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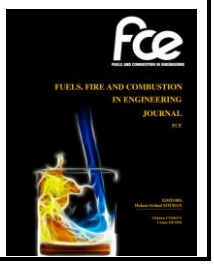

# Endüstriyel Yakıtların Yanma Termodinamiği ve Çevresel Etkileri: Bir Karşılaştırma Çalışması

Ahmet ELBİR*

## ÖZ

Yanma süreçlerinin enerji üretiminde ve çevresel etkilerinde oynadığı kritik rol göz önüne alındığında, bu çalışma benzen, bütan, etan, hidrojen, metan ve propan gibi farklı yakıt türlerinin yanma süreçlerini incelemekte ve bu süreçlerin termodinamik etkilerini, atmosfere salınan gazların miktarları üzerindeki etkilerini değerlendirmektedir. Elde edilen bulgular, her bir yakıt türünün yanma verimliliği, ısı salınımı ve atmosfere salınan kirletici maddeler açısından farklılık gösterdiğini ortaya koymaktadır. Bu analizler, enerji üretimi, endüstriyel uygulamalar ve çevre politikaları açısından önemli sonuçlar sağlamaktadır. Gelecekteki çalışmalar, daha derinlemesine yakıt karşılaştırmalı analizleri, ileri yanma teknolojilerinin değerlendirilmesi ve yanma süreçlerinin dinamik modellemesi gibi alanlarda odaklanabilir, böylece daha sürdürülebilir yakıt kullanımı ve çevresel etkilerin azaltılması için stratejiler geliştirilebilir.

**Anahtar Kelimeler:** atmosfere salınan gazlar, çevresel etkiler, endüstriyel uygulamalar, yakıt karşılaştırması, enerji üretimi

# Thermodynamics of Combustion and Environmental Impacts of Industrial Fuels: A Comparative Study

## ABSTRACT

Given the critical role that combustion processes play in energy production and their environmental impacts, this study examines the combustion processes of various fuel types such as benzene, butane, ethane, hydrogen, methane, and propane, evaluating their thermodynamic effects and the amounts of gases released into the atmosphere. The findings reveal that each fuel type differs in terms of combustion efficiency, heat release, and the pollutants emitted into the atmosphere. These analyses provide significant insights for energy production, industrial applications, and environmental policies. Future studies could focus on more in-depth comparative analyses of fuels, the assessment of advanced combustion technologies, and the dynamic modeling of combustion processes, thereby developing strategies for more sustainable fuel use and the reduction of environmental impacts.

**Keywords:** gases released into the atmosphere, environmental impacts, industrial applications, fuel comparison, energy production

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## 1. INTRODUCTION

Industrial fuels play a crucial role in supporting a significant portion of economic activities worldwide and are a cornerstone of modern industry. These fuels are utilized in various industrial processes such as energy production, heating, transportation, and manufacturing. Resources like coal, natural gas, oil, and nuclear energy are commonly used industrial fuels for electricity generation. Industrial facilities, buildings, hospitals, and schools rely on these fuels for heating and cooling purposes. Petroleum and petroleum-based products constitute the primary source of transportation globally, while the use of fuels is widespread in many areas of industrial processes such as metal production, chemical manufacturing, and glassmaking. In the agricultural sector, vehicles like tractors and combines operate on fossil fuels, and industrial fuels are also used in processes like greenhouse heating systems and drying facilities. However, widespread use of industrial fuels can lead to environmental impacts, making it essential to enhance energy efficiency and adopt clean technologies. The aim of this study is to examine the thermodynamic properties of combustion processes of industrial fuels and their environmental impacts in detail. Specifically, the combustion thermodynamic properties of different fuels such as methane, propane, benzene, ethane, butane, and hydrogen will be compared, and their effects on environmental impacts will be analyzed. This study will address the combustion processes of industrial fuels such as methane, propane, benzene, ethane, butane, and hydrogen. Factors such as combustion temperature, energy efficiency, and emission profile will be examined, and their effects on environmental impacts will be determined. Additionally, the effect of excess air percentage change on the change in exit temperature due to combustion will also be investigated. The comparison conducted in this study aims to determine which fuel is more efficient, has less environmental impact, or produces fewer greenhouse gas emissions by comparing the thermodynamic properties and environmental impacts of different industrial fuel combustion processes. This comparison can provide valuable insights for the energy sector, environmental protection policies, and industrial processes.

Some references in the literature: The explosion limits of methane, ethane, and propane under different air equivalence ratios were investigated. In methane-air mixtures, it was observed that as the equivalence ratio increased, the Negative Temperature Coefficient (NTC) response emerged. In ethane-air mixtures, the NTC response remained relatively constant, but it was determined that the explosion limit shifted to the high-pressure region. In propane-air mixtures, it was observed that at high equivalence ratios, both the explosion limit curve in the NTC response region and the shift of the high-temperature region to high pressure led to a dual NTC response. Detailed reaction pathway analysis confirmed that the reaction pathway of methyl radicals shifted from oxygen addition reactions to reaction reactions, resulting in the NTC response and decreased reactivity [1]. In their research, combustion characteristics of three different hydrocarbon fuels were investigated in a micro-scale combustor. Experiments were conducted to analyze flame stabilization, temperature distribution of the outer wall, and differences in combustor channel heights. The results indicated that hydrogen-air mixture had a wider and more stable combustion range at different equivalence ratios. The reaction positions of methane and propane boxes significantly shifted downward with increasing mixture flow velocity. Under the same chemical energy input, methane box had the most uniform outer wall temperature distribution and the highest average wall temperature among the three fuels [2]. In their study, propane ($C_3H_8$) was used to simulate hydrocarbon combustion, and the results were compared with another study on methane ($CH_4$) combustion to examine the difference in combustion temperature and the effect of specific heat change on temperature. The results showed that the maximum temperature for propane was lower than that for methane under both constant and specific heat change conditions [3]. The research attributed this difference to methane having a higher octane number than propane and linked this to its effects on flame propagation velocity and flame temperature. Their studies predicted the flammable range of different hydrocarbons using the freely propagating flame method. The effects of operating conditions were examined, and the model was found to be consistent with experimental data. The model yielded successful results for the upper flammability limit with an average deviation of 20%. Additionally, model performance was

improved by incorporating an approach involving soot radiation effects. A kinetic mechanism was used to predict soot formation in rich flames. The advantages of a model incorporating chemical kinetics effects were discussed, and sensitivity analysis was conducted to determine how chemistry influenced the process. This study demonstrated that the chemical interaction between different fuels was the main reason for deviation from thermal behavior. Finally, it was found that chemistry was significant in predicting the weak flammability limits of low alkanes when pure $N_2O$ was used as an oxidant [4]. Their study, the first part of a series focusing on molecular models between alkanes and air components and combustion products, examined vapor-liquid equilibrium phase diagrams of four alkanes (methane, propane, octane, and dodecane) with nitrogen, carbon dioxide, and water mixtures found in characteristic components of natural gas, liquefied natural gas, gasoline, and kerosene. The results generally showed good agreement with experimental data, particularly in alkane-nitrogen and alkane-carbon dioxide binary mixtures. However, it was observed that the model did not accurately represent the near-critical and high-pressure phase boundaries for the dodecane-water system [5]. In their study, methane, ethylene, and propane, three hydrocarbon fuels, were used as a quantitative method to compare carbon dioxide emissions with Exergy analysis. The effect of flame temperature and excess air amount on emission Exergy was examined. The results indicated sensitivity to excess air and flame temperature. Additionally, the results showed that as the carbon/hydrogen ratio (C/H) increased, the environmental impact of carbon dioxide (higher emission Exergy) increased [6].

Widespread use of industrial fuels can lead to environmental impacts, so improving energy efficiency and switching to clean technologies is extremely important. The aim of this study is to examine in detail the thermodynamic properties and environmental effects of the combustion processes of industrial fuels. In particular, the combustion thermodynamic properties of different fuels such as methane, propane, benzene, ethane, butane and hydrogen will be compared and their environmental impacts will be analyzed. The study will examine factors such as combustion temperature, energy efficiency and emissions profile and determine their impact on environmental impacts. Additionally, the effect of excess air percentage on the change in exit temperature resulting from combustion will also be investigated. This study aims to determine which fuel is more efficient, has less environmental impact or produces less greenhouse gas emissions by comparing the thermodynamic properties and environmental impacts of the combustion processes of different industrial fuels. This comparison can provide valuable insights for the energy sector, environmental protection policies and industrial processes.

## 2. MATERIAL AND METHOD

### 2.1. Reacting fuels:

***Methane ($CH_4$):*** Methane is the simplest alkane hydrocarbon. It is a colorless, odorless, combustible gas. As the simplest compound of hydrogen and carbon, it is the main component of natural gas. Methane is widely used as a fuel for electricity and heat production. It is utilized as a source of natural gas for heating and cooking in homes, workplaces, and industrial facilities. Additionally, it is used in power plants, as fuel for vehicles, and in various processes in the chemical industry.

***Propane ($C_3H_8$):*** Propane is a hydrocarbon consisting of three carbon atoms and having an alkyl group ($CH_3$-). It is a colorless, odorless gas that liquefies under pressure. Propane is used as a fuel for various purposes such as home heating, cooking, providing hot water, and industrial processes. Additionally, it is used as a fuel for vehicles and serves as an important raw material in the petrochemical industry.

***Benzene ($C_6H_6$):*** Benzene is an aromatic hydrocarbon consisting of six carbon and six hydrogen atoms. It is a colorless liquid with a characteristic taste and odor. Benzene is used as an intermediate in the production of many organic compounds in the petrochemical industry. It plays a significant role in the production of various products such as plastics, fibers, pharmaceuticals, paints, adhesives, and chemical solvents. Additionally, it is not used as a fuel but rather as a raw material in industrial processes.

***Ethane ($C_2H_6$):*** Ethane, a hydrocarbon consisting of two carbon and six hydrogen atoms. It is a component of natural gas and is a colorless, odorless gas. ethane is an important monomer in the chemical industry and is used in the production of many types of plastics, such as polyethylene. Additionally, it can be used as a fuel for heating and energy production.

***Butene ($C_4H_8$):*** Butene is a hydrocarbon consisting of four carbon and ten hydrogen atoms. It exists as a colorless gas or liquid and has many isomers. Butene is a monomer used in the production of many organic compounds in the petrochemical industry. It plays a significant role in the production of plastics, rubber, solvents, and other chemical products. Additionally, it can be used in some heating and energy production applications.

***Hydrogen ($H_2$):*** Hydrogen is the simplest and most abundant element. It is a colorless, odorless, and flammable gas. Being a lightweight element, it is not found freely in the atmosphere but typically forms compounds with other elements. Hydrogen is a versatile gas used in many industrial applications. It finds applications in the chemical industry, petrochemical industry, metallurgy, electronic production, and food processing industry. Additionally, it is gaining increasing popularity in environmentally friendly applications such as electricity generation in hydrogen fuel cells and as a fuel for vehicles.

## 2.2. Assumptions for Combustion Equations

In general, this script sets up a calculation in EES (Engineering Equation Solver) to determine the adiabatic combustion temperature of methane at different excess air levels. The Parametric Table functionality is used to iterate over different values of ($Theo_{air}$) and solve for the corresponding adiabatic combustion temperature for each value of ($Theo_{air}$).

The given equation represents the complete combustion reaction of a hydrocarbon, denoted by $C_xH_y$. On the left side of the equation, there is a mixture of the hydrocarbon molecule and theoretical air quantity ($Theo_{air}$), along with oxygen ($O_2$) and nitrogen ($N_2$) present in air. This mixture represents the provision of oxygen necessary for the complete combustion of the fuel [7].

$$C_xH_y + \left(\frac{y}{4} + x\right)\left(\frac{Theo_{air}}{100}\right)(O_2 + 3.76\ N_2) \text{ <--> } xCO_2 + \left(\frac{y}{2}\right)H_2O + 3.76\left(\frac{y}{4} + x\right)\left(\frac{Theo_{air}}{100}\right)N_2 + \left(\frac{y}{4} + x\right)\left(\frac{Theo_{air}}{100} - 1\right)O_2$$

On the right side of the equation, the products resulting from the reaction are depicted. These products include carbon dioxide ($CO_2$), water vapor ($H_2O$), nitrogen gas ($N_2$), and the excess oxygen remaining after the reaction. This indicates that under ideal conditions, complete combustion does not occur entirely, and the presence of excess oxygen after the reaction.

This equation represents the reaction process and products during the combustion of hydrocarbon fuels. However, in real combustion processes, consideration may need to be given to some by-products and combustion efficiency.

The equations used to calculate the mole numbers of substances involved in and produced by the combustion reaction are as follows:

Moles_$O_2$: This equation calculates the number of oxygen ($O_2$) molecules consumed during the combustion reaction. For each $C_xH_y$ molecule, (y/4 + x) oxygen molecules are consumed. The term $Theo_{air}$/100 represents the theoretical air/fuel ratio. The -1 term indicates that one oxygen molecule cannot efficiently participate in the combustion process (e.g., oxygen molecules can exit without fully reacting with the fuel).

Moles_$N_2$: This equation calculates the number of nitrogen gas ($N_2$) molecules produced during the combustion process. For each $C_xH_y$ molecule, 3.76*(y/4 + x) nitrogen molecules are produced.

Moles_$CO_2$: In this equation, the number of carbon dioxide ($CO_2$) molecules produced during the combustion process is equal to the value of x. Each $C_xH_y$ molecule produces $xCO_2$ molecules in the combustion reaction.

Moles_$H_2O$: In this equation, the number of water ($H_2O$) molecules produced during the combustion process is equal to y/2. Each $C_xH_y$ molecule produces y/2 water molecules in the combustion reaction.

These equations help determine the composition and balance of the combustion reaction. Accurately calculating the mole numbers of substances consumed and produced during the combustion process is important for evaluating fuel efficiency and emissions.

*For Methane ($CH_4$) Calculations:*

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2$$

Analysis: This equation represents the complete combustion reaction of methane. Upon combustion of methane, carbon dioxide ($CO_2$) and water ($H_2O$) are formed, while nitrogen gas ($N_2$) from the atmosphere also participates in the

reaction, contributing to the nitrogen content ($N_2$) in the product.

*For Propane ($C_3H_8$) Calculations:*

$C_3H_8+5(O_2+3.76N_2)\rightarrow 3CO_2+4H_2O+18.8N_2$

Analysis: This equation represents the complete combustion reaction of propane. Upon combustion of propane, carbon dioxide ($CO_2$) and water ($H_2O$) are formed, while nitrogen gas ($N_2$) from the atmosphere also participates in the reaction, contributing to the nitrogen content ($N_2$) in the product.

*For Benzene ($C_6H_6$) Calculations:*

$C_6H_6+7.5(O_2+3.76N_2)\rightarrow 6CO_2+3H_2O+28.2N_2$

Analysis: This equation represents the complete combustion reaction of benzene. Upon combustion of benzene, carbon dioxide ($CO_2$) and water ($H_2O$) are formed, while nitrogen gas ($N_2$) from the atmosphere also participates in the reaction, contributing to the nitrogen content ($N_2$) in the product.

*For Ethylene ($C_2H_4$) Calculations:*

$C_2H_4+3.5(O_2+3.76N_2)\rightarrow 2CO_2+3H_2O+13.16N_2$

Analysis: This equation represents the complete combustion reaction of ethylene. Upon combustion of ethylene, carbon dioxide ($CO_2$) and water ($H_2O$) are formed, while nitrogen gas ($N_2$) from the atmosphere also participates in the reaction, contributing to the nitrogen content ($N_2$) in the product.

*For Butene ($C_4H_{10}$) Calculations:*

$C_4H_{10}+6.5(O_2+3.76N_2)\rightarrow 4CO_2+5H_2O+24.44N_2$

Analysis: This equation represents the complete combustion reaction of butene. Upon combustion of butene, carbon dioxide ($CO_2$) and water ($H_2O$) are formed, while nitrogen gas ($N_2$) from the atmosphere also participates in the reaction, contributing to the nitrogen content ($N_2$) in the product.

For Hydrogen ($H_2$) Calculations:

$H_2+0.5(O_2+3.76N_2)\rightarrow H_2O+1.88N_2$

Analysis: This equation represents the complete combustion reaction of hydrogen. Upon combustion of hydrogen, water ($H_2O$) is formed, while nitrogen gas ($N_2$) from the atmosphere also participates in the reaction, contributing to the nitrogen content ($N_2$) in the product [8].

## 2.3. Environmental Impact Analysis

Analyze the amounts of greenhouse gases ($CO_2$, $H_2O$, $N_2O$, $NO_x$, etc.) and other harmful emissions (particulates, CO, $SO_x$, etc.) released into the atmosphere as a result of the combustion of each fuel. Compare the environmental impacts at different parameters (greenhouse gas emissions, air quality, climate change effects, etc.). Environmental impacts have become a significant topic of discussion regarding the use of industrial fuels. To evaluate these impacts, factors such as greenhouse gas emissions, air quality, and climate change must be considered. The combustion process of each fuel type may vary in terms of environmental impacts. This study aims to better understand the potential environmental impacts of industrial fuels by comparing environmental impacts at different parameters.

Based on the provided data, we can compare the amounts of gases released into the atmosphere as a result of the combustion of different fuel types using Table 1.

Table 1. The amount of gases released into the atmosphere as a result of the combustion of fuel types

| Yakıt | $CO_2$ (kg/gün) | $H_2O$ (kg/gün) | $N_2$ (kg/gün) |
|---|---|---|---|
| Methane ($CH_4$) | 1000 | 2000 | 7520 |
| Propane($C_3H_8$) | 3000 | 4000 | 18800 |
| Benzene($C_6H_6$) | 6000 | 3000 | 28200 |
| Ethane ($C_2H_6$) | 2000 | 3000 | 13160 |
| Butene ($C_4H_{10}$) | 4000 | 5000 | 24440 |
| Hydrogen ($H_2$) | 0 | 1000 | 1880 |

In this table 1, the amounts of $CO_2$, $H_2O$, and $N_2$ released into the atmosphere as a result of burning 1000 kg of each fuel type daily are shown. These data can be utilized to compare the environmental impacts of different fuels. For instance, carbon-based fuels like propane and benzene exhibit higher $CO_2$ emissions, whereas hydrogen, a fuel without hydrocarbons, does not produce $CO_2$ emissions. Smaller hydrocarbons like ethene have moderate levels of emissions.

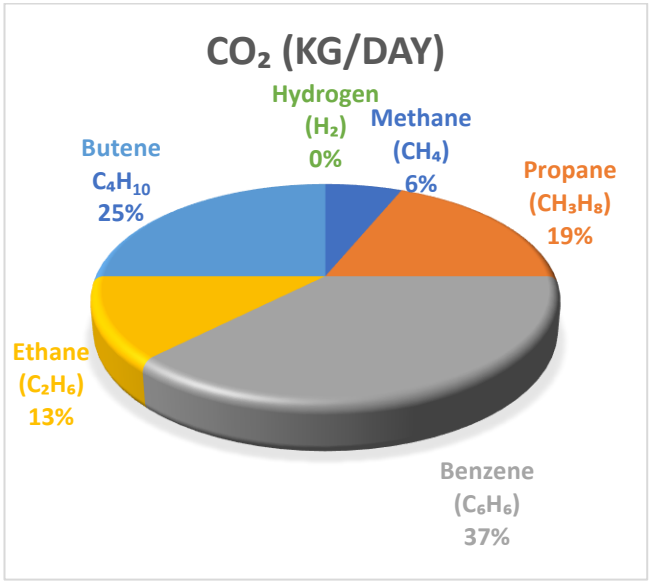


Figure 1. Percentage of daily $CO_2$ emission amounts of fuels

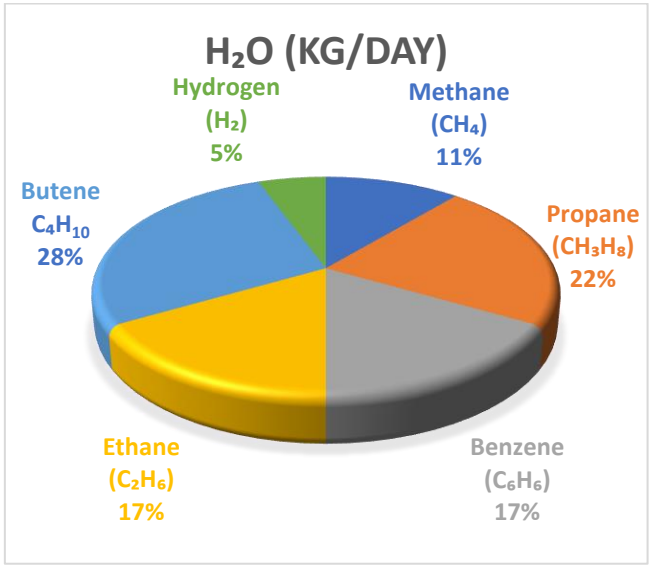


Figure 2. Percentage of daily $H_2O$ emission amounts of fuels

This table presents the daily $CO_2$ emission amounts of different fuels. $CO_2$ has a significant impact on the greenhouse effect and climate change. Therefore, it is important to either reduce these emissions or transition to alternative energy sources.

Natural gas types such as methane and propane are considered cleaner compared to other fossil fuels, but they still contribute to $CO_2$ emissions. However, petrochemical products like benzene and hydrocarbons like butene have higher $CO_2$ emissions and thus larger environmental impacts.

Alternatively, shifting towards clean energy sources (e.g., wind, solar, hydroelectric) and technologies that reduce carbon emissions (e.g., electric vehicles, energy efficiency measures) can be crucial steps in reducing atmospheric $CO_2$ levels. Such actions can mitigate the effects of climate change by reducing greenhouse gas emissions and enhancing environmental

In Figure 2, the daily production amounts of water ($H_2O$) from different fuels are provided. Except for hydrogen ($H_2$) fuel, the production of water by other fuels originates from the hydrogen and oxygen atoms released during the combustion process.

Hydrogen ($H_2$) fuel, on the other hand, produces water ($H_2O$) during the combustion reaction. Therefore, one reason hydrogen is considered a cleaner fuel compared to $CO_2$ is due to this factor.

Petrochemical products like benzene and hydrocarbons like butene produce water during the combustion process, along with the release of $CO_2$ and other pollutants. Thus, the role of water in the combustion process is a factor to consider when evaluating the environmental impacts of a fuel.

However, while hydrogen combustion produces water, the hydrogen production process (e.g., electrolysis) typically requires other energy sources, which can also have environmental impacts. Therefore, when assessing the overall environmental impacts of hydrogen, it is important to consider all stages from production to consumption.

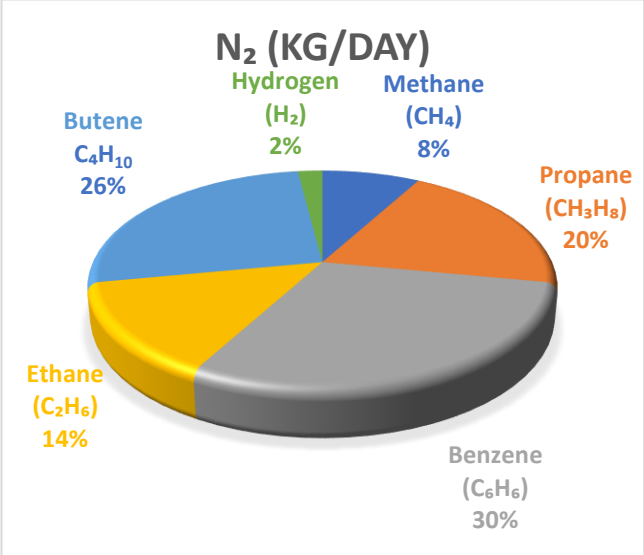


Figure 3. Percentage of daily $N_2$ emission amounts of fuels

In this table, the daily emission amounts of nitrogen ($N_2$) from different fuels are provided. Nitrogen ($N_2$) is a naturally occurring gas that constitutes a large part of the atmosphere. However, the data in this table indicate additional nitrogen emissions to the atmosphere during the combustion process of these fuels.

Nitrogen can react at high temperatures during the combustion process to form nitrogen oxides (NOx). NOx is a significant source of air pollution and can contribute to the formation of acid rain, tropospheric ozone, and deterioration of air quality. Therefore, controlling nitrogen emissions is environmentally important.

According to the data, the nitrogen emission from fuels varies significantly. In particular, fuels such as benzene and butene have relatively high nitrogen emissions. This may indicate that more NOx is formed during the combustion of these fuels, and therefore, their environmental impacts are greater.

Alternatively, clean fuels like hydrogen have lower nitrogen emissions. This suggests that hydrogen may be more environmentally advantageous compared to other fossil fuels. However, nitrogen emissions during the production process of hydrogen should also be considered. Overall, nitrogen emission is an important factor to consider when evaluating the environmental impacts of fuels, and appropriate measures should be taken to reduce such emissions. This may include transitioning to cleaner energy sources, using more efficient combustion technologies, and implementing emission control systems [9].

## 2.4. Thermodynamic Analysis

HR represents the total enthalpy of the reaction. This expression calculates the total enthalpy difference between the initial enthalpy of the fuel (at T_fuel temperature) and the enthalpy of the air and nitrogen required for the combustion of the fuel (at T_air temperature). First, the enthalpy of the fuel is calculated, and then it is multiplied by the enthalpy of the oxygen and nitrogen required for the combustion of the fuel. The enthalpies of the reactants (methane, oxygen, nitrogen) are considered at 25°C.

HP represents the adiabatic work of the reaction. Adiabatic work refers to the work performed by a system without any heat or matter flow to another system. The HP expression calculates the difference between the enthalpy of the final state of the reaction and the initial enthalpy of the reaction. The enthalpies of the products (carbon dioxide, water vapor, nitrogen, oxygen) are considered at the adiabatic combustion temperature.

The purpose of these expressions is to calculate the heat changes and energy transformations occurring during a chemical reaction. These calculations help us determine the energy balance of reactions based on thermodynamic principles [10].

HR = enthalpy(Fuel; T=T_fuel) + ( $\frac{y}{4}$ + x) * ($\frac{\text{Theo}_{\text{air}}}{100}$) * enthalpy($O_2$; T=T_air) + 3.76 * ($\frac{y}{4}$ + x) * ($\frac{\text{Theo}_{\text{air}}}{100}$) * enthalpy($N_2$; T=T_air)

HP = HR "Adiabatic"

HP = x * enthalpy($CO_2$; T=T) + ($\frac{y}{2}$) * enthalpy($H_2O$; T=T) + 3.76 * ($\frac{y}{4}$ + x) * ($\frac{\text{Theo}_{\text{air}}}{100}$) * enthalpy($N_2$; T=T) + ($\frac{y}{4}$ + x) * ($\frac{\text{Theo}_{\text{air}}}{100}$ - 1) * enthalpy($O_2$; T=T)

These equations are used to calculate the heat changes and energy transformations during a chemical reaction, specifically combustion. HR computes the total enthalpy change from reactants to products, accounting for fuel enthalpy and enthalpies of air components. HP then calculates the adiabatic work, representing the energy released or absorbed under adiabatic conditions (no heat exchange with surroundings), considering

the enthalpies of combustion products. These calculations adhere to thermodynamic principles to determine the energy balance of the reaction process.

## 3. RESULTS AND DISCUSSION

Table 2. Changes in Thermodynamic Parameters According to Theoretical Air Values in the Benzene Combustion Process

| $Theo_{air}$ | T [K] | HP [kJ/kmol] | Moles $N_2$ |
|---|---|---|---|
| 0 | 9247 | 82473 | 0 |
| 22,22 | 6025,8 | 81330 | 6,267 |
| 44,44 | 4295,2 | 80188 | 12,53 |
| 66,67 | 3322,4 | 79045 | 18,8 |
| 88,89 | 2736 | 77902 | 25,07 |
| 111,1 | 2346,6 | 76759 | 31,33 |
| 133,3 | 2068,5 | 75616 | 37,6 |
| 155,6 | 1859,3 | 74474 | 43,87 |
| 177,8 | 1695,7 | 73331 | 50,13 |
| 200 | 1564 | 72188 | 56,4 |

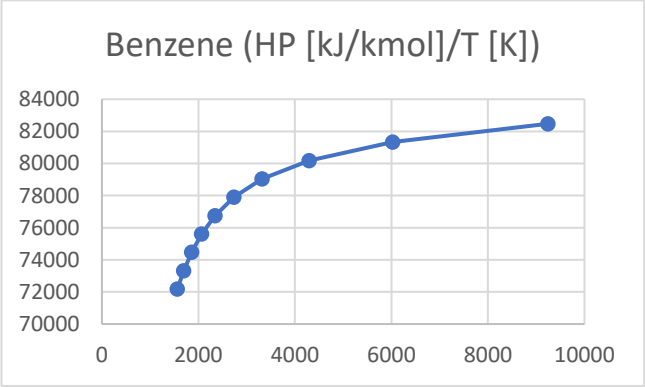


Figure 4. Benzene outlet temperature [K]/adiabatic work[kJ/kmol]

Theoretical air quantity represents the amount of air required for complete combustion. This value signifies the adequate oxygen amount to achieve complete combustion. The system temperature is indicated in Kelvin. In the data, it is observed that as the theoretical air quantity increases, the system temperature decreases. This tendency suggests an absorption of heat generated during the combustion process with increased air intake.

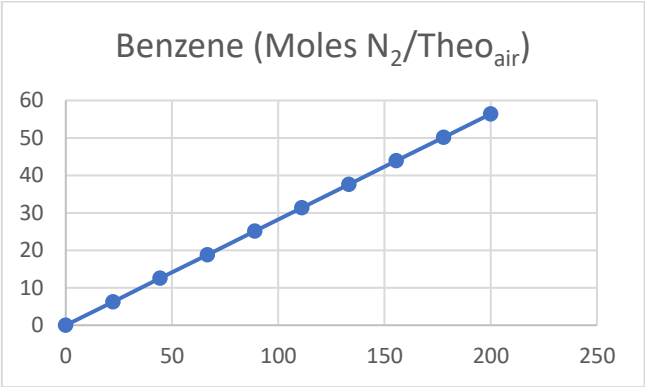


Figure 5. Benzene output Mole/Theoretical air ratio

The adiabatic work is expressed in kJ per unit mole. As the theoretical air quantity increases, the adiabatic work decreases. This indicates a decrease in the reaction's capacity to perform work with increased air intake. The molar quantity of nitrogen gas represents the amount of nitrogen gas entering the system. As the theoretical air quantity increases, the molar quantity of nitrogen gas also increases. This indicates that with increased air intake, more nitrogen gas enters the system.

These observations help us understand the thermodynamic effects during the combustion process of butene. The data illustrate changes in temperature, work capacity, and the gas components entering the system during the combustion process. Such information aids in understanding the combustion performance and environmental impacts of the fuel. This dataset illustrates variations in thermodynamic parameters such as temperature (T), adiabatic work (HP), and molar quantity of nitrogen gas (Moles_$N_2$) corresponding to different theoretical air ($Theo_{air}$) values during the combustion process of butene ($C_4H_{10}$).

Table 3 Changes in Thermodynamic Parameters According to Theoretical Air Values in the Butene Combustion Process

| $Theo_{air}$ | T [K] | HP [kJ/kmol] | Moles $N_2$ |
|---|---|---|---|
| 0 | 8490,8 | -126264 | 0 |
| 22,22 | 5451,3 | -127254 | 5,431 |
| 44,44 | 3938,5 | -128245 | 10,86 |
| 66,67 | 3101,4 | -129235 | 16,29 |
| 88,89 | 2584,1 | -130226 | 21,72 |
| 111,1 | 2233 | -131216 | 27,16 |
| 133,3 | 1978,4 | -132207 | 32,59 |
| 155,6 | 1784,8 | -133197 | 38,02 |
| 177,8 | 1632,1 | -134187 | 43,45 |
| 200 | 1508,6 | -135178 | 48,88 |

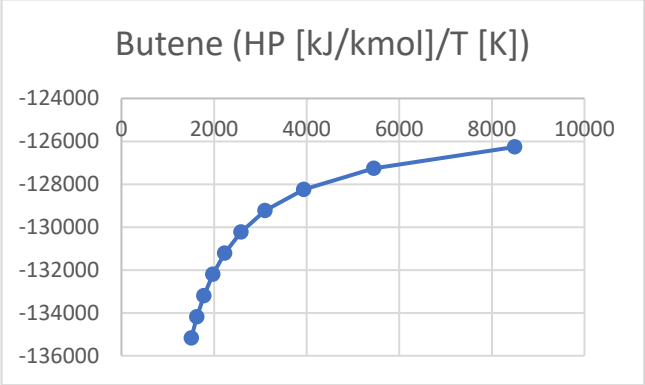


Figure 6. Butene outlet temperature [K]/adiabatic work[kJ/kmol]

The theoretical air quantity represents the amount of air required for complete combustion. This value represents the sufficient oxygen quantity necessary for complete combustion. The system temperature is indicated in Kelvin. In the data, it is observed that as the theoretical air quantity increases, the system temperature decreases. This indicates a tendency to absorb the heat generated during the combustion process with increased air intake.

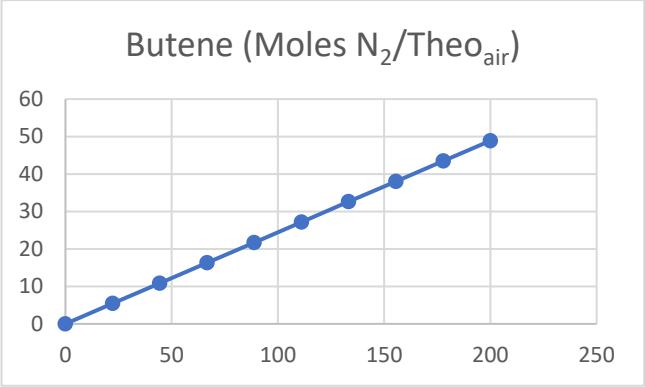


Figure 7. Butene output Mole/Theoretical air ratio

The adiabatic work is expressed in kJ per unit mole. As the theoretical air quantity increases, the adiabatic work decreases. This indicates a decrease in the reaction's capacity to perform work with increased air intake. The molar quantity of nitrogen gas represents the amount of nitrogen gas entering the system. As the theoretical air quantity increases, the molar quantity of nitrogen gas also increases. This indicates that more nitrogen gas enters the system with increased air intake. These observations help us understand the thermodynamic effects during the combustion process of butene. The data illustrate changes in temperature, work capacity, and the composition of gases entering the system during the combustion process. This information assists in understanding the fuel's combustion performance and its environmental effects. This dataset demonstrates the variations in thermodynamic parameters such as temperature (T), adiabatic work (HP), and molar quantity of nitrogen gas (Moles_$N_2$) corresponding to different theoretical air ($Theo_{air}$) values during the combustion process of ethane ($C_2H_6$).

Table 4. Changes in Thermodynamic Parameters According to Theoretical Air Values in the Ethane Combustion Process

| $Theo_{air}$ | T [K] | HP [kJ/kmol] | Moles $N_2$ |
|---|---|---|---|
| 0 | 8324,9 | -84107 | 0 |
| 22,22 | 5344,9 | -84640 | 2,924 |
| 44,44 | 3881,2 | -85173 | 5,849 |
| 66,67 | 3068,6 | -85707 | 8,773 |
| 88,89 | 2563 | -86240 | 11,7 |
| 111,1 | 2218,2 | -86773 | 14,62 |
| 133,3 | 1967,4 | -87307 | 17,55 |
| 155,6 | 1776,1 | -87840 | 20,47 |
| 177,8 | 1625,1 | -88373 | 23,4 |
| 200 | 1502,7 | -88907 | 26,32 |

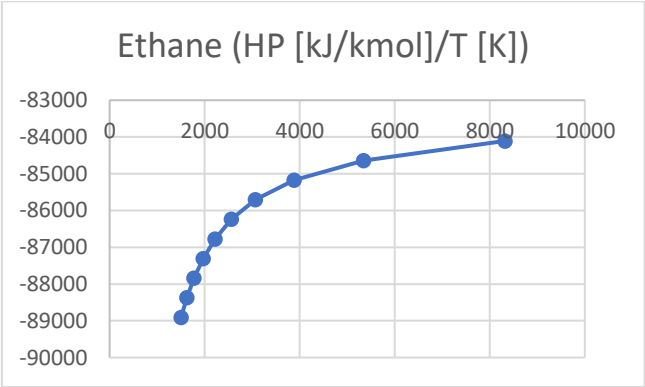


Figure 8. Ethane outlet temperature [K]/adiabatic work[kJ/kmol]

The theoretical air quantity represents the amount of air required for complete combustion. This value represents the adequate oxygen quantity necessary for complete combustion. The system temperature is indicated in Kelvin. In the data, it is observed that as the theoretical air quantity increases, the system temperature decreases. This tendency suggests that with increased air intake, there is a tendency for the combustion process to absorb more heat.

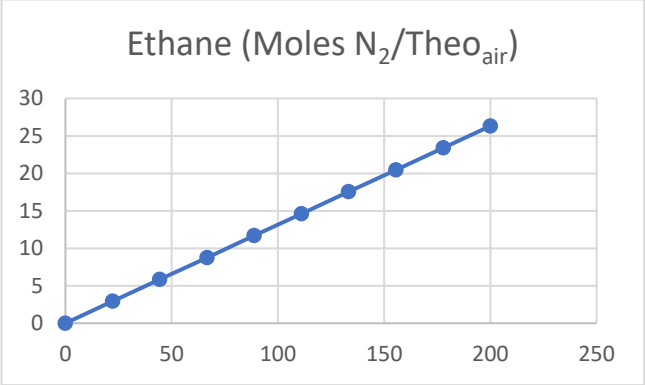


Figure 9. Ethane output Mole/Theoretical air ratio

The adiabatic work is expressed in kJ per mole. As the theoretical air quantity increases, the adiabatic work decreases. This indicates a decrease in the reaction's capacity to perform work with increased air intake. The molar quantity of nitrogen gas represents the amount of nitrogen gas entering the system. As the theoretical air quantity increases, the molar quantity of nitrogen gas also increases. This indicates that more nitrogen gas enters the system with increased air intake. These observations help us understand the thermodynamic effects of ethane combustion. The data illustrates the changes in temperature, work capacity, and the composition of gases entering the system during the combustion process. This information assists in understanding the combustion performance and environmental impacts of the fuel. This dataset demonstrates the variations in thermodynamic parameters such as temperature (T), adiabatic work (HP), and the molar quantity of nitrogen gas (Moles_$N_2$) corresponding to different theoretical air quantities during the combustion process of hydrogen ($H_2$).

Table 5. Changes in Thermodynamic Parameters According to Theoretical Air Values in the Hydrogen Combustion Process

| $Theo_{air}$ | T [K] | HP [kJ/kmol] | Moles N2 |
|---|---|---|---|
| 0 | 7075,8 | -143 | 0 |
| 22,22 | 4914 | -219 | 0,4178 |
| 44,44 | 3816,9 | -295 | 0,8356 |
| 66,67 | 3144,2 | -372 | 1,253 |
| 88,89 | 2690,7 | -448 | 1,671 |
| 111,1 | 2364,4 | -524 | 2,089 |
| 133,3 | 2118 | -600 | 2,507 |
| 155,6 | 1925,1 | -676 | 2,924 |
| 177,8 | 1769,9 | -753 | 3,342 |
| 200 | 1642,2 | -829 | 3,76 |

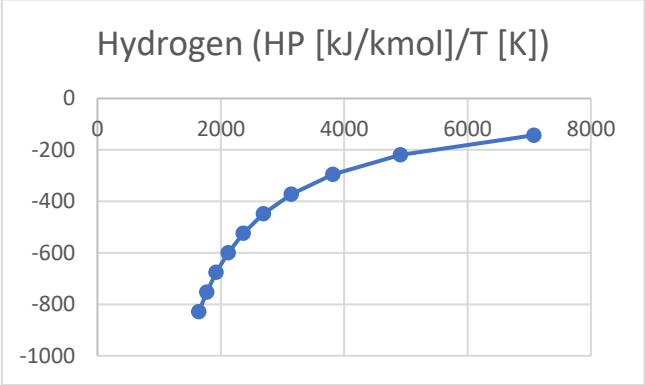


Figure 10. Hydrogen outlet temperature [K]/adiabatic work[kJ/kmol]

The theoretical air quantity represents the amount of oxygen required for complete combustion. This value signifies the presence of sufficient oxygen to achieve complete combustion. The system temperature is indicated in Kelvin. According to the data, as the theoretical air quantity increases, the system temperature also increases. This reflects the increase in heat generated during the combustion process with greater oxygen input.

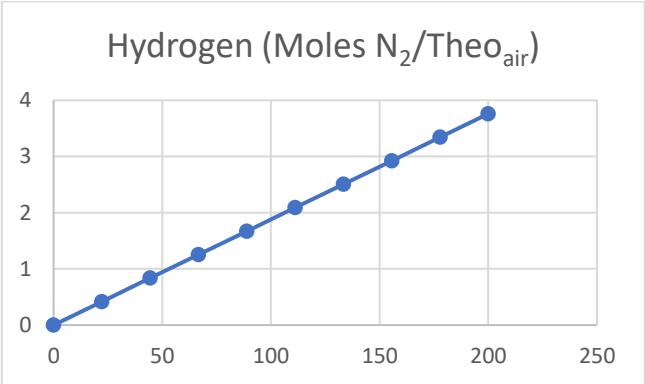


Figure 11. Hydrogen output Mole/Theoretical air ratio

Adiabatic work is expressed in kJ per mole. As the theoretical air quantity increases, adiabatic work also increases. This indicates that the reaction's capacity to perform work increases with more oxygen input. The molar quantity of nitrogen gas represents the amount of nitrogen gas entering the system. As the theoretical air quantity increases, the molar quantity of nitrogen gas also increases. This indicates that more nitrogen gas enters the system with increased air input. These observations help us understand the thermodynamic effects during hydrogen combustion. The data illustrate changes in temperature, work capacity, and the composition of gases entering the system during the combustion process. Such information aids in understanding the combustion performance and environmental impacts of the fuel. This dataset depicts the variations in thermodynamic parameters such as temperature (T), adiabatic

work (HP), and molar quantity of nitrogen gas (Moles_N2) corresponding to different theoretical air quantities during methane ($CH_4$) combustion.

Table 6. Changes in Thermodynamic Parameters According to Theoretical Air Values in the Methane Combustion Process

| $Theo_{air}$ | T [K] | HP [kJ/kmol] | Moles N2 |
|---|---|---|---|
| 0 | 7990,3 | -74773 | 0 |
| 22,22 | 5120,3 | -75077 | 1,671 |
| 44,44 | 3747,2 | -75382 | 3,342 |
| 66,67 | 2981,9 | -75687 | 5,013 |
| 88,89 | 2500,8 | -75992 | 6,684 |
| 111,1 | 2170,2 | -76296 | 8,356 |
| 133,3 | 1928,3 | -76601 | 10,03 |
| 155,6 | 1743,2 | -76906 | 11,7 |
| 177,8 | 1596,7 | -77211 | 13,37 |
| 200 | 1477,6 | -77515 | 15,04 |

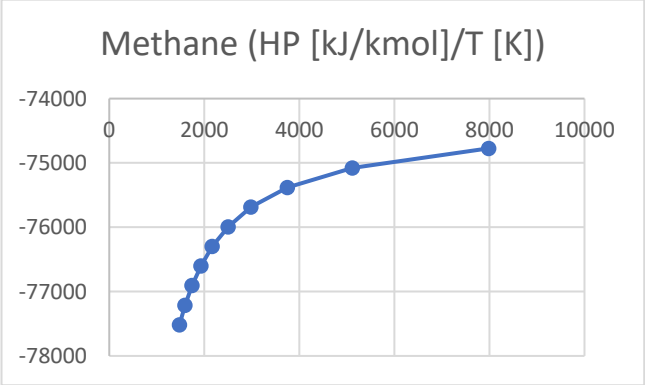


Figure 12. Methane outlet temperature [K]/adiabatic work[kJ/kmol]

The theoretical air quantity represents the amount of oxygen required for complete combustion. This value signifies the presence of sufficient oxygen to achieve complete combustion. System temperature is indicated in Kelvin. According to the data, as the theoretical air quantity increases, the system temperature also rises. This reflects the increase in heat generated during the combustion process with more oxygen input.

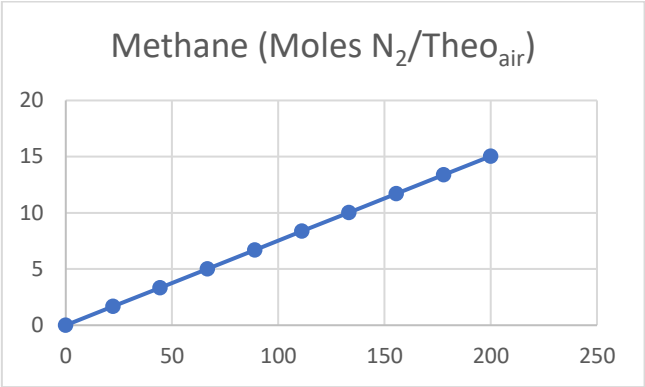


Figure 13. Methane output Mole/Theoretical air ratio

Adiabatic work is expressed in kJ per unit mole. As the theoretical air quantity increases, adiabatic work also increases. This indicates that with more oxygen input, the reaction's capacity for work increases. The molar quantity of nitrogen gas represents the amount of nitrogen gas entering the system. As the theoretical air quantity increases, the molar quantity of nitrogen gas also increases. This demonstrates that with more air intake, more nitrogen gas enters the system. These observations help us understand the thermodynamic effects of propane combustion. The data illustrate changes in temperature, work capacity, and the influx of gas components during the combustion process. This information aids in understanding the fuel's combustion performance and its environmental impacts. The dataset depicts the variations in temperature (T), adiabatic work (HP), and the molar quantity of nitrogen gas (Moles_N2) corresponding to different theoretical air ($Theo_{air}$) values in the combustion process of propane ($C_3H_8$).

Table 7. Changes in Thermodynamic Parameters According to Theoretical Air Values in the Propane Combustion Process

| $Theo_{air}$ | T [K] | HP [kJ/kmol] | Moles N2 |
|---|---|---|---|
| 0 | 8433,3 | -105033 | 0 |
| 22,22 | 5414 | -105795 | 4,178 |
| 44,44 | 3918,5 | -106556 | 8,356 |
| 66,67 | 3090 | -107318 | 12,53 |
| 88,89 | 2576,8 | -108080 | 16,71 |
| 111,1 | 2227,9 | -108842 | 20,89 |
| 133,3 | 1974,6 | -109604 | 25,07 |
| 155,6 | 1781,8 | -110366 | 29,24 |
| 177,8 | 1629,8 | -111128 | 33,42 |
| 200 | 1506,6 | -111889 | 37,6 |

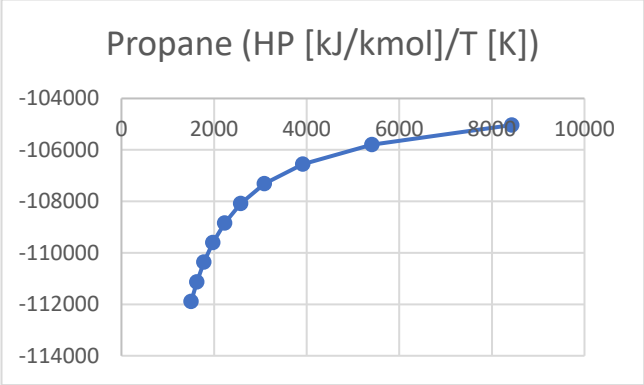


Figure 14. Propane outlet temperature [K]/adiabatic work[kJ/kmol]

The theoretical air quantity represents the amount of oxygen required for complete combustion. This value signifies the presence of sufficient oxygen to achieve complete combustion. The system temperature is indicated in Kelvin. According to the data, as the theoretical air quantity increases, the system temperature also increases. This reflects the increase in heat generated during the combustion process with greater oxygen input.

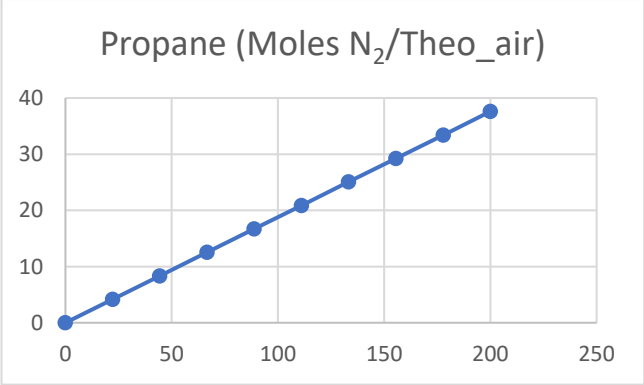


Figure 15. Propane output Mole/Theoretical air ratio

The adiabatic work is expressed in kJ per mole. As the theoretical air quantity increases, the adiabatic work also increases. This indicates that with more oxygen input, the reaction's capacity to perform work increases. The molar quantity of nitrogen gas represents the amount of nitrogen gas entering the system. As the theoretical air quantity increases, the molar quantity of nitrogen gas also increases. This indicates that more nitrogen gas enters the system with greater air intake. Understanding the thermodynamic effects of propane combustion helps us comprehend the combustion process's temperature changes, work capacity, and the composition of gases entering the system. This information assists in understanding the fuel's combustion performance and environmental impacts.

The analysis of the given thermodynamic parameters allows for the examination of the combustion processes of different fuels (benzene, butane, ethane, hydrogen, methane, and propane). Based on the results of these analyses, various conclusions can be drawn about the combustion efficiency and performance of each fuel.

Firstly, it is generally observed that as the values of $Theo_{air}$ increase, the system temperature and adiabatic work also increase. This indicates that with more oxygen input, the combustion process is more efficient and generates more energy.

However, this increase is not always linear, and in some cases, it is observed that the rate of increase in adiabatic work slows down or decreases. This could be due to changes in the ratios of the components involved in the combustion process.

Increases in the molar quantity of nitrogen gas are typically observed in conjunction with increases in $Theo_{air}$ values. This indicates that with greater air intake, more nitrogen gas enters the system.

In conclusion, the analysis of the thermodynamic effects of each fuel's combustion process helps us understand important parameters such as combustion efficiency, heat release, and energy production. This information provides valuable guidance in fuel selection, optimization of combustion conditions, and reduction of environmental impacts.

When comparing the given thermodynamic analysis with the quantities of gases emitted into the atmosphere, it is evident that different types of fuels exhibit variations in both thermodynamic effects and environmental impacts.

In the thermodynamic analysis, it is observed that as the $Theo_{air}$ values increase during the combustion process, the system temperature generally increases, along with an increase in adiabatic work. However, when considering the quantities of gases emitted into the atmosphere, we see that the $CO_2$, $H_2O$, and $N_2$ emission quantities vary for each type of fuel.

It is observed that the emission quantities of $CO_2$ and $H_2O$ into the atmosphere are the lowest as a result of methane combustion, while the emission quantity of $N_2$ is relatively higher. On the other hand, benzene combustion exhibits the highest emission values for $CO_2$ and $N_2$, with moderate levels of $H_2O$ emission.

Among other fuel types, various differences are observed. For instance, propane combustion

results in higher emission quantities of $CO_2$, $H_2O$, and $N_2$ compared to others, whereas the absence of $CO_2$ emission from hydrogen combustion is notable.

In conclusion, examining both thermodynamic analysis and the quantities of gases emitted into the atmosphere helps us understand the environmental impacts of each fuel type's combustion process. This information serves as an important guide for fuel selection and energy production processes to minimize environmental impacts.

## 4. CONCLUSION

Based on the results of the study, it is crucial to identify the factors influencing the combustion processes of fuels used in industrial facilities and evaluate their effects on emissions. Subsequently, updating or tightening emission standards can lead to a reduction in pollutants released into the atmosphere.

The findings of the study highlight the variations in the environmental impacts of different types of fuels during combustion processes. Therefore, policymakers can provide incentives for the promotion of less polluting and more efficient fuels, as well as increasing the utilization of renewable energy sources.

The research indicates that higher $Theo_{air}$ values are generally associated with lower adiabatic work. This suggests the necessity of developing new technologies and processes to enhance energy efficiency. Policymakers should support policies that promote energy efficiency and provide incentives for the development and implementation of innovative technologies.

Comparative analyses of different fuels can be conducted in future research to delve deeper into the thermodynamic effects of combustion processes. Comprehensive comparative analyses can particularly focus on the combustion efficiency, emission profiles, and environmental impacts of different fuel types.

Advanced combustion technologies have the potential to increase the efficiency of combustion processes and reduce emissions. Future research can assess the potential and environmental impacts of these technologies in industrial applications.

Developing more detailed and dynamic models of fuel combustion processes can provide more accurate predictions for fuel selection and optimization of combustion conditions in industrial applications.

These recommendations and future research areas can serve as a forward-looking guide for developing strategies to promote more sustainable fuel use and reduce environmental impacts in industrial applications.

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