ISSN: 0974 - 7516 Volume 10 Issue 7

Organic CHEMISTRY

An Indian Journal

Full Paper

OCAIJ, 10(7), 2014 [251-262]

Role of membrane in concentrate of oxygen: Experimental study of thermal efficiency of combustion process by concentrated oxygen

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ABSTRACT

The effect of oxygen concentration on performance of combustion process with basic fuels such as methane, ethane and propane is evaluated in this paper. Different concentrations of oxygen are provided by membrane and injected in to combustion chamber. The flame temperature, combustion thermal efficiency, NO_x emissions in different torques, the amount of exhaust unburned carbon and the amount of saved fuel gas are investigated in different oxygen concentration. Also, the mole fraction of exhaust basics such as; O_2, OH, H_2, H, O and HO_2 from combustion chamber are measured for precious evaluation of this process. In addition, the effluent side components such as; N_2O, N, HCO, NH_2, NH_3 and HCN are surveyed in this paper. Experiments show that the highest flame temperature is caused by Propane burning in 60% oxygen concentration however this phenomenon produces higher thermal NO_x. Also, the highest thermal efficiency is about 38.3% by burning methane fuel in 21% oxygen volume percentage. Experiments indicate that there is an optimum amount of engine speed accompanied with oxygen concentration to increase the thermal efficiency and decrease the amount of unburned carbon. Obtained results in this paper were used to determine optimal control points in the burner design stage.

KEYWORDS

Membrane;
Combustion;
Temperature;
Fuel gas;
Thermal efficiency.

INTRODUCTION

Total yield is defined as the effectiveness of any combustion apparatus to convert the internal energy contained in the fuel into heat energy for use by the industrial process[1]. It's clear that heat losses lower the efficiency of the process. For instance, a radiant loss from heat escaping through the surfaces of the boiler is one case of efficiency losses. Combustion efficiency can be defined as the total energy contained per unit of fuel minus the energy carried away by the flue gas and unburned fuel exiting the stack[2]. Burning efficiency losses are a big part of total efficiency losses[3]. Before making large capital investments to improve boiler and heat exchanger performance, make sure you maximize combustion efficiency. The best way to maximize combustion efficiency is to measure oxygen and combustibles in the flue gas on a continuous basis.

Combustion theory and stoichiometric combustion

The three essential components of combustion are fuel, oxygen and heat, finally. Stoichiometric combustion is defined as having just the accurate amount of oxygen and fuel mixture so the most heat is released. In almost fossil fuels, the chemical ingredients that react with oxygen to release heat are carbon and hydrogen[4].

Stoichiometric reactions for pure carbon, hydrogen and oxygen are as follows:

$$C+O_2 \Rightarrow CO_2 + 14{,}093 Btu/lb \quad (1)$$

$$H_2 + 1/2O_2 \Rightarrow H_2O + 61{,}100 Btu/lb \quad (2)$$

For these stoichiometric combustion reactions, only heat and water or carbon dioxide is resulted. Common fuels consist of compounds containing certain amounts of hydrogen and carbon elements which are fuels are commonly called hydrocarbons. For example, methane is a hydrocarbon gas that burns as follows:

$$CH_4 + 2O_2 \Rightarrow CO_2 + H_2O + 1{,}013 Btu/ft^3 \quad (3)$$

In burning processes the air stream is used instead of pure Oxygen, regularly[5]. Clearly, air contains about 21% oxygen and 79% nitrogen by volume, and is readily available. Pure oxygen must be processed and on most applications the cost to process oxygen outweighs the benefit of increased combustion control. In the other hand, when we use air instead of oxygen, one cubic foot of methane (at standard temperature and pressure) will burn completely with 9.53 cubic feet of air as shown below:

$$CH_4 + 2O_2 + 7.53N_2 \Rightarrow CO_2 + 2H_2O + 7.53N_2 + 1{,}013 Btu/ft^3 \quad (4)$$

The ratio of 9.53 cubic feet of air to one cubic foot of methane is known as the stoichiometric air/fuel ratio. The heat energy released when the fuel burns is known as the heat of combustion. Ideally, Scientifics want to provide just the right amount of air to completely burn all the fuel[6].

But this proves elusive for a number of reasons, including inadequate mixing of air and fuel, burner and combustion performance, ambient conditions and fluctuating operating, and burner tear and wear. Usually, to ensure that the fuel is burned with little or no combustibles, some amount of excess air is provided[7]. To ensure no more excess air than required is used, we can measure excess oxygen in the flue gas. To ensure the amount of carbon monoxide or hydrogen in the flue gas is minimized, combustibles are measured.

Flue gas heat loss is the single largest energy loss in a combustion process. It is impossible to remove all flue gas heat loss because the products of combustion are heated by the combustion and burning process. But flue gas heat loss can be minimized by reducing the amount of excess air supplied to the combustion chamber[8]. Since the oxygen in the flue gas is directly related to the level of excess air supplied, an oxygen flue gas analyzer is the best way to effectively measure and control the amount of excess air in the flue gas and the associated heat loss. Zirconium oxide O_2 flue gas analyzers are the preferred combustion control analysis method.

Unburned fuel loss

For burning and combustion yield, Scientifics never want to operate a burner with less air than is required for stoichiometric combustion. Not only does this result in a smoking stack, but it significantly reduces the total energy released in the combustion process due to unburned fuels.

If a combustion chamber is operated with a deficiency of air, or the air and fuel are mixed improperly, all the fuel will not combust[9]. As a result, ingredients such as hydrogen and carbon monoxide will appear in the products of combustion[10]. Clearly, hydrogen and Carbon monoxide, collectively referred to as combustibles, result from incomplete combustion. When insufficient excess air or oxygen is available, the amount of combustibles in the flue gas increases dramatically.

In practice, some trace levels of unburned fuel appear in the flue gas stream even with some amount of excess air, due to imperfect mixing of fuel and air at the burner or other operating conditions of combustion chamber. As a real, combustion processes are not operated at the stoichiometric level. Instead, combustion processes are operated with sufficient excess air or oxygen to keep the amount of combustibles minimized. Combustibles levels of a few hundred parts per million (ppm) in the flue gas have an insignificant influence on combustion efficiency. For every combustion process, the optimum amount of excess air depends on several variables such as the type of fuel, the amount of load, the size and condition of the burner. There is no single O_2 level which is right for all burning processes.

Since of in the past, it was not practical to continuously calculate unburned fuel loss and flue gas heat loss to maintain the most efficient level of excess air.

Oxygen enriched combustion

Excess air applications are followed by the flue gas heat NO_x loss and emissions. Membrane technology development, improves the utilization of Oxygen enriched membrane in combustion processes. In addition to maximizing efficiency, oxygen enriched air firing has the benefit of reducing NO_x emissions. This should be the first step in any NO_x reduction strategy[11].

Under the impetus of pressure difference between two sides of membrane, oxygen in air pass through membrane first and get oxygen enrichment gas[12]. There are two kinds of membrane modules managed to use in the oxygen enrichment process which are spiral wound and hollow fibre. Some commercial types of this kind are followed as: Spiral-wound membrane module which produces 27-31% oxygen purity, hollow fibre membrane module which produces 30-45% oxygen purity and they are operated under air flow rate of 0.04-50000NM3/h. The investment, maintenance and operation cost on membrane system is 2/3 to 3/4 of that of Cryogenic and PSA. Some advantages of membrane oxygen enrichment in combustion process are: higher flame temperature, reducing gas displacement, increasing the using rate of heat quantity and saving energy obviously.

In this experimental work, one poly sulfonic hollow fiber membrane is applied to produce the rich oxygen stream for a combustion engine. Three important hydrocarbon fuels methane, ethane and propane are used in different engine speeds. The effect of oxygen concentration in the air stream is investigated on the flame temperature, NO_x emissions, unburned Carbon, thermal efficiency, the amount of saved fuel and the amounts of the released components on the discharge stream. Results illustrate the combustion improvements by using the enriched oxygen membrane.

MATERIALS AND METHOD

In this experiment, feed line of one SI engine is connected with the poly sulfonic hollow fibre membranes, accurately. The adjusted amount of air flow rate is fed

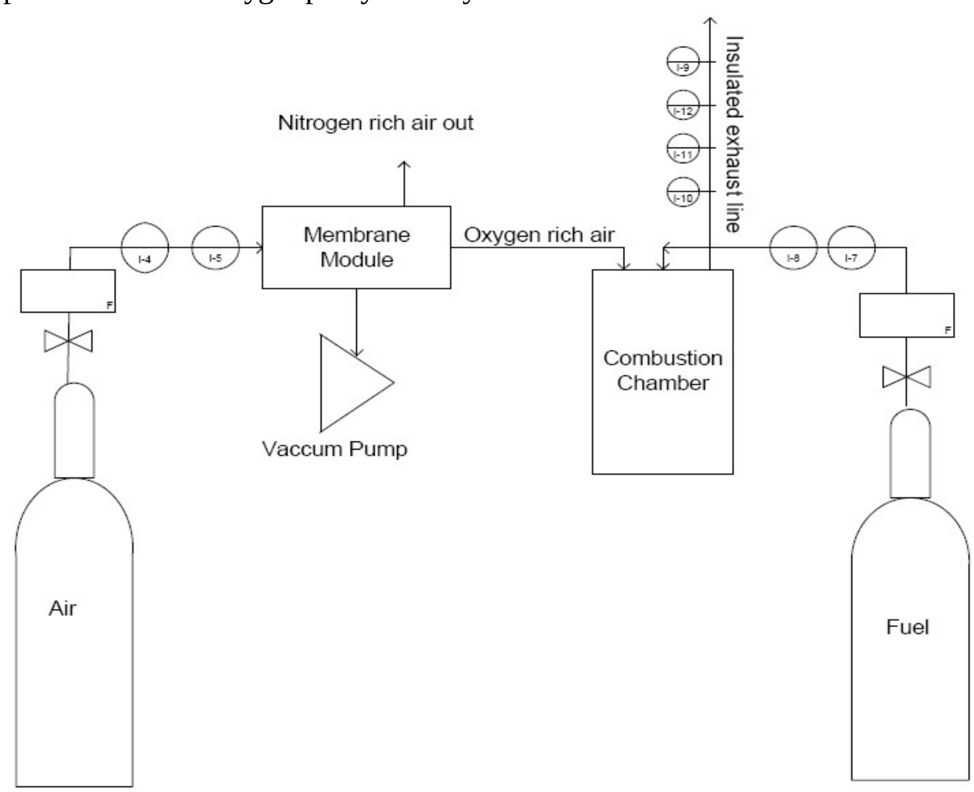

Figure 1 : A schematic of the experimental set up.

in the engine after enriching through the membrane module. Fuels, methane, ethane and propane are injected respectively into the engine. Zirconium Oxide analyzers measure the oxygen concentration on the engine feed line and also in the flue gas. The amount of measured oxygen shows the combustion efficiency. The combustion chamber and the discharge line of the engine are insulated to prevent the flue gas condensation. The instruments for measuring the flue gas components are installed at this line. The engine speed governor is also changes the speeds. Figure 1 shows a schematic of the experimental set up.

RESULTS AND DISCUSSION

In this section, the results of experiments are illustrated. All experiments are held at 1 atm operating pressure.

Adiabatic flame temperature

Figure 2 illustrates that the enhancement in the feed oxygen concentration increases the temperature of the flame during a complete combustion. Also, the fuel which contains more carbon atoms releases higher amounts of heat during combustion and produces higher flame

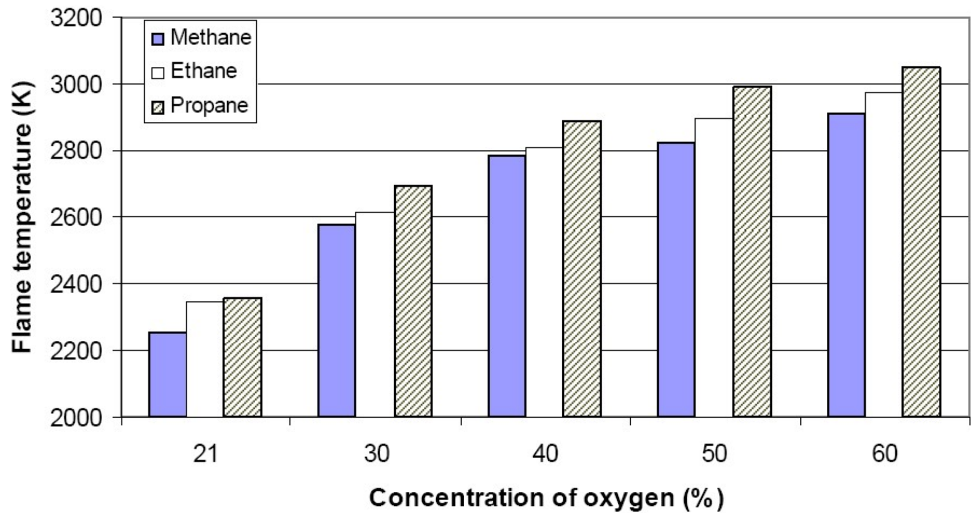

Figure 2 : The effect of oxygen concentration on the flame temperature

temperature. The oxygen concentration percentage varies in the range 21% to 60%. So, the highest flame temperature belongs to the propane fuel at 60% of oxygen concentration. About 691 k increase is obtained in the amount of adiabatic flame temperature when Propane is burned.

NO_x emission

The effect of oxygen content on the NO_x emission is investigated by varying the inlet oxygen molar concentration in 21%, 30%, 40% and 50%. Experiments are held for methane, ethane and propane as three fuel gases with high heating values. Results are shown in Figures 3, 4 and 5.

Also, Figures 3, 4 and 5 show the amounts of engine torques due to oxygen concentration. The increase in the engine torques increases the amount of released pollutant as NO_x at all oxygen concentrations till reaches the maximum value and then causes the decrease in the amount of NO_x emission. Totally, the higher amount of feed oxygen concentration makes the lower amount of emission.

The maximum amount of pollution is obtained on the 21% oxygen concentration and makes 40 *N.m* engine torques, by propane as fuel. The increase in the amount of oxygen in feed line reduces the fraction of nitrogen in air and reduces the NO_x emission. It indicates that the amount of NO_x emission is enhanced by higher number of carbon in the fuels since of the higher flame temperature which is produced. Since, the thermal NO_x is formed by the high-temperature reaction of nitrogen with oxygen. So, the least amount of pollution is obtained by burning the methane in 50% oxygen and 60 *N.m* engine torques.

Unburned carbon

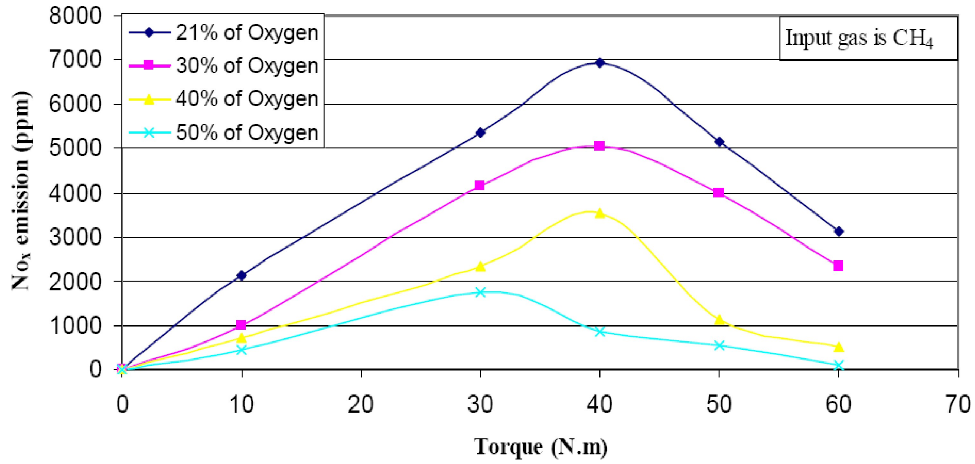

Figure 3 : The effect of oxygen concentration and engine torque on NO_x emission for methane fuel

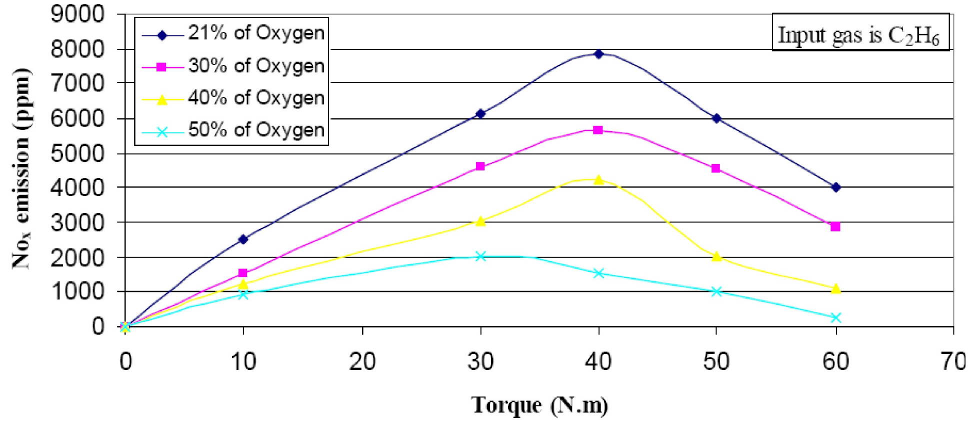

Figure 4 : The effect of oxygen concentration and engine torque on NO_x emission for ethane fuel

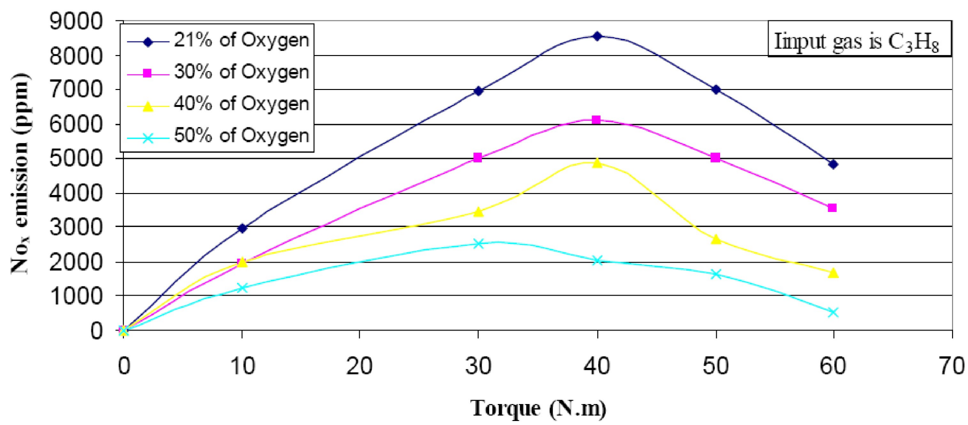

Figure 5 : The effect of oxygen concentration and engine torque on NO_x emission for propane fuel

The effect of feed oxygen content on the amounts of the unburned carbon is evaluated for methane, ethane and propane as fuels at different engine speeds. Results are illustrated by Figure 6, 7 and 8 and for 1500, 2000 and 3000 *rpm* engine speeds.

There are decrease-increase behaviors in curves which show the amount of unburned carbon. So, there are minimum points which indicate the least amounts of unburned carbon at 1500 *rpm* for all fuels. If the combustion process operates with insufficient air, or the air and fuel are mixed improperly, all the fuel will not burn. Consequently, carbon monoxide and hydrogen will be obtained in the products.

Results illustrate on this fact that there is an optimum amount of oxygen concentration to produce the minimum amount of unburned carbon.

The amount of basic components

Figures 9, 10 and 11 show the effect of oxygen concentration on the amount of basic ingredients produced during combustion process. For CH_4, C_2H_6 and C_3H_8, the higher oxygen content in feed enhances

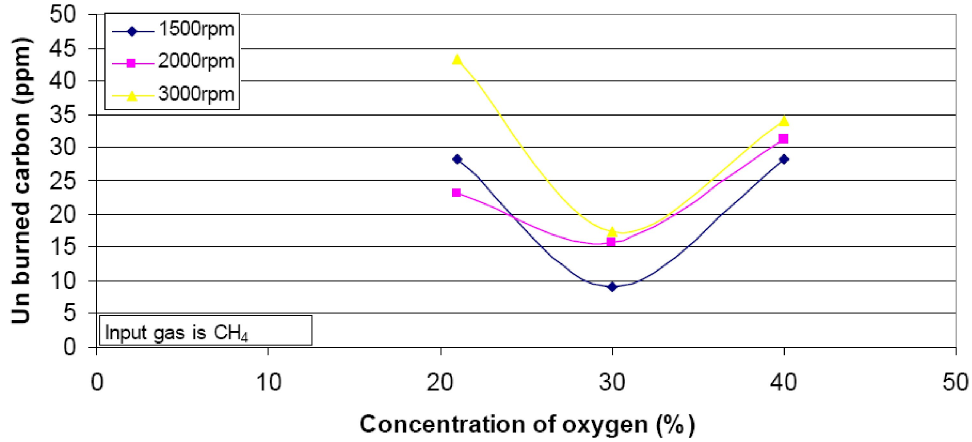

Figure 6 : The effect of oxygen concentration and engine speed on the unburned carbon in methane burning

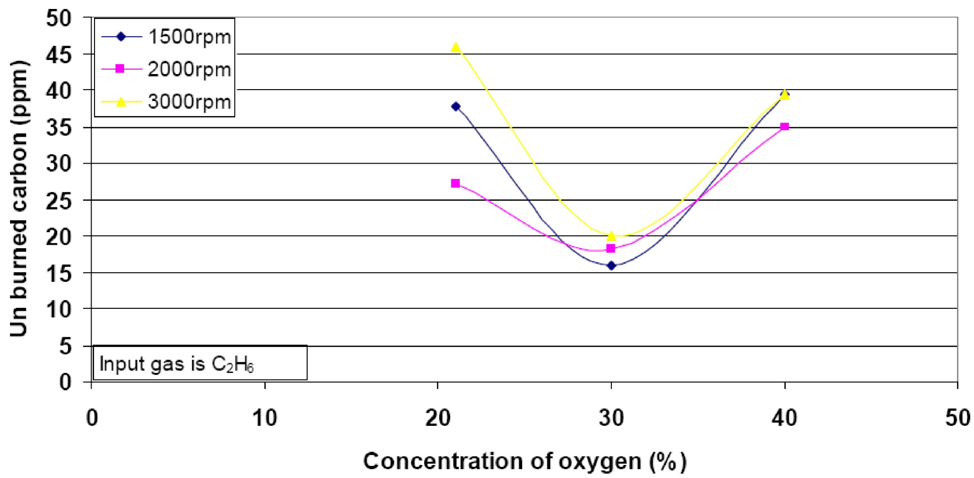

Figure 7 : The effect of oxygen concentration and engine speed on the unburned carbon in ethane burning

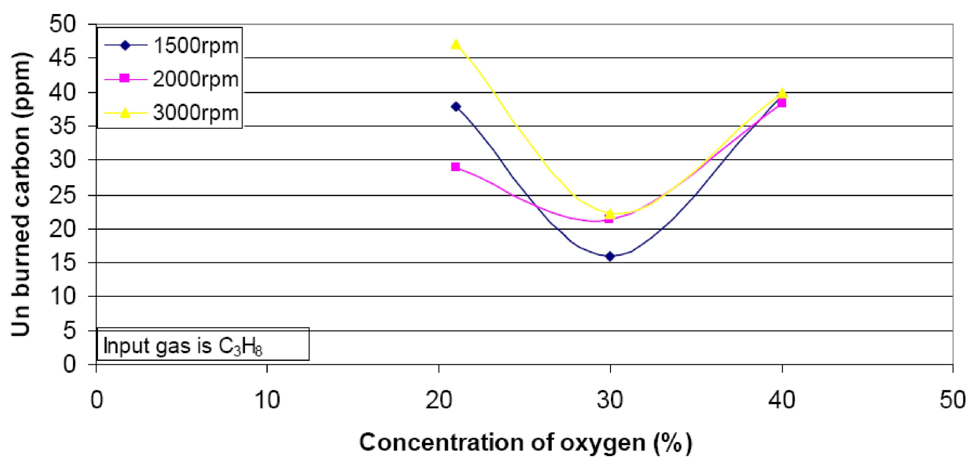

Figure 8 : The effect of oxygen concentration and engine speed on the unburned carbon in propane burning

the amounts of H, O_2, O, OH and HO_2. This occasion is related to the higher flame temperature which is reached at higher oxygen concentration. So, thermal decomposition of basic compounds like H_2O and CO_2 is occurred. On the other hand, when the amount of oxygen increases, all the reactions which depend on the oxygen concentration are progressed and completed comparing with the reactions which depend on the Nitrogen concentration.

Also, the amounts of O_2 and OH are more than the other components and the amounts of HO_2 is negligible.

The amounts of side ingredients

The components which lose the released energy in

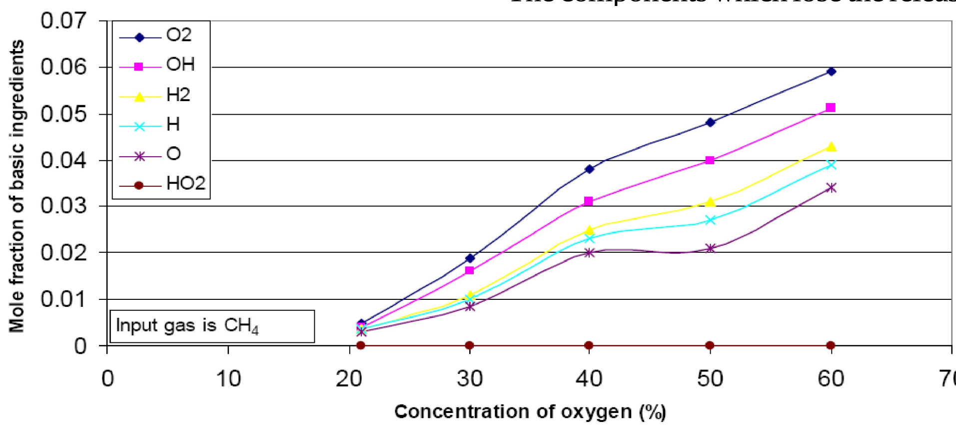

Figure 9 : The amount of basic components in different oxygen concentration for methane burning

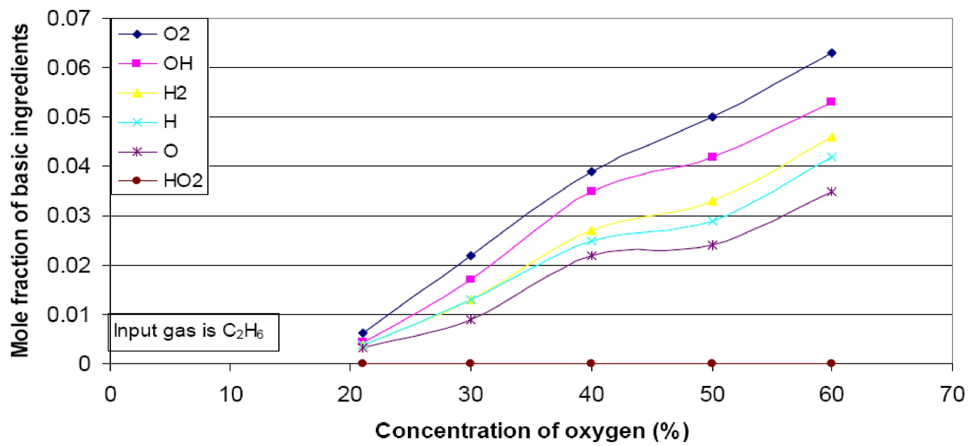

Figure 10 : The amount of basic components in different oxygen concentration for ethane burning

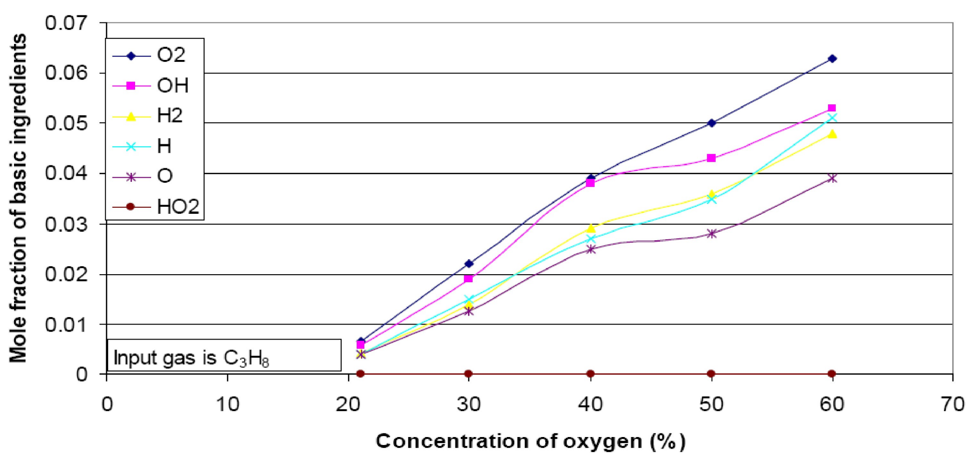

Figure 11 : The amount of basic components in different oxygen concentration for propane burning

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the combustion process are named as side ingredients in this work. This group consumes the released energy by the combustion process and decreases the flame temperature. Figure 12, 13 and 14 show the amounts of N, HCO, N_2O, NH_2, NH_3 and HCN liberated during burning of CH_4, C_2H_6 and C_3H_8. Because the oxygen concentration increases the endothermic adverse reactions progress, however the Nitrogen concentration decreases so there is a challenge between reactions which depends on the Nitrogen. On the other hand,

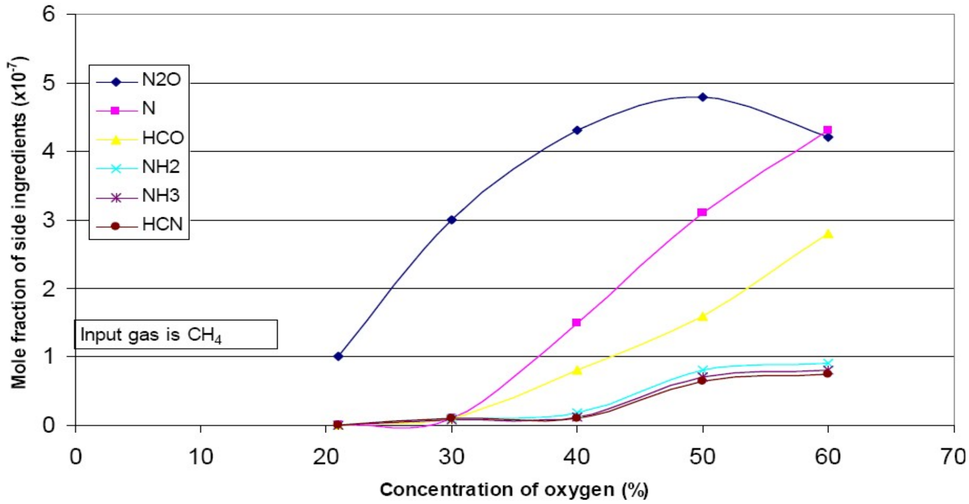

Figure 12 : The amount of side components of methane burning in different oxygen concentration

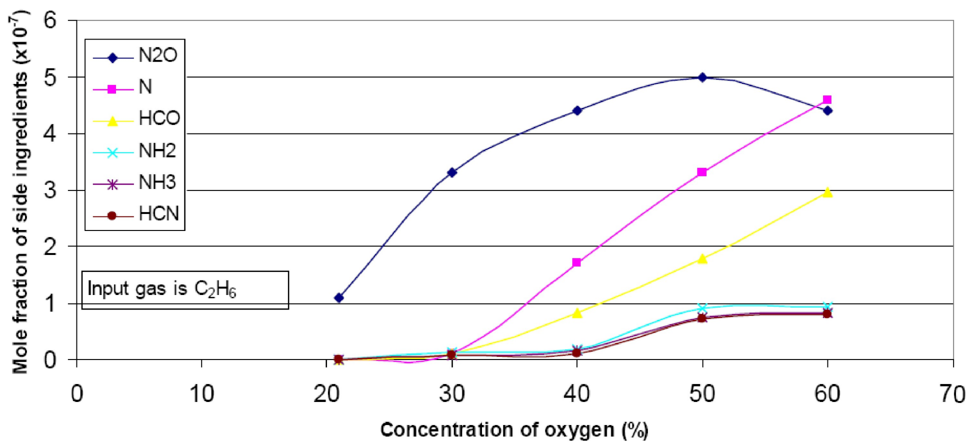

Figure 13 : The amount of side components of ethane burning in different oxygen concentration

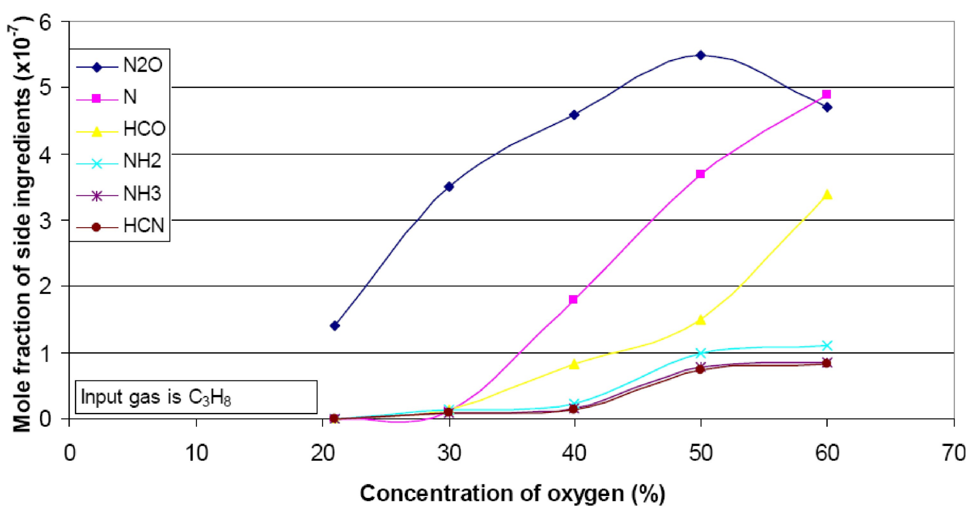

Figure 14 : The amount of side components of propane burning in different oxygen concentration

higher oxygen concentration increases the adiabatic flame temperature and makes thermal decomposition in progress so the Nitrogen concentration is increased. There are competitive occasions. So, a maximum point is obtained in N_2O curve. The amount of N_2O and N is higher than the other components.

The thermal efficiency

The thermal efficiency of combustion process in different engine speeds 1500, 2000 and 3000 rpm are shown in Figures 15, 16 and 17. There is a definition for thermal efficiency which is shown as Equation 5. The lost enthalpy which is leaved the combustion chamber by the effluent gases and the total enthalpy produced of combustion process are defined as H_{lost} and $H_{comb.}$ respectively. If the effluent gases are reduced so the thermal efficiency will be increased.

$$\eta_{therm.} = \frac{H_{comb.} - H_{lost.}}{H_{comb.}} \qquad (5)$$

The efficiency profile obeys the decreasing trend by increasing the oxygen concentration for all fuels. Also, the higher engine speeds decrease the efficiency.

It may depend on that the higher speed prevents the proper collision between fuel and oxygen and also the reaction time is limited at higher engine speeds. Then, gases are discharged from the combustion chamber without attending in any effective combustion reactions. So, H_{lost} is increased.

Therefore, propane shows the lower thermal efficiency at the same conditions comparing with the lighter fuels on the combustion process. This may since of the higher required combustion time for propane than Ethane and Methane.

The amount of saved fuel

Both, higher temperature and higher oxygen content makes combustion process to release sufficient heat with lower amount of fuel. So, the increase in the tem-

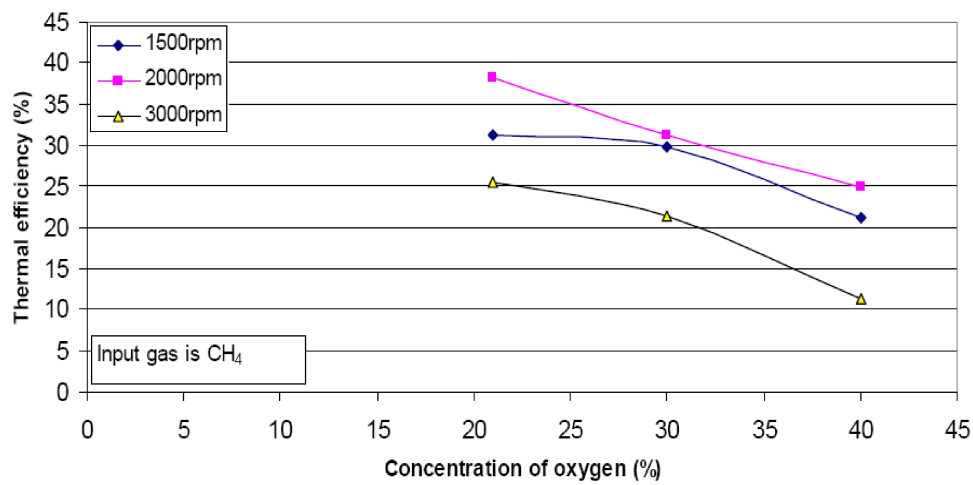

Figure 15 : Thermal efficiency of combustion in different engine speed and oxygen concentrations for methane burning

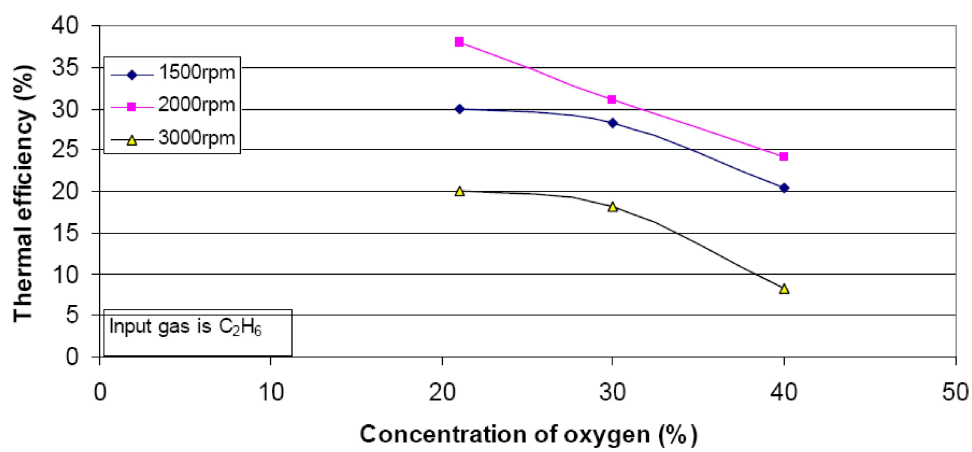

Figure 16 : Thermal efficiency of combustion in different engine speed and oxygen concentrations for ethane burning

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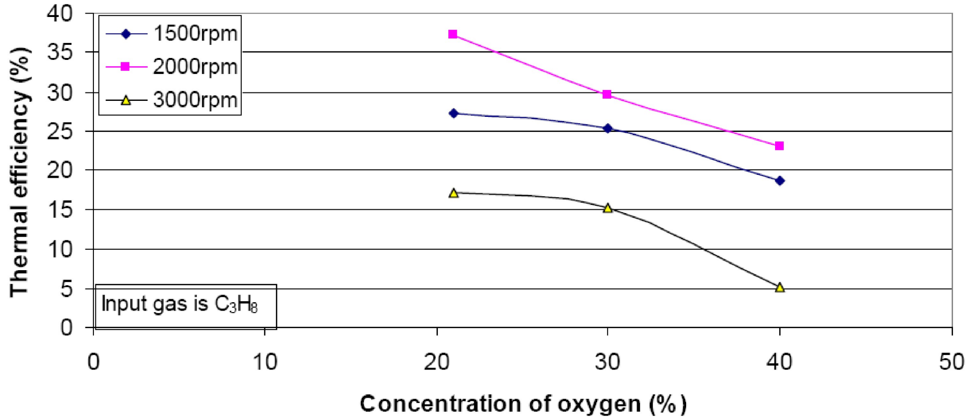

Figure 17 : Thermal efficiency of combustion in different engine speed and oxygen concentrations for propane burning

perature provides the proper condition for combustion and saves much more fuel.

The required fuel for combustion decreases with higher oxygen and higher operating temperature. Figures 18, 19 and 20 show the dependency of the saved fuel to oxygen content and operating temperature for three volatile hydrocarbon fuels.

There is not any considerable increase in the amount of saved fuel when oxygen increases from 21% to 30%, at 800°C, 900°C and 1500°C. However, the increase of about 58% is obtained in the saved Methane gas percentage, when the oxygen concentration uptakes from 20% to 30% at 2000°C. This relates on this fact that the high temperature is one of the major constitutes for combustion besides oxygen and fuel. So, higher temperature provides the initial heat to combustion reactions, prop-

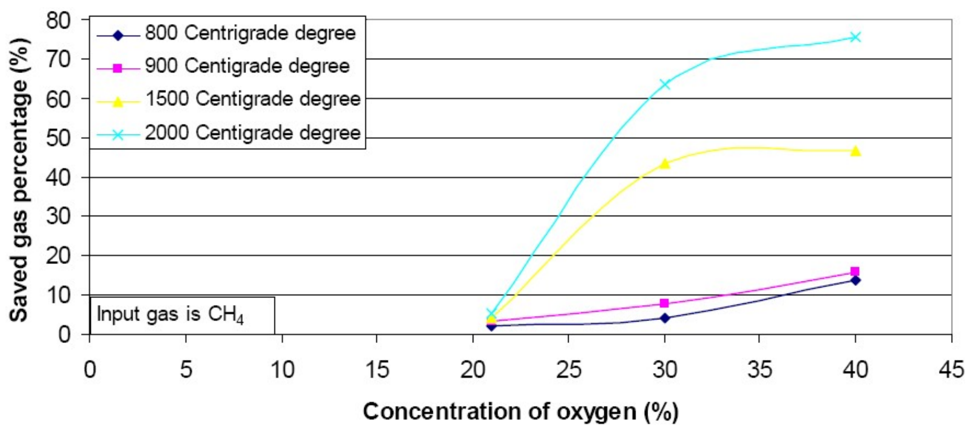

Figure 18 : The effect of oxygen concentration and combustion temperature on the amount of saved gas for methane burning

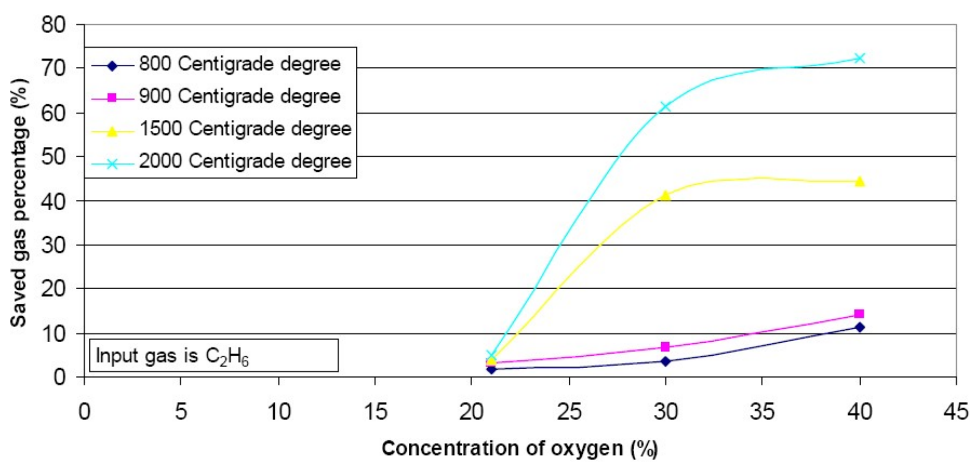

Figure 19 : The effect of oxygen concentration and combustion temperature on the amount of saved gas for ethane burning

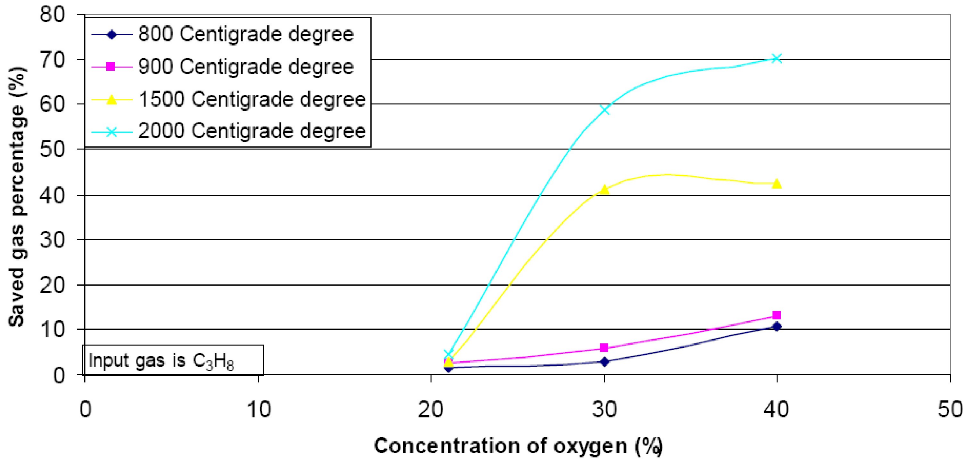

Figure 20 : The effect of oxygen concentration and combustion temperature on the amount of saved gas for propane burning

erly. Also, the higher amount of gas is saved at 40% oxygen content while methane is burned at 2000°C.

CONCLUSIONS

In this work, membrane module is used to produce the oxygen enriched air which is fed into one SI engine. Experiments are held to investigate the effect of oxygen concentration on the important parameters in combustion process. The flame temperature, the saved fuel, the amounts of unburned fuel, the amounts of basic and side components and thermal efficiency are considered and surveyed by experiments. Curves are illustrated for various fuels such as methane, ethane and propane. Values of oxygen concentrations are 21%, 30%, 40%, 50% and 60% by volume. Results show that the highest flame temperature is obtained from propane burning using 60% oxygen enrichment air. Thermal efficiency is measured for different speed engines, 1500, 2000 and 3000 rpm and with 21%, 30% and 40% oxygen volume percentage in air. Results show that the highest thermal efficiency is about 38.3% by burning methane fuel in 21% oxygen volume percentage. Also the effect of amount of oxygen on the NO_x emissions is considered and the propane fuel produces higher pollution as NO_x because of higher flame temperature. The value of NO_x concentration in the outlet stream is 8542 ppm and is obtained when the torque is 40 *N.m.*s. The results extracted in this paper can be used to determine optimal control points in the combustion design stage. Also, help man to determine the expected efficiency of an engine and to assist in making cost/benefit decisions. These results can be used to make a rough estimate of the efficiency improvements that can be made by decreasing the amount of excess air and the level of combustibles in the flue gas in combustion engines.

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