RESEARCH PAPER

Evaluating the combustion process of methane fired cross draft ceramic kiln for efficiency and sustainability

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Abstract. Sustainable ceramic production is not only dependent on the adoption of renewable fuel, but also on combustion proficiency, efficient fuel utilization, and thermal energy released. This study reports on the thermal evaluation of a cross-draft ceramic kiln, with a view to determine the efficiency of the combustion process. The methodology involved firing the kiln to determine the equivalent ratio, stoichiometric air-methane ratio, enthalpy of formation of reactants and products, and the thermal energy liberated from the firing process. The results indicated that: 1000°C is attainable in 7 hours and 30 min at a firing rate of 136.97 sec/°C, fuel consumption rate of 1L/61.6 sec and average temperature of 613.4°C. The results also showed that, enthalpies of formation of products and reactants of -74,897 and -557,376.843 were generated at air-methane equivalent ratio of 1 : 5 and stoichiometric ratio of 9.818. This translated to 57.18% of air available for the combustion process and a 42.82% deficiency. The study concluded that though the combustion process of the methane fired kiln was weak, resulting in thermal energy loss of 39.9%, there was an energy utilization of up to 60.1%.

Keywords: Ceramic kiln; combustion efficiency; methane; sustainability; thermal energy

1. Introduction

The environmental and health impacts of greenhouse gas emissions and other gaseous pollutants, increased demand for energy and rising energy prices as well as the depletion of traditional sources of energy, have prompted the adoption of non-fossil alternative sources of energy for industrial and domestic purposes (Pourkiaei et al., 2021; Elrahmani et al., 2020; We et al., 2012; International Energy Agency (IEA, 2021; WHO, 2021; Choi et al., 2017). The shift towards the use of renewable energy for urban street lighting, for example, has resulted in reduction of 21.2 million tons of greenhouse gas emissions (Chang et al., 2021). Biomass, wind, and sea wave have also been used to generate hydrogen fuel to mitigate the impact of greenhouse gas from public transport systems (Franzitta et al., 2017). Similarly, renewable energy derived from hydrogenated biogas/carbon dioxide have also been deployed as fuel for domestic and transportation purposes (Connolly et al., 2014). Renewable energy generation through gasification, steam electrolysis, and carbon capture for domestic and industrial purposes is also gaining momentum (Connolly et al., 2014). However, given the increasing demand for

environmental protection and sustainability, more renewable energy sources will be explored in the future to meet the increasing need of a clean and eco-friendly fuel.

Ceramic kiln firing at both small and medium scale which previously depended on fossil-based fuels, especially in low income countries such as Nigeria have now shifted focus towards the use of renewable and sustainable fuels (Abubakar & Sadiq, 2018). The shift towards eco-friendly fuels is geared towards making the firing process more efficient and sustainable. Other factors associated with the shift include the quest for reduce cost of production, reducing carbon foot print and improving the green credentials of the firing process, through the elimination of gaseous pollutants (Abubakar & Sadiq, 2018; Abubakar et al., 2022). However, it is evident that the adoption of renewable energy such as biogas as alternative ceramic firing fuel has not eliminated the emission of carbon dioxide – a major constituent of Greenhouse gases (Fiehl et al., 2017). For example, up 75% CO_2 has been found as a by-product in the exhaust flue gas stream of incomplete combustion of renewable fuels (Ghasemzadeh et al., 2018). Although the growth in the use of renewables have reduced the emission of sulphur dioxide (SO_2) and nitrogen dioxide (NO_2), it has, however, increased the emission of carbon monoxide (CO) and particulate matter (PM) from residential wood burning (Couvidat, et al., 2021). For example, global CO emission stood at 888.17 teragram per year, with 68% of these emissions coming from anthropogenic activities which include industrial and domestic operations (Zhang et al., 2017). Johnson et al. (2004) reported that PM emissions from biomass fired burner for domestic source of heat energy is 180 times higher than those emitted by modern pellet burner; while manually operated boilers emits up to 70% PM (Schmidl et al., 2011).

Similarly, the incomplete combustion of renewable fuel which occur as a result of poor mixing of air and fuel, insufficient fuel residence time, insufficient temperature, and low total excess air has also been linked to the emissions of CO (Caillat & Vakkilainen, 2013). It is pertinent to state that CO is a very toxic gas with a global warming potential of 2 and atmospheric life span of up to 5 years (Jaffee, 2012). Meanwhile, CO_2 has a global warming potential of 1 and atmospheric life span of between 300 to 1000 (Buis, 2019). The emission of these gaseous pollutants, alongside traces of nitrogen, particulate matter, and argon produced from the incomplete combustion of renewable fuels have deleterious consequences on the environment, human health, and the climatic system (Fiehl et al., 2017).

To prevent the damaging effect of these gases, emission recovery, and purification process such as carbon dioxide capture and recycling equipment should be put in place (Koohestanian & Shahraki, 2021; Saponelli, et al, 2019; Payne et al., 2007). However, given the current financial limitations and constraints in developing economies, as well as the lack of requisite skills and technology required for the deployment of gaseous emission prevention technology, the feasibility of adopting emission prevention techniques such as carbon capture, injection of carbon, and carbon bed control in low income countries is therefore remote (Cudahy & Helsel, 2000).

Efficient and sustainable ceramic firing in low income countries will therefore require an integrated approach of deploying renewable energy with pollutant emission prevention strategy that is not only tailored toward the operating condition but consistent with the existing economic realities. Previous studies geared towards efficient and sustainable ceramic firing include the use of raw biogas derived from anaerobic digestion municipal waste from closed landfill to fire ceramic kiln to 700ºC and 900ºC respectively (Harnetty & Baker, 2008; Ayatz et al., 2007). There has also been documented usage of biogas from the digestion of cow dung to fire ceramic kiln to 900ºC (Sadiq, 2004). Raw biogas has also been deployed as a co-firing fuel in ceramic processing industries (Fiehl et al., 2017). However, the impurities contained in raw biogas have limited its efficient use in ceramic kiln firing (Shah & Nagarsheth, 2015). This necessitates the need for the upgrade of biogas (Abubakar et al., 2022). The adoption of upgraded biogas as a fuel for ceramic kiln firing is not without flaws (Fiehl et al., 2017). This study is designed to overcome the previous gaps by providing a viable pollution prevention and mitigation strategy for efficient and

sustainable ceramic kin firing. The present study combined approach of using methane as firing fuel and the application of thermodynamic equations with the view to make ceramic combustion process efficient and sustainable.

The present study has four objectives. The first one is to appraise the combustion processes of a 4.5 CF cross-draft methane fired kiln based on equivalent ratio (air-fuel ratio). The second one is to determine the stoichiometry of air- methane mixture. The third one is to compute the enthalpy of formation of reactant and products. The last one is to estimate the heat liberated from the ceramic kiln firing process, with a view to determine the appropriate pollution emission prevention strategy.

2.   Trends in ceramic kiln combustion process

Conventional ceramic fuels such as wood, coal, and waste oil are broken down and oxidized in the fire box to generate the thermal energy required for the change of state and permanent chemical transformation of ceramic from green ware to earthenware, porcelain, or stoneware at high temperatures (Olsen, 2001). The moisture content of green ceramicware is usually removed at room temperature before it is placed in the kiln, where organic content of the ware is carbonized between the firing temperature of 300°C to 500°C (UNIDO, 2022). The clay mineral content of the ware is hydrated and decomposed between 500°C to 700°C, and oxidation of the carbonized material content of the ware occurs at 800°C (UNIDO, 2022). Active sintering of the ware takes place at 900°C, resulting in the shrinkage of the ware. However, depending on the quality and strength requirement, the firing temperature could be raised to 1150°C for earthenware, while temperature could go as high as 1150°C to 1250°C for advance gasification process to produce stoneware. Similarly, above 1250°C, a translucent ware with increased glass phase known as porcelain is produced (UNIDO,2022).

However, traditional kiln designs and burner systems, as well as the use of traditional firing fuels, have been liked to inefficiency, energy losses, increased exploitation of energy resources, high energy consumption, as well as the emissions of gaseous pollutants (Oliveira et al., 2020; Cantore et al., 2018; Kumari et al., 2015). For example, report have shown that, 90% of CO_2 emissions and 55% of energy usage are associated with ceramic production processes (Le, 2018; Monfort, et al., 2010). While up to 77% of the thermal energy in ceramic kilns are lost through radiation (50%) and convection (27%) which occur at the side walls, base, and ceiling of the kiln (Gomez et al., 2019).

 Globally up to 1.9 billion cubic metric tons of wood resources are exploited for the generation of energy for domestic and industrial purposes (Fernendez, 2023). While in sub-Saharan Africa, about 600 million m^3 of wood resources are exploited for domestic energy use, including ceramic kiln firing (UNEP, 2019). This translates to about 92% of domestic and industrial energy source (UNEP, 2019). However, the exploitation of this resource has been linked to the continued degradation of the African environment and ecosystem biomass (Sulaiman & Abdul-Rahim, 2022). This trend is expected to continue as long as population and demand for energy continue to increase (UNEP, 2019).

The health and environmental concerns associated with these emissions, coupled with the current global call for sustainable production and consumption have caused a shift in approach towards the development of efficient kiln, adoption of efficient fuels and firing systems, as well as the development of techniques and strategies for preventing the emissions of gaseous pollutants into the environment and the climate system (Fiehl et al., 2017; Sinton, 2015; Plesu et al., 2015; O'Reilly & Jeswiet, 2014; Mezquita, et al., 2014). Similarly, energy preservation and minimizing the release of gaseous pollutants from the combustion process are now a key demand in ceramic production process (Oliveira et al., 2020; Delpech et al., 2018; Chuenwong et al., 2017). Furthermore, current research trends in ceramic firing are centered on maximizing combustion efficiency, by understanding the thermodynamics of the ceramic kiln and the firing systems, in

terms of quantum and rate of thermal energy generated from the combustion chamber, the how and where, the thermal energy generated is effectively utilized as well as the volume of energy lost. In view of the foregoing, Le (2018) reported on the optimization of energy usage in ceramic kiln using pinch technique. Meanwhile, Monfort et al. (2010) reported on energy consumption analysis and carbon dioxide emissions in ceramic kiln. Similarly, Oliveira (2020) reported on the use of technologies and strategies for waste heat recovery in a ceramic kiln. Likewise, Gomez et al. (2019) reported on heat loses through the base, side walls and ceiling of the kiln, as well as the role of convection and radiation on heat loses. These studies were conducted to enhance effective and sustainable use of energy as well as efficient firing process. The focal point of this study, therefore, is to assess the thermal efficiency and sustainability of firing a ceramic kiln to 1000°C using a combination of upgraded methane gas as firing fuel and the thermodynamic system of heat released approach. This is based on the premise that previous studies on energy efficiency in ceramic kiln were limited to tunnel kilns (Hussain et al., 2021) and those with superlative firing atmosphere (Kumari et al., 2015). As a result, data on kiln drafting system, the fuel air-ratio, and stoichiometry is limited.

3. Methodology

The Glaze composition of 15% Feldspar, 35% Cullet, 35% Bagasse Ash, and 15% Clay was compounded, applied on a bisque ware. This was loaded in cross-draft kiln with a North-south fire box orientation and fired to 1000°C kiln temperature using methane gas in 7 hours 30 min and 37°C ambient temperature. Heat release approaches based on thermodynamic energy equations were used to evaluate the combustion process through the determination of equivalent ratio (air-fuel ratio), stoichiometric air-methane mixture, the heat liberated from the kiln firing process, and percentage energy utilized for the ceramic crystallization process. The adoption of heat release approach was based on its suitability in determining the quantum of energy released from the combustion process as well as the efficiency of the thermodynamic process (Winterbone, 1997).

3.1 Firing

One thousand degree centigrade (1000°C) of kiln temperature was attained in 7 hours, 30 mins using methane gas and improvised venturi burner (Figure 1.a) made from steel. The burner was placed at a distance of seven inches from the bag wall of a combustion chamber measuring 4 x 4 inches (Figure 1.b).

3.2 Equivalence ratio

The equivalent ratio of air to methane gas used in the firing process was determined based on UNIDO's (2021) Handy Manual on Energy Conservation in Ceramic Industry as denoted by Equation (1), where Ø is equivalent ratio, Ava is actual volume of air, and Thva is theoretical volume of air.

$$\emptyset = \frac{A_a}{Thv_a} \tag{1}$$

The actual volume of air used in Equation (1) was calculated based on Avogadro's hypothesis that one mole of gas occupies 22.4 L (0.0224 m³) at constant pressure, while the theoretical volume of air was calculated based on ideal air-fuel stoichiometry ratio of 1 : 17. Following the above equation, the volume of air at ambient kiln temperature of 37°C was determined based on Charles law (Ewelukwa, 2003) as denoted by Equation (2):

$$\frac{V_1}{T_1} = \frac{V_2}{T_2} \tag{2}$$

where, V_1 = volume of gas at 0°C (273 °K), T_1 = temperature at 0°C (273°K), V_2 = volume at 37°C (310°K), T_2 = temperature at 310°K.

(a)

(b)
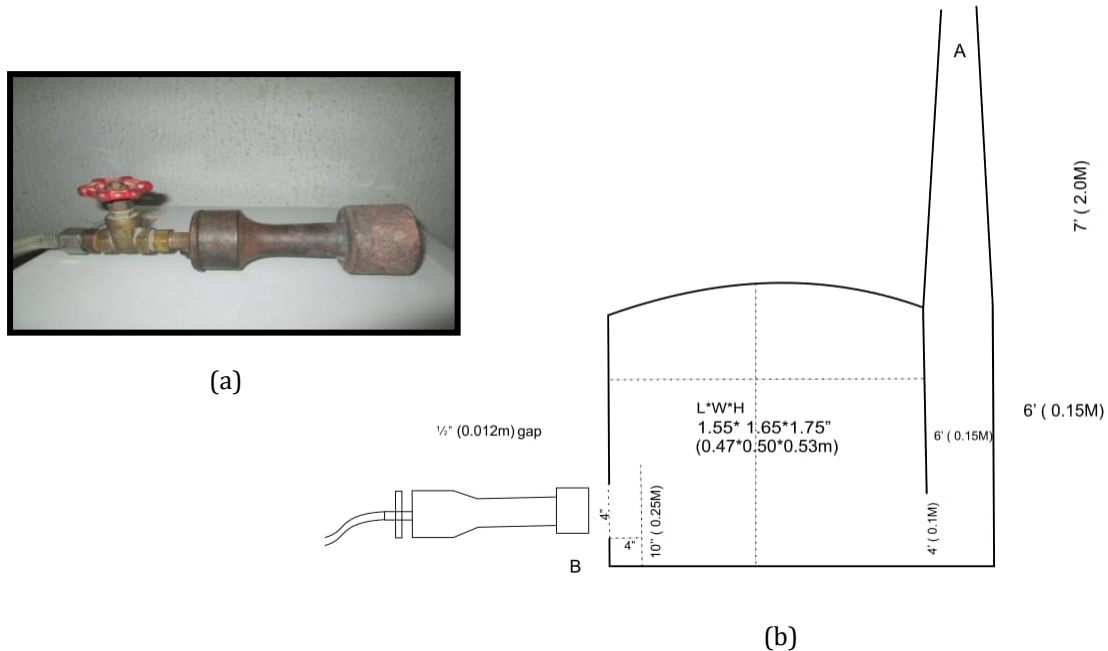
Figure 1. (a) Improvised venturi burner, (b) Schematic diagram of a 4.5 CF methane fire kiln

3.3   Fuel-air stoichiometry

The stoichiometric methane – air ratio was calculated based on theory of thermodynamics of combustion (Winterbone, 1997) as denoted by equation using Equation (3). The mass of fuel (methane) was determined by multiplying the density of methane (0.6682 kg/m³) and the volume (0.45 m³) used in the firing at ambient temperature; while the mass of air was determined by multiplying the density of air (1.225 kg/m³) and its volume at ambient temperature.

$$\varepsilon_{stoic} = \frac{\text{Mass of air}}{\text{Mass of fuel}} \tag{3}$$

3.4   Enthalpy of formation of reactants

The enthalpy of formation of reactants was determined based on the theory of thermodynamics of combustion (Winterbone, 1997) as denoted by equation (4):

$$(\Delta H_R) = \left(\Delta H_f\right)_{CH_4(g)} + 2\left(\Delta H_f\right)_{O_2(g)} \tag{4}$$

where (ΔH_R) is enthalpy of formation of reactant, $\left(\Delta H_f\right)_{CH_4}$ is enthalpy of formation of CH_4, and $\left(\Delta H_f\right)_{O_2}$ is enthalpy of formation of O_2.

3.5.   Enthalpy of formation of products

The standard enthalpy of formation of elements and compounds at 25°C, the combustion equation of methane (Equation 4), and the enthalpy reaction (Equation 5) were used to determine the enthalpy of formation of the products of the reaction between CH_4 and O_2.

$$CH_4 + 2O_2 = CO_2 + 2H_2O \tag{4}$$

$$\left(\Delta H_f\right)_p = \left(\Delta H_f\right)_{CO_{2(g)}} + \left(\Delta H_f\right)_{H_2O_{(g)}} \tag{5}$$

$\left(\Delta H_f\right)_p$ is enthalpy of formation of product, $\left(\Delta H_f\right)_{CO_2}$ is enthalpy of formation of CO_2, and $\left(\Delta H_f\right)_{H_2O}$ is enthalpy of formation of H_2O.

3.6 Energy liberated from the combustion process

The energy liberated from the combustion process is the energy released from the reaction between the reactants. The first stage in determining the energy liberated from the ceramic firing process involved putting in the values of the equivalent ratio Ø, calculated from Equation (1) into the methane combustion reaction based on 79% nitrogen and 21% oxygen composition of air into Equation (6). The values derived from Equation (6) were then inputted into Equation (7) and (8) to determine the enthalpies of formation of product and reactants.

Finally, the energy liberated from the methane combustion process was computed by determining the difference between enthalpy of formation of reactants (Equation 7), and the enthalpy of formation of products (Equation 8) using Equation (9).

$$CH_4 + \frac{2(O_2 + 3.7N_2)}{\emptyset} = \frac{2H_2O(4-2)CO}{\emptyset} + \frac{(3-4)C}{\emptyset} + \frac{7.52N_2}{\emptyset} \tag{6}$$

$$(\Delta H_R) = \left(\Delta H_f\right)_{CH_4} + 2\left(\Delta H_f\right)_{O_2} \tag{7}$$

$$\left(\Delta H_f\right)_p = 0.333\left(\Delta H_f\right)_{CO_2} + 2\left(\Delta H_f\right)_{H_2O} + 0.667\left(\Delta H_f\right)_{CO} \tag{8}$$

$$(Q_p)_{25} = (\Delta H_f)_p - (\Delta H_f)_R \tag{9}$$

4. Results and discussions

4.1. Firing

The firing process started with a zero-thermocouple reading at firing time of two seconds (Figure 2), and then progressed steadily at a firing rate of 136.97 sec/°C, fuel consumption rate of 1L at 61.6 seconds and average firing time and temperature of 4.45 seconds and 613.4°C respectively. A total of 450 L of methane was expended to attain a ceramic vitrification temperature of 1000°C in 7 hours 30 min (Figure 3). Although the study expected a lesser duration of firing, the recorded firing time was attributed to the influence of high ambient wind speed (1.8 mph), which affected the combustion process. Thus, the rise in the temperature of the combustion chamber was limited, and the firing time increased.
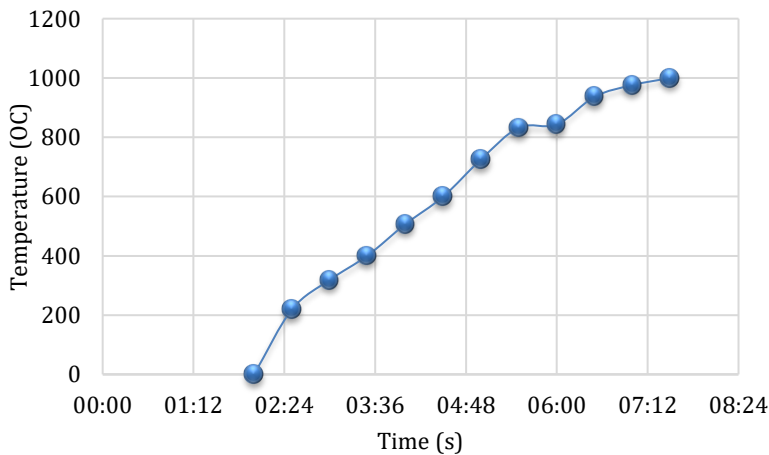
Figure 2. Relationship between temperature and time   **Figure 3.** Ceramic fired to 1000 °C

When compared to a previous study (Abubakar et al., 2022), this result showed a reduction of up to 42 L in fuel consumption. This finding, though at variant with Sheth and Babu (2009) who reported an increase in fuel consumption due to increase in air flow rate, it is consistent with Kummitha (2023), who reported a decreased in fuel consumption due to an improved firing system. However, there was a 30°C difference in firing temperature between the current and the previous study; but attaining the kiln temperature of 1030°C at the firing rate of 136.97 Sec/°C will require 463.5 L instead of 492 L. This resulted in a 28.5 L decrease. Similarly, using 492 L of methane to fire the same kiln at the rate 136.97 sec/OC will increase the firing temperature to 1,093.3°C, which translated to an increase of 63.3°C. Therefore, the study attributed the decrease in fuel consumption and the decrease in firing temperature to the efficiency of the combustion process when compared to a study by Abubakar et al. (2022).

4.2. Equivalent ratio

Actual air volume of 0.381 m³ and theoretical air volume of 0.254 m³ was used to calculate the equivalent ratio of 1.5 for the combustion process (Table1). However, this value is above the value of 1.2 recommended for complete combustion (Winterbone, 1997). It nonetheless falls within the ratio scale of 1.2 to 1.5 (UNIDO, 2021). The 1.5 equivalent ratio recorded indicated a weak combustion, resulting from a deficiency in the volume of oxygen required for the complete combustion of the carbonaceous material present in the fuel (Methane). The deficiency has impacted negatively on the combustion behavior by limiting the combustion efficiency, volume of energy release and fuel utilization.

Similarly, the shortage in the requisite volume of oxidant in the combustion process led to reduction in volume of thermal energy release from the combustion process, and subsequent emission of gaseous pollutant from unburn carbon. However, several reports have shown that an equivalent ratio of up to 1.5 has no effect on oxidizing kiln atmospheres. On the other hand, a value below 1.2 has been linked to severe deficiency of oxygen required for the reaction between fuel and oxidant, leading to a huge temperature difference within the kiln chamber (UNIDO, 2021). Furthermore, equivalent ratio above 1.5 has also been linked to excessive combustion of fuel and smaller temperature difference in the kiln chamber (UNIDO, 2021). Furthermore, the equivalent ratio recorded in this study neither exceeded 1.5 nor fall below 1.2. It has, however, aided the generation of -557,376,843 enthalpy of formation of products and a significant amount of air required for the combustion process.

Table 1. Actual theoretical and equivalent ratio of air

Actual volume of air at constant pressure	0.381 m³
Theoretical volume of air at 37°C	0.254 m³
Volume of methane at 37°C	0.45 m³
Equivalent ratio	1.5
Ambient wind speed	1.8 mph

4.3. Stoichiometric ratio

The stoichiometry of methane to air in the combustion chamber was determined to be 9.818kg which translated to 57.18% (Table 2). Based on the standard of 1kg of methane to 17.17 kg of air (Winterbone, 1997), this value is in deficit of 7.352 kg which translate to 42.82% of air required for efficient combustion of the fuel. The inadequacy of the air required for the oxidation of the fuel led to the release of carbon monoxide, which is a toxic gas as a byproduct of the combustion process. However, reports have shown that an addition of excess air to an incomplete combustion process will not stop the formation of CO, but the provisions of sufficient air to the combustion process will limit the volume of CO generated (Rogoff & Screve, 2011). It is imperative, therefore, to state that even though methane is considered a renewable and environmentally

friendly fuel, improper combustion process can impact negatively on its green credentials and limit its efficiency and thermal energy potential.

ε_{stoic}	Available air for combustion (%)	Air deficiency (%)
9.818	57.18	42.82

### 4.4. Enthalpy of reaction of methane and formation of products

Enthalpy of formation of reactants and enthalpy of formation of products of -74,897 and -557,376.843 were recorded in the study. Although the value for the enthalpy of methane is always constant, the value for the enthalpy of formations of products varies depending on the nature of the reaction, the equivalent ratio, and by-products formed and the molecular weight of the products. Similarly, combustion reactions, whose by-products contained CO_2, H_2O and CO, tend to have higher enthalpies of formation of products than those with only H_2O, and CO as by-products. Furthermore, higher enthalpies of formation of products which are linked to complete combustion of the carbon contained in the fuel translate to high energy release.
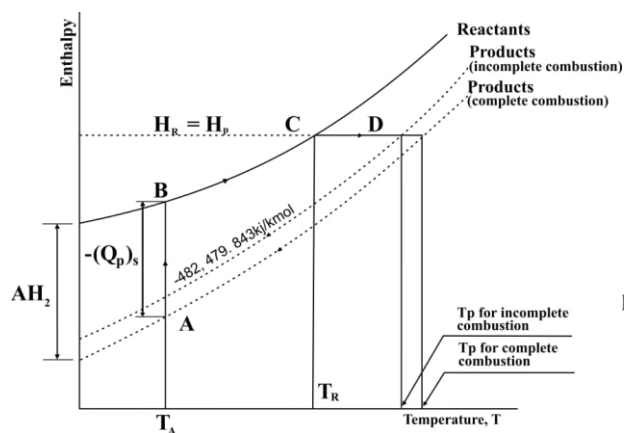
Figure 4. Change in combustion pathway at equivalent ratio of 1.5
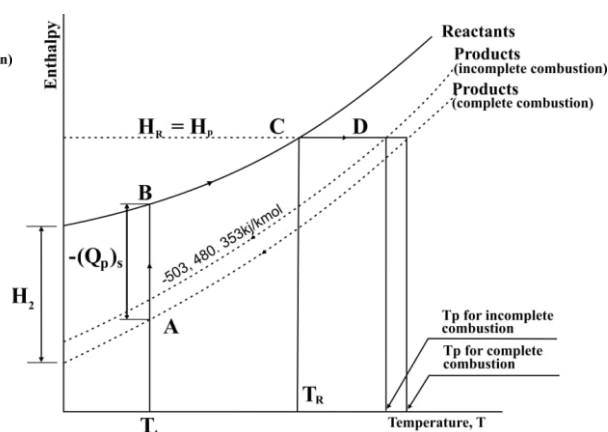
Figure 5. Change in combustion pathway at equivalent ratio of 1.4
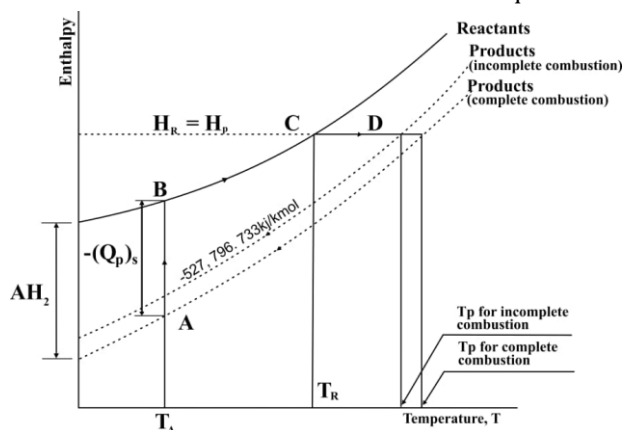
Figure 6. Change in combustion pathway at equivalent ratio of 1.3

The by-products of enthalpy of formation of products recorded in the study only contained H_2O and CO due to a shortage in the volume of air required for full oxidation of the carbon content of the fuel. This led to a change from complete to incomplete combustion pathway, reduced enthalpy and energy release (Figure 4, 5, and 6), reduced enthalpy, and the production of carbon

monoxide. This is consistent with Thomas's (2003) research, which linked high emissions of CO, soot, and other unburned pollutants to a lack of oxygen in a combustion carbon-based fuel.
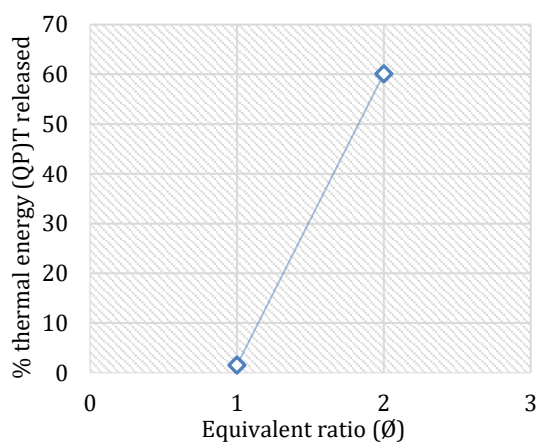
4.5.   Energy liberated

The study showed that -482,479.843 of thermal energy, which translated to 60.1% (Table 3), was utilized when the kiln was fired to 1000°C, while the thermal energy equivalent of 188,761 kg/mol, or 39.9%, was not available due to insufficient air for the combustion process. Table 3 also showed that at high equivalent ratio, less thermal energy is released, while at low equivalent ratio, more thermal energy is released. Similarly, at high equivalent ratio, more thermal energy is lost, while at low equivalent ratio, less thermal energy is lost.

This indicated a linear correlation between high equivalent ratio of 1.5 and thermal energy loss of 39.9 kj/kmol and an inverse correlation between high equivalent ratio of 1.5 and thermal energy release of 60.1%. Similarly, the results also established a linear correlation between low equivalent ratio of 1.3 and thermal energy loss of 34.21 kj/kmol and an inverse correlation between low equivalent ratio of 1.3 and thermal energy release of 65.79% (Figure 7 and 8).

Table 3. Thermal energy generated, percentage utilized and lost

Thermal energy ($Q_P)_T$ released (kj/kmol)	Thermal energy ($Q_P)_T$ released (%)	Thermal energy lost (%)
-482,479.843	60.1	39.9
-503,480.353	62.76	37.24
-527,796.733	65.79	34.21
-556,092.157	69.31	30.69

Figure 8. Linear correlation between equivalent ratio and energy release
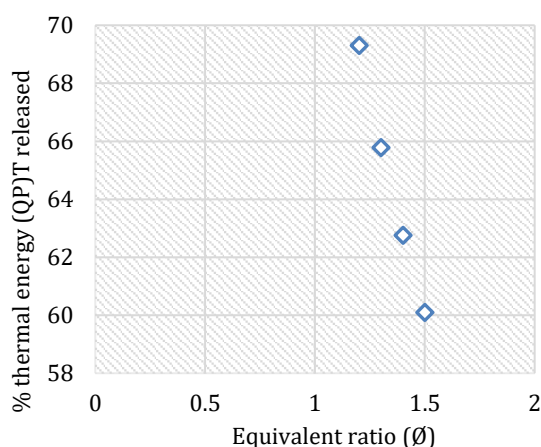
Figure 9. Inverse correlation between equivalent ratio and thermal energy release

4.6.   Recommendations for a sustainable and efficient ceramic firing process

In the study, feldspar, cullet, bagasse ash, and clay were compounded into glaze and fired to a maturing temperature of 1000°C at 7 hour 30 mins firing time. The kiln was fired at ambient wind speed of 1.8 mph, north-south fire box orientation, and a flue flowing perpendicular to the arch. The study attributed the recorded firing time, temperature and the low firing efficiency of the combustion process to the composition of the glaze recipe, fire box orientation, uneven heat distribution within the kiln chamber, and ambient wind speed. As a result, the following strategies to improve combustion process and efficient firing were proposed. First, glaze and bodies that mature at temperatures below 1000 degrees centigrade should be used to limit the firing time,

fuel consumption, and emissions of gaseous pollutants. Secondly, kilns should be fired at ambient wind speed of less than 1mph to enhance vertical movement of flue for efficient chimney draft. Thirdly, kilns should be designed to facilitate vertical flue movement to reduce uneven firing and enhance even heat circulation within the kiln chamber. Fourthly, kilns should be built with an east-west orientation for the firebox, which will provide better inflow of primary and secondary air, enhancing appropriate air-fuel mixture for the combustion process.

5. Conclusion

Kiln firing temperature of $1000^{0}C$ was attained at a firing rate of 136.97 sec/°C in 450 minutes. Stoichiometric ratio of less than one led to weak combustion process, reduced fuel and energy utilization, as well as the emission of toxic gaseous pollutants. Equivalent ratio of 1.5 generated enthalpy of -482,497.843 worth of thermal energy, which translated to 60.1%. Improper combustion, resulting in a high ambient speed and inappropriate air fuel mixture, can shorten the combustion pathway, limit thermal efficiency, and undermine the green credentials of renewable fuels. Design modification of kiln chamber and fire box will reduce fuel consumption, enhance the firing efficiency, and increase sustainability.

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