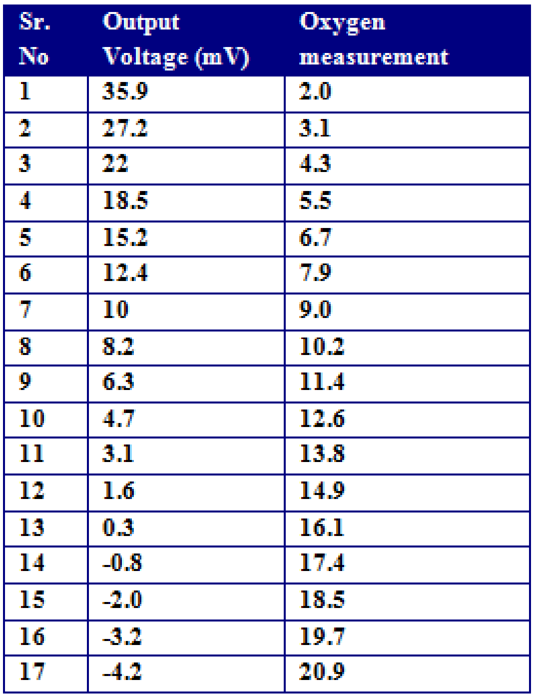
Fig 5. SCADA

IV. RESULT & DISCUSSION

Following is the final result of the Low cost Oxygen Analyzer using Lambda sensor

2.0% Oxygen – Zero gas

Table 4. 2.0 % Test Gas Result



Sr. No	Output Voltage (mV)	Oxygen measurement
1	35.9	2.0
2	27.2	3.1
3	22	4.3
4	18.5	5.5
5	15.2	6.7
6	12.4	7.9
7	10	9.0
8	8.2	10.2
9	6.3	11.4
10	4.7	12.6
11	3.1	13.8
12	1.6	14.9
13	0.3	16.1
14	-0.8	17.4
15	-2.0	18.5
16	-3.2	19.7
17	-4.2	20.9

V. CONCLUSIONS

If we see significance of Stack Oxygen monitoring is important.

Oxygen Analyzers from ABB, Yokogawa and Fuji Electric etc are highly expensive due to their origin & brand.

Hence a low cost option shall be highly beneficial for Indian domestic market where the customers are not spending much on instrumentation due to cheap labor etc.

VI. ACKNOWLEDGMENT

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