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Performance Analysis of Straight-Line Natural Draft Brick Kiln: A Case Study of Bishal Brick Factory, Kapilvastu, Nepal

by

Keshab Pun

A THESIS

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LALITPUR, NEPAL

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The undersigned certify that they have read, and recommended to the Institute of Engineering for acceptance, a thesis report entitled **"Performance analysis of straight-line natural draft brick kiln: A case study of Bishal brick factory, Kapilvastu, Nepal"** submitted by Keshab Pun (079MSREE006) in partial fulfillment of the requirements for the degree of Master of Science in Renewable Energy Engineering.

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ABSTRACT

In Nepal the brick manufacturing industry helps to play a significant role in construction and employment but remains a major source of energy consumption and air pollution. This study focusses on performance analysis in Straight Line Natural Draft Brick Kiln (SLNDBK) at Bishal Brick Factory, Kapilvastu, Nepal. This research incorporates field measurements, analytical calculations, and computational simulations to evaluate thermal efficiency and combustion performance.

For this research primary data have been obtained through infield measurements of temperature, air velocity, and fuel characteristics, while secondary data has been collected from relevant literature review of research papers and industrial reports. The specific energy consumption (SEC) has been found to be 1.29 MJ/kg of fired bricks, which lies within the range of 1.0–1.4 MJ/kg reported for fixed chimney natural draft kilns in South Asia. By calculating furnace efficiency using both direct and indirect methods, is 37.66 % and 38.65 % respectively**,** helps to know the significant heat losses through openings (28.67 %), flue gases (25.24 %), and radiation/convection (3.46 %). Simulation results show that in existing condition the brick doesn’t get temperature for cooking so fuel flow rate with increased velocity which means that induced draft fan must implement in brick factory. Simulation results show that in existing condition the brick doesn’t get temperature for cooking so, with increased velocity which means that induced draft fan and zigzag kiln with fuel ratio of 60:40 (Coal and sawdust) must be implemented in brick factory. The temperature of brick kiln in existing condition is quite low but after induced draft fan implement then the temperature increases above 900˚C which is good for firing bricks and bricks must get good temperature. Efficiency of brick kiln after implementation of induced fan and retrofitting into zigzag kiln has found to be 50.74% and specific energy saving has found to be 14.51%. CO_2 emissions has been calculated and it comes to 900 tCO_{2eq} per year according to fuel consumption. After implementation of new design style (zigzag kiln) implementation of induced draft of furnace the CO_2 emission decrease which helps in reduction of marginal abatement cost up to is 270 tCO_{2eq} in a year and is 90 tCO_{2eq} respectively. The payback period after implementation of zig-zag kiln and induced draft fan are 11.62 and 3.06 months which very good and benefit cost ratio are 4.57 and 3.78 respectively.

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LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
CO_2	Carbon dioxide
CO	Carbon monoxide
CH_4	Methane
FCBTK	Fixed Chimney Bulls Trench Kiln
FY	Fiscal Year
GDP	Gross Domestic Product
GJ	Gigajoule
ICIMOD	International Center for Integrated Mountain Development
kWh	Kilowatt Hour
kCal	Kilo Calories
MCBTK	Movable Chimney Bulls Trench Kiln
MJ	Mega Joule
MT	Metric ton
NDLBKs	Natural Draft Zigzag Firing Linear Brick Kilns
NO_x	Nitrogen oxides
PM	Particulate Matter
SAARC	South Asian Association for Regional Cooperation
SEC	Specofic Energy Consumption
SPM	Suspended Particulate Matter
VSBK	Vertical Shaft Brick Kiln
WECS	Water and Energy Commission Secretariat

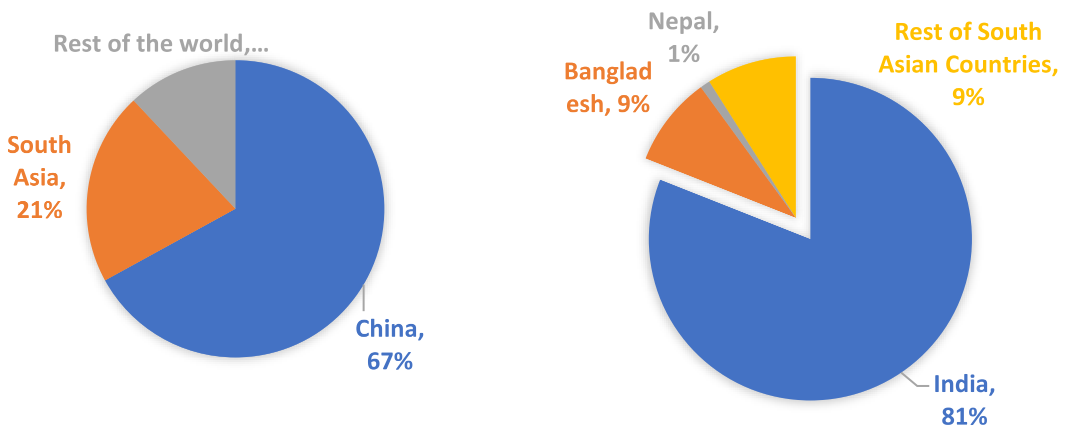
CHAPTER ONE: INTRODUCTION

1.1 Background

Brick is one of the most important materials for the construction of various buildings like residential, commercial and industries. Basically, bricks are made up of clay, sale and sand among them clay is one of the main raw materials with variety of uses and properties, they are naturally fine-grained minerals commodities composed of an aluminate. For fuel consumption. Nowadays bricks are still the most popular choice for wall construction, construction of buildings and many other structures and they are projected to remain so due to their widespread availability and aesthetic appeal. The widespread usage of burnt clay bricks is partly dependent on the availability of clay deposits, which are often found on productive agricultural fields in bottoms. In countries such as Nepal, India, and Bangladesh, where urbanization and population growth are quickly expanding, the need for economical and long-lasting building materials remains high, maintaining the brick industry's importance for decades to come. Its not only supports housing and infrastructure projects, but it also provides significant local employment, particularly for rural migrant laborers, Similarly, in India, the sectors generate billions of bricks each year, fueling the construction boom in urban and semi-urban areas. Clay is naturally abundant raw material consists of fine-grained earthy minerals of secondary origin. It naturally consists of aluminosilicate structures, with additional elements such as iron, alkaline and alkaline earth metals. Common types of clay exhibit sufficient plasticity for easy molding and when firing it vitrify at temperatures below 1100°C(Shakir & Mohammed, 2013).

Brick making has long been a traditional craft in Nepal, serving as a primary construction material, especially in the Kathmandu Valley and the Terai region. With the rising demand for bricks, a technological shift occurred in the early 1950s, replacing traditional clamp kilns (locally called “Thaado Bhatta”) with Bull’s Trench Kilns (BTKs), also known as "Chimney Bhatta," a technology introduced from India. Currently, Fixed Chimney Bull’s Trench Kilns (FBTKs) are the most used method for brick production, following the government's ban on Moving Chimney BTKs in the Kathmandu Valley in 2002 (WECS, 2022).

Across South Asia, brick manufacturing is primarily carried out in informal, traditional, and seasonal coal-fired kilns, where workers manually mold bricks. These brick kilns are among the largest sources of greenhouse gas and particulate matter emissions in the region, significantly contributing to air pollution. South Asia accounts for 21% of global brick production, making it the second-largest producer after China, which leads with 67% of the world's total output. The brick manufacturing technologies commonly used in South Asia have remained largely unchanged for over a longer period of time and are characterized by their inefficiency, low productivity, and significant pollution levels (Eil et al., 2020).



(Eil et al., 2020)

Figure 1.1: Brick manufacturing trend worldwide and South Asia

Despite its historical significance, the brick production industry faces modern challenges, such as the imperative to minimize environmental impact, enhance energy efficiency, and ensure the sustainable use of raw materials. These challenges are intensified by the growing demand for high-quality, durable bricks in rapidly urbanizing regions. As the industry progresses, there is an increasing focus on adopting innovative technologies and processes that not only improve production efficiency but also meet global environmental standards.

According to the study, the main greenhouse gas released throughout the brick-making process is carbon dioxide CO_2, with an estimated 1.30 million tons of CO_{2e} emitted overall. According to the viability assessment, there is a medium level of financial and resource feasibility for the brick sector in Nepal to embrace cleaner technology. Nonetheless, it showed very high technological and legal viability as well as high environmental viability, indicating a high overall viability for the adoption of cleaner technology in the Nepalese brick sector(Thakuri et al., 2024).

1.2 Overview of Straight Line Natural Draft Brick Kiln Technology

The fixed Chimneys Bull's Trench Kiln is one of the most traditional kiln technologies in South Asia. This technology is a continuous, moving-fire kiln arranged in an oval trench, and has a brick chimeny that is fixed for ventilation. Compared to more recent designs, FCBTKs are an older design with a moderate level of energy efficiency. According to field evaluations, well-run FCBTKs use about 1.2 MJ of energy per kilogram of burnt brick (MinErgy, 2012).

Straight Line Natural Draft Brick Kiln is an adaptation of the fixed chimney bull's Trench Kiln (FCBTK), designed to increase the efficiency and environmental performance. In fixed chimney raw bricks stacked in straight line pattern for baking and coal is used as main fuel for baking raw green bricks made from mud that has been treated in pug mills. This technology depends on natural draft for combustion and flue gas movement, reducing the need for forced ventilation systems. This design follows a straight- line configuration, optimizing space utilization and operational efficiency. The FCBTK has an elliptical shape and measures about 250 feet long and 60 feet wide . Majority of its construction takes place in open fields, either above ground or partially below. In sidewalls and bottom parts bricks are line. After being sun-dried, the green bricks are placed into the kiln using a uniform procedure that has been refined over to include coal stoking and airflow. For insulation, the layers of bricks and dirt are placed on top of the green bricks after they have been loaded into the kiln.(Environment, 2017) In this mechanism the chimney height and kiln structure facilitate air flow, ensuring proper fuel combustion and reducing energy consumption and compared to traditional kiln this type of mechanism minimizes particulate matter (PM), carbon monoxide (CO), and carbon dioxide (CO_2) emission. In Nepal, the majority of brick kilns primarily rely on coal as their main fuel source, supplemented by various biomass fuels such as bagasse, rice husk, and charcoal. The predominant kiln types are fixed chimney bull's trench kilns (FCBTKs) and zigzag kilns, accounting for approximately 70% and 30% of all kilns, respectively.

Among FCBTKs and induced-draught zigzag kilns (IDZKs), the latter are believed to be more efficient in reducing emissions due to their enhanced technical features. However, this assumption still requires validation through concrete measurement-based evidence. Furthermore, brick kilns in developing countries often operate with minimal regulation and oversight, leading to significant variability and uncertainty regarding their emissions.

1.3 Statement of problem

Brick manufacturing is one of the most energy-intensive small industries in Nepal, where most kilns are operated using traditional combustion practices by using coal or coal-biomass mixtures as fuel. Among these, Straight Line Natural Draft Brick Kilns (SLNDBKs) are used mainly in Nepal. Its major benefit is due to their low construction cost and simple operational system.

- Significant heat losses and poor fuel utilization leads to low thermal efficiency and high fuel wastage in straight-line natural draft brick kilns
- Poor brick quality and inefficient use of coal–sawdust fuel mixtures result to inadequate firing temperature results to incomplete combustion
- Lack of optimized kiln design and airflow management, resulting in uneven heat distribution, higher emissions, and increased operational costs.

1.4 Objectives of the study

The main objective of the study is to evaluate the energy consumption and perform the performance assessment in Straight-line Natural Draft Brick Kilns: A case study of Bishal Brick Factory, Kapilvastu, Nepal

Specific objectives of the study are

- To analyze the furnace thermal efficiency via. direct and indirect method
- To measure and analyze specific energy consumption
- To develop the mathematical model and simulate the performance of kiln
- To analyze potential fuel-saving interventions and financial analysis

1.5 Limitations

Although a comprehensive study was undertaken to determine the study's outputs, there were certain limitations that arose during the research. These limitations include:

- The research is based on a specific region or case study, which may not fully represent all NDLBKs in different locations

- Real-time monitoring of energy consumption and emissions is limited by available instruments and resources
- Lack of long-term performance data for analyzing seasonal variations
- Alternatives fuels (biomass, agri-waste) are discussed, practical field implementation and long-term may not be feasible within the study period

CHAPTER TWO: LITERATURE REVIEW

Nepal has access to alternative fuels like natural gas and biomass, which can be used in cleaner brick kilns, reducing dependence on traditional fuels like coal or wood. However, the availability and consistent supply of these alternative fuels may vary across different regions, posing challenges for some brick manufacturers. The brick industry also requires management or administrative, skilled, semi-skilled and unskilled human resources. Management and administrative staff are quite sufficient, but the supply of technical staff is limited and is an issue to the industry. About 22 % of workers in the brick industry are Nepalese and the rest are Indian. Skilled technicians for installations, operations and maintenance of the plants are unavailable in the country for the brick industry (Thakuri et al., 2024).

2.1 Nepal's energy landscape

According to Nepal 2022 synopsis report, the country overall energy consumption was 640 PJ. But in energy consumption gradually decrease so in 2023 from the synopsis report the total energy consumption is 532 PJ this seems that there is a technology shifting towards energy efficient machines, appliances. (WECS, 2024)

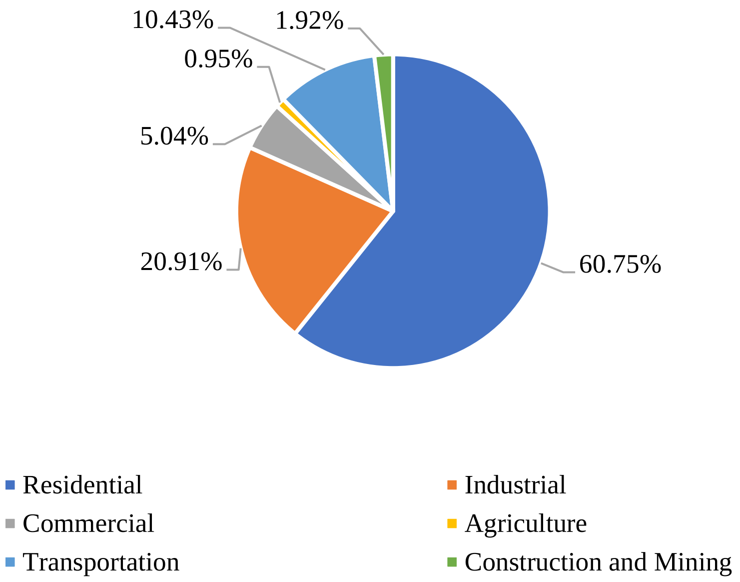


Figure 2.1: Sectoral energy consumption of Nepal in FY 2079/80

2.2 Status of energy usage in industries of Nepal

From this report, industrial sectors, energy consumption, accounting for 20.91% of total energy consumption which is about 111.30 PJ. Among the total energy consumption, coal is the largest contributor, accounting for 30.21% and it is followed by fuelwood which is 28.66%, while electricity comprises 11.57% of the energy mix. Diesel contributes 10.46% and agricultural residues make up 14.68 %. But there are various fuels for small contributions on this sector. In addition to these energy sources, diesel remains a key component in industry, primarily used for providing motive power, such as in the operation of generators. Moreover, diesel and furnace oil are also employed for thermal purposes, especially in boilers, underscoring the continued reliance on traditional fuels within the sector(WECS, 2024).

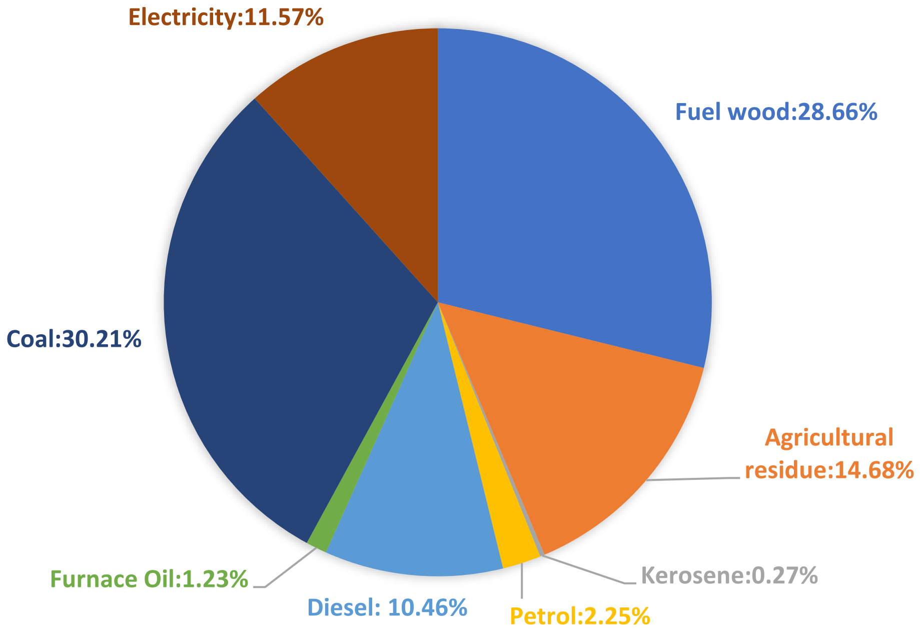


Figure 2.2: Energy consumption of industrial sector in Nepal

2.3 Brick industries in Nepal

Findings of this study reveal that in 2020, There were total of 1236 operational brick kilns spread across 41 districts of Nepal. Madhesh province acquired most of these brick kilns which were concentrated in them. amongst the recorded brick kilns operating in Nepal, most were categorized as either straight-line Fixed Chimney Bull’s Trench Kilns (FCBTKs) or Zigzag FCBTKs . So that the given significant presence of unregistered brick kilns operating informally, actual brick consumption is likely to be even higher. The estimation of annual brick production is shown in Table 2.1.

Table 2.1: Estimation of annual brick production

S.N.	Kiln Type	Kiln composition in %	Number of kilns	Per unit annual production capacity	Total production (in thousands)
1.	Clamp Kiln	7	49	344,000	16,856
2.	MCBTK (Movable Chimney Bulls Trench Kiln)	59	413	4,000,000	1,562,000
3.1.	FCBTK inside Kathmandu Valley	-	103	8,100,000	834,300
3.2.	FCBTK outside Kathmandu Valley	-	135	4,221,000	569,835
4.	VSBK (Vertical Shaft Brick Kiln)	-	26	2,884,615	75,000
5.	Hoffman kiln	-	2	17,500,000	35,000
Total					3,182,991

(Maskey et al., 2013)

In Nepal, production of brick experienced a significant growth of 87.5% in between 2009 and 2012. Currently, around 1000 bricks kilns operate across various regions of the country, collectively manufacturing approx. about 6 billion bricks each year. This accounts for 1.81% of total brick production in South Asia. The bricks are ready for the firing stage after the drying process. Green bricks are directly placed on kiln cars, which transport them through the kiln, during this process, the bricks are heated to a temperature range of 800-1000°C. But brick remain at the peak temperature for about

2 to 5 hours to know the proper body formation before being gradually cooled down to about 50 °C. as per plan. The entire firing process takes around 17 to 25 hours(Almeida et al., 2015).

2.4 Energy consumption in brick industries of Nepal

In brick kilns solid fuels often utilized include coal, wood, sawdust and agricultural leftovers such as mustard stalks, rice husks as well as industrial wastes and byproducts such as discarded rubber tires and pet-coke. In addition to solid fuels, natural gas, diesel, biogas and are all used in fire bricks. In Nepal, coal is the primary fuel for most of the brick kilns, often also mixed with biomass fuels such as bagasse, rice husk, and charcoal. In Nepal bricks kilns consume nearly 30% of the coal used in the country's industrial sector. And majority of the kilns in the country are either fixed chimney bull's trench kilns (FCBTKs) or zigzags kilns, accounting for approx. 70% and 30% of totals kilns respectively. Burning coal for brick production contributes around 1.2% of global anthropogenic carbon dioxide (CO_2) emissions (Nepal et al., 2019).

Most brick manufacturing units in the country rely on handmade green brick production, with minimal mechanization, except for large Hoffman Kilns and a few Fixed Chimney Bull's Trench Kilns (FBTK). This industry is largely seasonal, operating for about 6-7 months from November to May, apart from large, mechanized kilns that have storage facilities for bricks. The process consumes a significant amount of energy, with specific energy consumption varying based on the technology used. The brick industry struggles with inefficiencies, excessive fuel consumption, and high pollution levels, all of which require attention. Energy costs contribute to approximately 30-40% of total production expenses(WECS, 2022). It was observed that kilns owners who adopted the intervention, compared to non-adopters, achieved a 13.2% reduction in fuel consumption. Additionally, they produced 14.1% more high-quality, reduced fuel costs per brick by 19.\%, and increased the expected production per brick by 6.9% (Brooks et al., 2024). From the study it was revealed that pollutant emission from brick kilns vary depending on this type of fuel used for brick firing. Wood fuels release significantly higher levels of carbon-rich pollutant compared to other fuels. In the brick fields of the Greater Khulna region, The ratio of coal-to-wood fuel consumption ratio is 55:45. Despite wood fuel being used a lower rate than coal, it generates more carbon-containing pollutants when burned (Darain et al., 2016). In traditional thermal systems rapid rise in temperature, followed by a stabilization phase, generates an initially high consumption of wood to reach operating temperature. Once the temperature stabilizes at roughly 1000 C, fuel usage drops, but heat losses increase, primarily through radiation, followed by conduction and convention. As energy losses increase, energy efficiency decreases as waste heat dissipates a major percentage of the given energy (Bouchahma et al., 2025).

Depending on the type of clay and the molding technique used, green bricks have a moisture level of between 20% and 25% right after molding. Before the brick is loaded into the firing kiln, the moisture content should be as low as possible throughout the drying process. The amount of fuel needed to remove moisture from the kiln would increase with the amount of moisture in the loaded green bricks. The moisture content of the dried green bricks varies greatly, ranging from 3% to 10%, and this has an immediate effect on SEC(BEE, 2023).

2.5 Specific energy consumption of brick kiln

The specific energy consumption of brick industries inside Kathmandu valley is 1.25 MJ/kg of fired bricks and outside the valleys is also 1.25 MJ/kg of bricks (MinErgy, 2012). The energy consumption varies significantly between different types of kilns so that the consumption of coal for brick kilns during firing is between 11 and 70 tons for firing 100,000 bricks. or that every brick (of 3 kg weight) consumes between 110 to 700 grams of coal (TERI, 2008). From the study of report A roadmap for efficient brick production in Nepal, According to study of (Bashir et al., 2023) the specific energy consumption of zig-zag bricks kilns requires 30% lower than that of conventional FCBTK and in terms of emission in combustion zig-zag kilns lead to approximately 30% lower CO_2 emissions, which can be further reduced by up to 80% when taking into account black carbon emissions and this zigzag technology can result in a 355 decrease in $PM_{2.5}$ emissions. Due to this replacement of FCBTKs with zigzag method is better options for fuel consumptions scenario along with quality of brick. The specific thermal energy consumption as mentioned by the energy audit guidelines of WECS is found to be 0.95 while the industry has the specific energy consumption of 0.75 (WECS, 2022),

2.6 Performances of brick kilns

The performance evaluation of brick kilns based on observed values revealed the following trends: For carbon monoxide (CO) emissions, 23% of the kilns were rated as good or moderately good, while 87% fell into the fair, moderately poor, or poor categories. In terms of carbon dioxide (CO_2) emissions, 56% were classified as good or moderately good, whereas 44% ranged from fair to poor. For PM_{10} particulate matter, 33% of the kilns demonstrated good to moderately good performance, while 67% were rated from fair to poor. Similarly, $PM_{2.5}$ measurements indicated that 28% of the kilns performed within the good to moderately good range, while 72% were categorized as fair to poor (Melo-Monterrey et al., 2025).

The concentration of suspended particulate matter (SPM) emissions in Zigzag kilns during monitoring ranged from 30 to 260 mg/Nm^3. Apart from SPM emissions, a Zigzag kiln emits 20% less CO_2 emissions and 75% less BC emissions as compared to those of an FCBTK (Lalchandani & Maithel, 2013). Both kiln technology and operational characteristics influence energy efficiency. To effectively calculate the quantity of energy consumed, brick production must be estimated at the subnational level, categorizing it by the individual technologies and operational features used (Tibrewal et al., 2023).

From the modeling and optimizing cooking zone of furnace to predict optimal feeding location and fuel with secondary air mass flows, to minimize energy consumption. Mathematical models were utilized to simplify heat transfer with which coal and pulverized coal combustion, gas flow phenomena. The results indicated that the overall energy balance forecasts an energy consumption of 3385 kJ/kg of brick, or 2.75 more than the optimum results (Kaya et al., 2009). As fire temperature rises from 700°C to 1100°C, brick strength increases and water absorption decreases. In the same temperature range, the bricks density and firing shrinkage increase. Extending the firing length beyond the required period has no substantial effect on the measured attributes: hence excessively extended firing times should be avoided to save both time and energy (Karaman Tokat Gaziosmanpaşa Üniversitesi et al., 2015).

A study said that the compressive strength of industrial bricks and those made without solid media were 3.03 N/mm^2 and 3.32 N/mm^2 respectively. When sandstone sheets and alumina balls were used, the pressure increased to 5.95 N/mm^2. This solid medium could be used to create stronger bricks. This simple approach suggests novel uses for brunt clay bricks, including, retaining walls, fireplaces and industrial applications (Pattiya, 2023). Clay bricks are fired in high-temperature kilns during the energy-intensive brick-making process. Each kilogram of fired brick can be produced using a wide range of energy, from as little as 0.5 MJ/kg in sophisticated kiln technologies to as much as 5 MJ/kg in the least effective conventional kilns (Olsson et al., 2025).

2.7 CFD modelling of brick-kiln furnaces

CFD has been shown to be a dependable approach for simulating the combustion process inside a kiln. There are few studies that employ CFD simulation to assess a tunnel kiln's performance, and even fewer that concentrate on fixed chimney kilns and zigzag kilns.

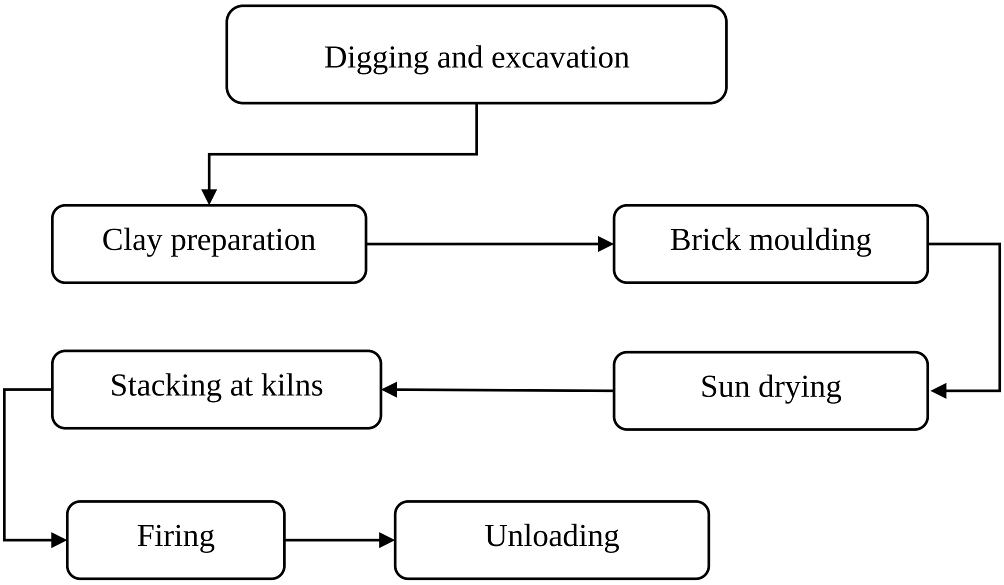
(Tasnim et al., 2019) performed a 3-D CFD investigation of conventional brick kilns using ANSYS Fluent to resolve temperature profiles, outlet species mass fractions (CO_2, NOx), and velocity fields; they used RANS turbulence and combustion models to produce a validated picture of kiln thermofluidic behavior and identify retrofit opportunities. This is a practical, widely cited reference for brick-kiln CFD in South Asia. (Kaya et al., 2009)modelled and optimized the firing zone of a tunnel kiln, focusing on optimal injection locations and mass fluxes of pulverized fuel and secondary air; the work shows how parametric CFD studies can minimize fuel costs and is useful for defining injection and feeding strategies in coal-fed brick kilns. (Refaey et al., 2018)experimentally and numerically investigated enhancements in the cooling zone of tunnel kilns (guide vanes) to augment convective heat transfer — illustrating the combination of experimental validation with CFD for kiln retrofit design.

Likewise, from the study a transient CFD combustion study of a natural-gas-fired kiln using a PDF flamelet combustion model coupled with the DO radiation model. Their work clearly shows the improved prediction of flame chemistry and pollutant formation including NOx and CO (Štoller & Dubec, 2017). For combustion, the non-premixed mixture-fraction model combined with finite-rate/eddy-dissipation coupling that has been widely adopted because brick kilns are primarily operated under diffusion flame combustion conditions (Kaya et al., 2009). While doing simulation radiation heat transfer, which dominates kiln heating, is typically modeled using either the P1 model or the Discrete Ordinates model, both of which have been validated for high-temperature furnace flows (Beyene et al., 2018). For the investigation of problem of energy consumption and production process the flow characteristics and heat transfer around brick model settings are very important. The present paper introduces a numerical investigation of convective heat transfer for lattice settings in brick tunnel kiln. A numerical CFD analysis using the ANSYS-FLUENT package is used to simulate convective heat and fluid flow inside the cooling zone of the tunnel kiln and any other brick kiln (Refaey et al., 2021).

2.8 Process flow diagram of brick making process.

The brick production process involves several key stages. This stage helps to know how a brick was made from raw mud or clay into complete form. First, raw materials like clay or mud are extracted by digging and prepared by removing impurities and blending them in precise proportions. The prepared clay is then shaped into bricks through extrusion, where the material is forced through a die and cut into individual units. After molding, the bricks undergo a drying process in open sky to remove excess moisture for certain intervals of time, which is important factor to prevent cracking during firing, and it helps for less energy consumption during firing. Finally, the dried bricks are shifted towards kilns by transportation through workers and bull carts and then fired in kilns at high temperatures, there are three parts in kilns that impart strength and durability to the finished product. Each of these stages is essential to producing high-quality bricks suitable for construction purpose (WECS, 2022). The general process flow diagram of brick industries is given in Figure 2.3 (WECS, 2024)

Figure 2.3.



(WECS, 2024)

Figure 2.3: Process flow diagram of brick industries

From the study it was found that 97% of brick kilns have been operating continuously for at least 20 years. Additionally, 65% of these kilns employ more than 5 workers. Regarding respondents' demographics, 85% identified as men and 15% as women. Age distribution 27% were between 18 and 39 years old, 56% between 40 and 59 years old, and 17% were between 60 and 79 years old. In terms of the educational background, 35% of business owners had completed primary education, 53% had secondary education, 42% had high school education, 8% held a bachelor's degree, and 4% had a postgraduate degree (Melo-Monterrey et al., 2025).

CHAPTER THREE: METHODOLOGY

This research conduct through a review of literature on Nepal’s brick industry focusing on emission estimation and energy efficiency and technological advancements. The methodology has been designed to capture real- world operating data, develop present kiln model, and perform detailed thermal and flow analysis. The research process is mainly divided into four steps. Firstly literature review has performed to identify the exiting research gaps to understand the parameters that help in analyzing the energy consumption patterns and various model that are able to know how the combustion process occurs and what are the parameters that has need to identify the while doing simulation of kilns, and to identify the various parameters for the energy saving opportunities in brick kilns. After this collection of primary data has been done from a site visit by using various instruments and in-person with industry experts and stakeholders of the brick factory for the analysis energy consumption, energy saving procedures. To validate the results obtained from analysis the findings were compared with another similar research. Additionally, the heat flow pattern in combustion of kiln computational fluid dynamics (CFD) has been used as software for better results. The overall methodology of this research to be adopted is shown in Figure 3.1.

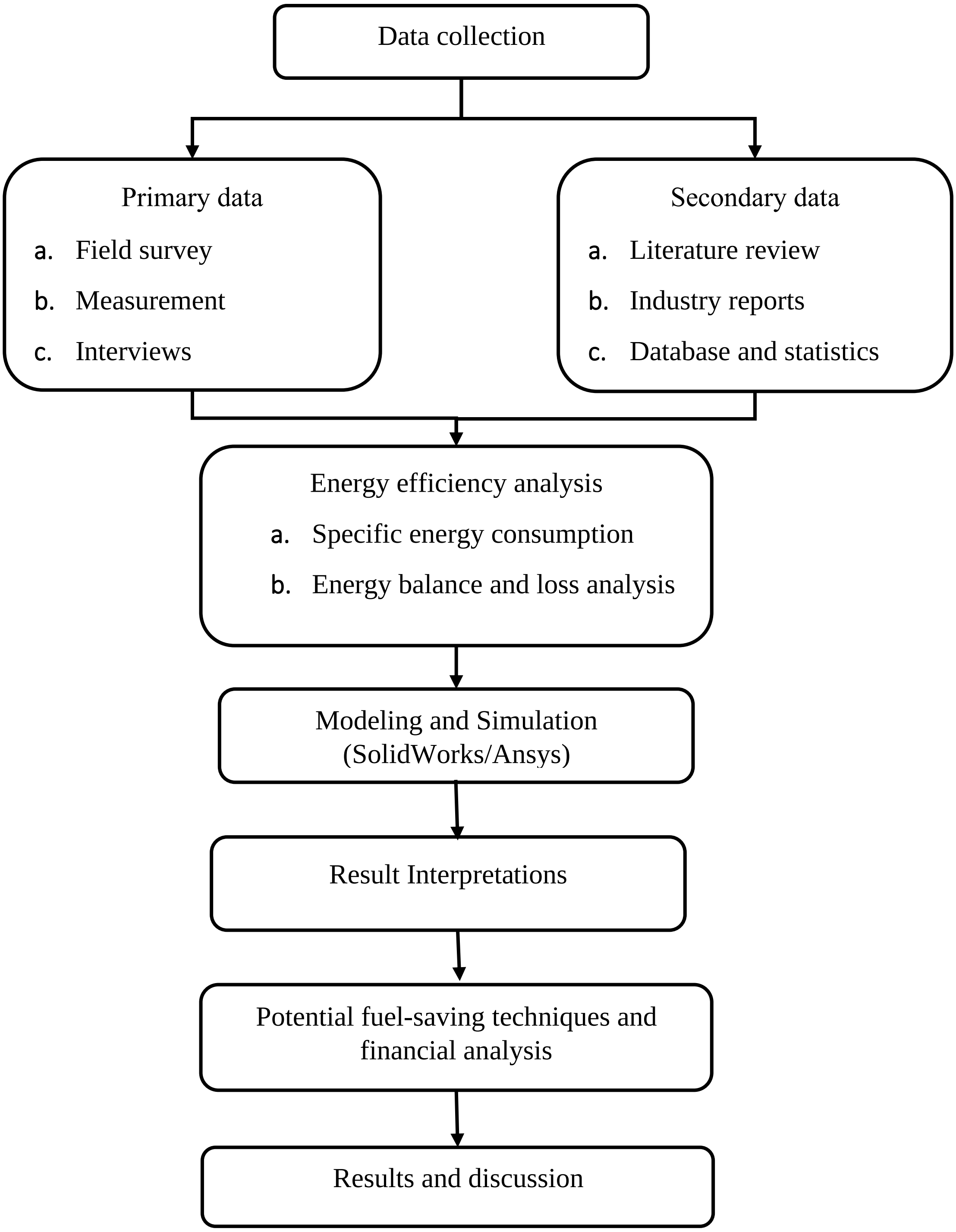


Figure 3.1: Research methodology

3.1 Data collection

For the research on analysis of this study both primary and secondary data collection methods have been employed to know the complete assessment of natural draft straight line bricks kilns. The primary data are gathered directly through on-site measurements observations, and structured interviews with kiln operators and workers of Bishal brick factory located at Maharajgunj Municipality-3, Kapilvastu. Parameters such as fuel consumption, brick production rate, kiln temperature distribution, and stacking patterns were recorded to understand the operational efficiency and energy usage of the kiln. And secondary data has been collected by literature review of various reports, and industry publications to provide contextual information on brick kiln energy consumption, standard efficiency benchmarks, and previous energy-saving interventions. The combination of these data collection methods helps that the study captured both accurate site-specific information and relevant background knowledge, enabling a comprehensive assessment of energy consumption and potential energy-saving opportunities in the kiln. Conducting the overall efficiency analysis in brick industry, various tools were used for data collection for identification of temperature, air flow measurement, combustion of fuel and various other parameters. Data collection Instruments**:** Accurate measurement of energy usage requires specialized instruments, including:

- Flue gas analyzer: To know the combustion of fuel in the firing chamber in brick kiln
- Thermal gun temperature: Employed to track temperature profiles within kilns, ensuring optimal thermal efficiency and identifying potential energy losses.
- Anemometer: To identify the velocity flow of air inside the brick kiln
- Measuring tape: To measure the various dimensions of brick kilns with diameter of chimney hole. stacking of bricks, dimension of air flow inside the kilns etc.
- Moisture meter: To measure the moisture content of raw clay and molded bricks before firing
- Weighing machine: To measure the quantity of raw materials and finished bricks

Secondary data were collected through literature reviews of various research papers related to the brick kilns. By analyzing all the previous data from the literature that helps to compare with the existing results.

3.2 Specific energy consumption

The calculation of specific energy consumption (SEC) and energy balance in the brick kiln has been carried through the data of field measurements and analytical estimations. The kiln operational parameters, including type, production capacity, running hours, and fire cycles have been recorded as part of the primary data and daily measurements of fuel used were made, and proximate analysis are calculating its calorific value. The SEC of the kiln has determined using the ratio of total fuel energy input to the mass of fired bricks produced. The specific energy consumption of brick kiln calculated by using the relation:

$$\text{SEC} = \frac{m_f \times GCV}{M_{bricks}} \qquad \text{...(3.1)}$$

Where,

- m_f = the mass of fuel consumed (kg)
- GCV = the gross calorific value of fuel (MJ/kg)
- M_{bricks}= total mass of fired bricks produced (kg)

(Eil et al., 2020)

3.3 Efficiency analysis of brick kilns

The efficiency of the brick kiln has analyses by assuming the kiln during the time of combustion in a furnace along with stacking of bricks using the mixture of coal and saw dust as the source of fuel. Data on daily fuel consumption have been recorded during steady-state operations, the temperature of flue gas, the concentration of carbon dioxide and oxygen were measured to track the thermal conditions inside the kiln. To assess heat losses by radiation and convention, infrared thermometers are used to measure the surface temperature of the kiln walls and roof. To compare the overall energy input from fuel with the usable energy absorbed by bricks and other losses such as fuel gas, wall radiation, partial combustion, and cooling, an energy balancing approach was used to calculate efficiency. The efficiency calculation of the furnace has done both in direct and indirect method.

In the direct method the energy efficiency of a brick kiln is calculated by comparing the useful energy output to the total energy input supplied by the fuel. The useful energy output is considered as the energy required for the combustion of brick which were mass of fuel required and fuel gross calorific value, while the total energy input has been calculated from the mass of fuel consumed and its gross calorific value.

$$Furnace\ efficiency = \frac{Q_{useful}}{(q \times GCV)} \times 100 \qquad \text{…(3.2)}$$

Where,

- Q_{useful} = useful heat absorbed by the bricks and associated processes (kJ/h)
- q = fuel mass flow (kg/h)
- GCV= gross calorific value of the fuel (kJ/kg)

To compare the overall energy input from fuel with the usable energy absorbed by bricks and other losses such as fuel gas, wall radiation, partial combustion, and cooling, an energy balancing approach was used to calculate efficiency. The efficiency calculation of the furnace has been done both in direct and indirect method.

The main heat losses inside the brick furnace include moisture content in fuel, loss due to hydrogen, dry flue gas losses, heat loss due to opening, heat loss due to unburnt carbons and radiation and other unaccounted losses (Efficiency, 2022).

The heat loss due to evaporation of moisture present in the fuel is given in equation…(3.3).

$$\%\, Heat\ loss\ (L_2) = \frac{M \times \{584 + C_p \times (T_{fg} - T_{amb})\}}{GCV\ of\ fuel} \times 100\% \qquad \ldots(3.3).$$

where, M = kg of moisture present in 1 kg of fuel oil, T_{fg}= flue gas temperature, °C, T_{amb}= ambient temperature, °C, GCV = general calorific value of fuel, kCal/kg

The heat loss due to evaporation of water formed due to hydrogen is given in equation …(3.4).

$$\%\, Heat\ loss\ (L_3) = \frac{9 \times H_2\{584 + C_p \times (T_{fg} - T_{amb})\}}{GCV\ of\ fuel} \times 100\% \qquad \ldots(3.4)$$

where H_2= kg of H_2 in 1 kg of fuel

Similarly, the heat loss due to dry flue gases is given in equation…(3.5).

$$\%\, Dry\ flue\ gas\ loss\ (L_1) = \frac{m\ \times\ c_p\ \times\ \Delta T}{GCV\ of\ fuel} \times 100\% \qquad \ldots(3.5)$$

where, m = mass of flue gas (air + fuel), C_p = specific heat capacity, ΔT = temperature difference

Similarly, the openings of the furnace are also responsible for heat loss, which is maximum losses occurs. The heat loss due to furnace openings is given by equation … (3.6).

$$\% \, Heat\ loss\ (L_4) = \frac{B \times A \times \propto \times \, \sigma}{fuel\ feeding\ rate \times GCV\ of\ fuel} \times 100\% \qquad \ldots (3.6)$$

The heat loss through furnace skin is also responsible for reducing the efficiency of the furnace. The furnace skin heat loss is given by equation… (3.7).

$$\% \, Heat\ loss\ (L_5) = \frac{Heat\ loss\ \times Area\ of\ furnace}{fuel\ feeding\ rate \times GCV\ of\ fuel} \times 100\% \qquad \ldots (3.7)$$

The efficiency of furnace is then calculated using indirect method by using equation… (3.8).

$$Efficiency\ of\ furnace\ (\%) = 100 - L_1 - L_2 - L_3 - L_4 - L_5 \qquad \ldots (3.8)$$

3.4 Modeling and numerical simulations

The computational fluid dynamics (CFD) model has been simulated by the combustion process, heat transfer, and air flow inside the brick kiln. The modeling approach consisted of numerous essential stages, including geometry development, mesh generation, boundary conditions specification. This simulation has been performed by using ANSYS Fluent, which solves the governing equations of mass, momentum, energy, and species transport for three dimensional turbulent, reacting flow.

3.5 Geometry creation

The first step while doing simulation helps in establishing the computational domain. It involves creating the 3D geometry of model. The geometry of firing zone of the straight-line natural draft brick kiln at Bishal Brick Factory was created in SolidWorks 2024 including all features with firing channel, brick stacking arrangement, and inlet/outlet ports. In the designed only the firing zone is visualized to know how the combustion occurs and to watch how the temperature rises. Only the heating and soaking zones have been included in the geometry, where combustion takes place and bricks absorb most of the heat. To replicate flue gas exhaust and natural draft, the model was developed using on-site measurements, length and breadth of onsite measurement but height of stacking of bricks was considered as low while designing the model.

3.5.1 Brick kiln geometry

For modelling the kiln geometry, a raw brick with a dimension of 220 mm length, 110 mm breadth and height of 60 mm are used for stalking for firing the furnace the initial dimension as specified here is subjected to changes with simulation succession. The length and width of a typical kiln geometry have been taken as 2532 mm × 2300 mm and height of 542 mm as shown in Figure 3.2 and Figure 3.3. The size used for modeling has been same. This dimension has been chosen from a space constraint point of view, which is going to remain unvarying in subsequent trials of other dimensional changes. The height of the kiln is around 442 mm, which is also taken as another unvarying dimension. In this geometry around 704 bricks are stacked with four different stacking patterns for straight-line and 740 in retrofit zig-zag flow and these stacking have the distance of around 107 mm apart.

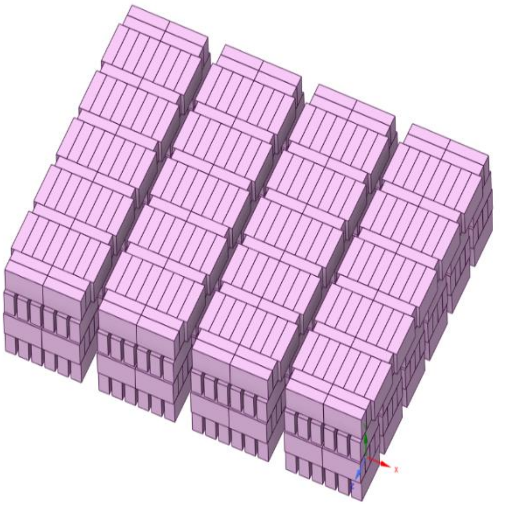


Figure 3.2: Geometry of straight-line flow brick kiln

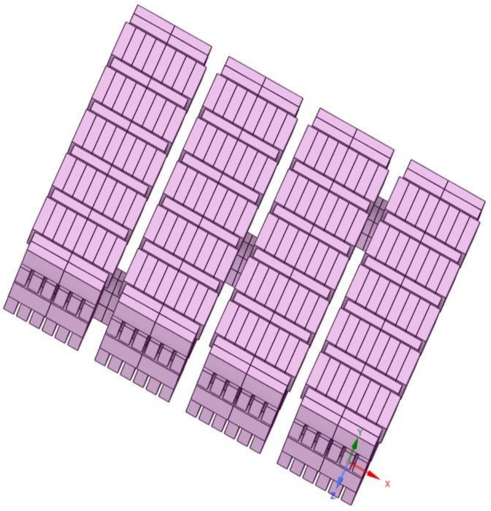


Figure 3.3: Geometry of zig-zag flow brick kiln

3.5.2 Mesh generation

Meshing transforms continuous geometry into a discrete grid for numerical solutions. After discretizing the computational domain into a structured and unstructured mesh, a mesh independence analysis has been conducted to make sure grid resolution had no effect on the outcomes. The finite volume approach is being used to solve the governing equations of mass, momentum, energy, and species transport. Fuel characteristics including calorific value, volatile matter, and elemental composition have been used as input parameters in the eddy dissipation of coal calculator species transport model of combustion. P1 radiation model is used to simulate radiation heat transport while taking wall emissive and gas radiation into account. Density, specific heat, and thermal conductivity are among the physical characteristics of the bricks and kiln walls that had assigned based on values from experiments or literature. The volume of the selected kiln geometry is discretized into finite elements called "cells" using appropriate meshing tool, ANSYS 2024 Mesh. These cells are the fundamental units of calculation, as all the algebraic equations derived are to be solved at each node of these cells. In hexahedral mesh, nodes are generated at equal distances giving quicker but accurate results. Local body sizing and face sizing have been done to improve the number of nodes and elements. shows the distribution and quality of meshing generated by ANSYS Mesh. Both the straight-line and retrofit zig-zag flow pattern mesh has been shown in Figure 3.4 and Figure 3.5 respectively.

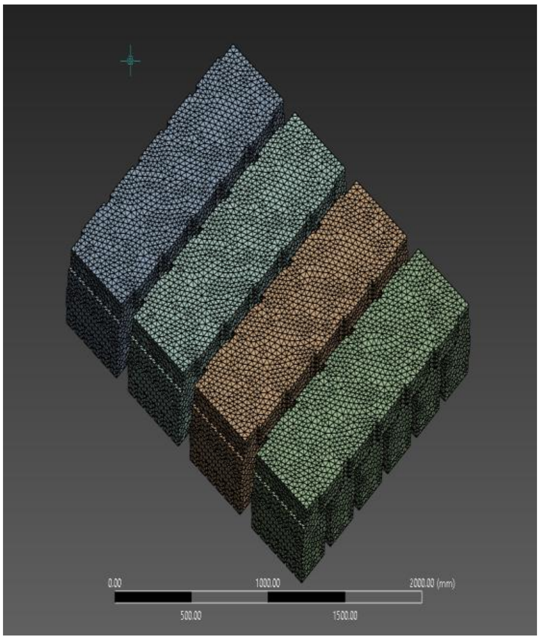


Figure 3.4: Mesh generation of straight-line brick stacking

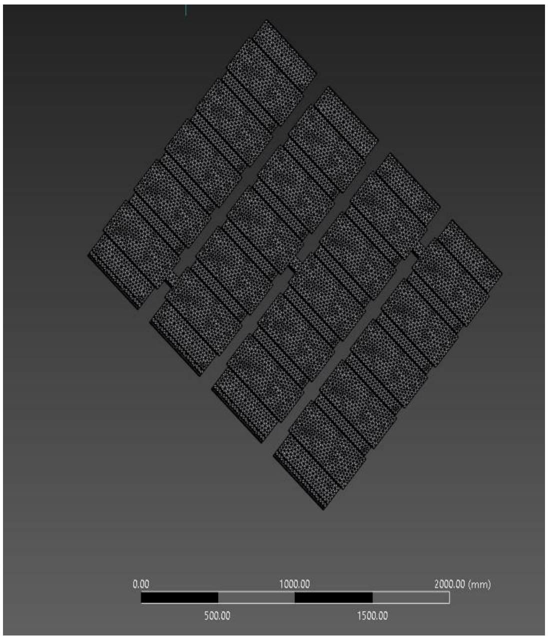


Figure 3.5: Mesh generation of after retrofit to zig-zag flow brick stacking

Table 3.1: Specification of mesh

Parameters	Straight-line	Zig-zag
Nodes	252,654	540,556
Elements	1,140,447	2,506,018
Element size	20 mm	20 mm
Max. element size	25 mm	20 mm
Min element size	15 mm	20mm
Growth rate	1.2	1.2
Smoothing	Medium	Medium
Maximum layers	10	5

3.5.3 Mesh controls

Sometimes automatically generated mesh does not have enough nodes or elements. In that case the number of nodes and elements have been increased by local and global mesh controls. Global mesh settings can be controlled using the following options: sizing, defeaturing, statistics, advanced options etc. Advanced sizing function was used to control the size of mesh. This has been important tool to generate appropriately sized mesh required for faultless and effective simulation. Advanced sizing function controls the growth and distribution of mesh in important regions of high curvature or proximity of surfaces.

3.6 Setup for modeling

The simulation works by numerically solving fundamental conservation laws across every cell of the mesh:

a. **Continuity Equation (Mass Conservation):** Helps to know that mass has neither created nor destroyed within the computational domain. For the flowing flue gas, this dictates that the mass flow rate entering any control volume must equal the mass flow rate exiting it.

b. **Navier-Stokes Equations (Momentum Conservation**): These equations have been solved to determine the fluid velocity and pressure fields. They represent Newton's Second Law ($\Sigma F = ma$) applied to the fluid element, accounting for forces like pressure gradients, viscous shear stresses, and gravity.

c. **Energy Equation (Energy Conservation):** This has been solved simultaneously in both the fluid and solid zones to model the Conjugate Heat Transfer (CHT). It accounts for all energy fluctuations:

Conduction: Heat transfer within the solid bricks and refractory walls.

Convection: Heat transfer between the hot flue gas and the brick surfaces.

Radiation: Heat transfer due to electromagnetic waves, which was crucial in the high-temperature environment.

a. **Model used in Ansys**

During simulation energy has on which helped in combustion, heat transfer, and temperature rise cannot occur without it When coal and sawdust burn inside the kiln, they release a large amount of heat, and Fluent calculate this heat only through the energy equation.

Energy equation (Fluent)

$$\rho \frac{\partial h}{\partial t} + \rho \vec{v} \cdot \nabla h = \nabla \cdot (k_{\text{eff}} \nabla T) + S_h \qquad \text{….(3.9)}$$

Where each term means:

ρ = density
h = enthalpy
t = time
v = velocity vector
T = temperature
k_{eff}= effective thermal conductivity
(conduction + turbulence effect)
S_h= heat source term

Fluent often expands it as:

$$\rho \frac{Dh}{Dt} = \nabla \cdot (k_{\text{eff}} \nabla T) + S_h \qquad \text{….(3.10)}$$

In combustion (brick kiln) the source term is important:

$$S_h = \sum(\dot{\omega}_i \, h_i) + S_{\text{radiation}} + S_{\text{DPM}} \qquad \text{….(3.11)}$$

Viscous model

The turbulent flow of hot flue gases in the firing zone of the brick kiln has been simulated using the turbulent viscous model in ANSYS Fluent. Due to high-temperature gradients and natural draft, the flow inside the kiln was highly chaotic and required a turbulence model to capture fluctuations and eddies. The standard k-ε model was selected, which solves two transport equations: turbulent kinetic energy (k) and turbulent dissipation rate (ε). Turbulence parameters, such as turbulence intensity**,** and turbulence viscosity, are defined at the inlets and walls. Wall functions were applied to account for near-wall turbulence effects. This model made it possible to accurately predict the firing zone's turbulent mixing, recirculation zones, and fluctuations—all of which have a direct impact on heat transfer and energy distribution.

Standard k-ε model equation

$$\frac{\partial}{\partial t}(\rho_m k) + \nabla(\rho_m \vec{v}_m k) = \nabla \frac{\mu_t}{\sigma_k} \nabla k) G_{k,m} + G_b - \rho_m \epsilon \qquad \text{....(3.12)}$$

$$\frac{\partial}{\partial t}(\rho_m \epsilon) + \nabla(\rho_m \vec{v}_m \epsilon) = \nabla \frac{\mu_{t,m}}{\sigma_\epsilon} \nabla \epsilon) \frac{\epsilon}{k} (C_{1,\epsilon} G_{k,m} - C_{2,\epsilon} \rho_m \epsilon \qquad \text{....(3.13)}$$

where μ_t represents the turbulent viscosity, v_m the velocity, and ρ_m the mixture density. The production of turbulent kinetic energy has been represented by $G_{k,m.}$ C is the linear anisotropic phase function coefficient, k is the turbulent kinetic energy, ϵ is the turbulent dissipation rate. σ_k and $\sigma\epsilon$, has scattering coefficients of k and ϵ, and t is the time (Tasnim et al., 2019).

Radiation model

Due to extremely high temperatures up to (1000 °C or more), thermal radiation have the dominant heat transfer mode. Heat transfer in the kiln occurs not only through convection but also via thermal radiation from high-temperature brick surfaces and flue gases. The P1 radiation model has been used in ANSYS Fluent to simulate this effect. This model calculates radiative heat exchange in participating media and accounts for absorption, emission, and scattering of thermal radiation. The radiation model, coupled with the turbulent flow solution, provided detailed insight into temperature distribution and energy losses in the firing zone. For radiation P1 model has been be used.

P1 model Equation

$$\frac{dI(\vec{\text{r}}.\vec{s})}{dx}+(\alpha+\sigma_s)I(\,(\vec{\text{r}}.\vec{s})=\alpha n^2\frac{\sigma T^4}{\pi}+\frac{\sigma_s}{4\pi}\int_0^{4\pi}I(\,(\vec{\text{r}}.\vec{s})\varphi\,(\vec{s}.\vec{s})d\Omega \qquad \text{....(3.14)}$$

where T is the kelvin local temperature, σ is the Stefan-Boltzmann constant, n is the coefficient of excess air, I is the radiation intensity, r is the position vector, s is the scattering direction vector, s is the direction vector, α is the absorption coefficient, and is the scattering coefficient, G is the incident radiation, C is the linear anisotropic phase function coefficient, t is the time, φ is the phase function, and **Ω** is the solid angle.

b. Heat transfer calculations

Heat was transmitted by convection from the hot gases to solid surfaces of brick through movement of hot gases. All the system is operated in steady state conditions. Following that, three measurements and recordings of each of the following parameters are made: pressure, temperature, velocity. Using these average values, energy balance is performed to get the local convective heat transfer coefficient for the settings in question using …. (3.15).

$$h_i=\frac{Q_i}{A_b(T_{s,i}-T_a)}=\frac{V_iI_i}{A_b(T_{s,i}-T_a)} \qquad \text{.... (3.15)}$$

where the index i, refers to either longitudinal or transversal brick in the middle or the right column (near walls) of the setting. Multiplying each local heat transfer coefficient by the area of bricks in that direction yields the average heat transfer coefficient, which is then connected to the setting's overall brick area.

$$h_{av}=\frac{\sum h_i}{\sum A_i} \qquad \text{... (3.16)}$$

The average velocity in the metering section and the area ratio of the test and metering sections is used to calculate the superficial velocity (u) in the empty test section.

Combustion calculation

For pure carbon

$$C+O_2\rightarrow CO_2$$

If oxygen hasn't enough:

$$2C + O_2 \rightarrow 2CO$$

Combustion of hydrogen

$$2H_2 + O_2 \rightarrow 2H_2O$$

Combustion of nitrogen

$$N + N \rightarrow N_2$$

Notation (per 1 kg dry fuel basis) mass fractions (kg/kg fuel) be $w_C, w_H, w_O, w_N, w_S$for C, H, O, N, S. (Ash and moisture handled separately.)

Stoichiometric air fuel ratio

$$\text{Air fuel ratio} = \frac{\mathrm{m_{air}}}{\mathrm{m_{fuel}}} \qquad \dots (3.17)$$

O_2 required (kg O_2 per kg fuel)
The stoichiometric oxygen requirement formula (kg O_2 per kg fuel) is:

$$m_{O2} = \frac{8}{3}C + 8H + S - O$$

Theoretical air (kg air/kg fuel):

$$m_{\text{air,th}} = \frac{m_{O_2,\text{stoich}}}{Y_{O_2,\text{air}}} \qquad \dots (3.18)$$

with $Y_{O_2,\text{air}} \approx 0.233$ mass fraction

Use actual air = (1 + excess air%) × $m_{\text{air, th}}$.
Calculate % excess air

$$\%\ \text{Excess air} = \left(\frac{\text{Actual air}}{\text{Theoretical air}} - 1\right) \times 100 \qquad \dots (3.19)$$

For efficiency calculatio by suing emperical inverse relation

$$\eta_2 = \eta_1 \times \frac{1 + \mathrm{EA_1}}{1 + \mathrm{EA_2}} \qquad \dots (3.20)$$

EA_1= Excess air at existing condition

EA_2= Excess air after increasing velocity

Boundary conditions

This model has been applied with appropriate boundary conditions: the fuel-air mixture was specified at the inlet with turbulence parameters, and the outlet was set as an atmospheric pressure outlet, and kiln walls were treated as no-slip surfaces with wall functions for turbulence. So, the process starts with inlet conditions, where there must specify the velocity or mass flow rate, temperature (which may be ambient or preheated), and species mass fractions of the combustion air and fuel. Simultaneously, Outlet conditions were defined, most commonly as a pressure outlet set to ambient pressure, to allow the flue gas to exit realistically. Wall conditions dictate the fluid-solid heat exchange: the inner brick and kiln surfaces use the coupled wall condition to know the heat transferred from the gas equals the heat conducted into the solid (a requirement for Conjugate Heat Transfer), while external kiln surfaces use Convection/Radiation to model heat loss to the ambient environment. Finally, to optimize computational resources while maintaining geometric integrity, Symmetry or Periodic conditions has been applied to exploit repetition or mirroring within the kiln structure.

3.7 Potential fuel-saving techniques

The methodology for evaluating fuel-saving techniques in a straight-line natural draft brick kiln combines baseline assessment, simulation, and economic analysis. Baseline data, including fuel flow rate, air velocity, flue-gas temperature, and ambient conditions, are collected from field measurements, and the lower heating value of the coal–sawdust mixture has been determined. An energy balance of the kiln is prepared to quantify useful heat transferred to bricks, flue-gas losses, and wall losses. Based on these observations and literature review, potential fuel-saving measures are identified, such as reducing excess air, improving wall insulation, sealing leakages, optimizing fuel feeding, preheating combustion air, recovering flue-gas heat, maintaining uniform fuel particle size, proper brick stacking, and pre-drying bricks.

Emission analysis

Analysis of emissions has been carried out by calculation of CO_2 emissions this emission is calculated by combustion emission calculation which is presented below

$$CO_2 \text{ (ton /year)} = \text{Fuel mass / year} \times \text{emission factor of } CO_2$$

3.8 Financial analysis of implementation of new models

The improvement in useful heat has converted into fuel savings using the fuel’s lower heating value, and annual savings are estimated based on operating hours. An economic analysis has been performed for each technique, including capital cost, operational cost, payback period, and net present value, while sensitivity analysis assesses the impact of variations in fuel price, equipment cost, and operating conditions. This combined technical and economic assessment ensures that the most effective and feasible fuel-saving techniques are identified for implementation.

Practical measures to reduce fuel consumption in the studied straight-line natural-draft brick kiln, quantifies potential fuel savings using CFD results and energy balances, and evaluates the economic feasibility of each measure using discounted payback period, net present value (NPV).

Formula for present value of cash flow

For each year t:

$$PV_t = \frac{CF_t}{(1+r)^t} \qquad \text{…(3.21)}$$

Where:

- PV_t= Present value of cash flow in year t
- CF_t= Cash flow in year t
- r= discount rate
- t= year (1, 2, 3…)

Discounted payback period formula

There is no single closed-form formula because we must accumulate discounted cash flows year by year.

But the general expression is:

$$\text{DPP} = n + \frac{\text{Remaining unrecovered investment at end of year } n}{\text{Discounted cash flow in year } n+1} \qquad \text{…(3.22)}$$

Where:

- n = last year where cumulative discounted cash flow is still negative

The fraction determines how much for the next year is required to fully recover the investment.

Net present value (NPV) formula

Use annuity cost

$$\text{AF} = \frac{1-(1+r)^{-N}}{r} \qquad \text{…(3.23)}$$

Where:

- AF = annuity factor
- R= interest rate
- N= project lifetime (years)

- NPV= -capital cost + Net annual saving × AF

3.9 Marginal abatement cost

Marginal abatment cost is given by

$$MAC = \frac{Cost\ of\ Mitigation - Baseline\ Cost}{Baseline\ emissins - Mitigated\ emissions} = \frac{Ca - Cb}{Eb - Ea} \qquad \ldots(3.24)$$

(Vogt-Schilb & Hallegatte, 2014)

Where:

C_a= Cost of abatement measure (capital + operating)

C_b= Baseline cost (without mitigation)

E_b= Emissions after implementing the measure (tCO_2/year)

E_a= Emissions in baseline scenario (tCO_2/year)

Units: NPR/tCO_2

Benefit-cost ratio (BCR) formula

$$\text{BCR} = \frac{\text{Present value of benefits (PVB)}}{\text{Present value of costs (PVC)}} \qquad \ldots(3.25)$$

Where:

- PVB = Sum of all discounted benefits
- PVC = Sum of all discounted costs

Decision rule

- BCR > 1 → Project is economically viable
- BCR = 1 → Project breaks even
- BCR < 1 → Project is not viable

CHAPTER FOUR: RESULTS AND DISCUSSION

This chapter describes the outcomes of specific energy consumption and efficiency analysis of brick kiln and computational modeling aimed at gaining a deeper understanding of heat transfer in the brick kiln. Additionally, Experimental measurements have been included to verify the computational models, along with proposed energy saving opportunities in brick factory.

4.1 Energy consumption of brick kiln

In this industry coal crusher runs for 4 hours for crushing 25 tons of coal and mixing it with coal and saw dust at the ratio of 80:20 ratio and firewood consumed at total of 80 metric tons and coal used during 1 complete firing cycle is 80 tons. At that case about 8,75,000 pieces of brick was produced. There has been total of 4 cycles for production over a year. The specific energy consumption of the industry has been given in Table 4.1

Table 4.1: Specific energy consumption of the industry

Particulars	Value
Annual coal consumed (kg)	320,000
Annual saw dust consumed (kg)	80,000
GCV of coal (MJ/kg)	23.8
GCV of sawdust (MJ/kg)	18
Annual energy consumed by coal (MJ)	7,616
Annual energy consumed by saw dust (MJ)	1,440
Annual energy consumed by furnace (MJ)	9,056
Annual bricks produced (pcs)	3,500,000
Mass of each brick (kg)	2
Total mass of bricks (MT)	7000
Specific thermal energy consumption (MJ/kg of bricks)	1.29

The energy consumption during the production of bricks is 1.29 MJ/kg of bricks, which is relatively efficient compared to other research papers. According to report prepared by SAARC Energy Center the specific energy consumption, in Fixed chimney straight line natural draft brick kilns is 1.0 to 1.4 MJ/kg of fired bricks (Maskey et al., 2013).

This might be due to use of Coarse-grained coal and a proper mixture of coal and saw dust, implementation of straight-line technology in firing with double man firing.

4.2 Efficiency analysis of brick kiln

During the combustion various parameters including temperature distribution, flue gas velocity, and specific energy consumption, were assessed in the kiln performance analysis. Fuel is fed into feeding zone through holes in a diameter of 15 cm. Generally, there are 3 to 4 rows are fed at a time by double man feeding system. Coal came contact with hot gases and combustion takes place. Feeding coal is done every 15 minutes interval of time for 5-10 minutes, the temperature profile increased gradually in the preheating zone before peaking in the fire zone. The gross calorific value of coal and saw dust are 23.80 MJ/kg and 18 MJ/kg respectively (WECS, 2024). Similarly, areas with denser brick sets showed a greater pressure drop across the kiln, suggesting that structural layouts affect airflow resistance. Table 4.2 shows the performance analysis of brick kiln is carried out in both direct and indirect methods.

Table 4.2: Performance analysis of furnace in direct method

Parameters	Value
Types of fuel used in furnace	Coal and saw dust
Bricks mould (pcs)	3,500,000
Weight of a brick (kg)	2
Total weight (MT)	7,000
Specific heat capacity brick (kJ/kg°C)	0.84
Chimney height (m)	30
Temperature difference (°C)	580
Output energy (MJ)	3,410
Fuel coal (MT)	320
Fuel sawdust (MT)	80
GCV of coal (kJ/kg)	23.80
GCV of sawdust (kJ/kg)	18
Input energy (MJ)	9,056
Thermal efficiency (%)	37.66

The analysis is carried out to evaluate the thermal efficiency of brick kiln using coal and saw dust as a fuel. Using the direct method formula, the thermal efficiency of furnace is determined as 37.66 %, indicating that less than half of the fuel energy has been used in firing the bricks, which shows that there is significant loss. Unlike the direct method Unlike the direct method, which compares fuel input and energy absorbed by the bricks, the indirect method calculates efficiency by performing an energy balance, which helps considering all major heat loss components

Table 4.3: Parameters and performance analysis of furnace by indirect method

Sensible heat loss in flue gas	
Excess air (%)	650
Theoretical air required to burn 1 kg of fuel (kg)	7.10
Total air supplied (kg/kg of fuel)	52.65
Weight of flue gas (kg/kg of fuel)	53.65
Sensible heat loss (kCal/kg of fuel)	1,312.01
% Heat loss in flue gas (%)	25.24
Loss due to evaporation of moisture present in fuel	
Moisture present in 1 kg of fuel (%)	6.39
% Heat loss (%)	0.76
Heat loss due to evaporation of water formed due to hydrogen in fuel	
kg of H_2 in 1 kg of fuel (kg/kg of fuel)	0.06
% Heat loss (%)	3.22
Heat loss due to openings	
Shape of opening (D/X)	2.23
Factor of radiation	0.70
Black body radiation corresponding to 800°C (kCal/cm^2/hr)	20
Area of opening (cm^2)	14,240
Emissivity	0.80
Total heat loss (kCal/hr)	159,488
Equivalent fuel loss (kg/hr)	30.68
% of heat loss through openings (%)	28.67
Heat loss through furnace skin	
Heat loss through roof and sidewalls	
Total average surface temperature(°C)	125
Heat loss at 125°C (kCal/m^2/hr)	1075
Total area of heating + soaking zone (m^2)	17.52

Total heat loss (kCal/hr)	18,834
Equivalent fuel loss (kg/hr)	3.62
Total average surface temperature of area other than heating and soaking zone (°C)	40
Heat loss at 40°C (kCal/m^2/hr)	100
Total area ($m^{2)}$	4.08
Total heat loss (Kcal/hr)	408
Equivalent fuel loss (kg/hr)	0.08
Total loss of fuel (kg/hr)	3.70
Total percentage loss (%)	3.46
Furnace efficiency (%)	38.65

The flue gas temperature was measured at 95 °C with an oxygen concentration of 18.2 %, and the surface temperatures of the heating and soaking zones were 580°C, while other zones averaged 125 °C. The brick kiln has been firing for 90 days every year for production of total brick the specific heat capacity of fuel and bricks, and the areas of the kiln zones**,** the energy lost through each pathway was quantified. The total useful energy has been obtained by subtracting all identified losses from the total energy supplied by the fuel. Using this approach, the furnace efficiency has determined to be 38.65 %, closely matching the direct method result. By accounting for the total heat losses from flue gases accounted for 25.24%. Heat loss due to evaporation of water formed due to hydrogen in fuel is about 3.22%, Heat loss due to openings is 28.67 % and radiation /convention losses through roof and sidewalls is 3.46. The indirect method provides additional understanding into the energy loss mechanisms, highlighting that most of the energy has been lost through flue gases and heat radiation from the kiln surfaces, and can guide interventions such as improving insulation, preheating air, and recovering flue gas heat to enhance overall efficiency.

4.3 CFD simulation of brick kiln

This section presents the temperature distribution within the firing zone of the straight-line natural draft brick kiln, based on the numerical simulation performed using coal and sawdust as composite fuel. These flow and thermal fields are fundamental indicators of kiln performance because they govern the combustion intensity, heat transfer to the bricks, and the natural draft mechanism that drives the movement of hot gases along the firing direction. Since the study focuses exclusively on the firing zone, particular attention has been given to the behavior of the high-temperature combustion core. By analyzing the interaction between these fields, it becomes possible to evaluate whether the kiln operates under efficient combustion conditions, whether heat has distributed uniformly, and how effectively the natural draft transports energy through the kiln. While simulation species model is species transport with turbulence-chemistry interaction is eddy dissipation and chemistry solver is direct source of diffusion source and proximity and ultimate analysis is the combination of coal and sawdust with mechanism of one step reaction. In discrete phase injection type has been setup in surface with particle type inert type and injection surface is fuel inlet. After including all the parameters in the boundary conditions and solution initialization of hybrid methods the calculation has been done to know the temperature distribution in bricks.

4.4 Temperature distribution analysis

The simulation results establish a significant temperature differential across the system. The analysis of temperature contour, possibly representing a subsequent design iteration or an altered operational state

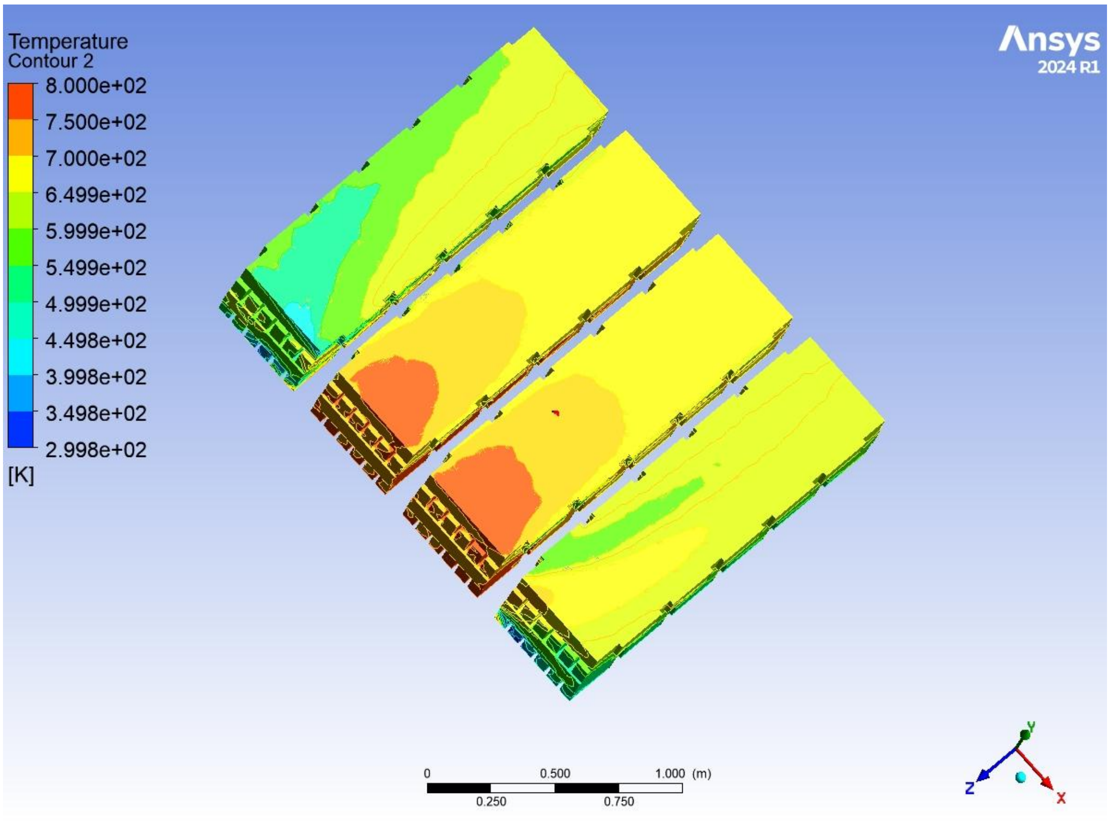


Figure 4.1: Temperature counter at existing 4 m/s

Figure 4.1 shows the existing ambient air velocity at 4 m/s, in this area and existing fuel (Coal and sawdust) the brick kiln firing zone is simulated in software (Ansys 2024). The temperature reached a maximum of 800 K (527℃) from the ambient temperature after firing. All the bricks are not fully cooked, some of them are not cooked properly, it means that in the brick kiln there is not proper distribution of temperature. This extreme temperature is visualized by the distinct red and orange contours dominating the core region. The temperature doesn't get optimum because of less thermal efficiency of furnace results show that the heat is dissipated by various regions so that heat is not fully heat transfer to the brick and temperature of brick doesn't get enough heat for firing.

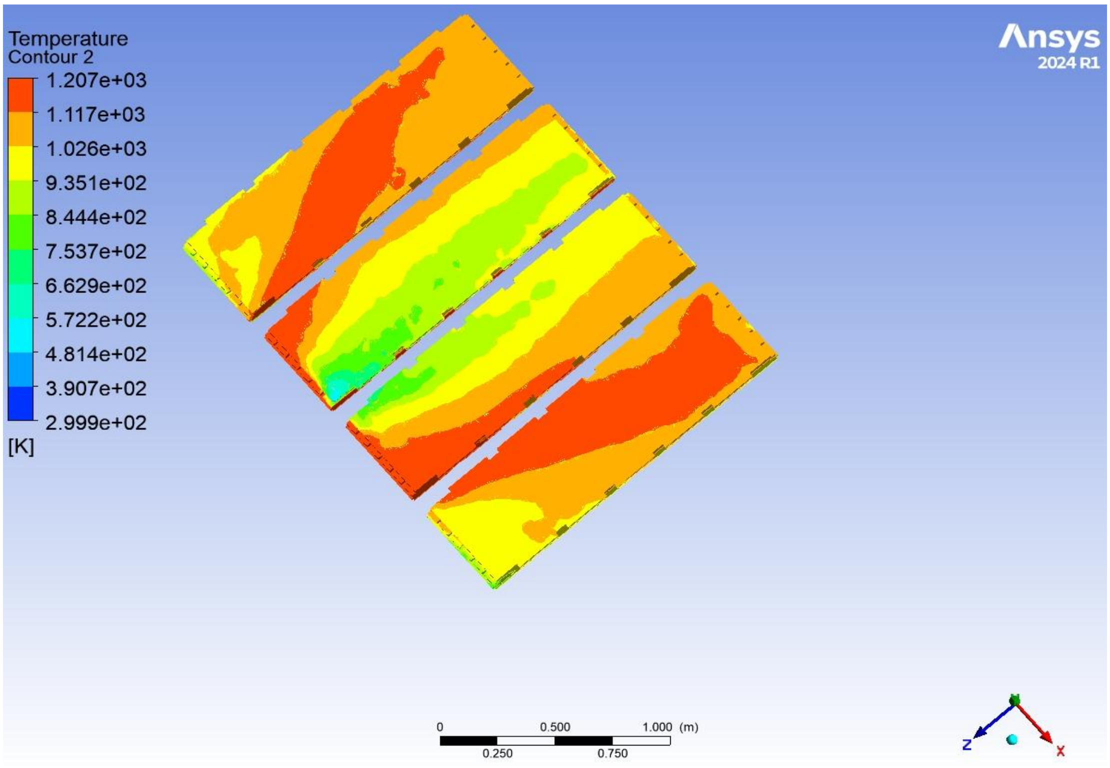


Figure 4.2: Temperature counter after air velocity 7 m/s

After implementation of induced draft fan then the inlet air velocity has increased with the fuel (coal and sawdust) ratio of 60:40 with average mass flow rate of 7 m/s. Then the temperature reaches up to 1207 K (934℃) contour plot which had been seen in temperature contour which reveals a significant and widespread thermal load across the component array, with most solid blocks exhibiting very high temperatures, peaking at 1207 K. The temperature gradually increases in different regions of brick at time of flow This geometrically defined cold region suggests a powerful, unmodeled cooling plenum, a non-physical void, or a deliberate modeling exclusion, which creates an abrupt thermal boundary that is a typical for continuous heat transfer and requires further investigation of the simulation setup. After increasing the air velocity with induced draft fan then the combustion zone achieved 934℃ so the brick has combustion at an optimum temperature.

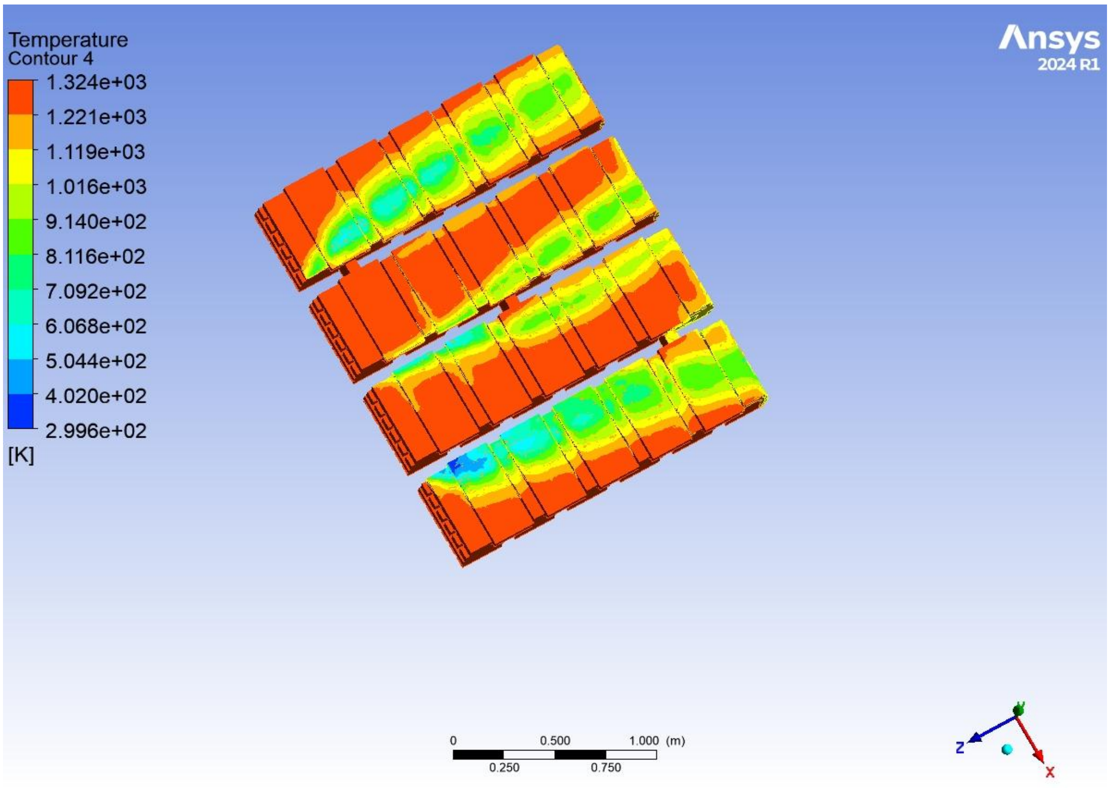


Figure 4.3: Temperature counter of zig-zag air flow pattern

Figure 4.3 shows the temperature distribution after retrofitting to zig-zag kiln by consuming same fuel consumption (coal and sawdust) the brick kiln firing zone. The temperature reached a maximum of 1324 K (1051℃) from the ambient temperature after firing which is good for retrofitting towards zig-zag air flow brick kiln. This extreme temperature is visualized by the distinct red and orange contours dominating the core region. The temperature has get optimum because of high thermal efficiency of furnace results show that the heat is consumed by bricks because of the zig-zag pattern of air flow which helps to hold the high temperature air inside the brick kiln for long period of time.

4.5 tCO_2 emission per year

After combustion of coal and saw dust in firing zone there must be producing various gases like nitrous oxide, Carbon dioxide, carbon monoxide, and sulfur oxide. So, these gases affect environment degradation. So, calculation of CO_2 of emissions is calculated which is shown in Table 4.4.

Table 4.4: tCO_2 emission per year

Parameters	Value
Fuel consumption coal (tons/years	320
Fuel consumption sawdust (tons/years)	80
Fuel percentage share (ratio)	75:25
Kiln operating hours (hours)	3600
Emission factor for coal (tCO_2/ton)	2.4
Emission factor for saw dust (tCO_2/ton)	1.65
Annual CO_2 emissions (tCO_{2eq}/year)	900

From the combustion the total CO_2 emission is 900 tCO_{2eq} tons in year.

4.6 Potential for energy saving opportunities

To evaluate the potential energy savings and economic benefits of different efficiency-improving techniques in a straight-line natural draft brick kiln, a detailed set of baseline operational and financial parameters has defined. After implementation of induced draft fan and retrofitting of zigzag kiln the combustion heat is maximum used for heating of brick at optimum temperature so that the production of brick is high which helps in increasing the thermal efficiency of brick kiln

After implementation of induced fan with air inlet velocity of 7 m/s then the temperature of brick increase above 900 °C so calculation has been done by using the fuel (coal and saw dust) ratio by 60:40. The ultimate analysis fuel after mixing has been shown in Table 4.5.

Table 4.5 Ultimate analysis of fuel (coal and sawdust) ratio

Element	Mass fraction
Carbon	0.702
Hydrogen	0.0596
Oxygen	0.2174
Sulfur	0.0108

4.7 Oxygen requirement per kg fuel

Use the standard formula (kg O_2/kg fuel):

$$m_{O2} = \frac{8}{3}C + 8H + S - O$$

Substitute:

$$m_{O2} = \frac{8}{3} \times 0.702 + 8 \times 0.0596 + 0.0108 - 0.2174$$

$$m_{O2} = 1.872 + 0.4768 + 0.0108 - 0.2174$$

$$= 2.1422 \text{ kg } O_2\text{/kg fuel}$$

Convert O_2 to air

Mass fraction of O_2 in air ≈ 0.23→ theoretical (stoichiometric) air:

$$Air_{th} = m_{O2}/0.23.$$

$$= 2.1422/0.23$$

$$= 9.31 \text{kg air/kg fuel}$$

Theoretical air =9.31kg air/kg fuel

Stoichiometric air–fuel ratio (mass)=9.31:1

Table 4.6: Improved brick kiln parameters

Parameters	Value
Fuel mixture (Coal and saw dust) ratio	60:40
Fuel flow (kg/s)	0.19
Air inlet area(m^2)	1.2
Air velocity (m/s)	7
Air density (kg/m^3)	1.204

From calculation

Stoichiometric air required = 9.31 kg air/kg fuel

Theoretical air flow = 0.19 × 9.31 = 1.77 kg/s

Actual air mass flow

m_{air} = Air velocity×Cross-sectional area×Air density

$$m_{air} = 7\times1.2\times1.204$$

$$= 10.11 \text{ kg/s}$$

For excess air

$$\%\text{Excess air} = \left(\frac{\text{Actual air}}{\text{Theoretical air}} - 1\right) \times 100$$

$$= \left(\frac{10.11}{1.77} - 1\right) \times 100$$

$$= (5.71 - 1)\times100$$

$$= 471\%$$

For efficiency analysis by using standard emperical inverse relation

existing efficiency of furnace is 38.65% with excess air (EA_1) is 650% and excess air after modification of kiln has (EA_2) 471%

$$\eta_2 = \eta_1 \times \frac{1 + EA_1}{1 + EA_2}$$

$$= 38.65\times1.313$$

$$= 50.74\%$$

From the calculation the thermal efficiency of brick kiln has been increased up to 50.74% after implementation of induced fan and zig-zag kiln respectively.This calculation has been done by using the excess air calculation.

In the Bishal brick factory there has been found that the fuel has placed in furnace kiln for continuousof 5 minutes for every 15 minutes interval and brick firing time has 90 days in every year so that from the fuel mass flow rate the calculation has been done for specific energy consumption after implementation of induced and zig-zag kiln.

Table 4.7: Parameters after implementation into new system

Parameters	Value
Fuel mass flow rate (kg/s)	0.19
Fuel supplied (min/hours)	15
Duration (days)	90

Parameters	Value
Gross calorific value of coal (MJ/kg)	23.8
Gross calorific value of saw dust (MJ/kg)	18

From the 60: 40 ratio of fuel it means that the mass flow rate of coal and saw dust has been calculate. So,

Mass flow rate of coal=0.19×0.6=0.114 kg/s

Mass flow rate of saw dust=0.19×0.4=0.076 kg/s

Total hours for firing of brick furnace in year

=(90×24×(15/60)

=540 hours in a year

So, total fuel consumption in year

=0.19×540×3,600

=369.36 MT/year

For firing of 7000 metric ton of bricks the total amount of fuel consumption has need to be 369.36 MT.

the fuel (coal and saw dust) used is 60:40 so that fuel used is

Total mass of coal=221.62 MT

Total mass of saw dust=147.74 MT

The energyfuel energy consumption in a year is

=(221,620×23.8+147,740×18) MJ

=5,274.56+2,659.32

=7,933,880 MJ

For calculation of specific energy consumption

$$\text{SEC} = \frac{\text{Total fuel energy used (MJ)}}{Total\ kg\ of\ bricks\ (kg)}$$

$$= \frac{7{,}933{,}880}{7{,}000{,}000}$$

=1.13 MJ/kg of bricks

By comparing the straightline naturaldraft with induced draft brick kiln the specific energy consumption of both induced and zigzag kiln have less energy consumption so the fuel saving per kg of bricks has found 0.16 MJ per kg of bricks. Therefore the total fuel saving has 14.15 %. From the study of (BEE, 2023) 15–30% fuel savings switching straight to zig-zag and adding a small induced-draft fan can increase savings and throughout further.

4.8 Financial analysis

For financial analysis, include kiln characteristics, annual operating hours, fuel properties, project lifetime, and the capital and operating costs associated with the selected improvement techniques. All the key input values used for energy, cost, and payback period calculations has been calculated in this study.

4.9 Installation of zigzag kiln

This is the cost that helps to know the reduction of CO_2 implementation of new technology so, after using a zigzag kiln in replace of this straight-line natural draft brick kiln the calculation is done. The cost required to retrofit an FCBTK into natural draft zigzag kiln is about 30 lakhs (Yadav, 2017). Fuel emission factor (tCO_2 per ton fuel) is 2.4 (Heede, 2014). It has been achieved that in switching into zig-zag patterns about 20-30% reduction in coal use and it helps in reducing black carbon a suspended particulate matter. so that proper heat is transfer in every brick that helps in production of good quality of bricks (Lopez et al., 2012). Discount rate the calculation of carbon reduction is 10% shown in Table 4.8.

Table 4.8: Marginal abatement cost using zigzag kiln

Parameters	Value
Annual production (tons bricks/year)	7000
Operating hours per year (h/year)	3600
Baseline fuel consumption coal and saw dust (tons/year)	320
Baseline fuel consumption sawdust (tons/year)	80
Baseline fuel consumption (tons/year)	400
Post-measure coal consumption (tons/year)	224
Post-measure sawdust consumption (tons/year)	56
Total post-measure coal and saw dust consumption (tons/year)	280

Parameters	Value
Fuel emission factor for coal (tCO2 per ton fuel)	2.4
Fuel emission factor for saw dust (tCO_2 per ton fuel)	1.65
Annual CO_2 baseline (tCO_2/year)	900
Annual CO_2 new (tCO_2/year)	630
Annual CO_2 reduction (tCO_2/year)	270
Baseline fuel price (NPR per ton)	26,750
Annual fuel cost baseline (NPR/year)	10,700,000
Annual fuel cost new (NPR/year)	7,490,000
Annual fuel cost change (NPR/year)	3,210,000
NPV of incremental cost (NPR)	17,094,185
Cost before abatement (NPR)	13,104,000
Cost after abatement (NPR)	10,449,354
Marginal abatement cost (NPR/tCO_2)	9,832.02

The baseline fuel consumption means fuel consumption at existing condition and post-measure fuel consumption means after implementation of new machines. From the above calculation after implementation of zigzag kiln, the total CO_2 emission reduction from 900 tCO_{2eq} per year to 630 tCO_{2eq} per year which is 270 tCO_{2eq} in a year. This zig-zag arrangement helps the flow of hot gases in more controlled and extended path that results the better heat distribution throughout the kiln. This result helps with uniform heating and reducing chances of under-fired or overburnt bricks.

Table 4.9: Payback period calculation after impletation of zigzag kiln

Parameter	Zig-zag kiln
Baseline fuel consumption (tons/year)	400
Total post-measure fuel consumption (tons/year)	280
Baseline fuel price (NPR per ton)	26,750
Annual baseline fuel consumption cost (NPR/ton)	10,700,000
Annual post-measure fuel consumption cost (NPR/ton)	7,490,000
Annual CO_2 saving (tCO_2 /year)	270
Cost per ton of carbon emission (NPR)	710
Total cost saving from CO_2 emission (NPR)	191,700
Investment (NPR)	3,000,000

Parameter	Zig-zag kiln
Annual electricity cost of 7.5 kW induced draft (NPR)	255,690
Present value of costs (NPR)	1,571,104
Annual cost saving (NPR/year)	3,401,700
Project lifetime (years)	10
Discount rate (decimal)	0.1
Net benefit (NPR)	20,901,974
Total cost (NPR)	4,571,104
Discounted payback period (months)	11.62

So, the discounted payback period after retrofitting to zig-zag kiln is 11.62 months

4.10 Installation of induced draft fan

Proper selection of induced fan can be done based on the various parameters like airflow capacity (CFM). The installation of induced fan helps to reduce carbon emission by 10%(Kapp et al., 2024). So, the marginal abatement carbon reduction is calculated in Table 4.10.

Table 4.10: Marginal abatement cost after installation of induced fan

Parameter	Value
Annual production (tons bricks/year)	7000
Operating hours per year (hrs/year)	3600
Baseline coal consumption (tons/year)	320
Baseline sawdust consumption coal (tons/year)	80
Baseline fuel consumption (tons/year)	400
Post-measure coal consumption (tons/year)	288
Post-measure saw dust consumption (tons/year)	72
Total post-measure fuel consumption (tons/year)	360
Fuel emission factor for coal (tCO_2 per ton fuel)	2.4
Fuel emission factor for saw dust (tCO_2 per ton fuel)	1.65
Fuel price (NPR per ton)	26750
Implementing induced draft fan (7.5 kW) (NPR)	272,000
Annual CO_2 baseline (tCO_2 /year)	900
Annual CO_2 new (tCO_2 /year)	810

Parameter	Value
Annual CO_2 reduction (tCO_2 /year)	90
Time to run ID fan (hours/ year)	3,600
Electrical energy required (kWh/year)	27,000
Electrical energy cost (NPR/kWh)	9.47
Electrical energy cost (NPR/year)	255,690
Cost after abatement (NPR)	12,329,944
Cost before abatement (NPR)	13,127,000
Marginal abatement cost (NPR/tCO_2)	8,856.17

After implementation of induced fan, the total CO_2 emission reduction from 900 tCO_{2eq} per year to 810 tCO_{2eq} per year which is 90 tCO_{2eq} in a year.

Table 4.11: Payback period calculation after impletation induced fan

Parameter	Value
Baseline fuel consumption (tons/year)	400
Total post-measure fuel consumption (tons/year)	360
Baseline fuel price (NPR per ton)	26,750
Annual baseline fuel consumption cost (NPR/ton)	10,700,000
Annual post-measure fuel consumption cost (NPR/ton)	9,630,000
Annual CO_2 saving (tCO_2 /year)	90
Cost per ton of carbon emission (NPR)	710
Total cost saving from CO_2 emission (NPR)	63,900
Investment (NPR)	272,000
Annual electricity cost of 7.5 kW induced draft (NPR)	255,690
Present value of costs (NPR)	1,571,104
Annual cost saving (NPR/year)	1,133,900
Project lifetime (years)	10
Discount rate (decimal)	0.1
Net benefit (NPR)	6,967,325
Total cost (NPR)	1,843,104
Discounted payback period (months)	3.06

Then the discounted payback period after installation of induced fan in existing brick kiln is 3.06 months.

The marginal abatement cost has been calculated after installation of induced fan and retrofitting of zig-zag kiln.

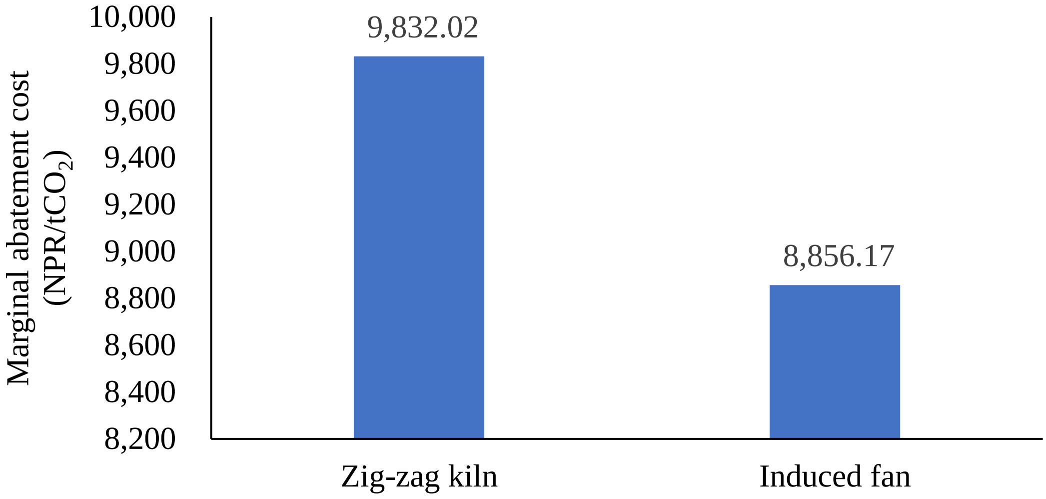


Figure 4.4: Marginal adaptement cost analysis

The marginal abatement cost of both zigzag kiln and induced fan implementation is NPR 9,832 per ton of CO_{2eq} and NPR 8,856 per ton of CO_{2eq} respectively.

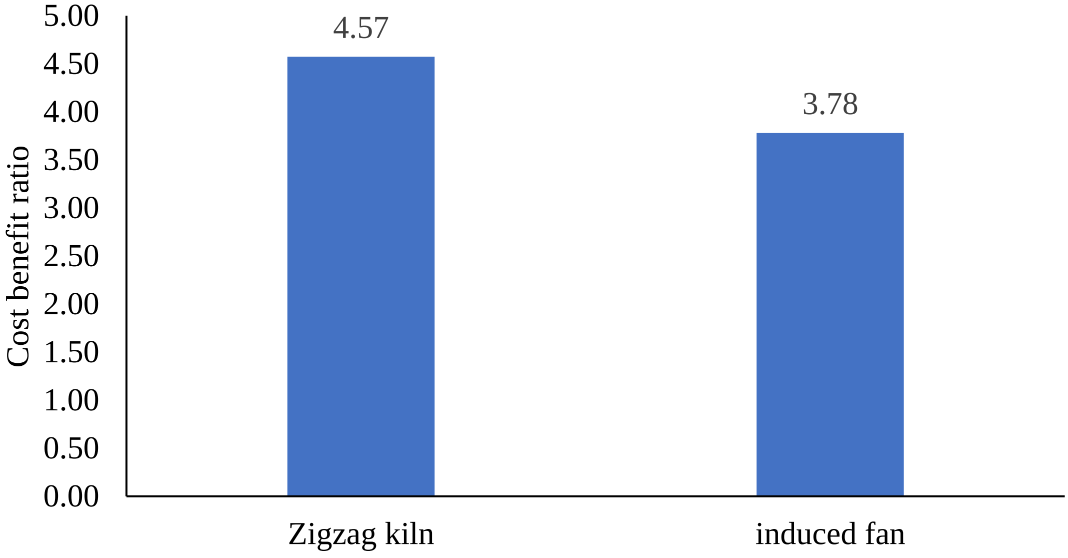


Figure 4.5: Cost benefit ratio analysis

The cost benefit ratio of both after implementation of zigzag kiln and induced draft fan are 4.75 and 3.78 respectively

4.11 Using the flue gas as air preheater

The exhaust flue gas has been used to preheat the inlet air to increase the inlet air temperature by 35°C to reduce the fuel consumption by 0.6% that saves NPR 43,392 annually.

Table 4.12: Cost benefit analysis for using air preheater

Parameters	Value
Annual fuel consumption (Tons)	320
Reduction in annual fuel consumption (%)	0.6%
Reduced fuel consumption (Tons)	318.08
Annual fuel saving (Tons)	1.9
Installation of flue gas treatment system (NPR)	250,000
Annual cost saving from coal (NPR)	43,392.0
Discounted payback period (years)	9.01

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- The performance assessment of furnace has been done by both direct and indirect method and found to be 37.66 % and 38.65% respectively, but the efficiency is quite low due to such as unburnt coal was left due to lack of complete combustion of fuel.
- Specific energy consumption of brick factory is 1.29 MJ/kg of bricks.
- Simulation results show that in existing condition the brick doesn't get temperature for cooking so, with increased velocity which means that induced draft fan must be implemented in brick factory And implementation of zig-zag kiln also increased the thermal efficiency of brick furnace. The temperature of brick kiln in existing condition is quite low but after fuel rate increases then the temperature increases above 900 ˚C which is good for firing of brick and brick must get good temperature
- Efficiency of brick kiln after implementation of induced fan and retrofitting into zigzag kiln has found to be 50.74% and specific energy saving has found to be 14.51%
- CO_2 emissions are low due to less combustion efficiency which means that the coal and saw dust do not combust properly and gas like carbon monoxide and gas produced which affect the quality brick
- After implementation of new design style (zigzag kiln) implementation of induced draft of furnace the CO_2 emission decrease which helps in reduction of marginal abatement cost up to is 270 tCO_{2eq} in a year and is 90 tCO_{2eq} respectively.
- Analysis of financial the payback period after implementation of zig-zag kiln and induced draft fan are 11.62 and 3.06 months which very good and cost benefit ratio are 4.75 and 3.78 respectively

5.2 Recommendations

The industry uses a mixture of 80% coal and 20% sawdust as a source of fuel. As coal which is not crushed finely is not easily flammable, the use of sawdust is a good practice for utilizing industrial waste as a supplementary fuel. For the improvement of energy efficiency of the furnace the following methods can be implemented.

Converts flow path to Zig-Zag patterns: The main advantages of a zig-zag kilns is its lower specific energy consumption as compared to FCBTK and its range of 0.95-1.23 MJ/kg fired brick so that in comparison to conventional FCBTK zigzag kilns requires about 20% less energy (Lalchandani & Maithel, 2013). It was achieved that in switching into zig-zag patterns about 20-30% reduction in coal use and it helps in reducing black carbon a suspended particulate matter. so that proper heat is transfer in every brick that helps in production of good quality of bricks (Lopez et al., 2012).

Installation of induced fan: At present the brick industry has natural draft within their chimney. During the extreme hot summer season (March- June); the ambient air temperature becomes relatively close to that of the flue gases inside the chimney. To overcome this challenge installation of a Low hp Fan powered by an outside motor inside the chimney to increase the draft inside the chimney increase the, can effectively enhance the draft. This mechanically induced draft increases the exhaust flow rates, helps in consistent removal of flue gases and improves combustion efficiency . Proper selection of induced fan can be done based on the various parameters like airflow capacity (CFM).

Refining the fuel: During preparation of coal for feeding, it can be crushed in fine grains for increasing combustion during firing. Coal was not properly grinding that effects on fuel efficiency and increase the fuel consumption that directly effects the efficiency of furnace and in production cost.

Improving insulation through in floor, side wall and roof: It was observed that the industry uses bricks, clay and dust of bricks for insulating the roof and sidewalls of the furnace The best use of insulation material is aluminum foil which helps to minimize heat loss while firing, that helps in reducing the fuel consumption. The openings, roof and sidewalls are responsible for 32.13% of loss during the combustion. This improved insulation helps in increasing the efficiency of furnace during combustion.

REFRENCES

Efficiency, B. of E. (2022). *2. Energy Performance Assesment of Furnaces 31 Bureau of Energy Efficiency 2.1 Industrial Heating Furnaces*.

Almeida, M. I., Dias, A. C., Demertzi, M., & Arroja, L. (2015). Contribution to the development of product category rules for ceramic bricks. *Journal of Cleaner Production, 92*, 206–215. https://doi.org/10.1016/j.jclepro.2014.12.073

Bashir, Z., Amjad, M., Raza, S. F., Ahmad, S., Abdollahian, M., & Farooq, M. (2023). Investigating the Impact of Shifting the Brick Kiln Industry from Conventional to Zigzag Technology for a Sustainable Environment. *Sustainability (Switzerland), 15*(10). https://doi.org/10.3390/su15108291

BEE, I. (2023). *Energy and Resource Efficiency Action Plan (MSME Sector)*. 1–16.

Beyene, A., Ramayya, V., & Shunki, G. (2018). CFD Simulation of Biogas Fired Clay Brick Kiln. *American Journal of Engineering and Applied Sciences*, *11*(2), 1045–1061. https://doi.org/10.3844/ajeassp.2018.1045.1061

Bouchahma, A., Malaki, A., Moussaoui, R., Cherraj, M., & El Hachmi, D. (2025). Study of thermal transition in brick kilns: modeling wood consumption and energy efficiency. *Multidisciplinary Science Journal, 7*(7). https://doi.org/10.31893/multiscience.2025309

Brooks, N., Biswas, D., Maithel, S., Kumar, S., Uddin, M. R., Ahmed, S., Mahzab, M., Miller, G., Rahman, M., & Luby, S. P. (2024). Building blocks of change: The energy, health, and climate co-benefits of more efficient brickmaking in Bangladesh. *Energy Research and Social Science, 117*. https://doi.org/10.1016/j.erss.2024.103738

Darain, K. M. ud, Jumaat, M. Z., Islam, A. B. M. S., Obaydullah, M., Iqbal, A., Adham, M. I., & Rahman, M. M. (2016). Energy efficient brick kilns for sustainable environment. *Desalination and Water Treatment*, *57*(1), 105–114. https://doi.org/10.1080/19443994.2015.1012335

Eil, A., Li, J., Baral, P., & Saikawa, E. (2020). Dirty Stacks, High Stakes. *Dirty Stacks, High Stakes*. https://doi.org/10.1596/33727

Environment, D. of. (2017). *Brick Kiln Stack Emission Monitoring in Kathmandu Valley*. 60.

Heede, R. (2014). Carbon Majors: Accounting for carbon and methane emissions 1854-2010. Methods & Results Report. *Climate Mitigation Services*, *Abril*, 2–104. http://carbonmajors.org/wp/wp-content/uploads/2014/04/MRR-9.1-Apr14R.pdf

Kapp, S., Wang, C., McNelly, M., Romeiko, X., & Choi, J. K. (2024). A comprehensive analysis of the energy, economic, and environmental impacts of industrial variable frequency drives. *Journal of Cleaner Production*, *434*, 140474. https://doi.org/10.1016/J.JCLEPRO.2023.140474

Karaman Tokat Gaziosmanpaşa Üniversitesi, S., Ersahin, S., & Gunal, H. (2015). *Firing temperature and firing time influence on mechanical and physical properties of clay bricks*. https://www.researchgate.net/publication/267807532

Kaya, S., Mançuhan, E., & Küçükada, K. (2009). Modelling and optimization of the firing zone of a tunnel kiln to predict the optimal feed locations and mass fluxes of the fuel and secondary air. *Applied Energy*, *86*(3), 325–332. https://doi.org/10.1016/j.apenergy.2008.04.018

Lalchandani, D., & Maithel, S. (2013). *Towards Cleaner Brick Kilns in India A win-win approach based on Zigzag fi ring technology An initiative supported by 2 Towards Cleaner Brick Kilns in India*. 5. www.adcs.in

Lopez, A., Lyoda, N., Segal, R., & Tsai, T. (2012). Building Materials: Pathways To Efficiency in the South Asia Brickmaking Industry. *John Hopkins University SAIS Research Report*, 6–10. http://carbonwarroom.com/sites/default/files/reports/Pathways to Efficiency in the South Asia Brickmaking Industry %28Carbon War Room%29_0.pdf

Maskey, U., Sanu, M., & Dangol, B. (2013). *SAARC Energy Centre Islamabad Study on Evaluating Energy Conservation Potential of Brick Production in SAARC Countries A Report on Nepal Study Team*.

Melo-Monterrey, M. de J., Sánchez-Medina, P. S., & Reyes-Santiago, M. del R. (2025). Sustainable performance measurement in brick kilns: Proposal of an index with objective and subjective data. *Environmental and Sustainability Indicators, 26*. https://doi.org/10.1016/j.indic.2025.100623

MinErgy. (2012). *A Roadmap for Efficient Brick Production in*. *December*.

Nepal, S., Mahapatra, P. S., Adhikari, S., Shrestha, S., Sharma, P., Shrestha, K. L., Pradhan, B. B., & Puppala, S. P. (2019). A comparative study of stack emissions from straight-line and zigzag brick kilns in Nepal. *Atmosphere*, *10*(3). https://doi.org/10.3390/atmos10030107

Olsson, J. A., Hafez, H., Miller, S. A., & Scrivener, K. L. (2025). Greenhouse Gas Emissions and Decarbonization Potential of Global Fired Clay Brick Production. *Environmental Science and Technology*. https://doi.org/10.1021/acs.est.4c08994

Pattiya, S. C. and A. (2023). *View of Application of solid media for enhancing the temperature distribution within a downdraft kiln during clay brick firing.pdf*.

Refaey, H. A., Abdel-Aziz, A. A., Salem, M. R., Abdelrahman, H. E., & Al-Dosoky, M. W. (2018). Thermal performance augmentation in the cooling zone of brick tunnel kiln with two types of guide vanes. *International Journal of Thermal Sciences*, *130*, 264–277. https://doi.org/10.1016/j.ijthermalsci.2018.04.027

Refaey, H. A., Alharthi, M. A., Salem, M. R., Abdel-Aziz, A. A., Abdelrahman, H. E., & Karali, M. A. (2021). Numerical investigations of convective heat transfer for lattice settings in brick tunnel Kiln: CFD simulation with experimental validation. *Thermal Science and Engineering Progress*, *24*. https://doi.org/10.1016/j.tsep.2021.100934

Shakir, A. A., & Mohammed, A. A. (2013). Manufacturing of Bricks in the Past, in the Present and in the Future: A state of the Art Review. *International Journal of Advances in Applied Sciences (IJAAS)*, *2*(3), 145–156.

Štoller, J., & Dubec, B. (2017). Design and assessment of shape of protective structure by usage of CFD software environment ansys fluent. *Lecture Notes in Mechanical Engineering*, *PartF11*, 200–210. https://doi.org/10.1007/978-981-10-3247-9_23

Tasnim, F., Istiaque, F., Morshed, A. K. M. M., & Ahmad, M. U. (2019). A CFD investigation of conventional brick kilns. *AIP Conference Proceedings*, *2121*(July), 1–8. https://doi.org/10.1063/1.5115877

TERI, S. (2008). *Brick By Brick : the Herculean Task of Cleaning Up the Asian Brick Industry a Saga Narrated By Urs Heierli and Sameer Maithel Foreword By Walter Fust Poverty Alleviation As a Business Series*. www.teriin.org

Thakuri, S., Basnet, A., Rawal, K., Chauhan, R., Manandhar, R., & Rai, P. Y. (2024). Technologies, emission estimation, and feasibility of cleaner technologies in brick industry of Nepal. *Environmental Challenges*, *15*. https://doi.org/10.1016/j.envc.2024.100928

Tibrewal, K., Venkataraman, C., Phuleria, H., Joshi, V., Maithel, S., Damle, A., Gupta, A., Lokhande, P., Rabha, S., Saikia, B. K., Roy, S., Habib, G., Rathi, S., Goel, A., Ahlawat, S., Mandal, T. K., Azharuddin Hashmi, M., Qureshi, A., Dhandapani, A., … Sinha, B. (2023). Reconciliation of energy use disparities in brick production in India. *Nature Sustainability*, *6*(10), 1248–1257. https://doi.org/10.1038/s41893-023-01165-x

Vogt-Schilb, A., & Hallegatte, S. (2014). Marginal abatement cost curves and the optimal timing of mitigation measures. *Energy Policy*, *66*, 645–653. https://doi.org/10.1016/J.ENPOL.2013.11.045

WECS. (2022). *Energy audit guidelines for industrial sectors*. www.giefnepal.com

WECS. (2024). *Water and Energy Commission Secretariat , Nepal* (Vol. 180, Issue 4).

Yadav, R. K. and N. K. (2017). *Zigzag Kilns: A Design Manual*. 1–31. www.cseindia.org

ANNEXES

Annex 1: Performance assessment of brick kiln

Direct method

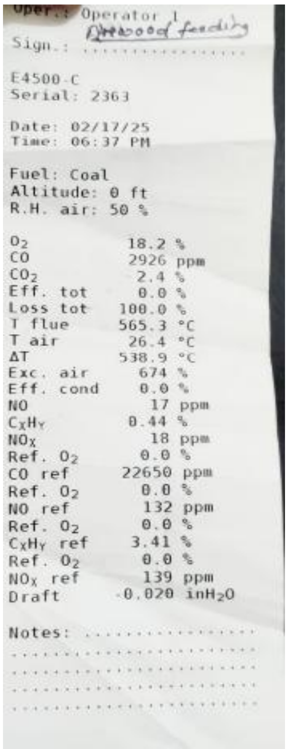
Parameters	Value
Types of fuel used in furnace	Coal and saw dust
Bricks mould (pcs)	500
Weight of a brick (kg)	2
Total weight (kg)	1,000
Specific heat capacity brick (kJ/kg°C)	0.84
Chimney height (m)	30
Temperature difference (°C)	580
Output energy (MJ)	487
Fuel coal (kg)	48
Fuel sawdust (kg)	12
GCV of coal (kJ/kg)	23.80
GCV of sawdust (kJ/kg)	18
Input energy (MJ)	1,358
Thermal efficiency (%)	35.87

Indirect method

Description	Value
Moisture content (%)	2-15
Carbon (%)	50-70
Hydrogen (%)	4.5-6
Oxygen (%)	4.5-10
Sulphur (%)	0.5-6
Ash (%)	4-15
Nitrogen (%)	0.5-2.5
Sensible heat loss in flue gas	
Excess air (%)	650
Theoretical air required to burn 1 kg of fuel (kg)	7.10
Total air supplied (kg/kg of fuel)	52.65
Weight of flue gas (kg/kg of fuel)	53.65
Sensible heat loss (kCal/kg of fuel)	1,312.01

Description	Value
% Heat loss in flue gas (%)	25.24
Loss due to evaporation of moisture present in fuel	
Moisture present in 1 kg of fuel (%)	6.39
% Heat loss (%)	0.76
Heat loss due to evaporation of water formed due to hydrogen in fuel	
kg of H_2 in 1 kg of fuel (kg/kg of fuel)	0.06
% Heat loss (%)	3.22
Heat loss due to openings	
Shape of opening (D/X)	2.23
Factor of radiation	0.70
Black body radiation corresponding to 800°C (kCal/cm^2/hr)	20
Area of opening (cm^2)	14,240
Emissivity	0.80
Total heat loss (kCal/hr)	159,488
Equivalent fuel loss (kg/hr)	30.68
% of heat loss through openings (%)	28.67
Heat loss through furnace skin	
Heat loss through roof and sidewalls	
Total average surface temperature(°C)	125
Heat loss at 125°C (kCal/m^2/hr)	1075
Total area of heating + soaking zone (m^2)	17.52
Total heat loss (kCal/hr)	18,834
Equivalent fuel loss (kg/hr)	3.62
Total average surface temperature of area other than heating and soaking zone (°C)	40
Heat loss at 40°C (kCal/m^2/hr)	100
Total area (m$^{2)}$	4.08
Total heat loss (Kcal/hr)	408
Equivalent fuel loss (kg/hr)	0.08
Total loss of fuel (kg/hr)	3.70
Total percentage loss (%)	3.46

Description	Value
Furnace efficiency (%)	38.65



```
Oper.: Operator 1
       Firewood feeding
Sign.: ..................

E4500-C
Serial: 2363

Date: 02/17/25
Time: 06:37 PM

Fuel: Coal
Altitude: 0 ft
R.H. air: 50 %

O2            18.2 %
CO            2926 ppm
CO2            2.4 %
Eff. tot       0.0 %
Loss tot     100.0 %
T flue       565.3 °C
T air         26.4 °C
ΔT           538.9 °C
Exc. air       674 %
Eff. cond      0.0 %
NO              17 ppm
CxHy          0.44 %
NOx             18 ppm
Ref. O2        0.0 %
CO ref       22650 ppm
Ref. O2        0.0 %
NO ref         132 ppm
Ref. O2        0.0 %
CxHy ref      3.41 %
Ref. O2        0.0 %
NOx ref        139 ppm
Draft       -0.020 inH2O

Notes: .................
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Flue gas parameters

Annex 2: CO_2 emissions in combustion analysis

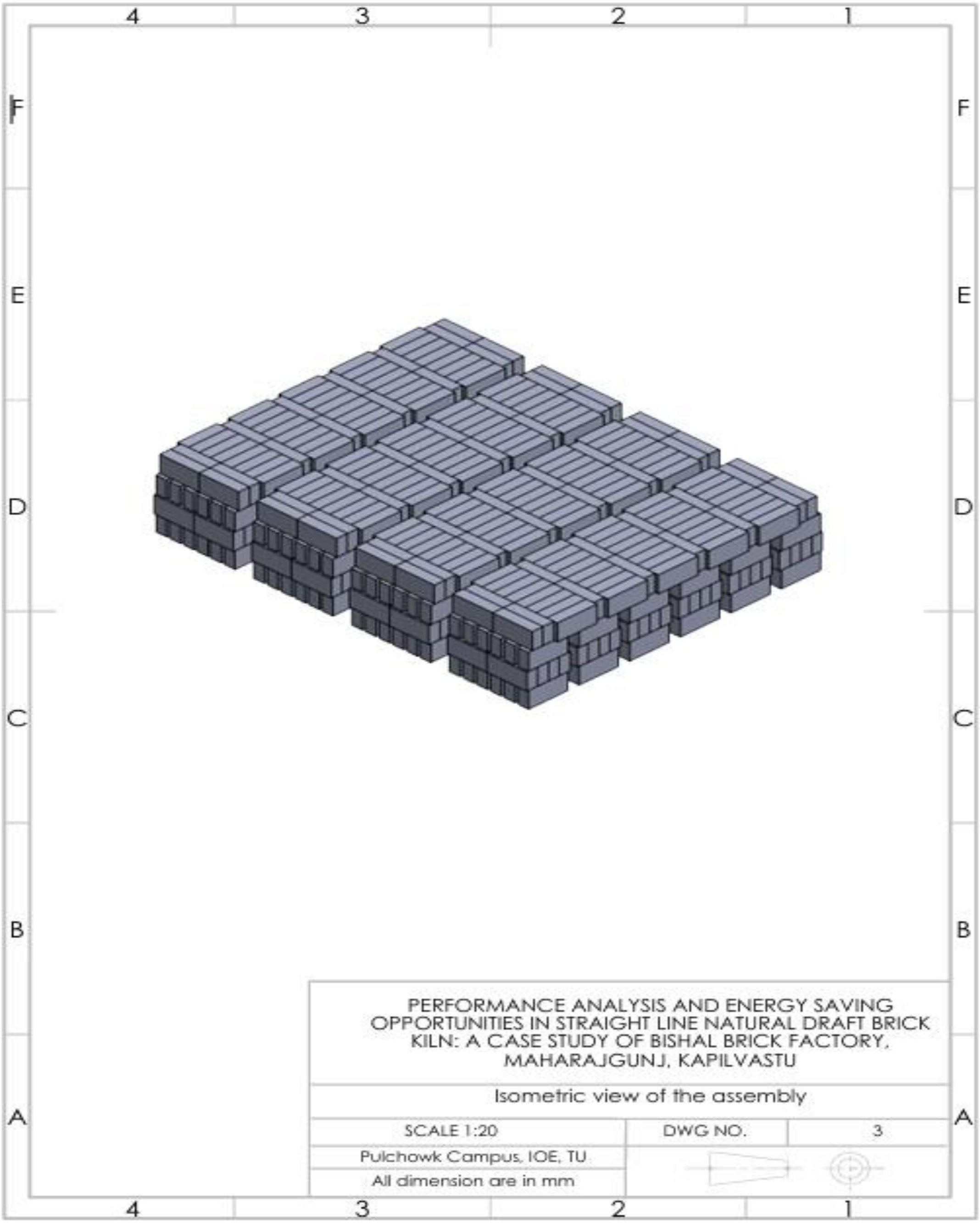
per ton of CO_2 emissions from combustion of fuels

Parameters	Value
Fuel consumption coal (tons/years	320
Fuel consumption sawdust (tons/years)	80
Fuel percentage share (ratio)	75:25
Kiln operating hours (hours)	3600
Emission factor for coal (tCO_2/ton)	2.4
Emission factor for saw dust (tCO_2/ton)	1.65
Annual CO_2 emission (tCO_2/year)	900
Combustion efficiency of furnace (%)	38.65
Actual annual CO_2 emission (tCO_2/year)	347.85

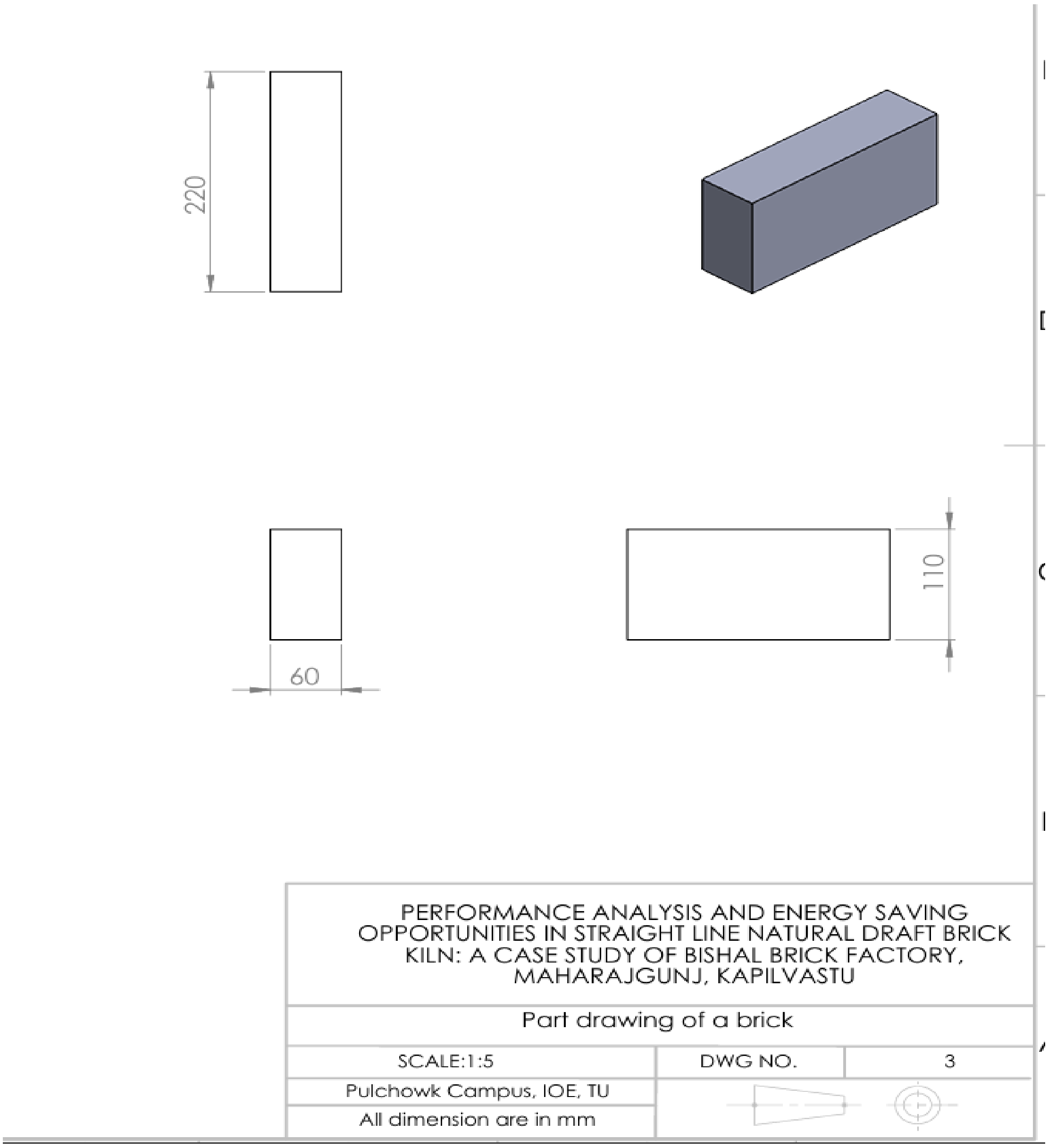
Annex 3: Comment matrix

S.N	Comments	Response	Remarks
1	Total mass of bricks = mass of bricks does not match with 7000 MT. Check it.	Page no. 33 (SEC)	Completed
2	In table 4.2, output and input energy is in KJ, not MJ, unit written is mistaken	Page no. 34 (direct method)	Completed
3	CO2 emission calculation checkit	Page no.41	Completed
4	Refine the problem statement and objectives in the report	Page no. 4	Completed
5	The simulation does not consider all model	Page no 22	Completed
6	The validation of your simulation result is important to give recommendations.	Page no. 45	Completed
7	The fuel% share mentioned in the report is 4:1, as coal:sawdust ratio = 320000:80000 please check it	Page no.33	Completed
8	Check this for other financial analysis too.	Page no. 45,46,47	Completed
9	Check of Marginal Abatement Cost (MAC)	Page no.45,46,48	Completed
10	References mistake	Page no 56	Completed
11	Check grammatical mistakes in the report, with repetition of sentences,	All pages	Completed

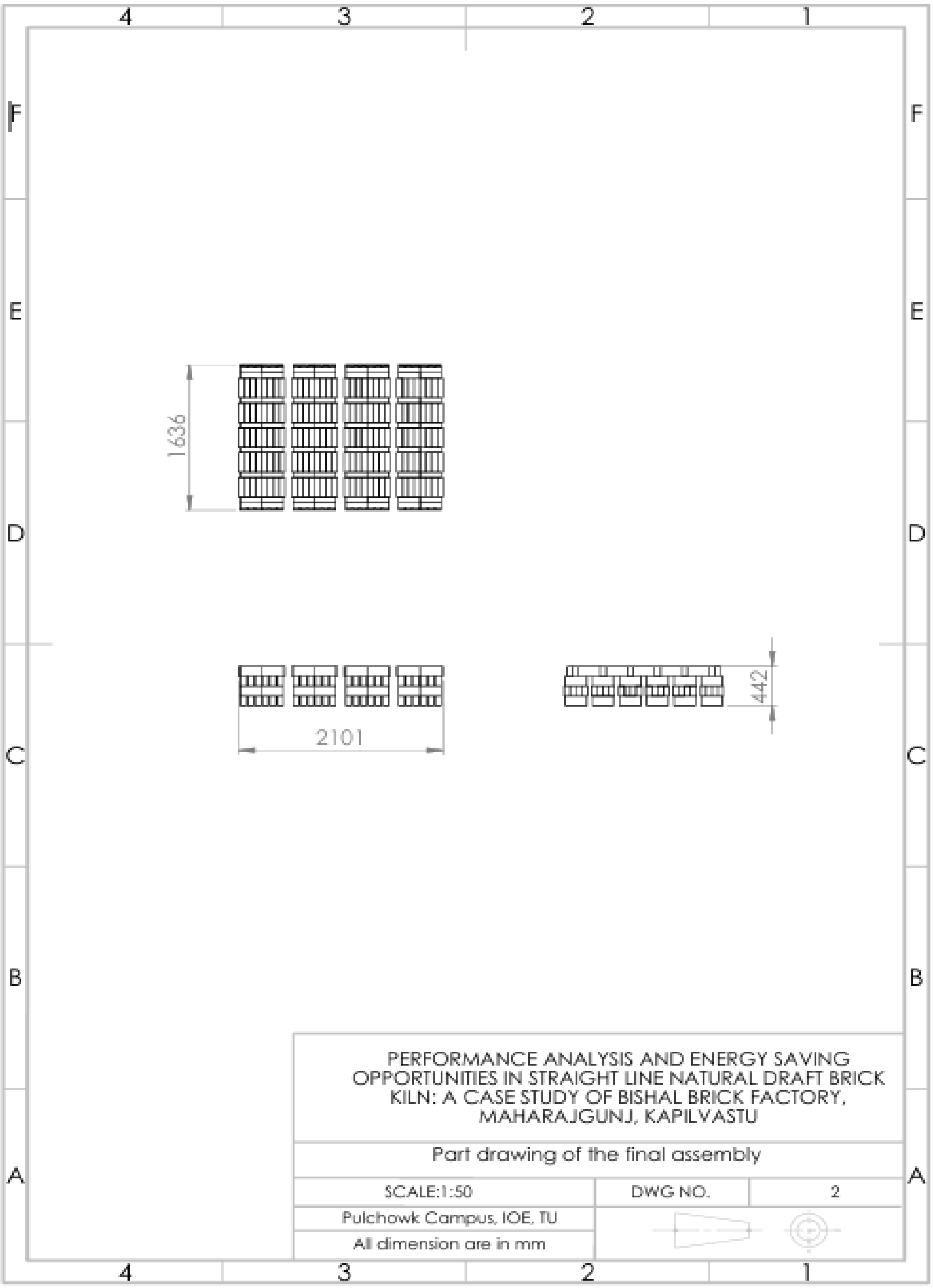
Annex 4: Assembly drawing of brick and brick stacking



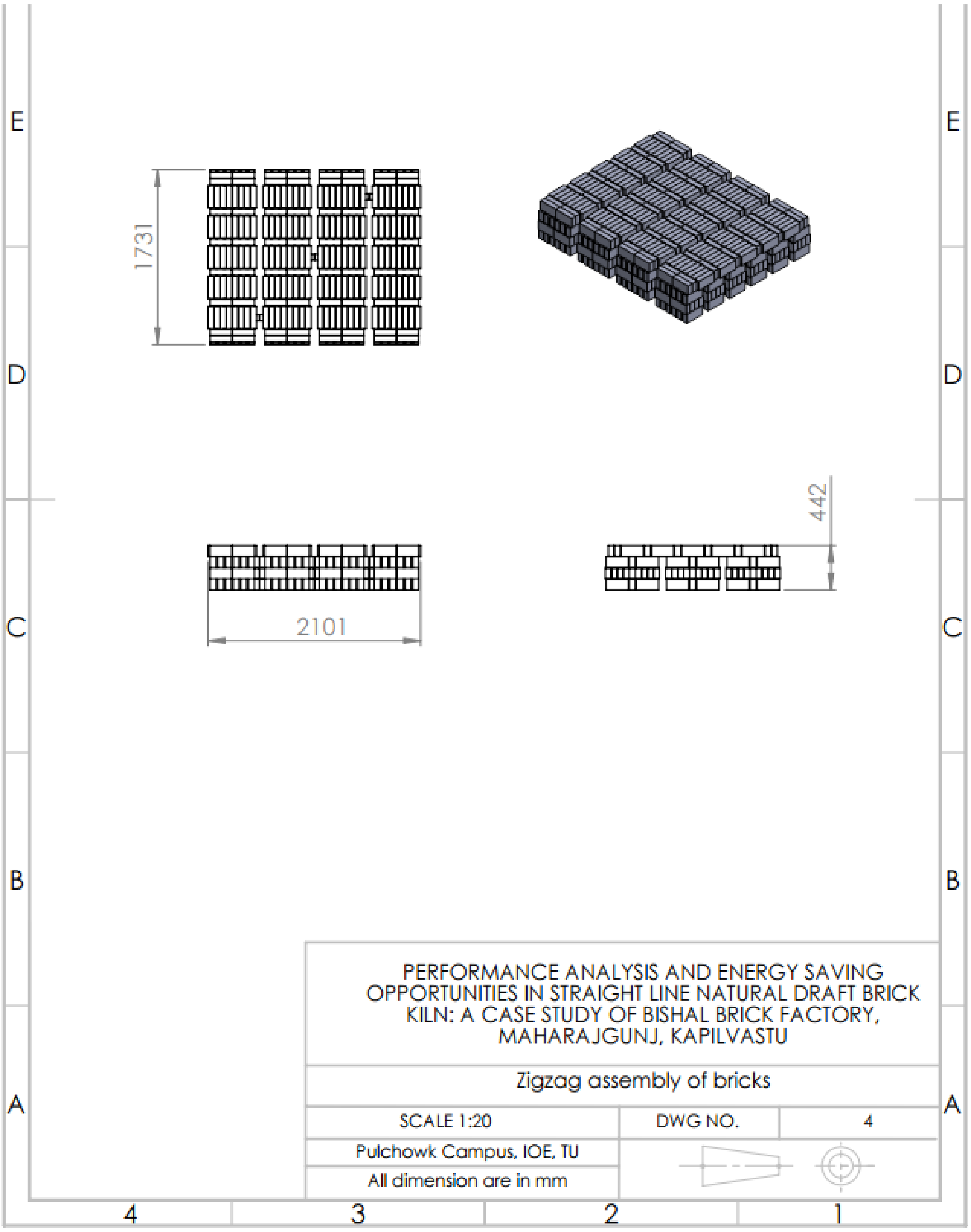
Assembly drawing brick stacking



Brick drawing

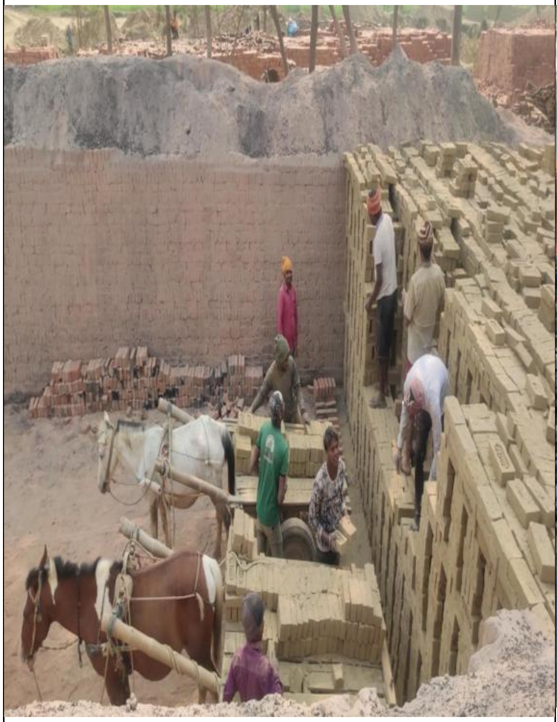


Orthographic view of brick stacking



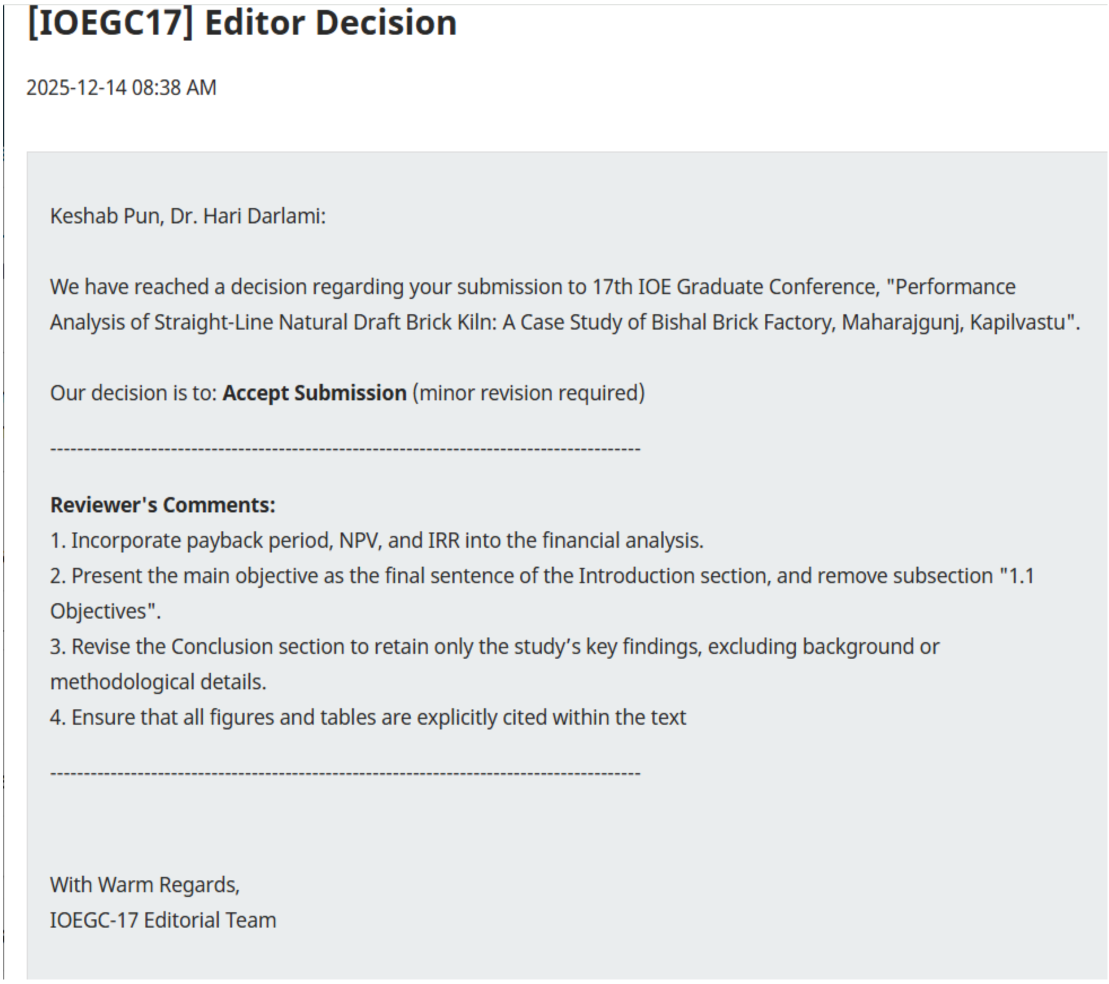
Orthographic view of zig-zag brick stacking

Annex 5: Photographs

	
Stacking of bricks	Crushing of coal
	
Raw Brick Size=22cm×11cm×6cm	Measurement of parameters in firing zone

 Manual fuel mixing (Coal and saw dust)	 Temperature measurement inside the firing zone

Annex 6: IOE GC acceptence letter



[IOEGC17] Editor Decision

2025-12-14 08:38 AM

Keshab Pun, Dr. Hari Darlami:

We have reached a decision regarding your submission to 17th IOE Graduate Conference, "Performance Analysis of Straight-Line Natural Draft Brick Kiln: A Case Study of Bishal Brick Factory, Maharajgunj, Kapilvastu".

Our decision is to: **Accept Submission** (minor revision required)

Reviewer's Comments:

1. Incorporate payback period, NPV, and IRR into the financial analysis.
2. Present the main objective as the final sentence of the Introduction section, and remove subsection "1.1 Objectives".
3. Revise the Conclusion section to retain only the study’s key findings, excluding background or methodological details.
4. Ensure that all figures and tables are explicitly cited within the text

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With Warm Regards,
IOEGC-17 Editorial Team

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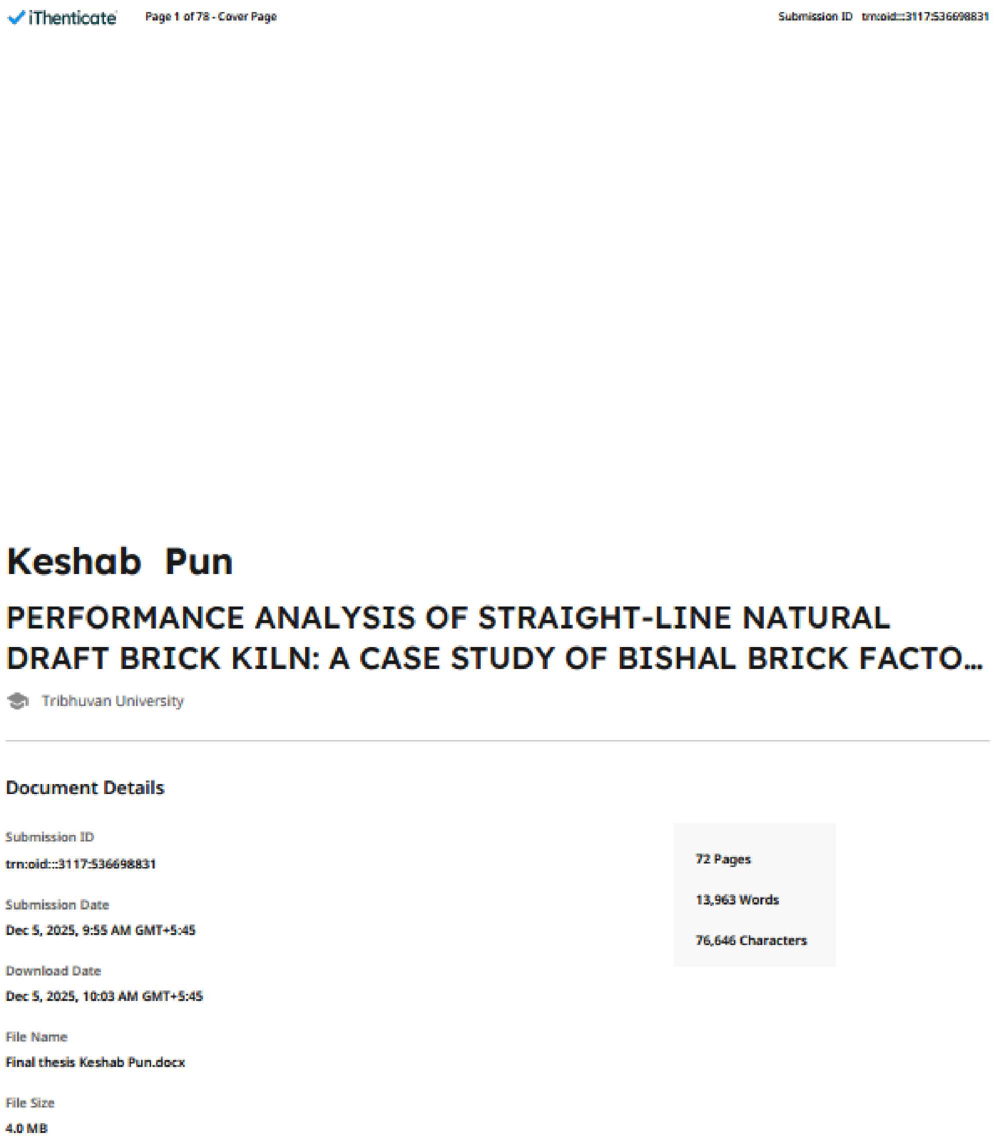

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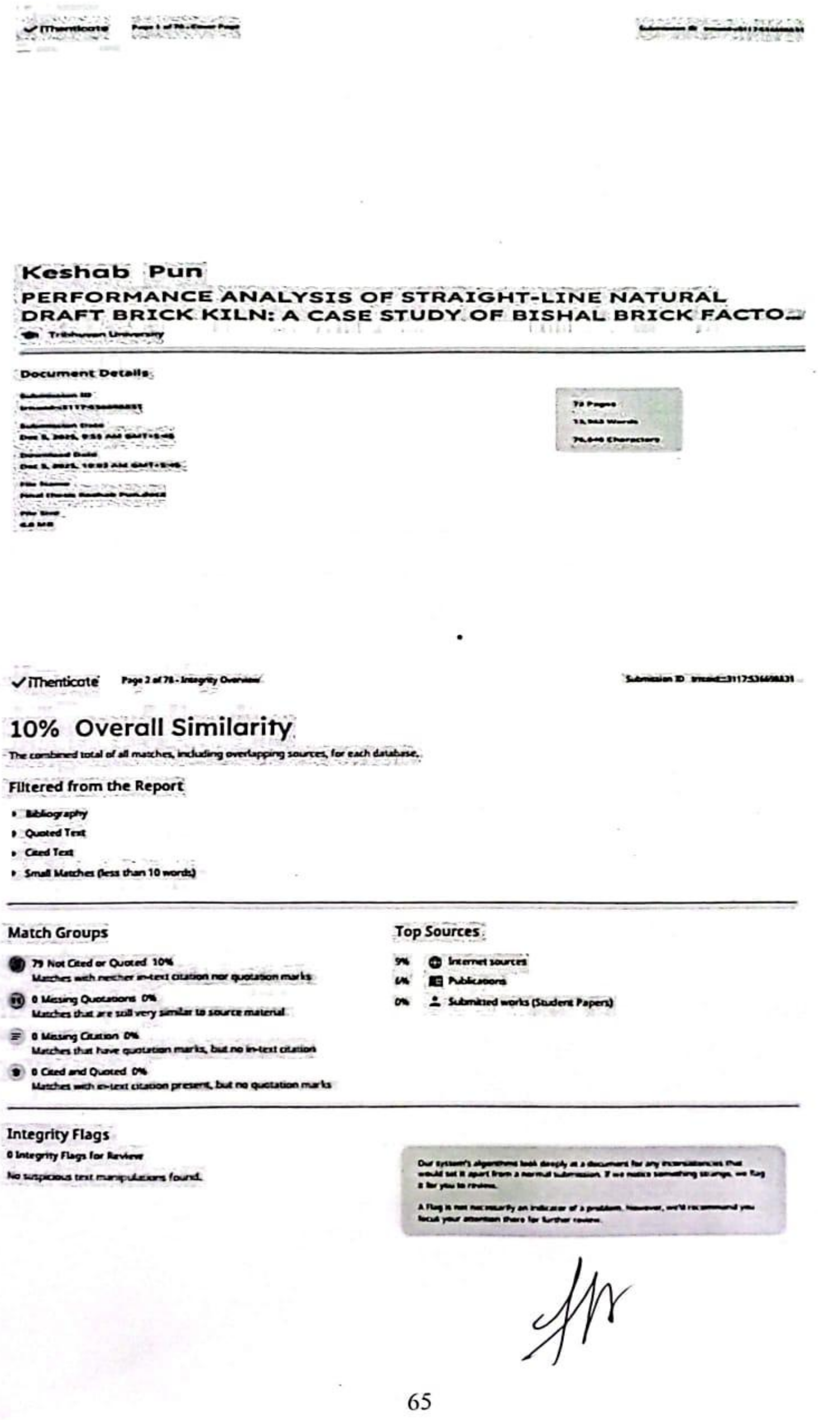

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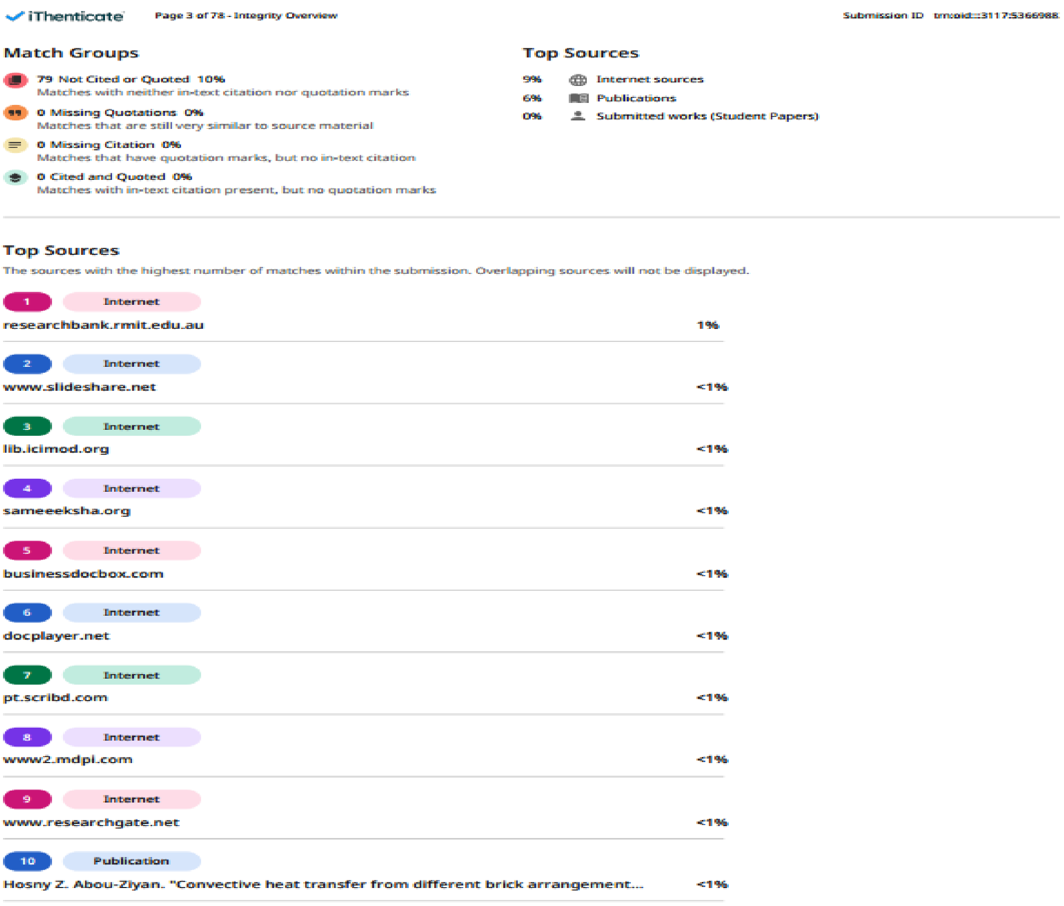

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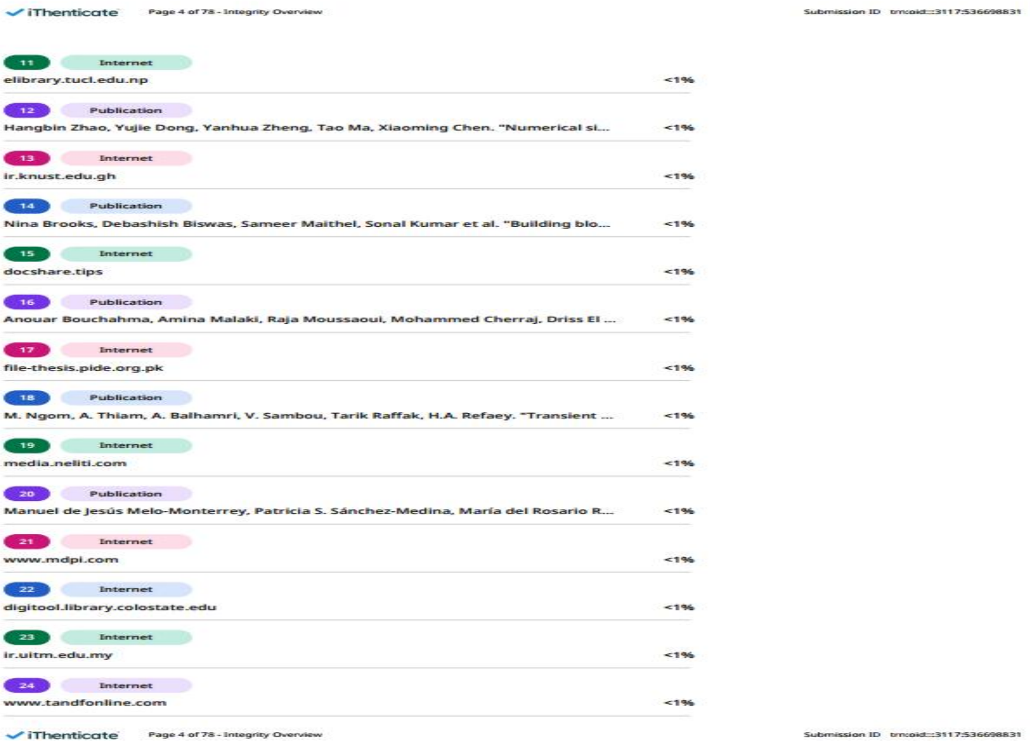

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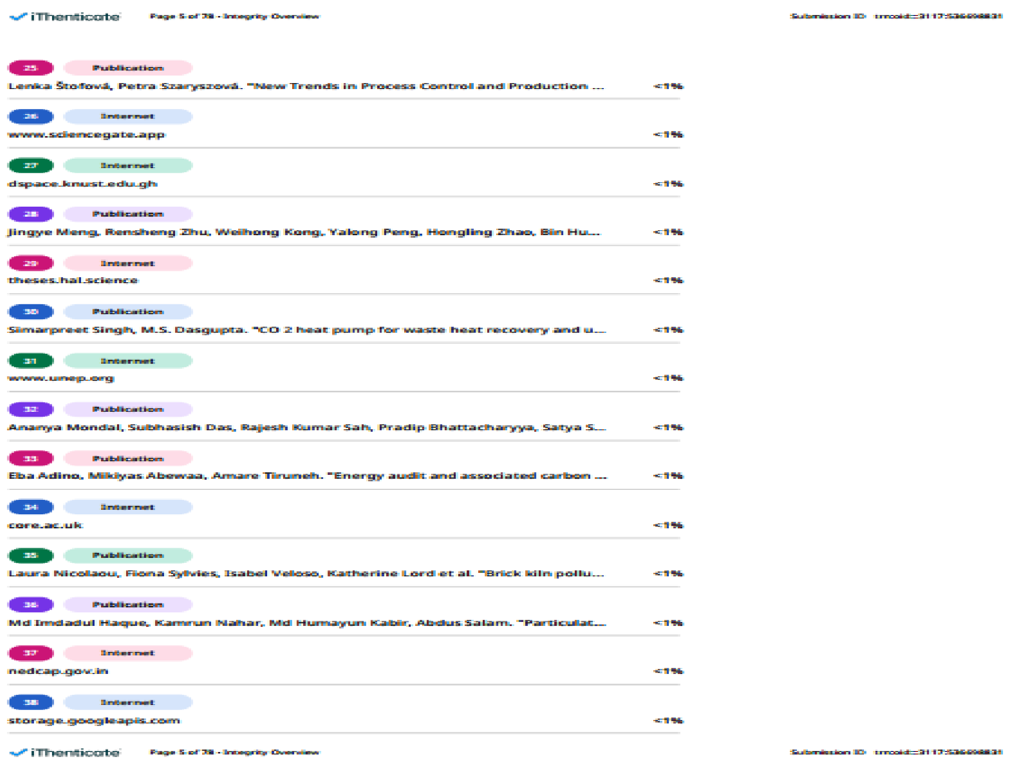

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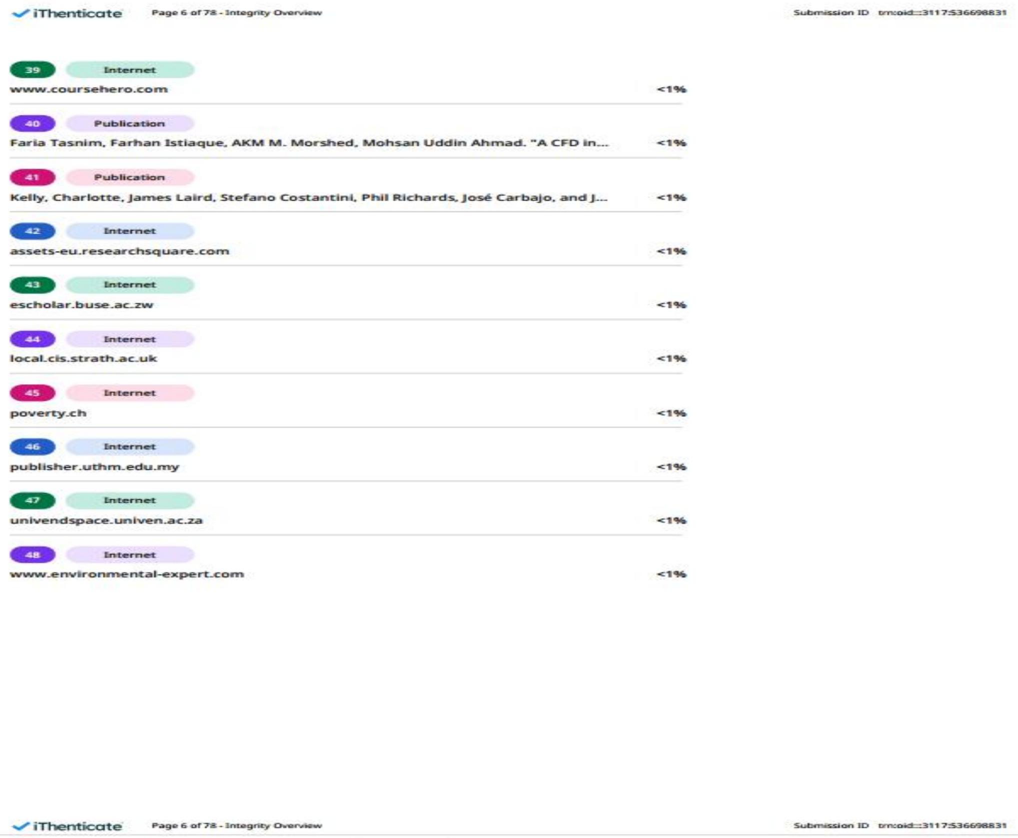

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Annex 8: Paper manuscript