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Impact of Varying Combustion Oxidizer from Air to Pure Oxygen: Performance, Emissions, and Efficiency

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Abstract

The transition from air to pure oxygen as a combustion oxidizer provides considerable benefits in flame temperature, fuel efficiency, and reduction of NOx and CO emissions, but it also raises safety, cost, and material integrity concerns. This study investigates the effects of varying combustion oxidizer from air to pure oxygen on flame temperature, emissions, thermal efficiency, and fuel savings across various fuels and combustion conditions. The results demonstrate that increasing the oxygen concentration in the oxidizer leads to higher adiabatic flame temperatures, enhanced combustion efficiency, and improved fuel economy, particularly in the transition from air-based to oxygen-enriched combustion. Among the fuels studied, acetylene exhibited the highest flame temperatures, making it more suitable for high-temperature applications. Emission analyses reveal that oxygen enrichment reduces inert nitrogen in the oxidizer and increases the concentrations of important combustion products such as H_2O and CO_2, though CO levels rise due to high-temperature dissociation. NO formation peaks at intermediate oxygen levels due to optimal thermal conditions and nitrogen presence, then declines as nitrogen is replaced. Fuel utilization efficiency improves with increasing oxygen levels but shows diminishing returns above 70% O_2, while fuel savings are more pronounced at higher exhaust temperatures. Overall, oxygen-enhanced combustion offers significant advantages in thermal performance and fuel efficiency, with optimal economic and operational benefits, achieved at moderate oxygen concentrations (30–50%). This study established that moderate oxygen concentration is suitable for reducing safety, cost and materials integrity concerns in retrofitted burners

Keywords: Oxy-fuel combustion; flame temperature; NO_x reduction; oxygen enrichment; combustion efficiency.

1. Introduction

Energy has been one of the most influential components in raising people's standard of living throughout human history, and it continues to play an important role in the advancement of economic and industrial growth. The prospect of explosive population growth, which is expected to reach 8.5 billion by 2030, raises serious concerns about future energy strategy, including increased consumption of energy resources, rising fuel prices, environmental pollution, climate change, and increased waste generation (Sadigov, 2022). The aforementioned challenges as well as the report of the United States Department of Energy which highlighted that industry demand for energy is expected to increase by 1.2% every year until 2040 (EIA, 2016), have inspired research interests focusing on strengthening the energy supply chain and optimizing energy conversion efficiency of thermal systems. While several alternative energy generation options, such as nuclear, solar, and wind energy, are being explored (Ang et al., 2022), combustion which is the rapid oxidation of fuels to liberate heat, still accounts for the vast majority of worldwide processes of energy conversion in a variety of industrial applications such as power production, transportation, chemical processing and waste incineration (Peng et al., 2023).

In most industrial practices, fuel combustion is achieved using air as an oxidizer. Dry air is made up of approximately 21% oxygen, 78% nitrogen, and 1% argon by volume. Carbon dioxide and other gases can also be found in trace amounts. When air is utilized as an oxidizer, nitrogen, which constitutes a large component of the oxidizer source, does not contribute to the combustion process but instead acts as an inert heat sink. In addition, nitrogen in the combustion air reduces the flame temperature, resulting in inefficient energy conversion and increased emissions of noxious pollutants (Janta-Lipinska et al., 2024).

Several researchers have demonstrated that the replacement of a portion or the entire combustion air with oxygen, reduces or eliminates the primary nitrogen source to achieve more promising results. According to Dong et al. (2024), the substitution of air-fuel with oxygen-fuel combustion results in approximately 80-90% reduction in combustion emissions, mainly oxides of nitrogen (NOx). Cravero and Domenico (2019) show that for a given stoichiometric ratio, employing pure oxygen as combustion oxidizer offers higher flame temperature, which is advantageous in high-temperature applications such as metal production, glass melting, rocket engines, and waste incineration. The increase in flame temperature also results in faster combustion rates, leading to a more complete oxidation of fuel and higher energy release per unit of fuel. Additionally, higher combustion temperatures facilitate the breaking of molecular bonds in fuel molecules, allowing for the use of less fuel. The study by Bouhentala, et al. (2024) found that the use of pure oxygen instead of air in combustion also reduces the volume of flue gas produced, which is particularly beneficial in processes where gas handling is a concern. The reduction in flue gas volume translates to smaller and more energy-efficient heat exchangers, improving overall system efficiency. Additionally, oxygen-fuel combustion can reduce carbon emissions by promoting more complete combustion, which reduces the production of CO and particulate matter (Duan & Lu, 2025). Additionally, the oxy-fuel combustion also improves thermal efficiency, reduces energy consumption and lowers emissions of pollutants such as carbon monoxide (Chu et al., 2024; Zhang et al., 2024; Hu et al., 2024).

Fakudze et al. (2023) demonstrated that besides the higher flame temperatures and reduced overall flue gas mass flow, using pure oxygen as a combustion oxidizer instead of air also results in a higher concentration of carbon dioxide (CO_2) in the exhaust stream, which improves the efficiency and efficacy of carbon capture process for reducing greenhouse gas emissions associated with energy production from fossil fuel. Despite the numerous advantages, a number of potential challenges have been identified with the use of pure oxygen as combustion oxidizer in many industrial heating and power generation processes. One of these disadvantages according to Asgari et al. (2017) is the undesirable rise in NOx emissions, especially in the case of organically bound nitrogen-fuel such as oil, coal or wastes. This is due to increased flame temperature which increases thermal formation of NOx. They established that NOx formation is highly temperature-dependent, and the higher temperatures resulting from oxygen-fuel combustion can increase the formation of these pollutants. However, the adoption of post-combustion treatment technologies such as selective catalytic reaction (SCR) or exhaust gas recirculation (EGR) has been shown to mitigate the impact of oxygen-fuel combustion on NOx emissions (Farhan & Wang, 2022). Thus, the use of advanced catalytic technologies can significantly reduce NOx levels in oxygen-fuel combustion applications, making it possible to meet regulatory standards for air quality.

Another disadvantage is the increased overheating and wear on equipment such as furnaces or burners due to flame instability (Li et al., 2024; Yilmaz et al., 2020). Hence, the need for specialized combustion technologies must be addressed to ensure the feasibility and reliability of oxygen-fuel combustion in industrial applications.

Furthermore, the cost of producing pure oxygen remains a major barrier to the widespread adoption of oxygen-fuel combustion in industries where cost-efficiency is a key consideration (García-Luna et al., 2022). This is because pure oxygen is typically produced through energy-intensive processes such as cryogenic distillation, which is very expensive.

However, recent developments in oxygen production technologies and increased emphasis on environmental protection have necessitated efforts to reduce pollutant emissions without impairing the efficiency and increasing the cost of combustion plants. Oxygen-enriched air rather than pure oxygen is gaining research attention due to its potential for higher thermal efficiency, reduced pollutant emissions, and adaptability in carbon capturing technologies. The study by Engin et al. (2020) suggest that oxygen-enriched air (containing 30-40% oxygen by volume) can provide many of the same combustion benefits as pure oxygen, but at a significantly lower cost. Additionally, the potential for fuel savings, improved efficiency, and reduced emissions can offset the initial investment in oxygen production systems over time, particularly in large-scale applications.

Although there are numerous studies on oxygen-enriched air combustion, there is still a need for further research in this area. This is because a key area of research has focused on low level of oxygen enrichment (30 – 40%) or the pure oxygen. Particularly, there is a need for studies that investigate the potential benefits and disadvantages of higher levels of oxygen enrichment in combustion process. Therefore, the goal of this study is to investigate the impact of varying oxygen concentration in combustion oxidizer from air to pure oxygen and to determine the optimum oxygen level that meets both energy and environmental criteria.

2. Methodology

The combustion of fuels is a thermo-chemical exothermic reaction which results in exhaust gas production with different mole percentages. In this study, the effect of oxygen content variation on combustion efficiency and efficacy was carried out using thermodynamic analyses method by (Brenda et al., 2025; Paulo et al., 2012). This method is based on the principles of thermodynamics and it involves the application of mass and energy balance equations, as well as the equilibrium relation between the specified species to determine the product compositions and flame temperature.

The stoichiometric combustion of hydrocarbon with air may be expressed by Equation 1.

$$C_x\,H_y + a\,(O_2 + \tfrac{0.79}{0.21}\,N_2) \;\rightarrow\; n_{CO_2}\,CO2 + n_{H2O}\,H_2O + 3.76n_{o_2}\,N_2 + \text{trace species} \quad (1)$$

For a reaction of methane (CH_4) with air, nearly 70% of the exhaust gas volume in Equation 1 is N_2. However, the volume of the exhaust gases is significantly reduced by elimination of N_2 through the use of pure oxygen as oxidizer as presented in Equation 2.

$$Ch4 + 2O2 \;\rightarrow\; n_{CO_2}\,CO2 + n_{H_2O}\,H_2O + \text{trace species} \quad (2)$$

The general stoichiometric oxygen enhanced combustion process for hydrocarbons may be expressed by Equation 3. The increase of oxygen concentration in the oxidizer leads to reduction of nitrogen content, and this is represented by $\frac{1\text{-}\Omega}{\Omega}$ in Equation 3.

$$C_x\,H_y + a\,(O_2 + \tfrac{1\text{-}\Omega}{\Omega}\,N_2) \;\rightarrow\; n_{co2}\,CO2 + n_{H_2O}\,H_2O + n_{N_2}\,N_2 + \text{trace species} \quad (3)$$

where a is the mole of oxidizer used, n_i is the mole of combustion products, Ω is the molar fraction of oxygen in the oxidizer, and trace species considered in this study include CO, OH, NO, H_2, O_2, H, O, and N.

The mass balance on each element of carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) are represented by Equations 4 -7, respectively.

$$n_{CO_2} + n_{CO} = x \quad (4)$$

$$2n_{H_2O} + n_{OH} + 2n_{H_2} + n_H = y \quad (5)$$

$$2n_{CO_2} + n_{H_2O} + n_{CO} + n_{OH} + n_{NO} + 2n_{O_2} = 2a \quad (6)$$

$$2n_{N_2} + n_{CO} + n_N = 2a\left(\frac{1-\Omega}{\Omega}\right) \quad (7)$$

The Equations 3-7 contains 11 unknown, which can be determine by introducing 7 additional equations obtained from consideration of equilibrium among products. The needed seven reactions related to the equilibrium description and their corresponding equilibrium constant and the Gibbs function relation to equilibrium constant are presented by equations Table 1.

The Gibbs functions for the seven needed equilibrium equations may be expressed in terms of specific enthalpy and entropy by Equations 8-14.

$$-\Delta G_1^0 = (h_{CO} - T_f S_{CO}) + \tfrac{1}{2}(h_{O_2} - T_f S_{O_2}) - (h_{CO_2} - T_f S_{CO_2}) \quad (8)$$

$$-\Delta G_2^0 = 2(h_O - T_f S_O) - (h_{O_2} - T_f S_{O_2}) \quad (9)$$

$$-\Delta G_3^0 = 2(h_N - T_f S_N) - (h_{N_2} - T_f S_{N_2}) \quad (10)$$

$$-\Delta G_4^0 = 2(h_H - T_f S_H) - (h_{H_2} - T_f S_{H_2}) \quad (11)$$

$$-\Delta G_5^0 = (h_{H_2} - T_f S_{H_2}) + \tfrac{1}{2}(h_{O_2} - T_f S_{O_2}) - (h_{H_2O} - T_f S_{H_2O}) \quad (12)$$

$$-\Delta G_6^0 = (h_H - T_f S_H) + (h_{OH} - T_f S_{OH}) - (h_{H_2O} - T_f S_{H_2O}) \quad (13)$$

$$-\Delta G_7^0 = 2(h_{NO} - T_f S_{NO}) - (h_{N_2} - T_f S_N) - (h_{O_2} - T_f S_{O_2}) \quad (14)$$

The general energy balance is represented by Equation 15.

$$\Delta h = \textstyle\sum_{i=0}^{n} n_k\left(\overline{h_k^o} + \Delta\bar{h}_k\right)_{prod} - \sum_{i=0}^{n} n_k\left(\overline{h_k^o} + \Delta\bar{h}_k\right)_{react} \quad (15)$$

where P is the total pressure, n_{tot} is the total mole of the combustion gaseous product, T_f is the flame temperature, $\overline{h_k^o}$ and $\Delta\bar{h}_k$ are respectively the specific enthalpy of formation (T_o = 25 °C, P_o = 1 atm) and variation of specific enthalpy with the increase of temperature of each component *k* of the stream *i*.

The above mass-balance, energy-balance and equilibrium composition equations were solved using computer program GASEQ, to evaluate all the species of the combustion products and adiabatic flame temperature with the increase oxygen concentration in the oxidizer. GASEQ is software written in Visual Basic 3 for combustion equilibrium calculations of different types of problem. The fundamentals of the program are based on the complex, balanced chemical calculations defined by Gordon and McBride (1976).

Table 1: Equilibrium constant equations.

S/N	Equilibrium equation	Equilibrium constant	Gibbs function
1	$CO_2 \leftrightarrow CO + \frac{1}{2}O_2$	$K_1 = \frac{n_{CO}n_{O_2}^{\frac{1}{2}}}{n_{CO_2}}\left(\frac{P}{n_{tot}}\right)^{\frac{1}{2}}$	$-\frac{\Delta G_1^0}{RT_f} = lnK_1$
2	$O_2 \leftrightarrow 2O$	$K_2 = \frac{n_O^2}{n_{O_2}}\left(\frac{P}{n_{tot}}\right)$	$-\frac{\Delta G_2^0}{RT_f} = lnK_2$
3	$N_2 \leftrightarrow 2N\,2$	$K_3 = \frac{n_N^2}{n_{N_2}}\left(\frac{P}{n_{tot}}\right)$	$-\frac{\Delta G_3^0}{RT_f} = lnK_3$
4	$H_2 \leftrightarrow 2H$	$K_4 = \frac{n_H^2}{n_{H_2}}\left(\frac{P}{n_{tot}}\right)$	$-\frac{\Delta G_4^0}{RT_f} = lnK_4$
5	$H_2O \leftrightarrow H_2 + \frac{1}{2}O_2$	$K_5 = \frac{n_{H_2}n_{O_2}^{\frac{1}{2}}}{n_{H_2O}}\left(\frac{P}{n_{tot}}\right)^{\frac{1}{2}}$	$-\frac{\Delta G_5^0}{RT_f} = lnK_5$
6	$H_2O \leftrightarrow H + OH$	$K_6 = \frac{n_H n_{OH}}{n_{H_2O}}\left(\frac{P}{n_{tot}}\right)$	$-\frac{\Delta G_6^0}{RT_f} = lnK_6$
7	$N_2 + O_2 \leftrightarrow 2NO$	$K_7 = \frac{n_{NO}^2}{n_{N_2}n_{O_2}}$	$-\frac{\Delta G_7^0}{RT_f} = lnK_7$

3. Results and Discussion

The results of the adiabatic flame temperature and the adiabatic composition of species concentrations with respect to oxygen levels in the combustion oxidizer are presented and discussed in this section. Also discussed are the thermal efficiency of the combustion process at different product gas temperatures and the fuel savings associated with varying oxygen concentration levels.

3.1 Flame Temperature

The variation of adiabatic flame temperature with respect to the variation of oxygen content in combustion oxidizer is shown in Figure 1. It can be observed that for all three fuels, the adiabatic flame temperature increases with increasing oxygen concentration in the oxidizer. This is expected, as higher oxygen availability enhances combustion intensity and completeness, reducing excess inert nitrogen from air (in oxygen-enriched conditions), leading to less heat loss and higher flame temperatures. The fuel C_2H_2 (Acetylene) consistently exhibits the highest adiabatic flame temperature across the entire oxygen concentration range. C_3H_8 (Propane) has a slightly higher flame temperature than CH_4 (Methane) at any given oxygen concentration. The flame temperature hierarchy is $T_{C2H2} > T_{C3H8} > T_{CH4}$

In the low oxygen concentration region (20–40%), the adiabatic flame temperatures of all three fuels increase. This region represents a transition from air-based combustion toward oxygen-enriched combustion. At 21% O_2 (roughly air), CH_4 has a flame temperature near 2220 K, while C_2H_2 reaches approximately 2550 K. The steep temperature rise is attributed to the higher carbon-to-hydrogen ratio of C_2H_2. The rate of temperature increase begins to flatten in the 40–70% oxygen range, indicating diminishing returns in flame temperature with further O_2 enrichment. Combustion reactions approach completion, and the heat capacity of the products begins to limit the temperature rise.

At high oxygen concentration (70 – 100%), the adiabatic flame temperature increase becomes more gradual. At nearly pure oxygen (100%), flame temperatures are 3150, 3200 K, and 3350 K, for CH_4, C_3H_8, and C_2H_2, respectively. In this regime, the system operates close to the ideal adiabatic limit, and further increases in O_2 have a limited effect on flame temperature.

This implies that increasing the oxygen concentration in combustion air, can improve thermal efficiency of combustion systems. However, this can also lead to increase NO_x emissions due to thermal fixation of atmospheric nitrogen. The use of higher level of oxygen concentration in combustion oxidizer may necessitate the use of refractory materials in combustion chambers to withstand higher temperatures. For most high flame temperature practices such as metal cutting or welding, C_2H_2 is the preferred fuel.

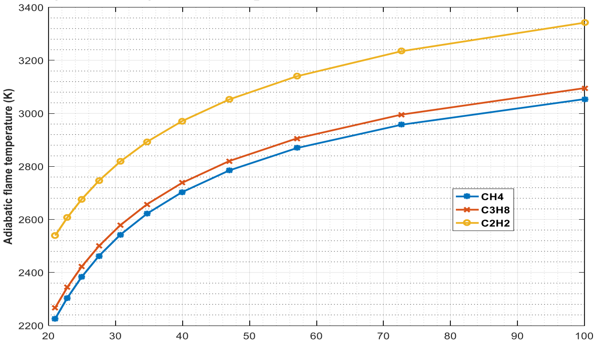

Figure 1: Effect of varying oxygen concentration on adiabatic flame temperature for adiabatic equilibrium stoichiometric methane, propane and acetylene.

3.2 Emission Characteristics

Figure 2 illustrates the major species concentration resulting from stoichiometric methane (CH_4) combustion under adiabatic conditions, while varying the oxygen concentration in the oxidizer from air-level (21%) up to pure O_2 (100%). It can be observed that nitrogen decreases sharply with increasing O_2 concentration. This trend indicates that at low O_2 concentrations (e.g., 21%), the oxidizer which is mostly air consists of approximately 79% nitrogen. As oxygen concentration increases, air is replaced by pure oxygen, reducing nitrogen from the oxidizer. Since N_2 is largely inert and does not participate in the ideal stoichiometric reaction, its mole fraction decreases significantly, approaching zero near 100% O_2.

Water vapour increases gradually from 21% to nearly 40% as O_2 concentration rises. This is attributed to less inert N_2 present in the oxidizer, which results to relative concentration of H_2O increases in the product gas. The increased flame temperature with higher O_2 also promotes complete combustion, enhancing H_2O formation. However, carbon dioxide (CO_2) slight increase with oxygen enrichment (from 9% to 12%). Its increase is less steep than H_2O because CO_2 formation is limited by the carbon content of methane and already near stoichiometric levels even at lower O_2 concentrations. Higher oxygen levels allow more complete oxidation of any intermediate carbon species (e.g., CO), slightly boosting CO_2 output.

Carbon monoxide (CO) increases steadily with O_2 concentration, from near 0% to 13% at 100% O_2. This may seem counterintuitive, as CO is typically a product of incomplete combustion. However, under high-temperature, adiabatic and stoichiometric conditions, CO becomes thermodynamically favored due to dissociation of CO_2 at high temperatures. As oxygen enrichment leads to higher flame temperatures, the equilibrium shifts toward more CO, despite overall oxygen sufficiency.

It can be inferred that oxygen enrichment leads to a reduction in inert species (N_2) and an increase in active combustion products. Higher H_2O and CO_2 concentrations signify more effective and concentrated combustion, benefiting thermal efficiency. CO levels increasing at high O_2 suggest that thermal dissociation at high temperatures is significant and must be considered for post-combustion emissions control. In thermal systems, this behavior influences emissions control strategies (e.g., CO and NO_x formation), material selection (due to higher water vapor and temperature corrosion), combustor design, especially in oxygen-enriched or oxy-fuel combustion.

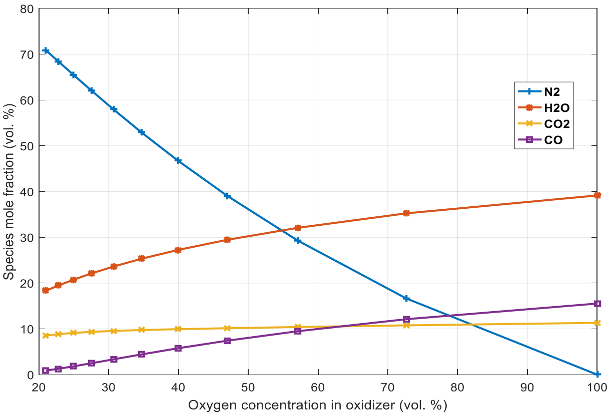

Figure 2: Effect of vary oxygen concentration on major species for adiabatic equilibrium stoichiometric methane.

Figure 3 shows the behavior of minor species produced during adiabatic, stoichiometric combustion of methane as the oxidizer is enriched with oxygen. It can be seen that the radical species OH, H and O increase steadily with increasing oxygen concentration in oxidizer. Their increase signifies greater combustion reactivity, enhanced flame speed, and more complete oxidation. These species are useful in modeling flame stability and propagation in high-performance burners or oxygen-enriched systems.

NO formation peaks at intermediate O_2 levels (60 – 70%) due to optimal temperature and N_2 presence, then declines as N_2 diminishes. As oxygen concentration continues to rise, N_2 is displaced from the oxidizer, limiting NO formation despite high temperatures. This nonlinear behavior reflects the balance between high temperature (promoting NO) and N_2 availability (required for NO formation). This species is critical for designing low-emission combustion systems, especially in gas turbines or furnaces using oxygen-enriched air.

The hydrogen (H_2) Increases with oxygen concentration, reaching about 3% at 100% O_2. The presence of H_2 at high oxygen concentrations indicates potential for syngas-like behavior or secondary fuel utilization. This is important in fuel reforming or hybrid combustion systems. Oxygen (O_2) increase linearly from 0.5% to 8% mole fraction as oxygen concentration increases. The presence of residual O_2 suggests incomplete utilization or limits on chemical equilibrium shifting fully to products, especially at higher temperatures.

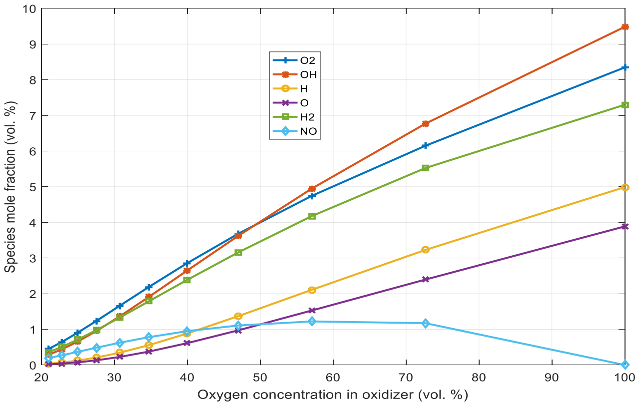

Figure 3: Effect of vary oxygen concentration on minor species for adiabatic equilibrium stoichiometric methane.

3.3 Thermal Efficiency

The combustion efficiency for different products gas temperatures are shown in Figure 4. It is observed that for all exhaust gas temperatures, fuel utilization efficiency increases with increasing oxygen concentration, but the rate of improvement decreases at higher oxygen levels. This trend is steeper at lower oxygen concentrations (20–50%) and flattens out above 70%. It implies that replacing air with oxygen, inert nitrogen is reduced, resulting in higher flame temperatures and lower specific heat capacity of the combustion products, improving the efficiency. However, efficiency is inversely related to the exhaust gas temperatures. The higher the exhaust gas temperature, the lower the efficiency, as more energy is carried away unused. This highlights the importance of heat recovery systems or exhaust gas recirculation (EGR) in industrial combustion. Furthermore, beyond 70–80% oxygen concentration in the oxidizer, the efficiency gains start to level off. This indicates a point of declining economic and practical benefit for further oxygen enrichment without heat recovery.

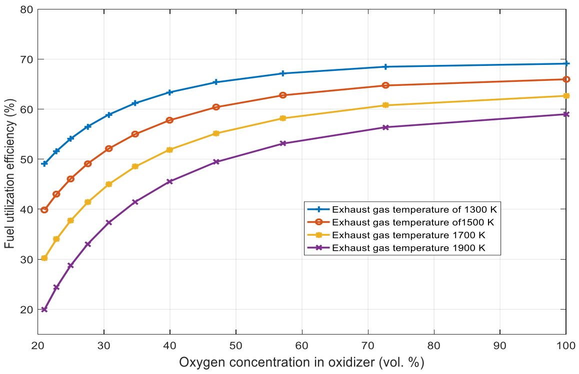

Figure 4: Effect of varying oxygen concentration on fuel utilization efficiency for stoichiometric methane at different exhaust gas temperatures.

3.4 Fuel savings

Figure 5 shows fuel savings for stoichiometric methane at different products gas temperatures. For all the products gas temperatures investigated, increasing oxygen concentration in the oxidizer leads to greater fuel savings. The rate of increase is rapid at lower oxygen levels (21% to 50%) and then flatten out between 70% and 100%. This indicates that, economically, moderate enrichment (30–50%) may offer the best trade-off between performance and cost. Fuel savings show a stronger positive correlation with exhaust gas temperature than fuel utilization efficiency. At 1900 K, fuel savings reach over 70% at 100% oxygen, while at 1300 K, the maximum saving is only about 27%. This result shows that higher exhaust temperatures yield greater savings, making oxygen enrichment especially useful for high-temperature industrial processes. However, diminishing returns beyond 70% O_2 suggest an optimum oxygen level for economic efficiency.

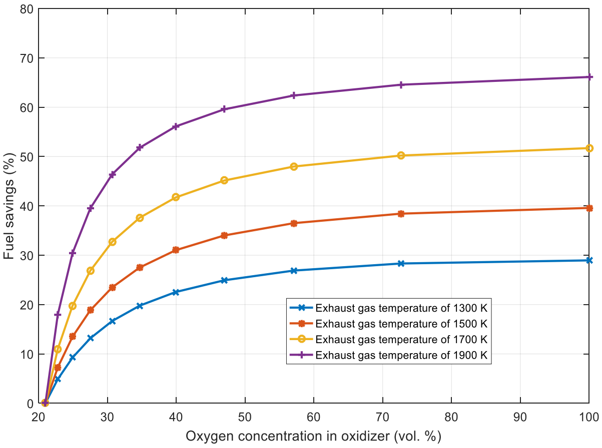

Figure 5: Effect of oxygen concentration on fuel savings for stoichiometric methane at different exhaust gas temperatures.

4. Conclusion

This study demonstrated that oxygen-enriched combustion significantly enhances the performance, efficiency, and fuel economy of combustion systems. Increasing the oxygen concentration in the oxidizer consistently improves adiabatic flame temperature, fuel utilization efficiency, and fuel savings, although the benefits show diminishing returns at higher oxygen levels. The adiabatic flame temperature increases significantly with oxygen enrichment, particularly in the transition from air-based to oxygen-enhanced combustion. Among the fuels analyzed, acetylene (C_2H_2) exhibited the highest flame temperature, making it suitable for high-intensity applications such as metal cutting. However, higher flame temperatures can result in increased thermal NO_x formation, especially at intermediate oxygen concentrations where nitrogen is still present, highlighting the need for emissions control strategies.

Emissions analysis revealed that oxygen enrichment reduces inert nitrogen in the combustion process and increases the mole fractions of key combustion products such as H_2O and CO_2, indicating more complete and efficient combustion. At high temperatures, CO formation rises due to CO_2 dissociation, and minor radical species (OH, O, H) become more prevalent, promoting flame stability and reactivity. However, NO formation peaks at mid-range oxygen concentrations and declines as nitrogen is displaced, necessitating the need for oxygen control in emission-sensitive applications. In terms of efficiency and fuel savings, oxygen enrichment offers clear advantages. Fuel utilization efficiency increases as nitrogen dilution decreases, though it declines with higher exhaust temperatures due to greater energy losses. In contrast, fuel savings are maximized at higher exhaust temperatures, as more efficient combustion offsets the energy loss. Optimal economic and thermal performance appears to be achieved at moderate oxygen concentrations (30–50%), beyond which the gains begin to plateau.

Therefore, the study established that oxygen-enhanced combustion offers a practical pathway to improving thermal efficiency, reducing fuel consumption, and lowering emissions in industrial systems. However, careful consideration must be given to the balance between oxygen concentration, exhaust temperature, material limitations, and emission regulations to optimize both performance and sustainability

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