

# Evaluating Energy Utilization and Exergy in Decorative Ceramic Kilns: A Novel Approach to Thermal Efficiency and Sustainability

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**Abstract** – The ceramic industry is a major consumer of resources and greenhouse gas emissions. Although the nature and volume of the energy consumption and gaseous emissions have been assessed in ceramic production; there appears to be a lacuna in literature on energy utilization and the firing process of decorative ware ceramic. In view of this, a novel method of combining heat flux, displacement and availability, based on the first and second laws of thermodynamics was used to evaluate the combustion processes and energy utilization of a decorative ware kiln. The results showed that 5, 936, 25 5.42 kJ/kmol was available for useful work, 605,520.42 kJ/kmol for displacement, and 119,065.0 kJ/kmol for work against limiting forces. The outcome also revealed that, while 1034.7 kJ/kgk of latent heat was used for the vitrification of the wares; 208, 4725 kJ/kgk of thermal energy was lost. Similarly, as the combustion temperature progressed to 1000OK, there was an increase in heat flux through the chimney, with thermal energy loss of up to 40.21% through conduction. The study therefore concluded that thermal energy loss through the chimney was higher than at any point in the kiln structure, thereby making the entire firing process inefficient and unsustainable.

**Keywords:** Ceramic industry, Decorative ware, Greenhouse gas, Thermal energy, Vitrification

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## I. Introduction

Sustainability and efficiency are two generic terms that revolve around the reduction in energy consumption, the management of resources, and the prevention of pollutant discharge into air, water and land [1]. The application of these concepts and their continued popularity in the industrial manufacturing of goods and services and other socio-economic activities is linked to increasing awareness of the impact of global warming and climate change and the need for environmental protection through the adoption of renewable energy and resource management [2].

Similarly, the projected 35% increase in global energy demand, market globalization and the demand for green products are also putting pressure on the adoption of sustainable approaches in manufacturing processes[3-4]. Furthermore, the benefits of sustainability and efficiency

in the manufacturing sector, include: cost and waste reduction through increased operational efficiency, increased competitive advantage through increased customer base, responding to regulatory constraints, protection and strengthening of brand and reputation, the building of public trust; and long term business viability, opportunities and success are also key drivers to the implementation of sustainability and efficiency [5-7].

The ceramic industry is a subdivision of the manufacturing industry that produces two broad categories of products, viz-a viz advance ceramics which consists of electrical and electronics ceramics, technical ceramics, bio-ceramics and ceramic coatings, and the traditional ceramic category which consists of ceramic tiles, table Wares, sanitary ware, bricks and decorative wares. The production of these ceramics is associated with the emission of carbon dioxide and the consumption

of large volumes of energy and raw materials. For example, global yearly CO<sub>2</sub> emissions from the ceramic industry stood at 400 metric Tones; while energy consumption is put at 182 Tetra Watt-hour of natural gas per annum. Aside from energy consumption and CO<sub>2</sub> emissions, other environmental challenges of the ceramic industry include environmental degradation and pollution due to the extraction of raw materials, waste disposal and landfilling [8].

To curtail the impact of ceramic production activities on the environment and the climate systems, researchers have recommended the following: the use of sluges, waste glass and organic waste as raw material for ceramic production, the substitution of bricks with wood-based building, fuel switching, substitution and adaption of hybrid kilns, process optimization, material reformulation and improve energy management. Other strategies include a reduction in energy consumption by up to 99% and 65% through the adaption of microwave and microwave-assisted drying and firing and the reuse of excess exhaust gas [9]. The adoption of these strategies are consistent with the United Nations Climate Change Conference (UNCCC), Cop 26 recommendations, for a shift from the use of fossil fuels, particularly coal which accounts for 40% of global carbon emissions, the adoption of green alternative energy sources; and the 13<sup>th</sup> goal of Sustainable Development Goals, which calls for immediate action for the prevention climate change and its attendant effects[10].

A review of literature on traditional ceramic processing which forms the bulk of manufactured ceramic showed that efficiency and sustainability studies have been conducted on a wide range of issues such as material reuse, addition of new material to existing ceramic recipes, water and energy saving, pollution prevention, carbon dioxide emission reduction, waste heat recovery, as well as the limitations to the implementation of efficiency strategies [11- 20]. A further review of the literature indicated that the majority of the studies conducted were focused on emission volume and type of fuel usage in the ceramic tile industry, with a few on red brick, tableware and sanitary ware industries (21-28).

There is therefore a lacuna in literature on displacement studies, energy quantification and content, thermal heat absorption, utilization and loss, in the decorative ceramic ware industry particularly at the small and medium scale. This study is therefore aimed at assessing the thermal energy utilization of bio-methane fired decorative ceramic ware kiln using the following objectives: (i) Enthalpy and exergy of methane (iii) Displacement (ii) Energy availability (iv) Chimney heat flux.

Efficiency is the utilization of less energy and less material resources, to achieve a desired result in any industrial process or human activity; while sustainability refers to continuous use of resources without detrimental effect on the environment. The concepts of efficiency and sustainability are increasingly becoming subjects of interest in the ceramic sector, largely due to a push for compliance from environmental standard regulatory agencies and the desire to align with current trends in resource management and environmental protection. This is against the backdrop of the effect ceramics production have on both the environment and health beginning from material sourcing to the end life of the product.

In view of these, Eco-design principles of 3R (Re-use, Reduce and recycle) and waste heat recovery strategies such as hot air recycling, and the use of air-gas heat exchangers have been incorporated into the ceramic production activities to reduce energy consumption, pollutant emissions and excessive waste generation and unnecessary use of raw material [29]. Similarly, textile waste, and recycling of rice husk ash, fly ash, blast furnace slag, bottom ash, waste polish tiles and petroleum waste are also being adopted as substitutes for natural ceramic raw materials [30]. All these efforts are geared towards making ceramic production sustainable by limiting the depletion of natural resources and environmental degradation. However, of significant interest to the ceramicist is how to reduce the high energy consumption [31] and loss in the form of exhaust flue gas which accounts for 55% of thermal energy usage [32].

Nevertheless, to limit these excesses and make the firing process efficient, a road map for efficiency strategy was proffered by [33]. Although, a variety of factors ranging from fuel type, purity of fuel, fuel-air stoichiometry, fuel-air equivalent ratio, burner type, kiln design, the scale of firing (industrial, cottage, individual or studio base) and the type of product fired have been identified as determinant to firing efficiency, [34-36]; however, the role of ceramic kiln exhaust in the efficiency of the firing process cannot be underrated.

The ceramic kiln exhaust, also known as the chimney serves as the lung of the kiln; providing the draft required for an efficient combustion process. However, as much as the chimney is important in the ceramic firing process, the bulk of the energy loss also occurs through the chimney. For example, an early study on kiln efficiency reported 74% heat loss through the chimney [37]; while a recent study showed up to 50% thermal energy is lost through the chimney [38]. Similarly, a study by [39] and [40], showed that waste heat account for 20% to 50% of the thermal energy lost in ceramic firing.

Given the backdrop of the enormous amount of thermal energy losses, and CO<sub>2</sub> emissions from kiln chimneys and the correlation between efficiency, sustainability and energy resource utilization; studies have been conducted to minimize these impacts and wastages. However, an appraisal of the literature revealed that most of the studies focused on exhaust gas recovery from generators, diesel engines, boilers, heat pumps and internal combustion engines. For example, [41] evaluated heat recovery from the exhaust of a gas generator, while [42] studied how to improve exhaust heat recovery from public heat pump systems. Liu et al. [43] investigated heat recovery from the exhaust of diesel engines, while a study by [44] reported a novel flue gas waste heat recovery with recovery efficiency of 106% and boiler efficiency of 88%. Similarly, [45] reported on a hybrid heat recovery system reusing thermal energy captured by exhaust gas to produce domestic hot water and generate electric power.

Furthermore, [46] reported on waste heat recovery from internal combustion engines via modelled heat exchangers. Waste heat availability from the exhaust of a 40 KW diesel engine was also reported by [47]. A further search of literature revealed the study of [48] who reported exhaust waste heat recovery of 40% from ceramic kiln chimneys. These showed a dearth of literature on exhaust heat recovery from the ceramic industry in general and the decorative ceramic industry in particular. Although, the outcome of most of the studies may find application in the decorative kiln industry, however, the scale and volume of consumption and emissions may limit such application. Consequently, this study seeks to quantify the heat losses through the chimney using the heat flux approach; to determine the volume and mode of energy loss, with the view to highlighting points of thermal energy loss for efficiency improvement and sustainability. Although, opine that, there are difficulties in identifying and evaluating waste heat in terms of quality and quantity, the researcher, however, posits that, knowing the volume of energy wasted in any ceramic firing and the potential to recover such will aid in reducing the cost of energy and the impact of the waste energy on the overall cost of production and the environment [49].

The objective of this study was to assess the thermal energy utilization of a bio-methane-fired decorative ceramic ware kiln. This was achieved by evaluating the enthalpy and exergy of methane, displacement, energy availability, and chimney heat flux. The novelty of this work lies in combining heat flux, displacement, and availability, based on the first and second laws of thermodynamics, to evaluate the combustion processes

and energy utilization specifically for a decorative ware kiln, addressing a gap in literature concerning energy quantification and loss in this particular segment of the ceramic industry.

## II. Methods and Materials

The research methodology involved the anaerobic digestion of fresh cow for the generation of bio-methane, and the utilization of the generated gas to fire a ceramic kiln. Exergy and availability approach based first and second laws of thermodynamics were used to evaluate the bio-methane combustion process, the internal energy of the fuel, the enthalpy formation of reactants and products of the combustion process; as well as work done by the firing system. Work done against the surroundings, useful work done by the system, the actual energy available for the combustion process as well as heat flux through the chimney wall were also evaluated.

### II.1. Bio-methane generation and the ceramic kiln firing process

Bio-methane was generated under a mesophilic temperature of 38 OC and pH of 8.5. Nitrogen, Carbon, Volatile Fatty Acid, Carbon- oxygen demand, Alkalinity, Carbon- Nitrogen Ratio and pH for both the raw and digested slurry were determined based on [50]. A cross draft kiln constructed with a lightweight kaolin refractory brick measuring 24cm x 10cm x 8cm using the stretcher kiln building method [51]; was used to fire a ceramic ware to 1000OK in 5 hour, 25 min. The firing was carried out at an ambient temperature, pressure, humidity and wind speed of 36OC, 10.009 bars, 40% and 10 m/s respectively.

A kiln firing temperature of 1000OK which is  $\frac{3}{4}$  of the stoneware firing temperature was selected to limit the impact of high temperature firing on man-hour, as well as reduction in firing time, cost of firing, energy consumption and greenhouse gas emission which are associated with long firing hours [52].

### II.2. Calculating the moles of bio-methane used in the firing process

Given that, the ceramic firing process is non-adiabatic, non-isentropic, and irreversible, the pressure of the gas used in the firing process was measured using a diaphragm pressure gauge, while mass and volume were determined using the relationship between density, mass and volume as depicted in Eq. (1). The mass derived from Eq. (1) was used to calculate the number of moles

of bio-methane used in the firing process as shown in Eq. (2).

$$D = M / V \quad (1)$$

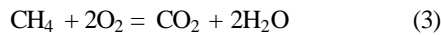
$$n = M / M_m \quad (2)$$

Where: D = Density, M =Mass, V= Volume , n = number of moles of bio-methane

M = Mass of bio-methane,  $M_m$  = Molar Mass of bio-methane

### II.3. Determining the enthalpy and exergy of the reaction of methane

The internal energy of bio-methane and the maximum energy derivable from the combustion of bio-methane was determined based on Eq. (3, 4 and 5). Combustion Eq. (3) was used as a guide for calculating the reactants and products of the combustion process of 18.8 moles of bio-methane, whilst exergy Eq. (4 and 5) were used to determine the enthalpy of reaction and exergy of the combustion process. Standard values of 25°C, 804.6x10<sup>3</sup> kJ/kmol/k, 214.07kJ/kmol/k, 188.17 kJ/kmol/k and 204.65kJ/kmol/k for enthalpy coefficients at s(T) and specific enthalpy at datum temperature ( $h_o$ ) for methane, carbon dioxide, water and oxygen based on thermodynamics table of properties for ideals gases and ideal gas mixtures were used in the evaluation of enthalpy changes, exergy of formation and internal energy [53].



$$\Delta B = \Sigma(b1)_P - \Sigma(b1)_R \quad (4)$$

Where:

$\Delta B$  = Change in exergy

$\Sigma(b1)_P$  = sum of specific exergy for product

$\Sigma(b1)_R$  = sum of specific exergy for reactant

$$\Delta B = (\Delta HR)_{CH_4} - T0 (S_{CO_2} + 2S_{H_2O} - S_{CH_4} - 2S_{O_2}) \quad (5)$$

Where:

$\Delta B$ = Exergy of formation of methane

$(\Delta HR)_{CH_4}$  =enthalpy of reaction of methane

$$W_{use|1-2} = W_{sy} = \int PdV = P(V_1 - V_2)V_1 - W_{sur|1-2} = \int PTdV = PT(V_1 - V_2)V_1 \quad (6)$$

### II.4. Displacement, useful and work done against the surrounding

In this study, atmospheric pressure, moisture content of the kiln chamber and warm secondary air required for the combustion process were considered to be the limiting forces that need to be overcome. Therefore, displacement work by the fuel against these external forces at firing temperatures of 500OK, 600 OK, 800 OK, and 1000 OK, were determined based on the pressure-volume equation

shown in Eq. (6); while useful work was determined by computing the difference between work done and work against the limiting forces as shown in Eq. (7). The adoption of these firing temperatures was based on the understanding that, removal of moisture, carbonization of organic substance, decomposition, hydration, vitrification and physio-chemical transformation of ceramic occur at these temperatures.

$$Workdone|1-2 = \int PdV = P(V_1 - V_2)V_1 \quad (7)$$

Where:

$V_1$ = Initial volume of Bio-methane

$V_2$  = Volume of Bio-methane

P = Pressure of Bio-methane

PdV = Change in volume

### II.5. Latent heat and heat loss in the kiln chamber and chimney

Heat absorbed by the ceramic ware in latent form and those lost in the form of unutilized energy were calculated using Eq. (8 and 9)

$$Q = MC(t_i - t_2) \quad (8)$$

$$Q = V \times CP \times \Delta t \quad (9)$$

$T0$  = Standard temperature for evaluating enthalpy (25°C)

S = specific enthalpy

### II.6. Computation of chimney heat flux density

Heat losses through the chimney surface (heat flux density), as well as through radiation conduction as well as through radiation conduction and convection were determined based on Eq. (10, 11, 12 and 13). Boltzmann constant of 1.380649x 10<sup>-23</sup> Joules/kelvin, the thermal conductivity of 3 Wm-lk-1, and kaolin emissivity range at temperature of 500OK to 1000OK were used in the computation [54,55].

$$Q = -Kdt/dx \quad (10)$$

$$Q_T = Q \times A \quad (11)$$

$$q = a\epsilon t^2 \quad (12)$$

$$Q/t = KA(T_1 - T_2)/L \quad (13)$$

Where: Q= Heat flux density, K = Thermal conductivity content , dt = Change in temperature (Temperature gradient), dx = Thickness of the heat emission surface,  $Q_T$  = Total heat loss, Q = heat loss , A = Area of heat lost surface, a= Stefan- Boltzmann constant ,  $\epsilon$ = emissivity, T= Temperature in Kelvin, Q/t = rate of heat transfer,  $T_1 - T_2$ = Temperature difference, L= Thickness of the surface.

### III. Results and discussion

#### III.1. Bio-methane generation and characterization

Table 1 shows that the values of 8.5, 8532, 1200, 45, 26:1, 555, and 3040 for pH, Carbon Oxygen Demand (COD), Carbon (C), Nitrogen (N), Carbon Nitrogen Ratio (C/N ratio), Volatile Fatty Acid (VFA), and Alkalinity (A) for the digested slurry all fall within the optimal values recommended by [56-58]. The result also showed that, while the nitrogen content of the cow dung reduced from 109 mg/l to 45mg/l in the digested slurry which is desirable; however, there is a four times increase in the carbon content from 3000mg/l to 1200mg/l, an indication of increased viability of the cow dung. Although the increase or decrease in pH and temperature of the anaerobic digestion process tends to affect the performance of methanogenic bacteria [59-61]. However, the digester appears to have provided a buffer against changes in pH and temperature of the digestion process which led to the stability of the methanogenic process and a steady gas production of 25 litres per day. This finding is consistent with [62], who reported that the well-being of a digester is indicated by its buffering ability and the stability of the digestion process, and [63], who showed that a plastic digester has the potential for maintaining high-temperature and providing buffers against variations in ambient temperature.

Table 1: Anaerobic digestion parameters for bio-methane generation

SN	Sample	pH	COD (mg/l)	C (mg/l)	N (mg/l)	C/N (mg/l)	VFA (mg/l)	Alkalinity (mg/l)
1	Raw slurry	9.5	102384	3000	109	27:1	600	1160
2	Digested Slurry	8.5	8532	1200	45	26:1	555	3040

#### III.2. Internal glass temperature

Table 2 shows that 18.8 moles of bio-methane has an enthalpy of formation -71408082.4kJ/kmol, and exergy of the reaction -71407593.3kJ/kmol. This showed a net difference of 488.7 kJ/kmol of energy between energy and enthalpy of formation of bio-methane. The data also showed that the value of the enthalpy which corresponds to 99.9993% of the exergy, is 0.0006854% less than the original enthalpy of formation of the fuel. This indicated that bio-methane has a very high internal energy potential and 100% displacement ability, which is its maximum ability to do work. This finding is comparable with an earlier study that reported 94.5% exergy for methane, a value which is 5.5% less than its enthalpy of formation [64].

Table 2: Parameters used to determine the exergy and enthalpy of formation of bio-methane

SN	Variables	Values
1	Number of moles contained in 300.69 g of methane	18.8 moles
2	Mass of Bio-methane	300.69 g
3	Molar mass of methane	16g/kmol
4	Density of Bio-methane	0.6682 kg/m <sup>3</sup>
5	Initial volume of Bio-methane (V1)	230M <sup>3</sup>
6	Final volume of Bio-methane (V2)	62.735M <sup>3</sup>
7	Enthalpy of formation of 1mole of methane	-74898 kJ/kmol
8	Enthalpy of formation of 18.8 moles of Bio-methane	-71408082.4 kJ/kmol
9	Exergy of 18.8 moles of Bio-methane	-71407593.3 kJ/kmol
10	Atmospheric pressure	10.009 Bars
11	Atmospheric temperature	30°C

The firing curve in Figure 1 showed a sharp increase in the firing temperature from 273OK up to 411OK. However, from 411OK up to the 90th minute of firing, a constant increase in temperature was observed. This was followed by a deviation of 12OK from the temperature trajectory at 105 minutes which corresponds 600OK. A further deviation of 22OK and 32 OK were observed at 135 minutes and 165 minutes which corresponds to 700OK and 800OK respectively. The fluctuations in firing temperature continued up to 180 minutes into the firing time. Thereafter a constant firing curve was observed until the firing ended at 1000OK.

The fluctuations observed on the firing curve were attributed to stalling, resulting from changes in the pressure of the compressed bio-methane as well as wind speed. Overall, One thousand degree kelvin of firing temperature was attained in 225 minutes at an average temperature of 646.1OC and an average firing time of 112.5 mins.

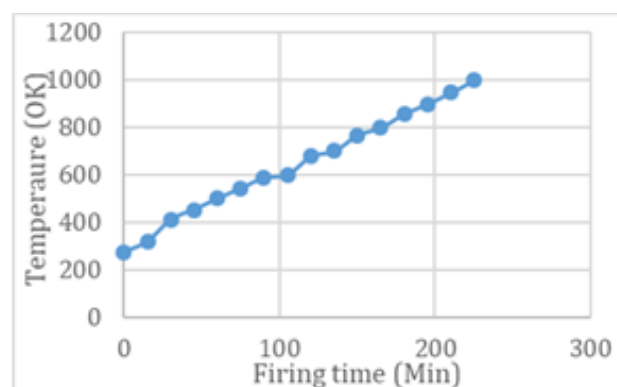


Figure 1: Temperature and time firing curve

#### III.3. Energy availability and displacement work at various firing temperatures

Displacement data in Table 3 indicated that, at 500OK, there was a corresponding work done of 119,065.02kJ/kgk which translated to 19.66% at bio-methane volume and pressure of 187.583 m<sup>3</sup> and of



13.213 bars respectively. As the firing progressed to 600 OK, work done increased to 154,486.10 kj/kgk which translated to 25.51%.

Similarly, a value of 190,003.40 kj/kgk for work done which translated to 31.38% was recorded at 800OK. However, the value of displacement work reduced to 141,965.90 kj/kgk at pressure and volume of 3.3927 bars and 62.735 m<sup>3</sup> and firing temperature of 1000 OK. Although the area under volume-pressure graph for work done is seen to increase as the firing progresses (Fig.2-4).

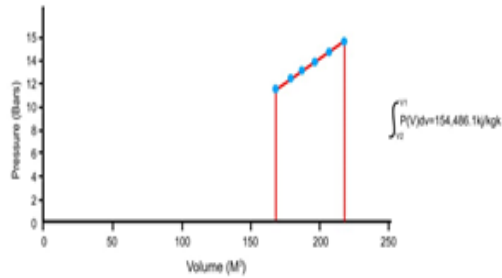


Figure 2. Volume-pressure work at 500 OK

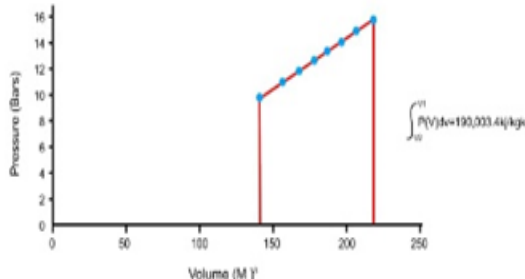


Figure 3. Volume-pressure work at 600 OK

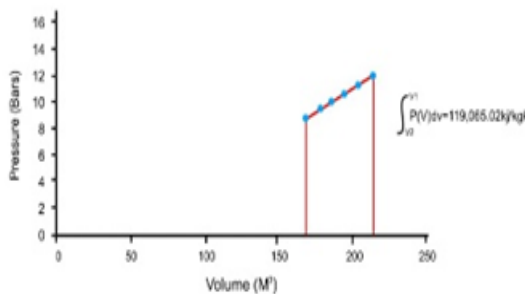


Figure 4. Volume-pressure work at 800OK

Table 3. Displacements and firing temperatures

Displacements temperature	Values of displacement Units (kj/kgk)
Work done at 500 <sup>o</sup> K	119,065.02
Work done at 600 <sup>o</sup> K	154,486.1
Work done at 800 <sup>o</sup> K	190,003.4
Work done at 1000 <sup>o</sup> K	141,965.9
Total work done	605,520.42
Work done against limiting forces	119,065.0
Useful work	5,936,255.42

The contraction under the volume-pressure graph for the work done at 1000<sup>o</sup>K is associated with the reduced pressure and volume of the fuel (Figure 5).

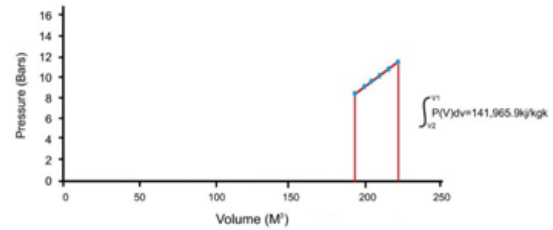


Figure 5. Pressure-volume work at 1000OK

Furthermore, the displacement data also showed a total work of 695,518.0 kj/kgk through the duration of the firing. However, while 576,453.0 kj/kgk of thermal energy was available for useful work, 119,065.0 kj/kgk of the value was used for work against limiting forces within the surroundings of the firing system. This infers that not all the displacement work done by the firing system is available for useful work. Similarly, data from the firing also showed that the pressure and volume of the fuel tend to decrease, as the firing process progresses. Although, this is at variance with the thermodynamics of internal combustion engines, where increased in heat results in an increased pressure, volume and work done; this aberration is attributed to the irreversible and adiabatic nature combustion process of a methane-fired kiln.

#### III.4 Thermal energy absorption and heat loss at various firing temperatures

Data on thermal energy absorption (Table 4) indicated that, while 16.78% of thermal heat was lost at 500OK, 17.23% which translated to 178.3 kj/kgk was absorbed by the body to expel the moisture (1% to 2%) content which would have escaped the drying process. The data also revealed that at 800OK, 27.6% which translated to 285.8kj/kgk of the latent heat was used to hydrate, decompose, and carbonize the organic content, and the water of crystallization of the ware. However, as the firing progressed, there was a corresponding increase in

both latent heat and heat losses; however only a slight percentage difference existed between the latent heat and heat loss.

Table 4. Latent heat and heat losses at various firing temperatures

Firing Temp (°K)	Latent heat (kj/kgk)	% latent heat	Heat loss (kj/kgk)	% heat Loss	% difference between latent heat and heat loss
500	178.3	17.23	12,330.4	16.78	0.45
600	214.0	20.68	14,917.9	20.30	0.38
800	285.8	27.62	20,272.5	27.59	0.03
1000	356.6	34.47	25,951.7	35.32	-0.85

Data in Figure 6, also revealed a positive value in the difference between latent heat and heat loss. However, at 1000 OK the difference turned negative. This indicated a reduction in heat absorption due to the sintering of the ware. The data also revealed that, from 500OK, to 1000OK; only a small percentage (17.23%, 20.68%, 27.62% and 34.47%) of the available thermal energy (-71407593.3 kj/kmol) was used for the physical and chemical transformation of the ceramic ware. This is consistent with [65], who reported that between 15 to 20% of energy input is used for crystallization of the ceramic tile and [66], who reported that only 26% of energy is utilized for the crystallization of a ware. Furthermore, firing through 1000OK also revealed that, a total of 1,034.7kg/kgk of latent heat was absorbed by the ceramic ware (Fig. 7 and 8), while 76,472.5kg/kgk of heat was lost.

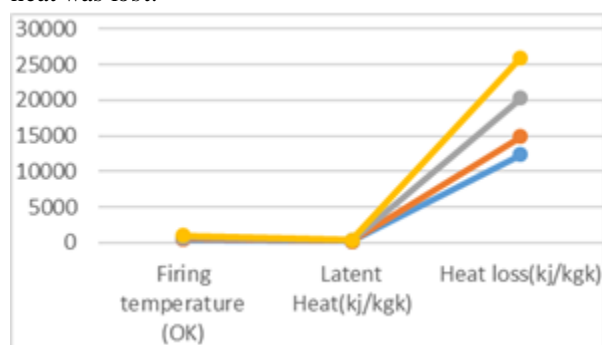


Figure. 6. Firing temperature, latent heat and heat loss



Figure. 7. Decorative item fired to 8000K



Figure 8. Decorative item fired to 1000OK

Similarly, the data also indicated that, while 100% of the useful thermal energy was absorbed by the ceramic ware in the form of latent heat, a significant proportion of the total generated thermal energy was lost. This finding is comparable with [67], who reported energy loss of up to 85%; with 5-10% of the thermal energy is lost with the fired wares, 10-15% lost through kiln wall and vault, and [68], who reported up to 95.8% of thermal energy lost. Furthermore, data in Table 4, indicted that while, 73,472.50 kj/kg of thermal energy, averaging 18,368.13kj/kg was lost through the duration of the firing, there was however, an increase in both latent heat and heat loss with differential values of 1kj/kg and 35.7 kj/kg between latent heat and heat losses.

### III.5 Heat flux and thermal energy through kiln chimney

Data for heat flux (Table 5), indicated that 12.55 %, 12.56% and 0.93% of the thermal energy were lost at 500OK, through the kiln chimney in the form of heat flux, thermal conduction, radiation and convection. Furthermore, firing to 600 OK showed, that 12,262.5 Wm-1k-1 and 752.505Jm-1k-1, which corresponds to 18.07% of thermal energy was lost through the chimney. The data also revealed that a cumulative sum of 67,800 Wm-1k-1 of heat flux was lost through the duration of the firing. This value is 61,806.48 Jm-1k-1 higher than the quantum of thermal energy lost through conduction, conduction and radiation which stood at 5993.52 Jm-1k-1. The data also showed that heat losses through the chimney in the gaseous form of Carbon dioxide (CO<sub>2</sub>), Moisture (H<sub>2</sub>O) and Nitrogen (N<sub>2</sub>) are greater than those lost in the kiln chamber. This result agrees with [69], who reported 20-25% heat loss through flue gas stock and 30-35 through cooling stock.

Table 5. Heat flux and total heat losses from the Kiln Chimney

Firing temp. (°K)	Heat flux (Wm <sup>-1</sup> k <sup>-1</sup> )	% Heat Flux	Heat loss through conduction (Jm <sup>-1</sup> k <sup>-1</sup> )	% Heat loss through Conduction	Heat loss through Radiation (Jm <sup>-1</sup> k <sup>-1</sup> )	% Heat loss through Radiation	Heat loss through convection (Wm <sup>-1</sup> k <sup>-1</sup> )	% Heat loss through Convection
500	8,512.5	12.55	752.505	12.56	2.69x10 <sup>-18</sup>	0.93	2.69x10 <sup>-18</sup>	0.93
600	12,262.5	18.07	752.505	18.07	3.88x10 <sup>-18</sup>	1.34	3.88x10 <sup>-18</sup>	1.34
800	19,762.5	29.15	1,747.005	29.15	6.89x10 <sup>-18</sup>	2.38	6.89x10 <sup>-18</sup>	2.38
1000	27,262.5	40.21	2,410.005	40.21	1.08x10 <sup>-17</sup>	3.72	1.08x10 <sup>-17</sup>	3.72

## IV. Conclusions

Ceramic production which is a sub-sector of the manufacturing industry consumes a large percentage of energy and material resources leading to environmental degradation and pollution. To reduce the impact of ceramic production activities, and enhance its green credentials, the adoption of green and clean environmental firing techniques and efficient resources and energy management have been proffered. This study evaluated the combustion process of a bio-methane-fired decorative ceramic ware kiln to determine its efficiency and sustainability.

Findings from the study indicated that 18.8 moles of Bio-methane generated from raw cow dung has an enthalpy of formation of -71408082.4 kJ/kmol and exergy of -71407593.3 kJ/kmol. These values imply a significant potential for the utilization of raw cow dung as an alternative renewable source of energy for ceramic kiln firing. The findings also show that the maximum thermal energy derivable from bio-methane and its displacement ability is almost 100%.

Findings also indicated that, although both latent heat and heat losses increased as the firing progressed through to 1000OK, there was no significant difference in the occurred losses. The study also revealed that significant heat loss from the firing processes occurs in the chimney area primarily through conduction, convection and radiation. However, while the fuel has a significant amount of internal energy, only a small portion is available for useful work. This therefore highlighted the importance of effective energy utilization in the ceramic firing process to curtail inefficiencies through energy leakages and wastages, which could be achieved through kiln structure modifications and adjustments using high refractory and insulating materials, the development of low-fired body and glazes and the re-use and re-circulation of exhaust thermal energy.

## Declaration

- The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.
- The authors declare that this article has not been published before and is not in the process of being published in any other journal.
- The authors confirmed that the paper was free of plagiarism

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