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Energy Transition in Zigzag Brick Kiln: A Case Study of H.T. Brick Factory, Bhaktapur, Nepal

by

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A THESIS

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The undersigned certify that read, and recommend to the Institute of Engineering for acceptance, a thesis entitled "Energy Transition in Zigzag Brick Kiln: A Case Study of H.T. Brick Factory, Bhaktapur, Nepal" submitted by Kshitiz Ghimire (PUL079MSREE008), in partial fulfillment of the requirements for the degree of Master of Science in Renewable Energy Engineering.

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ABSTRACT

Brick manufacturing process is a highly energy-intensive process that predominantly depends on fossil fuels, primarily, coal and biomass mixtures, providing a significant contribution in air pollution. This study focuses on the energy-saving opportunities and the minimization of environmental impacts associated with brick production with the application of fuel substitution in brick kilns, that focuses on optimized combustion velocity using coal-biomass mixture, and natural gas as an alternative fuel. A combination of onsite data collection as well as steady-state computational fluid dynamics (CFD) simulations was performed to study the thermal performance, airflow characteristics, and pollutant formation in an induced draft zigzag kiln. The study demonstrates the effect of varying inlet air velocities on fuel combustion, excess air, and the overall kiln efficiency. For coal-biomass mixture, the inlet air velocity ranging from 4.5 m/s to 6.1 m/s were employed, while natural gas was selected as an alternative fuel for coal and biomass mixture under optimum velocity.

The simulation results indicated that air velocity is a responsible factor for the thermal efficiency of the kiln and also helps to maintain the required quality of fired bricks. For kiln operating with coal-biomass mixture as a source of fuel, the optimum inlet air velocity ranges from 4.9 m/s to 5.4 m/s, which enables enhanced air-fuel mixing, helps in maintaining flame stability and provides uniform temperature distribution within the green bricks firing zone. The inlet air velocity lower than 4.9 m/s demonstrated lower temperature inside the combustion zone while air velocity higher than 5.4 m/s resulted higher temperatures, producing overcooked bricks. The kiln's thermal efficiency could be improved from 52% to 69% by maintain the air velocity in optimum range. When natural gas was used as an alternative fuel for combustion, the kiln efficiency increased to 80%, demonstrating uniform temperature distribution inside the combustion zone, improving the firing quality of bricks. Similarly, using natural gas reduced the CO_2 emissions by nearly 30% and almost eliminated the particulate matters highlighting its environmental advantages. This study finds out that substituting the existing induced draft fan by a 11 kW VFD controlled induced draft fan helps in regulating the air velocity, improving the operational control and energy utilization. Based on these findings, this study recommends to prioritize natural gas as a substitute fuel for improved energy performance in brick kilns.

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LIST OF ABBREVIATIONS

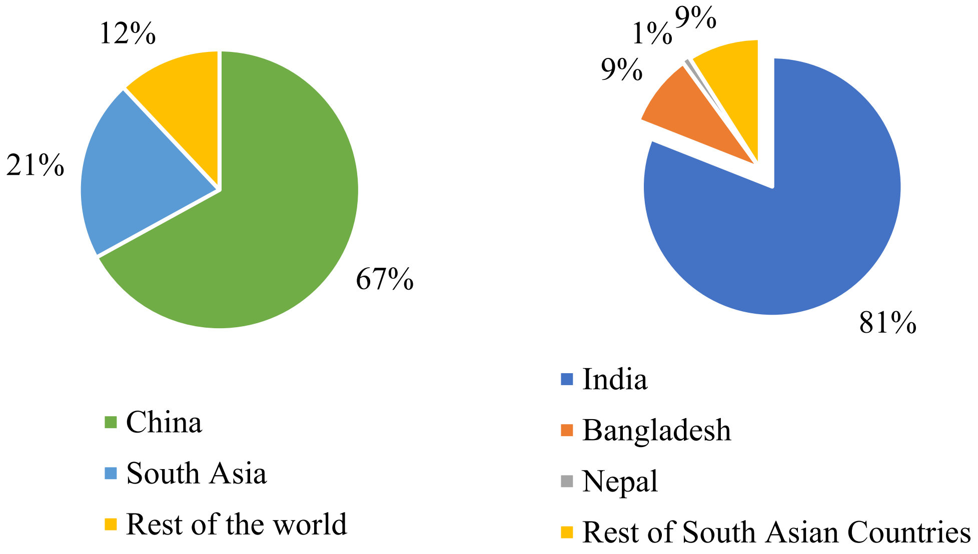
ANSYS	Analysis System
CFD	Computational Fluid Dynamics
CO_2	Carbon dioxide
CO	Carbon monoxide
EF	Emission Factor
FCBTK	Fixed Chimney Bulls Trench Kiln
GHG	Greenhouse Gases
ICIMOD	International Center for Integrated Mountain Development
IRR	Internal Rate of Return
kWh	Kilowatt Hour
kCal	Kilo Calories
MCBTK	Movable Chimney Bulls Trench Kiln
MW	Mega Watt
MJ	Mega Joule
NPV	Net Present Value
NSIC	Nepal Standard Industrial Classification
NO_x	Nitrogen oxides
PM	Particulate Matter
RANS	Reynolds-Averaged Navier-Stokes
SAARC	South Asian Association for Regional Cooperation
VFD	Variable Frequency Drive
WECS	Water and Energy Commission Secretariat

CHAPTER ONE: INTRODUCTION

1.1 Background

The brick manufacturing process provides an important contribution to the construction industry, playing a vital role in the infrastructure development of societies worldwide. Bricks are considered to be the oldest and mostly used materials in the construction industry. The bricks are appreciated for their aesthetic flexibility, strength, durability and structural integrity, making them essential in both traditional as well as modern construction practices. The production of bricks involves a number of steps, starting from the extraction of raw materials i.e. clay, the preparation of clay by mixing with sand and other materials, manual molding, sun drying and firing. Each stage is critical to improve the quality, performance, and sustainability of the final product.

South Asia has a huge contribution in global brick production i.e. 21% production of global market, making it the second-largest producer worldwide after China, that produces 67% of the world's total output alone. The brick manufacturing technologies used in South Asia have remained unchanged since ages and are considered as inefficient with lower productivity, and contributing to higher level of pollution (Baral et al., 2020).



(Baral et al., 2020)

Figure 1.1: Share of global brick production

Despite the historical significance of the bricks in construction industry, the brick production process faces modern challenges, like minimization of the environmental

impacts, improvement of the energy efficiency as well as the sustainable use of raw materials. These challenges are strengthened by the demand of high-quality and more durable bricks in rapidly urbanizing regions. As the industry's market is growing larger, they are also focusing on adapting innovative technologies that not only contributes to improve the production efficiency but also helps to meet environmental standards.
The brick industry is also a large contributor to the economy of Nepal, but is also contributes in greenhouse gas (GHG) emissions and increase the air pollution. The use of coal, fossil fuels, firewood and other conventional fuels as the main source of fuel for drying green bricks releases large amount of CO_2, SO_2, and particulate matters, contributing to air pollution and global warming. International Center for Integrated Mountain Development (ICIMOD) conducted a study in 2019 that estimated the brick industries existing in Nepal are responsible for the annual emission of 5.1 Metric Tons of CO_2 (ICIMOD, 2019). A total of 465,220 tons of coal equivalent per year is used as source of fuel for brick sector in Nepal producing total emission of 1,299,065 tons of CO_2 equivalent (Thakuri et al., 2024). The use of low-quality fuels, inefficient technologies, poor combustion practices and leakages from the combustion chamber are the primary factors contributing for higher fuel usage and greenhouse gases emissions from the brick industries.

This study investigates the brick production process in detail, identifying both the traditional and modern techniques, with a focus on identifying opportunities for energy efficiency and environmental impacts minimization. This study focuses on the thermal, economic, and environmental aspects of brick production, with an objective of providing the optimum techniques which can improve the overall efficiency and contribute towards sustainable brick production process. This research aims to provide valuable insights that suggests sustainable brick manufacturing practices, ensuring that they meet the demands of a rapidly changing world while minimizing their environmental footprint.

1.2 Statement of problem

The brick manufacturing industry plays a significant role for the economic growth in many developing countries. Though, industries can be considered as a backbone in industrial revolution and economic contribution, they contribute towards significant contribution in high level of energy consumption and environmental pollution. The traditional firing techniques used in the kilns particularly rely on fossil fuels like coal, firewood, diesel etc. resulting in higher amount of energy consumption and production of substantial emissions of greenhouse gases (GHGs) and particulate matter. These emissions contribute not only for global warming and climate change but also pose severe health hazards to communities living nearby the industries.

The major source of pollution in brick industries is the chimney, that releases a high concentration of pollutants responsible for environmental pollution including carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulfur oxide (SO_2) and particulate matters (PM). Although cleaner technologies like electric furnaces are available for these industries, the adaptation rate of these cleaner technologies remains low due to various constraints, including economic and regulatory challenges.

Similarly, the inefficient traditional firing technologies are responsible for higher energy consumption which will further intensify the carbon footprint of the industry. There is a critical need to identify energy-saving opportunities within the manufacturing process, emphasizing on the efficiency of kiln to optimize fuel usage and to reduce the pollutants. This research aims to explore and evaluate potential energy-saving measures, specifically their effectiveness in reducing emissions from brick kiln chimneys. Similarly, this study will assess the feasibility of using cleaner technologies in brick manufacturing process. The findings of this research will provide valuable insights for policymakers and support the transition toward more sustainable practices in the brick manufacturing sector.

1.3 Objectives

The major objective of this study is to perform efficiency analysis and identify energy transition potential to reduce emissions due to combustion in zigzag kiln.
The specific objectives of this research are:

- To determine the thermal efficiency of the existing zigzag kiln
- To find out the optimum air velocity for zigzag kiln operation
- To simulate and perform the analysis of the energy efficient fuels
- To carry out the environmental and economic assessment during use of different fuels in zigzag brick kilns

1.4 Limitations of the study

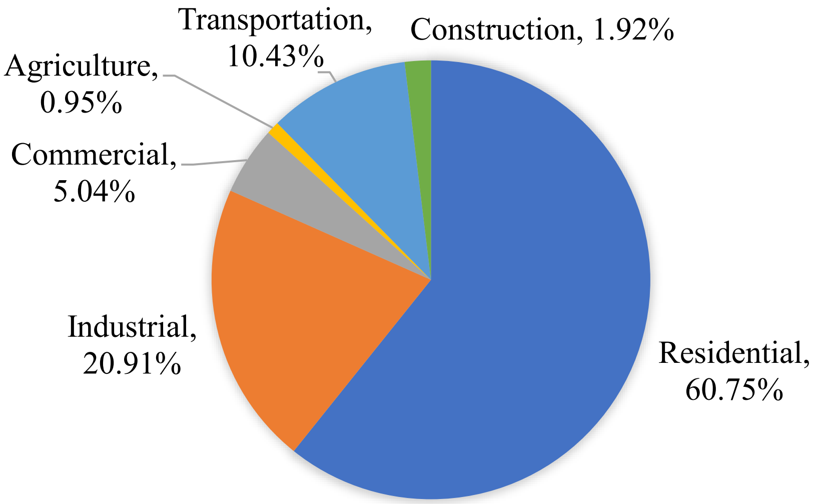
Although an extensive study was performed to achieve the output of this research, there were certain limitations that emersed during the period of this study. These limitations include:

- This study regards carbon dioxide (CO_2), carbon monoxide (CO) hydrocarbons (C_xH_y) and PM_{10} as GHG emissions
- The calorific value and efficiency information considered for different calculations have been taken from various peer-reviewed journals
- The simulation was performed assuming the conditions to be adiabatic
- This study considers the fuels using for firing process in brick production sector as other process are manual, uses sun or uses electricity

CHAPTER TWO: LITERATURE REVIEW

2.1 Energy consumption scenario of Nepal

Nepal's total energy consumption in the FY 2023/24 was found to be 532.42 PJ. Among the sectoral energy demand in Nepal, industrial sectors take the second share accounting to 22.17% after residential sectors. The large contribution of industrial sectors in the energy consumption is due to use of different kinds of fuels for various manufacturing and production processes.



(WECS, 2024)

Figure 2.1: Sector wise energy consumption in Nepal for FY 2079/80

Nepal has set its goal to achieve net zero emissions by 2045. However, the GHG emissions from energy usage in 2019 was found to be 17.18 CO_2 equivalent as illustrated in Table 2.1. The residential sector contributes to the majority of the emissions followed by the transportation and industrial sectors. The emission from industrial sector is reported to be 4.49 CO_{2eq}.

Table 2.1: Emissions in Nepal from various sectors

(Million metric tonnes)

Sectors	Carbon dioxide (CO_2)	Nitrous oxide (N_2O)	Methane (CH_4)	CO_2 equivalent
Residential	2.09	3.57	0.41	6.07
Industrial	4.45	0.02	0.02	4.49

Sectors	Carbon dioxide (CO_2)	Nitrous oxide (N_2O)	Methane (CH_4)	CO_2 equivalent
Transport	4.73	0.01	0.40	5.15
Agricultural	0.78	0.00	0.00	0.78
Commercial	0.54	0.13	0.01	0.69
Total	12.59	3.74	0.85	17.18

(MoFE, 2021)

Thermal energy plays a dominant role in the industrial sector, with coal being the most extensively used energy source, accounting for 30.21% of the total energy consumption. This is followed by fuelwood, which constitutes 28.66% and is predominantly used in furnace operations as indicated in Figure 2.2. In addition to these energy sources, diesel remains a key component in the industry, primarily used for providing motive power, such as in the operation of generators. Similarly, diesel and furnace oil are also used for generating thermal energy, especially in boilers and furnaces that demonstrates reliance on traditional fuels within the industrial sector. Despite these achievements, the industrial sector's shift towards more sustainable energy alternatives is still slow which requires higher efforts to achieve energy efficiency and environmental goals (WECS, 2024).

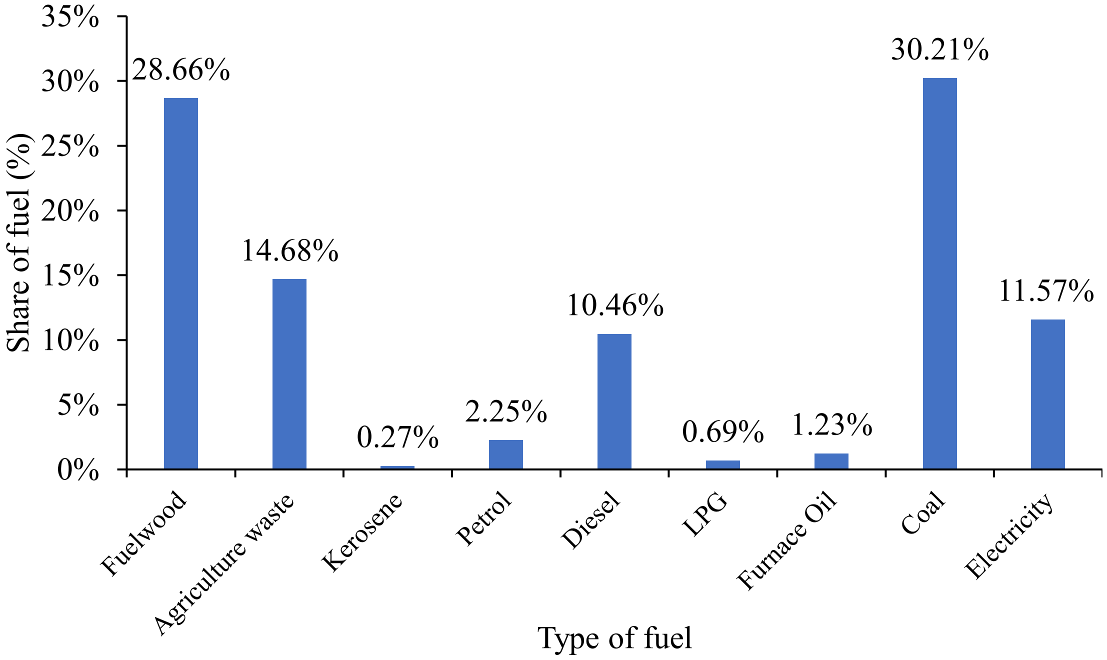


Figure 2.2: Energy consumption in industries of Nepal in FY 2023/24

2.2 Fuel consumption scenario in brick industries

Brick firing is an important phase in the brick manufacturing process, as it involves the removal of moisture along with drying of green bricks. This process requires higher initial investment and large operational costs. This stage is also considered important from the energy and environmental aspects. Five primary brick firing technologies are commonly applied in Nepal i.e. Movable Chimney Bulls Trench Kiln (MCBTK), Clamp Kiln, Straight-line Fixed Chimney Bulls Trench Kiln with both natural and forced draught, Zig-zag Fixed Chimney Bulls Trench Kiln with normal and forced draught, and Vertical Shaft Brick Kiln. The use of MCBTK was official restricted in the Kathmandu Valley from 2004, and the restriction was extended outside the valley from 2012 (Sameer Maithel, 2013).

The zigzag kiln is an improved version of the traditional fixed chimney kiln that is considered to have a better thermal efficiency by forcing flue gases to flow through a staggered brick stacking. This increases the path length and also improves heat transfer. Previous studies concludes that zigzag kilns can be 10–20% more fuel-efficient than FCKs and significantly reduce PM, SO_2, and CO emissions. However, the performance of zigzag kilns varies widely due to inconsistent construction standards and poor combustion control. Although zigzag kilns have demonstrated environmental and economic advantages, their manual operation, fluctuating draft control, and heterogeneous stacking patterns challenge consistent fuel efficiency and emission performance.

In Nepal's brick industry, an estimated 465,220 tons of coal equivalent are consumed annually, making it a significant energy consumer. Coal is the primary fuel used in the combustion process accounting for 82% of the total fuel usage. Diesel shares 8.9% of the total consumption and firewood has the total share of 8.7%. Similarly, other fuels like petroleum products, biomass, wood chips, pellets and rice husk are used in combustion inside brick kilns. These multiple fuel sources demonstrate the heavy reliance on traditional energy inputs, despite the need for more sustainable practices in brick kilns. The combination of these fuels highlights the challenges and opportunities within the sector as it seeks to balance production efficiency with environmental responsibility (Thakuri et al., 2024).

2.3 Process flow diagram in brick industries

Brick production process involves the following main processes: clay winning, clay molding and brick drying. The clay winning process involves digging and excavation of clay and mixing with water after manual removal of stones and large particles. The addition of carbonaceous materials is also done in this stage as per requirement. The processed clay is then molded to desired shape. The molding process can be done manually and mechanically using extrusion machines. The drying process involves thermal energy like drying in sunlight, drying inside kilns. The overall brick production process is illustrated in Figure 2.3.

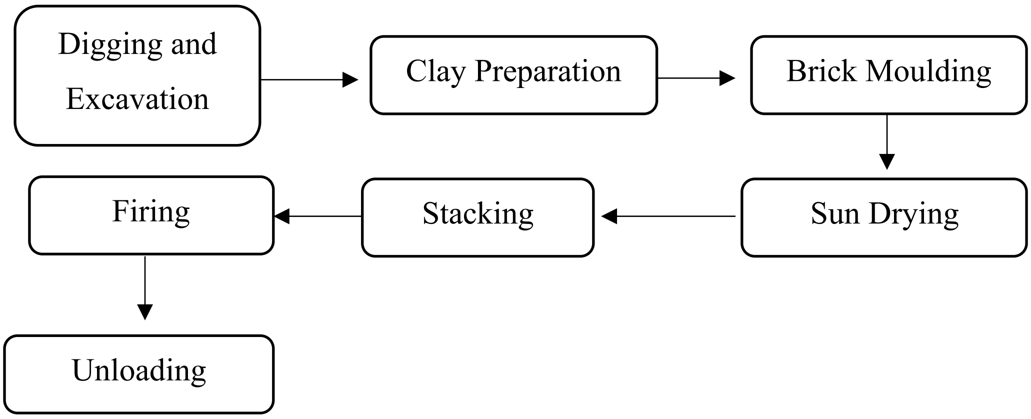


Figure 2.3: General process flow diagram of brick industries

2.4 Environmental impacts from brick production

The firing of different types of fuel during manufacturing of brick and ceramic products produce various GHGs that are responsible for various environmental impacts. Straight-line FCBTKs are the most significant emitters, consuming 330,644 tons of coal equivalent and releasing 923,276 tons of CO_2-equivalent emissions. Zig-zag FCBTKs follow, with 77,487 tons of coal equivalent consumed and 216,370 tons of CO_2-equivalent emissions. Other kiln types, including VSBK, Hoffmann, and tunnel kilns, contribute lesser amounts, with total emissions across all technologies amounting to 1,299,065 tons of CO_2 equivalent. The total GHG emission from various firing technologies in Nepal is shown in Table 2.2.

Table 2.2: GHG emission from brick kilns in Nepal

Technology	Number	Coal equivalent (ton)	Emission (ton)			
			CO_2	N_2O	CH_4	CO_2-Eq
Straight-line FCBTK (natural/forced draft)	817	330,644	916,711	14.5	96.9	923,276
Zig-zag FCBTK (natural/forced draft)	263	77,487	214,832	3.4	22.7	216,370
Clamp kiln	114	27,386	75,929	1.2	8.0	76,473
VSBK	25	5714	15,842	0.3	1.7	15,956
MCBTK	6	3962	10,984	0.2	1.2	11,063
Hoffmann kiln	6	10,624	29,455	0.5	3.1	29,666
Tunnel kiln	3	7139	19,793	0.3	2.1	19,935
HHK	2	2266	6282	0.1	0.7	6327
Total	1236	465,222	1,289,828	20	136	1,299,065

(Thakuri et al., 2024)

2.5 Energy efficiency and emission performance

Across South Asia and China, kiln design and operating practice are the dominant determinants of both energy efficiency and pollutant emissions. Comparative analysis determines that induced-draft zigzag (IDZK) and Vertical Shaft Brick Kilns (VSBK) consistently outperform traditional technologies like Fixed Chimney Bull's Trench Kilns (FCBTK) on specific energy consumption (SEC) and on primary pollutants (PM, BC, SO_2, NO_x). A study performed by Rajarathnam et al. verified that specific energy consumption ranged lowest for VSBK and IDZK and highest for FCBTK and some Hoffmann configurations, reflecting improved turbulence and heat-recovery in the cleaner designs (Rajarathnam et al., 2014). These patterns imply proportional reductions in combustion-related CO_2 and co-emitted species when modern designs are deployed and well-operated. Measured emission profiles confirm that both stack and fugitive releases matter for ambient impacts. Chen et al. (2017) directly quantified stack and near-source fugitive emissions of PM, CO, SO_2 and NO_x from typical brick kilns in China and demonstrated that non-stack (fugitive) losses can be a material share of the total, underscoring that efficiency upgrades must be paired with enclosure, good maintenance and operating discipline to realize ambient-air benefits (Chen et al., 2017).

The study performed in brick kilns of Nepal also mirrors similar findings. A Kathmandu Valley stack-monitoring program finds large difference in suspended particulate matter (SPM) concentrations from different kiln technologies, with zigzag and vertical shaft kilns emitting comparatively lower SPM than natural-draft BTK and some Hoffmann units. Although the absolute levels of emissions were still high enough to warrant further control, highlighting the importance of correct stacking, uniform firing and fuel quality even in better kilns (Sah et al., 2020). In parallel, documents and government monitoring authorities have set the emission limits and chimney requirements, reflecting the sector's outsized contribution to local $PM_{2.5}$ burdens.

In terms of energy efficiency, gas fired tunnel kilns are found to be more efficient due to process control technologies although they suffer thermal losses that makes their thermal efficiency in medium level. A study done by Hussain et al. concluded that heat-recovery processes like installation of metallic recuperators and electrical preventive measures like power-factor correction helps to reduce fuel and electricity use, with 8% savings in natural gas with a simple payback period of one year and also reduces CO_2 and NO_x reductions without changing the final product (Hussnain et al., 2021). Such results reinforce the general principle from coal-fired systems: interventions that cut SEC deliver proportional emissions co-benefits. Valdes et al. confirmed that the performance of artisan brick kilns can be improved through integration of mechanical fans, enhanced thermal insulation of kiln as well as automated control of operational activities (Valdes et al., 2020). Similarly, incorporating alternative materials having lower thermal conductivity along with proper insulation is also crucial for minimizing heat dissipation and maintaining stable temperature of the combustion zone (Bouchahma et al., 2024).

The highest reported energy and emission performance identifies that coupling two kilns can increase energy efficiency to 77% from 60.66% and can reduce emissions by approximately 53.83% (Chavez, 2021). The employment of agricultural waste consisting 15% of pomegranate peel waste in the fuel achieved energy savings of 17.55%-33.13% and CO_2 emission reductions of 7.50% - 24.50% (Ahmed et al., 2023). Arora et al. evaluated pellets made from paddy straw as a partial substitute of coal using fuel blends consisting of pellets ranging from 10-30% and concluded that 20% of coal can be replaced with paddy straw pellets without any change in the kiln performance (Arora et al., 2025). Likewise, decision-analytic assessments find out that prioritized technological modifications like switching to zigzag kilns from straight line kilns, use of energy efficient fuels and improvement of operational practices emerges as the most effective levers for mitigating environmental and health risks from brick production. A 2019 study by Khan et al. using multi-criteria methods to rank interventions in Pakistan found that kiln technology and fuel quality dominate risk reductions, aligning with the measurement literature and with earlier inventory-style work that identified modernization and fuel switching as the core avenues for cutting both CO_2 and local pollutants (Khan et al., 2019).

In a nutshell, moving from FCBTK/natural-draft BTK to IDZK or VSBK yields substantial efficiency gains and lower particulate matter emissions. Similarly, real-world outcomes depend heavily on operational discipline (stacking, firing uniformity, maintenance, enclosure) because fugitives can offset stack gains. It is also found that for gas-fired tunnel kilns, relatively low-cost heat-recovery and electrical improvements must be done. These findings support a combined strategy for Nepal and the broader region: targeted technology conversion, fuel and operations improvements, and enforcement of emission standards, with stack and fugitive controls considered together.

2.6 Optimum firing temperature for green bricks

The drying of green bricks plays an important role to produce high quality bricks by preventing the formation of cracks. Previous studies recommend the drying of green bricks for 24 to 48 hours by controlled combustion at 50-110 °C to achieve constant weight (Chapagain et al., 2020), (N. Bohara et al., 2020). Slow and uniform moisture removal at this stage helps avoid structural deformation before firing (Tsega et al., 2017). For clays found inside Kathmandu valley, mineralogical transformations like the formation of spinel and primary mullite occur between 900 °C and 1100 °C, suggesting that optimum firing lies within 900–1050 °C to achieve high strength and reduced porosity (N. B. Bohara et al., 2018), (Chapagain et al., 2020). Tsega et al. concluded that increasing the firing temperature and extending the soaking period enhances the compressive strength, improves brick densification, and decreases the water absorption from the fired bricks (Tsega et al., 2017).

2.7 Simulation approaches in brick kilns

Computational Fluid Dynamics (CFD) have been established as an important tool for studying the thermal behavior, flow dynamics, and emission characteristics of conventional brick kilns that are difficult to measure during the period of kiln operation (Tasnim et al., 2019). Simulation helps us to visualize the internal kiln phenomena like detailed temperature distribution, fluid flow behaviour that are difficult to obtain through direct measurement (Lara-Mireles et al., 2025). The visualization of heat transfer and fluid flow behaviours inside the kilns using numerical simulations has helped researchers to improve the design and operational behaviours of the kilns (Lezcano et al., 2025) . Studies demonstrates that CFD is highly effective in predicting temperature distribution, simulating the convective and radiative heat transfer, and estimating emissions from fuel combustions like CO, CO_2, NO_x, and black carbon (Tasnim et al., 2019). Araújo et al. performed numerical simulation using ANSYS® CFX and found out that increasing the air velocity leads to long-lasting temperature gradients on the brick surfaces and produces higher surface temperature for same exposure time (Araújo et al., 2017). Lezcano et al. studied the feasibility of replacing existing conventional burners with self-regenerative flameless combustion burners that achieved higher temperature of the combustion chamber that reduced the energy consumption and improved thermal efficiency (Lezcano et al., 2025). These advanced studies highlight the potential of CFD in brick kiln research, though most studies in Nepal remain limited to manual efficiency estimation methods and stack monitoring, with minimal integration of simulation tools (Sah et al., 2020). Some researchers have applied transient simulation studies while some of them have studied the brick kiln profile using steady-state simulation solver. The general schematic methodology applied for performing CFD simulation in the study of combustion behavior inside brick kilns is given in Figure 2.4.

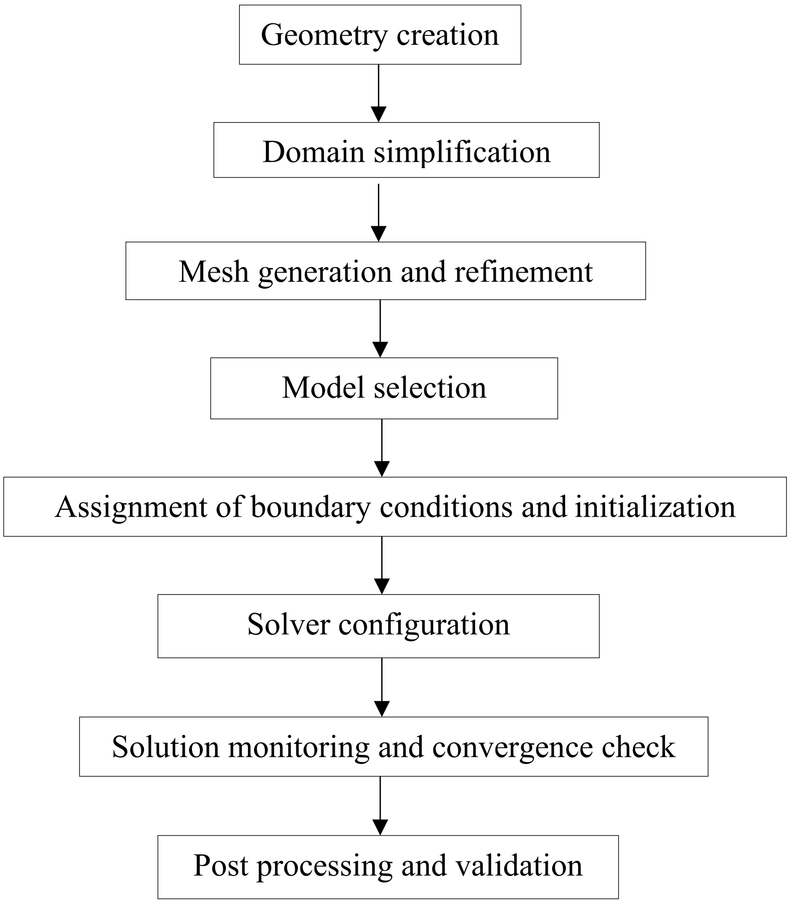


Figure 2.4: Workflow for CFD modeling

2.7.1 Geometry creation and domain simplifications

The initial step during CFD modeling is the creation of the computational domain. Most studies include the kiln cavity, combustion chamber, brick stacks, inlet ducts, and chimney in the domain, with either explicit brick geometries or porous media approximations used for stacked bricks (Refaey et al., 2021), (Alonso-Romero et al., 2024). Explicit geometries provide a high-fidelity representation of the internal flow and thermal patterns but demand significant computational resources. Porous media modeling helps to reduce mesh complexity and also maintains realistic predictions of heat and flow transfer. Many studies are performed by replicating the symmetry and periodicity of the model to reduce computational time, computational cost and for repetitive brick arrangements (Unterluggauer et al., 2024).

2.7.2 Mesh generation and refinement

Mesh generation has an important role in CFD modeling, as it influences the accuracy of the numerical model, convergence behavior of the residuals, and also help to improve the computational efficiency. Hybrid meshing strategies are frequently adopted in practice, where structured hexahedral elements are applied in relatively simple domains like channel regions or straight ducts regions. Similarly, unstructured elements are used in areas with geometrical complexity, like burner zones, intersection between chimney and ducts, and lattice brick arrangements. Hexahedral meshes are generally considered for their better numerical accuracy, while polyhedral and tetrahedral meshes have better flexibility in representing intricate geometrical features accurately. (Ngom et al., 2021).

For regions representing porous media, tetrahedral or polyhedral meshes are typically used to simulate the flow resistance as well as the heat transfer between medium without modeling each brick individually (Alonso-Romero et al., 2024). Boundary-layer inflation is also applied at brick surfaces as well as kiln walls to resolve thermal and velocity gradients in an accurate way. For wall-function-based Reynolds-Averaged Navier-Stokes (RANS) models, the first cell y^+ is targeted between 30–300 while low-Reynolds number like k–ω SST or LES models require $y^+ < 1$ (Unterluggauer et al., 2024). Mesh refinement is applied in regions where high velocity and temperature gradients are used, especially near the burners, chimneys as well as fluid interface regions. Adaptive mesh refinement (AMR) is often used in zones with higher temperature or species concentration gradients to make a balance between computational efficiency and solution accuracy (Alonso-Romero et al., 2025).

To confirm the solution independence in modelling, a grid convergence study is considered where simulations are performed on coarse medium as well as fine meshes. Key outputs like pressure drop, maximum brick temperature and species concentration are examined and acceptable convergence is typically defined as less than a 2-3% change between the medium and fine meshes (Tasnim et al., 2019), (Alonso-Romero et al., 2025).

2.7.3 Viscous models

Accurate prediction of flow, thermal, and chemical fields in brick kilns require proper turbulence, combustion, and radiation models selection. Most of the studies done in brick kilns implement RANS turbulence models like realizable k–ε, RNG k–ε, or k–ω SST, to simulate the recirculating buoyant flows. These models provide a balance between computational efficiency and prediction accuracy (Unterluggauer et al., 2024).

Large Eddy Simulation (LES) is generally done in research studies with higher resolution because of its high computational demand.

Combustion Modeling: Combustion modeling is done either using simplified global reaction schemes for general flow and temperature prediction or detailed finite-rate chemistry coupled with the Eddy-Dissipation Concept (EDC) for prediction of accurate species like CO, NO_x, soot formation. Non-premixed mixture fraction approaches are often used for solid-fuel kilns (Alonso-Romero et al., 2025).

Radiative Heat Transfer: The P1 radiation model is often used because of its lower computational time, lower computational cost and suitability for optically thick media. Similarly, the Discrete Ordinates (DO) model is generally preferred for anisotropic radiation and complex geometries that improves the prediction of surface heat fluxes and temperature distributions (Cintolesi et al., 2017), (Refaey et al., 2021). Combination of the turbulence, combustion, and radiation models help to ensure the realistic representation of the heat transfer processes that helps to govern temperature uniformity and emission formation for studies done in brick kilns.

2.7.4 Boundary conditions and initialization

Boundary conditions define the interaction of kiln with air, fuel, walls, and the external environment during simulation. Mass flow as well as velocity inlets are applied at fuel and air supply ducts, with specified temperature and species composition. Pressure outlets are also applied at chimneys or vents, and walls are modeled using adiabatic, convective, or conjugate heat transfer conditions, depending on whether external heat losses are considered. Simulation initialization typically assumes ambient temperature, zero velocity, and standard pressure, with reactive species fields initialized to zero except at fuel injection zones. Proper specification of boundary conditions and initialization is essential for ensuring numerical stability and achieving realistic steady-state or transient solutions.

2.7.5 Steady analysis

Steady-state CFD has become a widely used approach for analyzing brick kiln performance, particularly for predicting heat transfer, fluid flow, and emission characteristics under continuous operating conditions. By assuming constant fuel and air supply, the governing equations of mass, energy, momentum, species transport and radiation are solved until equilibrium is achieved.

Most studies employ k–ε turbulence models (Standard or Realizable) to balance computational efficiency with accuracy in high-temperature combustion flows (Giusti & Mastorakos, 2019). Combustion is typically modeled through species transport with finite-rate/eddy-dissipation methods, while radiative heat transfer is addressed using either the P-1 model for simplicity or the DO model for higher accuracy. For solid fuels such as coal, the Discrete Phase Model (DPM) is often applied to capture particle injection, devolatilization, and combustion (Ghose et al., 2023). Simulations generally use a pressure-based solver with SIMPLE coupling and second-order upwind schemes. Convergence is verified by reducing the residuals to 10^{-4} for species equations and 10^{-6} for energy (ANSYS, Inc., 2025). This methodology helps to enable dependable predictions of kiln temperature distribution, airflow, and pollutant formation, though it does not account for transient effects like flame fluctuations or unsteady fuel feeding.

2.7.6 Solver strategies and post-processing

ANSYS Fluent solvers are typically configured with SIMPLE or coupled schemes for steady-state simulations, and PISO or coupled schemes for transient simulations. Second-order discretization schemes are recommended for momentum, energy, and species transport to improve accuracy. Convergence is monitored using residuals alongside integral quantities such as total mass flow and energy. The study of convergence helps us to check global balances (mass, momentum, energy) and helps us to ensure that overall conservation laws are satisfied. ANSYS post-processing is the final stage after solving where the simulated results of the model are reviewed, visualized, and interpreted. Post-processing involves analyzing temperature distributions, velocity streamlines, species concentration contours, heat fluxes, and pressure drops, with results validated against experimental measurements or emission data to ensure reliability (Alonso-Romero et al., 2025).

2.8 Research gaps

Most studies in Nepal's brick sector are limited to manual efficiency estimation, field surveys, and emission testing, with very few incorporating simulation-based tools. The integration of CFD modeling with indirect/direct efficiency calculations remains unidentified. This study overcomes the gap between the research by:

- Simulating the combustion process of a zigzag FCBTK
- Evaluating temperature and velocity profiles
- Estimating CO_2 and NOx emissions
- Recommending operation and fuel optimization strategies for efficiency improvement

The findings are expected to contribute to meet the national energy efficiency targets and the objective of low-carbon industrial transition in Nepal.

CHAPTER THREE: METHODOLOGY

The systematic approach that will be used to study energy-saving opportunities and environmental impact minimization in the kiln of brick industry is outlined in this section. The research will employ a combination of data collection, analysis, and simulation to evaluate existing kiln operations, identify inefficiencies, and propose sustainable solutions.

3.1 Literature review

The literature review for this study is performed on the basis of relevant studies done in brick kilns from national and international level. National reports were studied to realize the energy consumption pattern, the types of kilns as well as emissions from brick kilns existing in Nepal. Different peer-reviewed journals and dissertations with studies made in brick kiln were studied to get information on kiln performance, energy-saving opportunities, and fuel transition practices done worldwide. To accompany this, primary data are be collected through questionnaires and field surveys that collects information on kiln operation, fuel consumption, air supply, and brick production rates. This helps to support the comprehensive analysis of thermal efficiency of the kiln, energy transition potential in existing zigzag bricks, and environmental impact minimization from brick kilns.

3.2 Data collection and compilation

The survey during the firing of kiln would be done for primary data collection. The fuel consumption, energy usage pattern and emission level from the kiln. The brick making process, total amount of fuel consumed during the cycle operation would be noted. Similarly, instruments like thermal gun, flue gas analyzers, anemometers would be used for data collection. The thermal gun would allow us to note the temperature of brick surface while the flue gas concentration would be measured using flue gas analyzer.

3.3 Research Framework

A systematic framework is needed to conduct the research so that the objectives of the research are fulfilled. The research framework listed below demonstrates the key concept of carrying out the study. The research framework adapted during the period of the study is represented in Figure 3.1.

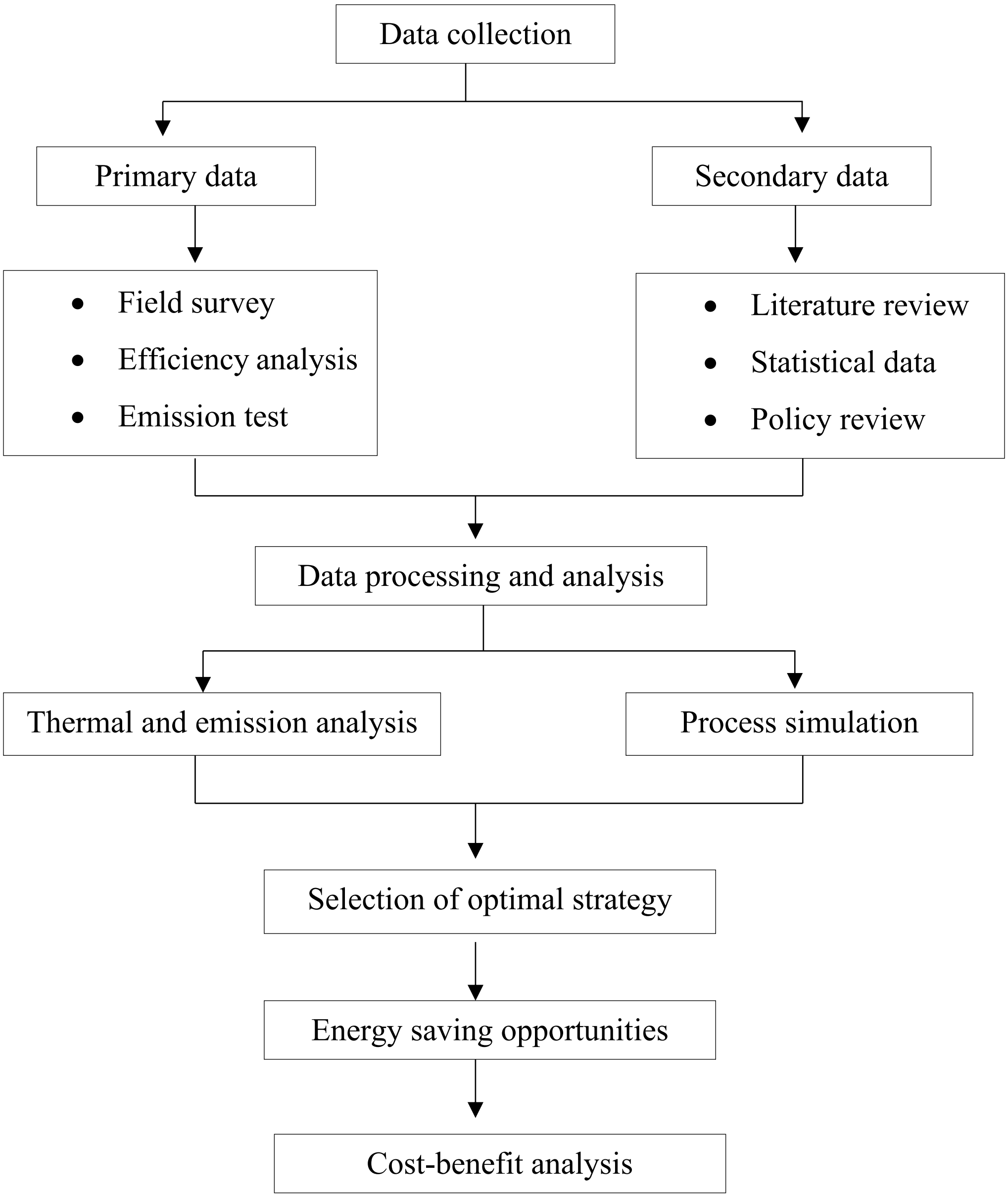


Figure 3.1: Research methodology

3.4 Efficiency analysis of brick kilns

The efficiency of the brick kiln is calculated assuming the kiln during the time of combustion is a furnace built with bricks using the mixture of coal and biomass as the source of fuel. The efficiency calculation of the furnace is done using direct and indirect method. The efficiency of the brick kiln using direct method is given in equation

$$Direct\ Efficiency = \frac{Output\ Energy}{Input\ Energy} \times 100\% \tag{3.1}$$

Similarly, the main heat losses inside the brick furnace include dry flue gas losses, loss due to hydrogen in fuel, loss due to moisture content in the fuel, loss sue to unburnt carbons and radiation and other unaccounted losses (Bureau of Energy Efficiency, n.d.).

The heat loss due to dry flue gases is given in equation (3.2).

$$\%\,Dry\ flue\ gas\ loss\ (L_1) = \frac{m \times c_p \times \Delta T}{GCV\ of\ fuel} \times 100\% \tag{3.2}$$

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

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

$$\%\,Heat\ loss\ due\ to\ moisture\ (L_2) = \frac{M \times \{584 + C_p \times (T_{fg} - T_{amb})\}}{GCV\ of\ fuel} \times 100\% \tag{3.3}$$

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).

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

where H_2= kg of H_2 in 1 kg of fuel

Similarly, the openings of the furnace are also responsible for heat loss. The heat loss due to furnace openings is given by equation (3.5).

$$\%\,Heat\ loss\ due\ to\ openings\ (L_4) = \frac{B \times A \times \propto \times\ \varepsilon}{Fuel\ feeding\ rate \times GCV\ of\ fuel} \times 100\% \tag{3.5}$$

where B= black body radiation corresponding to temperature, A= area of the openings, $\propto$ = factor of radiation, ε= emissivity

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 (3.6).

$$\begin{aligned} &\%\, Heat\ loss\ due\ to\ furnace\ skin\ (L_5) \\ &= \frac{Heat\ loss\ \times Area\ of\ furnace}{Fuel\ feeding\ rate \times GCV\ of\ fuel} \times 100\% \end{aligned} \tag{3.6}$$

The efficiency of furnace is then calculated using indirect method by using equation (3.7).

$$Efficiency\ of\ kiln\ (\%) = 100 - L_1 - L_2 - L_3 - L_4 - L_5 \tag{3.7}$$

3.5 Simulation methodology

This study utilizes Computational Fluid Dynamics (CFD) to study the thermal and flow behavior of a zig zag kiln operating at the HT Brick Factory, Jagati, Bhaktapur. The objective of the simulation is to identify energy-saving opportunities by evaluating different design and operating scenarios that influence heat transfer and combustion efficiency. The simulation work draws on methodologies and boundary setups similar to those used in (Alonso-Romero et al., 2024) and (Refaey et al., 2021), who demonstrated the value of CFD modeling in optimizing brick kiln performance.

3.5.1 Geometry creation

A simplified 3D model of the kiln was developed using SOLIDWORKS 2019 application and the design was imported into ANSYS Fluent 2024. ANSYS Design Modeler was used by representing a longitudinal section of the zigzag kiln including the brick chamber, fuel inlet region, air inlet region, combustion chambers, and air outlet to other chambers. Due to large geometry of the brick kiln and complexity in the calculation, only a specific chamber of the kiln was used for to study the combustion characteristics inside the zig-zag brick kiln. Brick stacks were modeled as solid blocks in order to prevent from the replication of their thermal resistance. The designed geometry for zig zag kiln in design modeler is given in Figure 3.2.

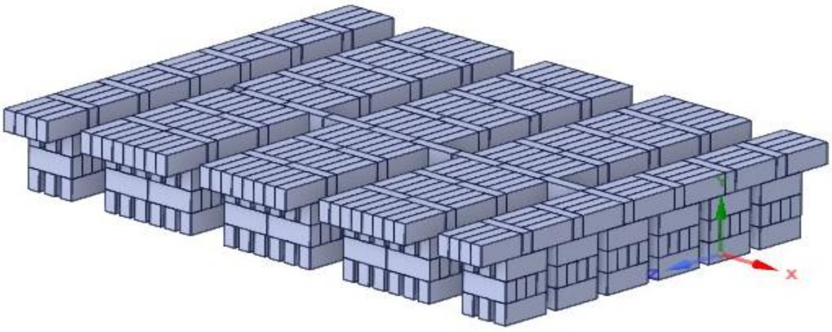


Figure 3.2: Designed geometry for zigzag kiln

3.5.2 Mesh generation

To account for the complex interior geometry of the brick kiln as well as the regular duct sections, the computational domain was discretized using a hybrid mesh. In order to balance computational efficiency and solution correctness, the mesh element size was chosen based on preliminary grid independence tests, with a minimum of 0.01 m and a maximum of 0.02 m. In order to resolve temperature and velocity variations within the boundary layer, boundary-layer inflation was applied close to brick surfaces and kiln walls. With aspect ratios below 20 and skewness values below 0.85, mesh quality measures were kept within suggested bounds, guaranteeing numerical stability and consistent convergence throughout the simulation.

A mesh independence analysis was performed to ensure whether that the selected mesh resolution had no effect on the simulation's outcomes. Elements of three mesh configurations i.e. coarse, medium, and fine, with sizes varying from 0.015 m – 0.03 m for coarse mesh to 0.005–0.015 m for fine mesh were evaluated. Maximum brick surface temperature, exit flue gas temperature, and pressure drop across the kiln were the main output characteristics that were watched for convergence. The findings indicated that, for all variables under observation, the medium mesh (minimum element size: 0.01 m; maximum element size: 0.02 m) and the fine mesh differed by less than 2%, whereas the coarse mesh displayed variances of up to 8%. The medium mesh was chosen for the final simulations based on this study that offered balance between computational efficiency and solution accuracy. The mesh generation for the designed geometry is given in Figure 3.3.

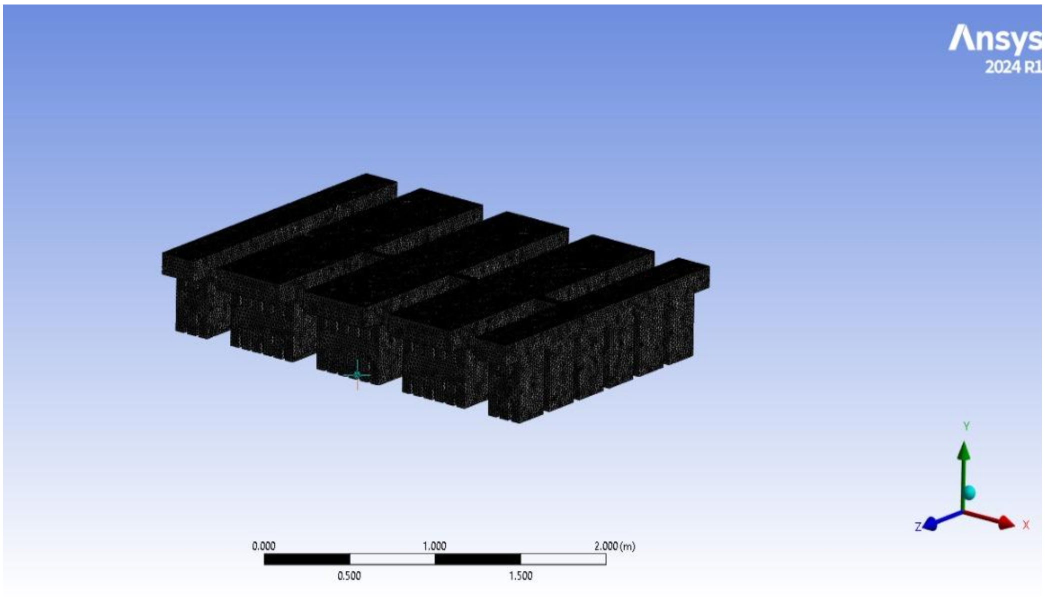


Figure 3.3: Mesh generation for the designed geometry

The computational domain was discretized using an unstructured tetrahedral mesh with prism layers near the wall to resolve boundary layer effects. The final mesh consisted of approximately 3.7 million elements and 0.74 million nodes. The maximum skewness was 0.84, within the acceptable limit (<0.95), ensuring reliable simulation accuracy. The mesh statistics of our modeled geometry are represented in Table 3.1.

Table 3.1: Mesh statistics

Parameter	Value
Total number of nodes	741,555
Total number of elements	3,706,186
Element type	Triangular
Minimum element size (m)	0.005
Maximum element size (m)	0.02
Mesh growth rate	1.2
Average aspect ratio	2.5
Skewness (max / average)	0.84 / 0.32
Orthogonality (min/ average)	0.15 / 0.79

3.5.3 Viscous models

The computational domain was meshed using unstructured tetrahedral cells, with inflation layers near the walls to detain the boundary layer effects. A mesh independence study was performed to ensure the numerical accuracy of the model. The pressure-based transient solver was employed in ANSYS Fluent, with the energy equation activated. Turbulence model was done using the standard k-ε model, and heat conduction through bricks and kiln walls was enabled. The equations solved in each computational cells were the Navier-Stokes equations given from equation (3.8) to equation (3.10).

Equation for conservation of mass:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{3.8}$$

Where ρ is the density of the fluid, t is the time taken, x_i is the Cartesian coordinate axis (x, y and z) and $u_i$is the velocity vector components (u, v, w)

Equation for conservation of momentum:

$$\frac{\partial}{\partial x_i}(\rho u_i) + \frac{\partial}{\partial x_i}(\rho u_i u_j) = - \frac{\partial \rho}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i \tag{3.9}$$

Where ρ is pressure, μ is the kinematic viscosity, and ρg_i is the body force in the x, y and z directions

Equation for conservation of energy:

$$\frac{\partial}{\partial x_i}(\rho T) + \frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i}\left[\frac{k}{c_p}\frac{\partial T}{\partial x_i}\right] + S_T \tag{3.10}$$

Where T is the temperature, c_p is the specific heat capacity, k is the thermal conductivity of the brick and S_T is the source term (ANSYS, Inc., 2025).

The standard-model is an experimental model that is based on model transport equations for turbulence kinetic energy (k) and specific dissipation rate (ω), which can also be considered as the ratio of ε to ω. The specific dissipation rate, ω and the turbulence kinetic energy, k are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\Gamma_k \frac{\partial k}{\partial x_j}\right] + G_k - Y_k + S_k + G_b \tag{3.11}$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j}\left[\Gamma_\omega \frac{\partial \omega}{\partial x_j}\right] + G_\omega - Y_\omega + S_\omega + G_{\omega b} \tag{3.12}$$

where G_k represents the generation of turbulence kinetic energy due to mean velocity gradients, G_ω represents the generation of ω, Γ_k and Γ_ω represents the effective diffusivity of k and ω respectively. Y_k and Y_ω represents the dissipation of k and ω due to turbulence. S_k and S_ω are user-defined source terms. G_b and $G_{\omega b}$ account for buoyancy terms (ANSYS, Inc., 2025).

3.5.4 Radiation models

The P-1 radiation model assumes that all surfaces behave as diffuse emitters and reflectors, meaning any incident radiation is scattered uniformly in all directions. Its application is limited to gray radiation or non-gray radiation treated with a gray-band approach. In the non-gray case, each wavelength band is assigned a constant absorption coefficient, and the weighted-sum-of-gray-gases model (WSGGM) cannot be applied to define these coefficients. Additionally, the model assumes that the wall emissivity remains constant within each spectral band, rather than varying with wavelength. The equations used in this radiation model is given in equation (3.13).

$$q_{r,\omega} = -\frac{\varepsilon_\omega}{2(2-\varepsilon_\omega)}\left(4n^2\sigma T_\omega^4 - G_\omega\right) \tag{3.13}$$

Where, $q_{r,\omega}$ is the flux of incident radiation, ε_ω is the emissivity, G_ω is the incident radiation on the wall, T_ω is the temperature, σ is the Stefan-Boltzmann constant, n is the refractive index of the medium (ANSYS, Inc., 2025).

3.5.5 Boundary conditions

Boundary conditions included a velocity or mass flow inlet at the combustion zone to simulate the real-time variation of flue gas temperature and velocity. This simulation-based approach allows a quantitative assessment of energy-saving interventions, helping to identify cost-effective upgrades to improve kiln efficiency and reduce emissions.

3.6 Determination of excess air inside kiln combustion

The calculation of excess air was performed to evaluate the combustion conditions of the fuels used in the kiln, namely a coal–biomass mixture (60:40 by weight) and natural gas. The analysis was performed on the basis of the stoichiometric and actual air–fuel (A/F) ratios, as studies performed by (Alonso-Romero et al., 2025). The stoichiometric

A/F ratio ($AF_{stoichiometric}$) was determined initially with the help of complete combustion reactions of the respective fuels:

Coal–biomass mixture (60:40): The ultimate composition of coal and biomass in the ratio of 60:40 by mass was used to determine an equivalent empirical formula for the fuel. With the help of the empirical formula, the oxygen requirement and theoretical air demand were determined. The stoichiometric combustion reaction for coal and biomass mixture is defined as:

Coal: $C + mH_2O + O_2 + 3.76N_2 \longrightarrow CO_2 + mH_2O(vapor) + 3.76N_2$

Biomass: $CH_{1.44}O_{0.66} + 1.03O_2 \rightarrow CO_2 + 0.72H_2O$

From the above combustion reactions, it was found that coal ($C + mH_2O$) burns with 1 mole of O_2 and 3.76 moles of N_2 to produce 1 mole of CO_2, m moles of H_2O, while biomass ($CH_{1.44}O_{0.66}$) requires 1.03 moles of O_2 to yield 1 mole of CO_2 and 0.72 moles of H_2O, with nitrogen from air accompanying combustion in the same 3.76 ratio per mole of O_2 supplied.

Natural gas: The stoichiometric combustion reaction for natural gas is defined as:

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$

which requires 2 moles of O_2 per mole of CH_4. The theoretical air demand for combustion process was computed accordingly.

The actual amount of air supply (AF_{Actual}) was calculated from the kiln's inlet air velocity and the air inlet area. The mass flow rate for the air was calculated using equation (3.14).

$$\dot{m}_{air} = \rho \times A \times v \tag{3.14}$$

where: ρ = air density (1.225 kg/m³ at standard conditions), A = inlet area of the duct and v = measured inlet velocity (m/s).

The air mass flow rate was then normalized to the corresponding fuel mass flow rate (coal–biomass: 0.0375 kg/s, natural gas: based on energy equivalence) to obtain the actual A/F ratio.)

Finally, the percentage excess air was determined using equation (3.15).

$$\% \, Excess \; air = \left(\frac{AF_{actual}}{AF_{stoichiometric}} - 1 \right) \times 100\% \qquad (3.15)$$

Similarly, if $AF_{actual} < AF_{stoichiometric}$, the deficiency of air needs to be computed using equation (3.16).

$$\% \, Deficiency \; of \; air = \left(1 - \frac{AF_{actual}}{AF_{stoichiometric}} \right) \times 100\% \qquad (3.16)$$

This methodology enabled quantification of the degree of excess air at different inlet velocities (4.5, 4.9, 5.4, and 6.1 m/s for coal–biomass, and 4.9 m/s for methane). The results were further linked with the analysis of heat loss due to flue gases, where higher excess air values directly contributed to greater sensible heat carried away by exhaust gases.

3.7 Identification of energy optimization opportunities

Based on the field visit and various calculations done from the primary data taken from the industries, the key areas where energy consumption can be reduced would be identified and the potential technological upgrades as well as changes in operational activities which can enhance the energy efficiency of the kiln would be done. The application of Computational Fluid Dynamics (CFD) using ANSYS Fluent would lead us to identify us the better techniques and fuels for combustion process to enhance the thermal efficiency of the existing zig zag kiln.

3.8 Emission analysis

The emission analysis due to combustion of different fuels used for brick firing operation was performed using emission factor obtained from different reports. The emissions were compared to each other under optimum operation and to study the environmental impact under fuel switching scenario. Emissions for specific species and fuel types are calculated using equation (3.17).

$$Em_{i,j} = \Sigma_j \, Fc_j \times EF_{i,j} \qquad (3.17)$$

where j = Type of fuel, $Em_{i,j}$ = Emission of pollutant i from fuel type j, Fc_j = Consumption of fuel type j (kg/yr), $EF_{i,j}$ = Emission factor specific to pollutant i from fuel type j (Ram M. Shrestha et al., 2013).

3.9 Economic analysis

The economic analysis was carried out to evaluate the economic feasibility of substituting the existing 60:40 coal–biomass fuel mixture with natural gas in the case of the brick kiln. The assessment was based on a 15-year project lifetime with a discount rate of 8%, in line with similar techno-economic studies conducted for cleaner fuel transitions in brick industries (Timilsina et al., 2025). The analysis further determines the potential economic and environmental impacts that arises due to fuel substitution.

The cost benefit analysis was performed by comparing the baseline scenario with the project scenario, where in case of the baseline scenario, the kiln continues to use the mixture of coal-biomass as fuel, and in case of the project scenario, natural gas is used as the primary fuel. The framework adopts a life-cycle cost approach, incorporating capital expenditure, operating expenditure and fuel costs. The incremental benefits and costs were assessed annually over the system's lifetime (typically 15 years) and discounted to present value using an appropriate discount rate.

The Net Present Value (NPV) for the scenarios were calculating using equation (3.18).

$$NPV = \sum_{t=0}^{T} \frac{A}{(1+r)^t} \tag{3.18}$$

where, A represents the annuity at time t and r is the discount rate for the project. The Internal Rate of Return (IRR) was also determined as the discount rate at which NPV equals zero (Chan S. Park, 2007).

3.10 Marginal abatement cost

The marginal abatement cost (MAC) provides the cost per tonne of CO_2-equivalent avoided, representing the cost-effectiveness of this fuel substitution as a mitigation measure (Kesicki & Strachan, 2011). The analysis considers two operational scenarios:

- Baseline scenario: The kiln currently operates using a coal–biomass mixture as fuel. Baseline data include fuel consumption, thermal efficiency, emission factors, fuel price, and maintenance costs.
- Alternative scenario: The same kiln retrofitted to operate on natural gas as a fuel by maintaining equivalent amount of thermal energy. Parameters include

natural gas consumption, efficiency, emission factor, fuel cost, and the incremental capital investment for burner replacement and pipeline installation.

The marginal abatement cost of this study is calculated using equation (3.19).

$$MAC = \frac{Cost_{new} - Cost_{baseline}}{Emissions_{baseline} - Emissions_{new}} \tag{3.19}$$

where $Cost_{new}$ indicates cost for using new fuel, $Cost_{baseline}$ indicates current cost, $Emissions_{baseline}$ represents current emissions and $Emissions_{new}$ represents emissions produced from using new fuel.

CHAPTER FOUR: RESULTS AND DISCUSSION

The brick industry is selected on the basis of the type of kiln and fuel used for brick production process. There are around 100-125 brick kilns operating inside Kathmandu Valley on seasonal basis. The most prominent technology used in existing brick industries is Fixed Chimney Bull's Trench Kiln and the stacking of the bricks are done in zig-zag pattern. Hence, similar industry is selected for data collection. For this, H.T. Brick Factory, located at Jagati, Bhaktapur was selected. This industry operates in winter season employing around 300 workers. The fire movement inside this type of kiln occurs due to the induced draft fan of 7.5 kW and the draft provided by the chimney which is 25 m high. The chimney is connected to the main duct using an underground duct. The data collection process is done in this industry using different devices like combustion analyzer, thermal gun, anemometer. After the collection of data, performance assessment of the kiln is done using direct and indirect method. The energy saving opportunities in the energy intensive field has been done using the references of previously done research in the respective fields.

The firing area of the industry covered an approximate area of 80 m^2 where the bricks were stacked in a zig zag pattern and the roof of the furnace was covered with dust of bricks. A mixture of coal and biomass was feed continuously and a batch of brick was heated for 24 hours. The different measured parameters of the zig-zag kiln are given in Table 4.1.

Table 4.1: Parameters of the zig-zag kiln

Parameter	Value
Exit flue gas temperature (°C)	102.30
Ambient temperature (°C)	19.30
Average fuel consumption (kg/hr)	135.00
Specific heat capacity of fuel (coal + biomass) (kCal/kg)	0.33
Average O_2 percentage in flue gas (%)	18.90
Specific heat capacity of bricks (kCal/kg)	0.20
Average surface temperature of heating zone (°C)	927.00
Average surface temperature of area other than heating zone (°C)	120.00
Total area of heating zone (m^2)	41.75

Parameter	Value
Total area other than heating zone (m^2)	36.25
GCV of fuel (coal and biomass mixture) (kCal/kg)	5133.79

4.1 Performance analysis of the kiln

The performance analysis of the kiln is done using both direct and indirect method. The efficiency of the kiln was found to be 58.89 % by direct method. In direct method, the fuel consumed, mass of the total fired bricks and calorific value of bricks and fuels are taken into account. The efficiency of the brick kiln using direct method is represented in Table 4.2.

Table 4.2: Efficiency of kiln using direct method

Parameters	Value
Type of fuel used in furnace	Coal and biomass
Brick (per firing)	55,000
Weight of a brick (kg)	2.8
Total weight (kg)	154,000
Specific heat capacity (kJ/kg°C)	1.38
Chimney height (m)	25
Temperature difference (°C)	83
Output energy (MJ)	17,640
Fuel (kg)	1,500
GCV of coal and biomass mixture (kJ/kg)	19,970
Input energy (MJ)	29,955
Thermal efficiency (%)	58.89

The efficiency of the brick kiln was also calculated using indirect method. Here, various areas from where losses occur are taken into account. The heat loss due to moisture in the fuel and loss due to fuel combustion and its residues were also considered as an area of heat loss. The heat loss through flue gas, heat loss due to openings and furnace skin are most responsible factors for heat loss through furnace. The efficiency of the kiln by indirect method was determined to be 52.63%. The performance analysis of the kiln is given in Table 4.3.

Table 4.3: Performace analysis of kiln using indirect method

S.N.	Description	Value
1.	Heat loss due to dry flue gas	
	Excess Air (%)	1,212.50
	Theoretical air required (kg)	11.50
	Total amount of air supplied (kg / kg of fuel)	103.62
	Weight of the flue gas (kg / kg of fuel)	104.62
	Sensible heat loss (kCal / kg of fuel)	1,623.27
	Heat loss in flue gas (%)	31.62
2.	Heat loss due to moisture present in fuel	
	Moisture present in 1 kg of fuel (%)	10.80
	Heat loss (%)	1.26
3.	Heat loss due to hydrogen in fuel	
	kg of H_2 in 1 kg of coal (kg/kg of fuel)	0.04
	Heat loss (%)	2.32
4.	Heat loss due to openings	
	Shape of opening (D/X)	2.66
	Factor of radiation	0.79
	Black body radiation (kCal/cm^2/hr)	16
	Area of single opening (cm^2)	6,358.50
	Area of total openings (cm^2)	127,170
	Emissivity	0.80
	Total heat loss (kCal/hr)	64,297.15
	Equivalent coal loss (kg/hr)	12.52
	Heat loss through openings (%)	9.28
5.	Heat loss through furnace body	
a.	Heat loss through roof and sidewalls	
	Average temperature of the surface (°C)	59
	Heat loss (kCal/m^2/hr)	350.00
	Total area of heating zone (m^2)	41.75
	Total heat loss (kCal/hr)	14,612.50
	Equivalent fuel loss (kg/hr)	2.85

S.N.	Description	Value
b.	Total average surface temperature of the area other than heating zone (°C)	40
	Heat loss (kCal/m^2/hr)	150
	Total area (m^2)	36.25
	Total heat loss (Kcal/hr)	5,437.50
	Equivalent fuel loss (kg/hr)	1.06
	Total loss of fuel (kg/hr)	3.91
	Total percentage loss (%)	2.89
Furnace efficiency (%)		52.63

The indirect method for efficiency calculation of the furnace indicated that flue gas (31.62 %), furnace openings (9.28 %) and furnace surface (2.89 %) are the major areas for energy loss. Previous studies concludes that kiln surface are responsible for around 4% heat loss that aligns with our findings (Lara-Mireles et al., 2025). To minimize the inefficiency, the loss from these areas must be minimized. The major causes of energy loss in each section are:

Flue gas: Flue gas exit through the chimney after combustion, as from a fireplace, oven, furnace, boiler or steam generator. Recovery of waste heat from the flue gas has a direct effect on improving the efficiency of the combustion process. The higher the temperature of flue gas, the higher would be the losses from the flue gases. For every temperature decrease of 22°C from the flue gas, the fuel consumption would be reduced by 1% (Bureau of Energy Efficiency, n.d.). The loss from the furnace could be minimized if the flue gas can be utilized for air preheating.

Furnace openings: The furnace has openings on various places for the input of fuels for combustion. The heat obtained from the combustion of the fuel would be utilized for drying the bricks. The larger the openings, the higher would be the heat loss that would lead to inefficiency of the furnace.

Furnace surface: The walls and roof of the furnace are not properly insulated. Hence a large amount of heat loss will be from these areas. The roof, walls and surface of the kiln could be properly insulated to reduce the heat loss from the furnace which can improve the thermal efficiency of the kiln.

4.2 Evaluation of brick kiln performance through simulation

The evaluation of the temperature distribution of the brick kilns was evaluated using computational fluid dynamics. The simulation was performed on the basis of the measured field data. The inlet air velocity was varied in this study to determine the optimum firing condition for brick stacking. The study was also performed by using natural gas as an alternative fuel.

4.2.1 Overview of simulation approach

To accompany the field measurements, a computational fluid dynamics (CFD) model of the brick kiln was modeled to determine the thermal performance of the brick kiln. Coal-biomass mixture, the conventional fuel used for the existing zigzag brick kiln, was considered as a baseline fuel, while natural gas was studied as an alternative fuel to determine the feasibility of energy transition in brick kilns. The model replicated actual kiln geometry as well as internal firing conditions. The boundary condition input was provided with the help of data collected from the field visit. Simulation enabled us to perform the analysis of temperature distribution and energy balance inside the kiln that was difficult to observe directly in the kiln. Previous researches has demonstrated the reliability of using numerical simulations with the help of CFD in brick kilns, representing that kiln dimensions and hole configurations strongly affect heat transfer and product quality (Ratanathavorn et al., 2015). In the same way, CFD has also been implemented to evaluate the energy and exergy efficiencies in brick production under different fuel scenarios (Ngom et al., 2021).

4.2.2 Boundary conditions

The simulation was performed by using the data obtained from the field results. The average fuel inlet was provided according to the fuel feed rate; the combustion of the fuel was also observed. The air velocity was measured at the air inlet region of the brick kiln. The capacity of the installed induced draft fan was also observed. To ensure this, the data was cross verified with the help of different peer reviewed journals. The initial simulation was performed in the brick stacks using coal-biomass mixture as a primary fuel. The simulation results replicated our data collected from the field and the model was used to study the potential of fuel substitution for natural gas. The boundary conditions used in our model are represented in Table 4.4.

Table 4.4: Boundary conditions

Particulars	Coal and biomass	Natural gas
Velocity inlet (m/s)	4.5 - 6.1	4.9
Fuel inlet (kg/s)	0.0375	0.017
Simulation system	Adiabatic	Adiabatic
Simulation solver	Steady state	Steady state
Solver used	Coupled (pressure and velocity)	Coupled (pressure and velocity)
Outlet (bar)	1	1

4.2.3 Temperature distribution in the bricks

The temperature profile of the brick kilns was observed in CFD Post-2024 after the iteration was performed for 500 times. The convergence graph during the simulation was observed carefully and the change in the residuals were observed. The contours of temperature in the brick stacks were observed and the required temperature for green brick combustion was found out from the temperature contours. The temperature of the green bricks was measured using thermal gun. The measured surface temperature of the brick combustion ranged from 900 °C to 1000 °C. The inlet air velocity of the kiln was ranged from 4.5 m/s to 6.1 m/s for coal-biomass mixture, while the fuel supply was kept constant. Similarly, the model was also simulated by using natural gas, which can be an alternative fuel with higher combustion value and of gaseous nature. Natural gas was simulated at an air velocity of 4.9 m/s and fuel feed rate of 0.017 kg/s. The lower heating value of coal was given as 22.732 MJ/kg, the LHV for biomass was given 17.209 MJ/kg and for natural gas the LHV was considered as 47.141 MJ/kg (Biomass Energy Data Book, 2011). The temperature distribution showed a marked difference between the mixture of coal and biomass as fuel and natural gas as a fuel for firing. In the mixture-fired simulation, localized hot spots developed near combustion zones, but heat dissipation was uneven, with significant gradients across the kiln chamber.

The simulation was performed in the brick The temperature contours of brick stacks at an air velocity of 4.5 m/s, the is the lowest among the five simulated conditions. The simulation result of the brick stacks in this air-fuel condition was observed in CFD Post-2024 and the temperature profile of the brick stack was found in the range of 800-850 °C. The lower velocity results in poor turbulence, reduced oxidation for fuel combustion and ultimately leads towards incomplete combustion. This condition is unable to provide sufficient thermal energy for efficient brick firing, which could not achieve proper quality for the brick. The contours of temperature of the simulated zigzag brick stacking at the fuel feed rate of 0.0375 kg/s and at an air velocity inlet of 4.5 m/s is represented in Figure 4.1.

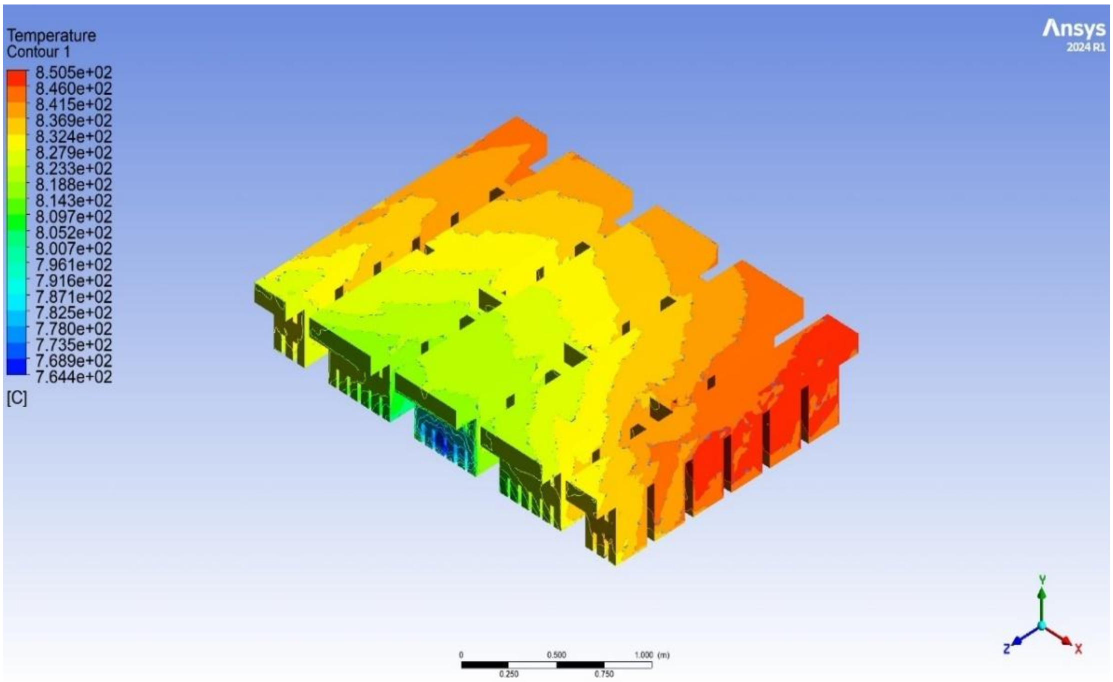


Figure 4.1: Contours of temperaure in the brick stack at an air velocity of 4.5 m/s

The brick kiln model was again simulated using coal-biomass mixture as a fuel in 60:40 proportion by mass to study the temperature profile of the brick stacks at a fuel inlet of 0.0375 kg/s and air inlet velocity of 4.9 m/s. When the air velocity increases to 4.9 m/s, the temperature distribution of the brick stack improves substantially, ranging from 950–990 °C. This temperature is considered better for the combustion of green bricks to produce proper fired bricks. The enhanced turbulence in zigzag kiln matching with the air velocity promotes better air-fuel mixing, ensuring more complete combustion for green bricks. However, the thermal output in this model still remains lower compared to higher air velocity input, that might lead to over cooking of bricks leading to bad quality of fired bricks. The temperature reading of the brick stacks inside the combustion zone during our experimental study was also found in the similar range. The temperature distribution throughout the brick stacks inside our simulated model using coal-biomass mixture as fuel at an air inlet of 4.9 m/s is represented in Figure 4.2.

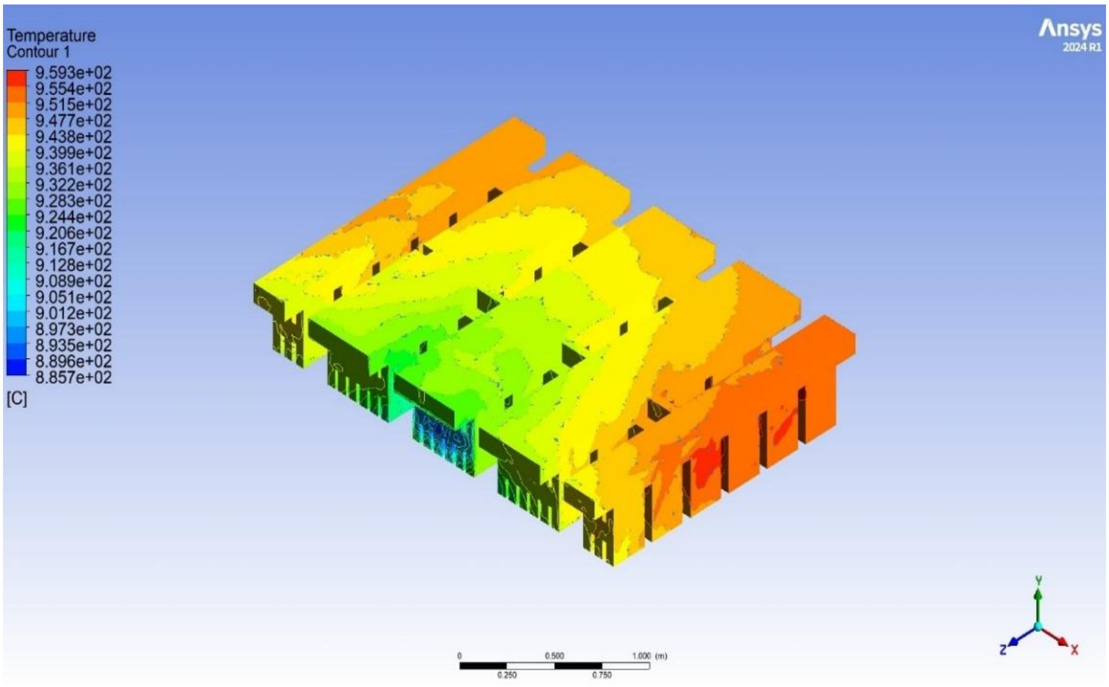


Figure 4.2: Contours of temperaure in the brick stack at an air velocity of 4.9 m/s

The temperature distribution along the length of the brick stack illustrates the higher temperature in initial length, peak combustion region, and subsequent decline towards the end due to heat transfer to the bricks. The horizontal axis corresponds to the distance from the initial length to final while the vertical axis shows the static temperature of the gas flow. This profile replicates the thermal behavior of the brick kiln obtained from the experimental data. This temperature distribution not only validates the effectiveness of heat transfer within the brick stacks but also provides insights towards the combustion behavior, uniform firing and potential areas where bricks might not reach proper firing temperature. The required temperature of the brick stack could be achieved to get properly fired bricks for if the air inlet velocity can be slightly equal to or higher than this inlet air velocity.

The inlet air velocity of 5.4 m/s demonstrated the temperature profile of the stacks ranging from 1030 °C to 1060 °C. The simulation results obtained from this velocity demonstrates the role of inlet air velocity in achieving the flame stability as well as to achieve proper combustion of the green bricks. The simulation results also demonstrated that the maximum range of air velocity must be limited to 5.4m/s to prevent the brick stacks form overcooking. The contours of temperature for the brick stacking at an air inlet velocity of 5.4 m/s are represented in Figure 4.3.

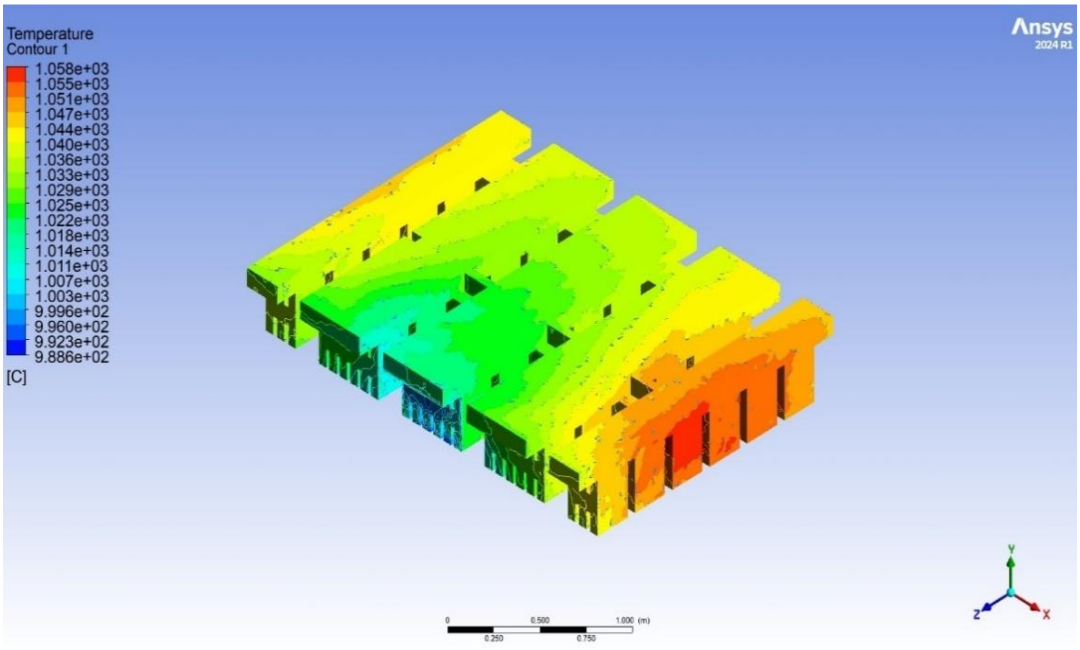


Figure 4.3: Contours of temperature at a velocity of 5.4 m/s

Similarly, the inlet air velocity of 6.1 m/s, the temperature of the brick stacks ranged from 1240 °C to 1270 °C. This gradual increase in temperature represents highly effective mixing and efficient fuel oxidation because of increased turbulence. The temperature falls above the optimum brick firing temperature i.e. 900 °C to 1050 °C. The higher firing temperatures leads to the issue of overcooked bricks. The temperature of the stacking at a velocity of 6.1 m/s is given in Figure 4.4.

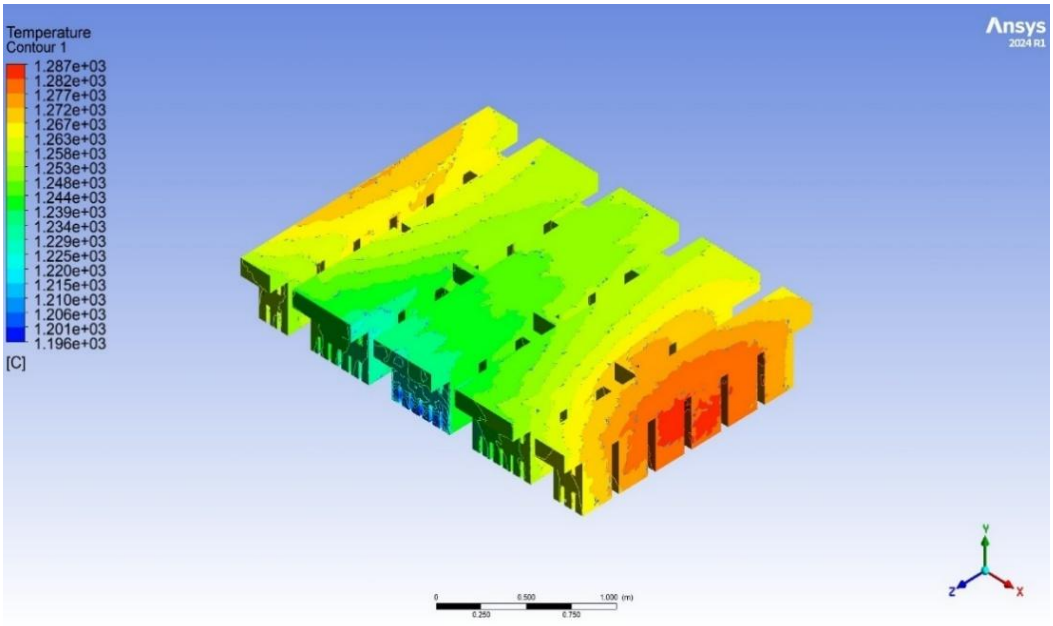


Figure 4.4: Contours of temperature at a velocity of 6.5 m/s

The simulation was also performed using natural gas as an alternative fuel to study the feasibility of fuel substitution in brick kilns. The use of natural gas generated more uniform temperature profile, with faster achievement of steady-state conditions. The distribution represents uniform heating throughout combustion chamber. As the gases flow downstream along the kiln passages, heat transfer occurs to the surrounding brick stacks, resulting in gradual temperature reductions (transitioning to green–blue zones). While compared with coal-biomass mixture as primary fuel, using natural gas generated more smooth and evenly distributed temperature. This reduced the formation of localized hot spots and enhanced uniformity in brick firing. The simulation results demonstrate the advantage of using natural gas as fuel that ensures more controlled combustion contributing towards improving kiln efficiency, and better fired bricks. The temperature distribution along the brick stacks in the simulated model using natural gas as fuel are represented in Figure 4.5.

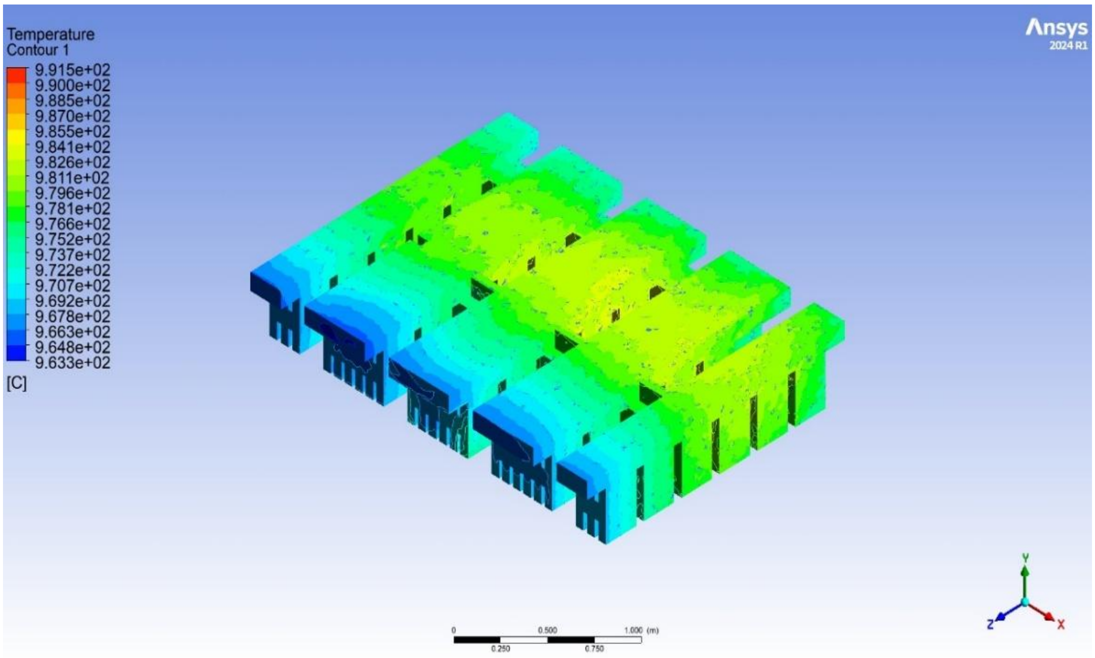


Figure 4.5: Temperature contours of the brick stack using natural gas

Natural gas combustion represents stable thermal characteristics that ranged from 960 °C to 990 °C. This temperature range is lower than that of coal at higher velocities (5.4 and 6.1 m/s). Natural gas generated fine temperature distribution and uniform flame stability compared to coal-biomass mixture. The temperature distribution along the brick stacks inside the combustion chamber using natural gas is almost constant and declines slowly towards the end. This stability is also advantageous in terms of operational perspective, as it utilizes 52.38 % less fuel compared with coal-biomass combustion.

The variation of temperature along the brick stack under various combustion conditions are represented in Figure 4.6. The length of the brick stack (0-1950 mm) is represented in x-axis, while the y-axis represents the corresponding temperature in degrees Celsius (°C). This analysis demonstrates coal combustion at varying air velocities (4.9 m/s and 5.4 m/s) compared to natural gas combustion under similar conditions. This comparison demonstrates the influence of fuel type as well as the inlet air velocity for combustion, flame stability, and the resulting thermal distribution along the brick stacks.

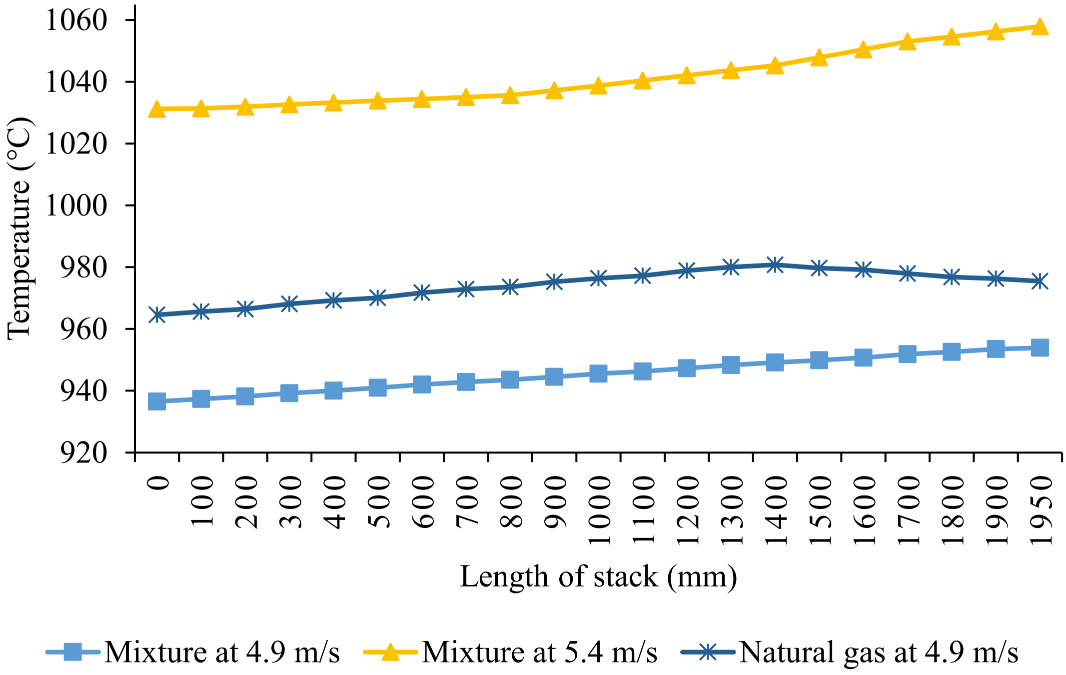


Figure 4.6: Temperature of brick stacks under different combustion conditions

The graph validates that air velocity plays an important role in determining the combustion behavior inside the brick kiln. The inlet air velocity is a governing parameter for better thermal performance of the kiln. Coal combustion at higher velocities generates higher temperature, but natural gas provides stable combustion behavior. For practical brick manufacturing, the choice of operating conditions should optimize between achieving sufficient thermal energy for sintering, minimizing thermal stress on the kiln, and reducing environmental emissions.

These results also align with earlier studies that concluded the optimization of kiln design reduced under-fired bricks from 10% to 4% (Ratanathavorn et al., 2015). Moreover, the uniform heating patterns align with sustainability assessments emphasizing fuel transitions in brick kilns (Refaey et al., 2021). The temperature of the brick stacks lies in the range of 900°C to 1050°C i.e. under optimum firing range found in previous studies (N. B. Bohara et al., 2018). A comparative analysis of the temperature distribution through the bricks is represented in Table 4.5.

Table 4.5: Temperature distribution under different fuels

Fuel type	Average temperature (°C)	Minimum temperature (°C)	Maximum temperature (°C)
Coal and biomass (Velocity: 4.9 - 5.4 m/s)	1,010.75	936.55	1,057.95
Natural gas (Velocity: 4.9 m/s)	974.12	964.57	980.79

4.2.4 Analysis of air-fuel proportion under the simulated conditions

The stoichiometric air requirement was obtained from the complete combustion reactions, while the actual air supply was derived from measured inlet velocities and duct area. The calculated excess air values for the coal–biomass mixture (60:40) by weight) and natural gas at different inlet air velocities are summarized in Table 4.6.

Table 4.6: Excess air under different air velocities

Fuel	Velocity (m/s)	$\dot{m}_{air}$ (kg/s)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{flue}$ (kg/s)	AF_{stoich}	AF_{actual}	Excess air (%)
Coal and biomass	4.5	0.54	0.0375	0.5775	2.912	14.40	394.51
	4.9	0.588	0.0375	0.6255	2.912	15.68	438.46
	5.4	0.648	0.0375	0.6855	2.912	17.28	493.41
	6.1	0.732	0.0375	0.7695	2.912	19.52	570.33
Natural gas	4.9	0.588	0.017	0.605	17.18	34.59	101.33

The results indicate that the actual air supply to the kiln is consistently higher than the stoichiometric requirement, leading to significant levels of excess air. For the coal–biomass mixture, excess air ranges from 394.51% at 4.5 m/s to 570.33% at 6.1 m/s, demonstrating that higher inlet velocities introduce considerably more air than necessary for complete combustion. In contrast, operating the kiln at 4.9 m/s using natural gas resulted in a much lower excess air value of 101.33%, indicating controlled combustion compared with coal-biomass mixture. This difference is also assigned with uniform chemical composition and gaseous nature of natural gas, which facilitates better mixing and reduces the need for high air margins.

These findings validate the importance of optimizing inlet air velocity to balance complete combustion with minimal heat losses. The coal–biomass mixture requires more careful control of inlet air velocity to prevent excess air levels, while natural gas combustion demonstrated better performance with lower excess air, reducing heat losses through dry flue gas (Alonso-Romero et al., 2025).

4.2.5 Kiln efficiency analysis

The simulation results concluded that using natural gas as fuel reduced the fuel consumption by 52.38 % and also achieved the required temperature (960 °C to 990 °C) more quickly. This was attributed due to higher combustion efficiency of natural gas and higher calorific value of the fuel. Coal combustion demonstrated higher thermal losses due to incomplete combustion and higher excess air. The comparison of thermal efficiency using coal-biomass mixture and natural gas under different inlet air velocities are represented in Table 4.7.

Table 4.7: Air velocity and thermal efficiency

Fuel	Velocity (m/s)	Excess air (%)	Flue gas loss (%)	Other losses (%)	Final efficiency (%)
Coal-biomass mixture	4.5	394.51	14.05	15.75	70.20
	4.9	438.46	15.58	15.75	68.67
	5.4	493.41	17.49	15.75	69.76
	6.1	570.33	20.16	15.75	64.09
Natural gas	4.9	101.33	3.86	15.75	80.39

For coal–biomass mixture, the flue gas losses change considerably with inlet air velocity. At 4.5 m/s, the loss is minimum i.e. 14.05%, increasing to 15.58% at 4.9 m/s and reaching the highest value of 20.16% at 6.1 m/s. This change in flue gas losses directly influences the overall efficiency, which drops from over 70% at lower velocities to just 64.09% at the highest velocity. Among the tested conditions, the kiln performs best at the velocity range of 4.9 m/s – 5.4 m/s as it ensures the brick stack temperature from the range of 900 °C to 1050 °C. This is the most balanced operating condition for solid fuel combustion inside the kiln. When natural gas is used, flue gas losses are significantly lower due to proper combustion and gaseous property of the fuel. The flue gas loss for natural gas is recorded 3.86% under 4.9 m/s condition. This minimal loss helps to achieve higher final efficiency of the kiln i.e. 80.39%. A comparative analysis between the flue gas loss and the overall efficiency of the kiln under various inlet air velocity using coal-biomass mixture and natural gas is represented in Figure 4.7.

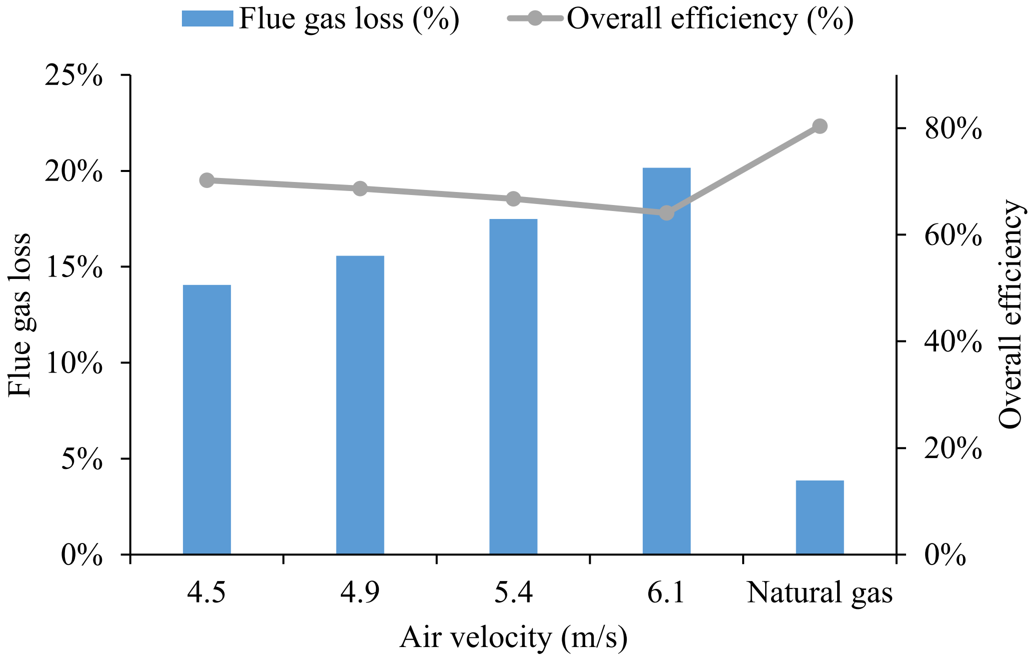


Figure 4.7: Comparison of overall efficiency under different air velocity

The comparative analysis also demonstrates that solid fuel combustion suffers higher thermal losses through flue gases loss, while gaseous fuel i.e. natural gas provides more controlled, stable and efficient energy utilization. While using coal-biomass mixture as fuel, maintaining the inlet air velocity at the range of 4.9-5.4 m/s avoids higher flue gas losses and also maintains the required temperature for brick kilns.

4.3 Energy optimization opportunities in brick kilns

The comparative analysis between the overall thermal efficiency of coal-biomass mixture under variable air velocity validates that air velocity is a determining factor for the combustion behavior inside brick kilns. Also, the comparison between the thermal efficiency of brick kiln using coal-biomass mixture and natural gas validates the adaptation of natural gas as a fuel has both technical and environmental advantages. Natural gas ensures temperature uniformity and reduced fuel consumption. Simulation results confirm field observations and provide predictive insights into operational improvements, supporting cleaner and more efficient production practices.

The required inlet air velocity can be obtained by installing a highly efficient induced-draft (ID) fan system. This fan ensures the required inlet air velocity of 4.9-5.4 m/s, corresponding to a volumetric flow of 20.3 m^3/s. The fan is driven by an 11 kW three-phase motor which is capable to maintain variable speed through a variable frequency drive (VFD). This helps to adjust the airflow to match kiln demand, that can optimize the electrical energy use while maintaining optimal air velocity. These findings align with earlier studies that validated power factor correction in the tunnel kiln which reduced energy consumption by approximately 8% (Hussnain et al., 2021). Integrating an efficient ID fan not only improves energy utilization but also contributes to reduced fuel consumption, lower emissions, and operational flexibility. The required characteristics of the induced-draft fan to be installed is given in Table 4.8.

Table 4.8: Specifications of the induced-draft fan

Parameter	Value
Fan Type	Centrifugal, backward-curved
Volumetric Flow	20.3 m^3/s (73,000 m^3/h)
Static Pressure	250 Pa
Inlet Area	3.90 m^2
Mechanical Power	9.4 kW
Motor Rating	11 kW, 3-phase, IE3-class
Motor Speed / Poles	1500 rpm, 4-pole (50 Hz)
Motor Protection	IP55, suitable for dusty industrial environment
Drive	VFD-capable for variable airflow control
Material	Stainless steel
Additional Features	Modulating damper for fine velocity control, inspection ports

In addition to ID fan installation, design modifications in the kiln, such as optimizing hole width, height, and changing the brick stacking pattern can further help to improve distribution of airflow, maintain uniform temperature and improve the overall energy efficiency of the kiln. These measures provide a practical approach to enhance energy efficiency, aligning with cleaner production strategies and the broader goal of decarbonization in the Nepalese brick industry.

4.4 Emission and environmental considerations

The comparative analysis between emissions generated from coal-biomass mixture and natural gas revealed significant environmental benefits using natural gas. Coal-biomass mixture generated higher levels of CO_2, CH_4 and particulate matter, contributing to visible black smoke and ash deposition while natural gas reduced particulate and CH_4 emissions, with CO_2 as the dominant by-product.

The coal–biomass mixture generates about 5.63 TJ of energy, while natural gas generates 6.23 TJ annually. In case of greenhouse gases, the coal-biomass mixture emits 496.39 tonnes of CO_2 compared to 349.62 tonnes from natural gas, meaning natural gas reduces direct CO_2 emissions by almost 30% for a similar energy output. For methane (CH_4), the mixture generates 0.10 tonnes compared to only 0.01 tonnes from natural gas. When combined into CO_2-equivalents, the mixture has a significantly higher footprint than natural gas, making natural gas as a much cleaner fuel choice for reducing climate impacts from brick kiln operations. On the local pollution side, the coal–biomass mix performs much worse in terms of particulate matter (PM_{10}), releasing 0.01 tonnes compared to nearly zero from natural gas. It also emits more carbon monoxide (CO: 4.44 tonnes vs. 12.46 tonnes from natural gas). This is likely due to incomplete combustion under kiln conditions rather than an inherent fuel property. If combustion efficiency is improved, natural gas should also outperform the mixture on CO. Overall, the coal–biomass mixture is both more carbon-intensive and more polluting locally, while natural gas offers a cleaner pathway for brick kiln combustion, provided proper burner and firing conditions minimize CO emissions. The various pollutants emissions using the fuels are represented in Table 4.9.

Table 4.9: Comparison of emissions for different fuels

Parameters	Coal-Biomass Mixture			Natural Gas
	Coal	Biomass	Total	
Final energy (TJ)	3.68	1.94	5.63	6.23

Parameters		Coal-Biomass Mixture			Natural Gas
		Coal	Biomass	Total	
Calorific value (MJ/kg)		22.73	18.00	20.37	47.14
GHG Emissions as kg/TJ	CO_2	96,100	73,300	169,400	56,100
	CO_2 tonnes	353.90	142.50	496.39	349.62
	CO	150	2,000	2,150	2,000
	CO tonnes	0.55	3.89	4.44	12.46
	PM_{10}	0.46	3.90	4.36	0.04
	PM_{10} tonnes	0.00169	0.00758	0.01	0.00
	CH_4	10	30	40.00	1.00
	CH_4 tonnes	0.037	0.05832	0.10	0.01

4.5 Economic analysis

This economic analysis was carried out to assess the economic feasibility and environmental implications of substituting the existing 60:40 coal–biomass fuel mixture with natural gas in the case study brick kiln. The analysis was based on a 15-year project lifetime with a discount rate of 8%.

Annual fuel consumption

The required fuel energy input is determined from the useful energy demand and thermal efficiency:

$$\text{For coal} - \text{biomass}, Q_{in,CB} = \frac{5{,}630}{0.70} = 8{,}042.85\ \text{GJ/year}$$

$$\text{For natural gas,} \qquad Q_{in,NG} = \frac{6{,}230}{0.80} = 7{,}787.5\ \text{GJ/year}$$

Annual fuel cost

The annual cost required for using different fuels in the kiln are:

For coal–biomass, $C_{fuel,CB} = NPR\ 26.56 \times 291{,}600 = 7{,}745{,}264.55$ NPR/year

For natural gas, $C_{fuel,NG} = NPR\ 60.14 \times 116{,}540 = 7{,}008{,}750$ NPR/year

Total annual operating cost

$$C_{op} = C_{fuel} + C_{OM}$$

- For coal–biomass:

$$C_{op,CB} = 7{,}745{,}265 + 2{,}000{,}000 = 9{,}745{,}265 \text{ NPR/year}$$

- For natural gas:

$$C_{op,NG} = 7{,}008{,}750 + 1{,}200{,}000 = 8{,}208{,}750 \text{ NPR/year}$$

Annual operation cost saving = 9,745,264.55 - 8,208,750 = 1,536,514.55 NPR/year

4.5.1 Economic indicators

The NPV, IRR and payback period are considered as economic indicators for the economic evaluation of a project. The economic analysis is carried out under two different scenarios i.e. when the kiln is operated by installing a new induced draft fan and when the kiln is operated by using natural gas as a combustion fuel. The economic analysis for the installation of new induced draft fan in the kiln is represented in Table 4.10.

Table 4.10: Economic parameters for ID fan installation

Parameter	Value
Annual useful energy required (GJ)	4,232.95
Biomass consumption at 52.6 % efficiency (Ton)	120
Coal consumption at 52.6 % efficiency (Ton)	180
Proposed coal consumption at 70 % efficiency (Ton)	135.25
Proposed biomass consumption at 70 % efficiency (Ton)	90
Annual coal saving (Ton)	44.74
Annual biomass saving (Ton)	30
Coal price per ton (NPR/Ton)	32,000
Biomass price per ton (NPR/Ton)	15,000
Annual price saving (NPR)	1,879,200
Blower (kW)	11

Parameter	Value
Price of blower (NPR)	350,000
Price of variable frequency drive (NPR)	120,000
Discounted payback period (Year)	0.27

The economic parameters when the coal-biomass mixture is substituted by natural gas as a primary fuel for combustion are represented below.

(a) Simple Payback Period

$$Payback\ period = \frac{C_{cap}}{B_{total}} = \frac{4{,}000{,}000}{1{,}536{,}515} = 2.60 \text{ years}$$

(b) Net Present Value (NPV)

The present worth factor (PWF) for a uniform annual series:

$$PWF = \frac{(1+r)^n - 1}{r(1+r)^n}$$

For $r = 0.08$ and $n = 15$,

$$PWF = \frac{(1.08)^{15} - 1}{0.08(1.08)^{15}} = 8.56$$

$$NPV = (1{,}536{,}514.55\ \times 8.56) - 4{,}000{,}000 = 13{,}152{,}565 - 4{,}000{,}000$$

$$= 9{,}152{,}565 \text{ NPR}$$

(c) Internal Rate of Return (IRR)

IRR is the discount rate that makes NPV = 0.

Approximating using interpolation between 30% and 35%, we get:

$$IRR = 30.8\%$$

The analysis shows that the annual energy requirement decreases from 8,042.85 GJ/year for the coal–biomass system to 7,787.5 GJ/year for natural gas, leading to a reduction in annual operating costs from NPR 9,745,265 to NPR 8,208,750, corresponding to an annual saving of NPR 1,536,515.

The Net Present Value (NPV) of the study is NPR 91.52 million, the Internal Rate of Return (IRR) is approximately 30.8%, and the simple payback period is 2.6 years. These results confirm that transitioning to natural gas provides numerous advantages like cost savings, reduced harmful emissions and is financially viable for zigzag kiln operation, highlighting the dual economic and environmental benefits of cleaner fuel adoption.

4.6 Marginal abatement cost

The marginal abatement cost of using coal-biomass mixture and natural gas as an alternative fuel was calculated by considering the fuel cost, operational costs and initial investment cost. It represents the additional cost required to reduce one unit of greenhouse gas emissions relative to baseline scenario. In this study, the MAC for coal-biomass mixture was found to be NPR 4,656 per tonne of CO_2 equivalent while for natural gas it was slightly higher i.e. NPR 4,708 per tonne of CO_2 equivalent. The results indicate that both kiln technologies achieve emissions reduction at relatively low incremental costs, with natural gas requiring slightly higher investment per ton of CO_2 mitigated. This difference arises due to higher capital cost and fuel expenditure associated with the natural gas system compared to the coal–biomass mixture. The marginal abatement cost of both the scenarios is represented in Figure 4.8.

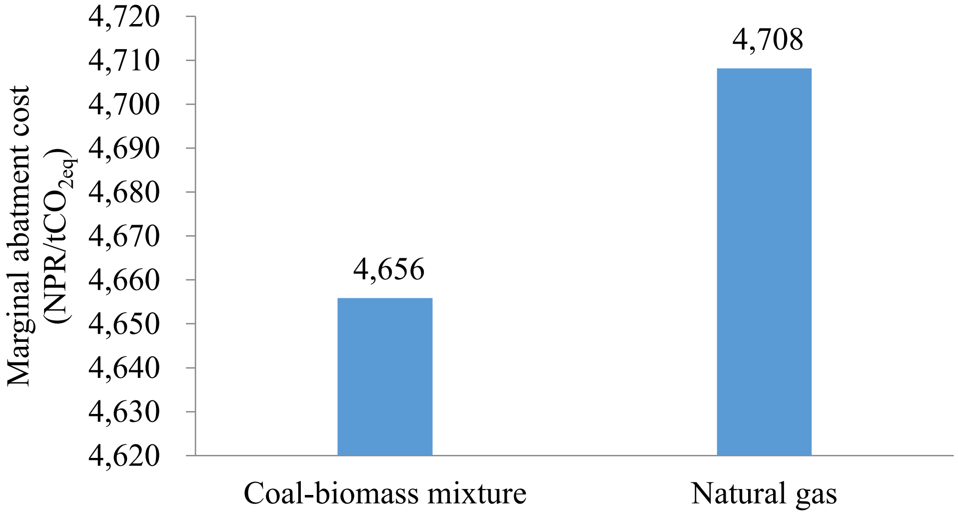


Figure 4.8: Marginal abatement cost

The cost benefit analysis provides an economic comparison between the coal-biomass mixture kiln and the natural gas kiln. The findings indicate that both options yield positive net benefits; however, the economic performance differs substantially between these two fuels. The coal-biomass mixture generates a net benefit of NPR 2,002,709, corresponding to a cost benefit ratio of 2.5. The findings suggest that for every unit of investment cost, the system returns 2.5 units of economic benefit. In contrast, the natural gas kiln yields a slightly higher net benefit of NPR 2,143,137, but the associated BCR is considerably lower at 1.4, indicating that each unit of investment produces only 1.4 units of benefit. The cost benefit ratio for implementation of the fuels is represented in Figure 4.9.

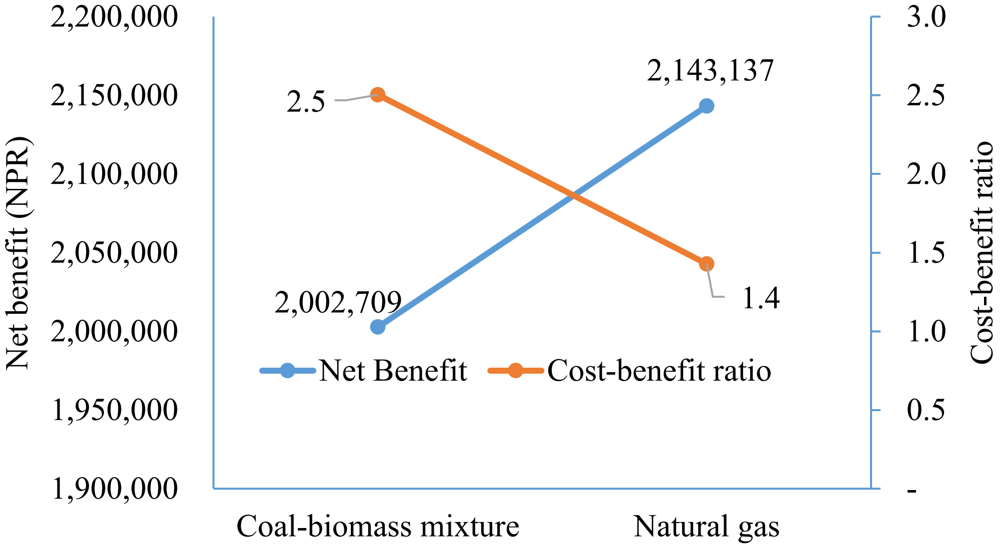


Figure 4.9: Cost-benefit ratio

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

Following conclusions have been drawn from the study.

5.1 Conclusions

- The thermal efficiency of the existing zigzag kiln was determined to be 58.89 % and 52.63 % using direct and indirect method.
- For coal-biomass mixture, the optimum air inlet velocity for combustion ranges from 4.9 m/s to 5.4 m/s, which allowed better air-fuel mixing, flame stability, and relatively uniform heat distribution, ensuring effective brick firing.
- The thermal efficiency of the brick kiln can be improved to 69% using the mixture of coal–biomass fuel when the air velocity is maintained at 4.9-5.4 m/s.
- Natural gas combustion provided more uniform and stable temperature distribution compared to coal–biomass mixture. The efficiency of the brick kiln was found to be 80.39% using natural gas as fuel.
- The use of a 11 kW VFD controlled, highly efficient motor in the induced draft fan ensures the inlet air velocity. The installation of VFD controlled fan had a discounted payback period of 0.27 years.
- Natural gas reduced CO_2 emissions by nearly 30%, while particulate matter and sulfur oxides were almost eliminated.
- Switching the fuel to natural gas is economically viable and environmentally beneficial, with an NPV of NPR 9.15 million, IRR of 30.8%, and a 2.6-year payback period.
- The marginal abatement cost for coal-biomass mixture was found to be NPR 4,656 per tonne of CO_2 equivalent while for natural gas it was found to be NPR 4,708 per tonne of CO_2 equivalent.

5.2 Recommendations

- Kiln performance can be further improved by design modifications, like optimizing width and arrangement of firing holes, adjusting the height of kiln, and improving insulation to maximize the kiln efficiency.
- Further research should extend the CFD analysis to transient simulations and include alternative fuels like biogas or hydrogen blends.

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ANNEXES

Annex-1: Reference data extracted from literature for calculations

1. Lower Heating Value (LHV) of fuels

S.N.	Fuel	Lower Heating Value (MJ/kg)
1.	Coal	22.732
2.	Biomass	17.209
3.	Natural gas	47.141

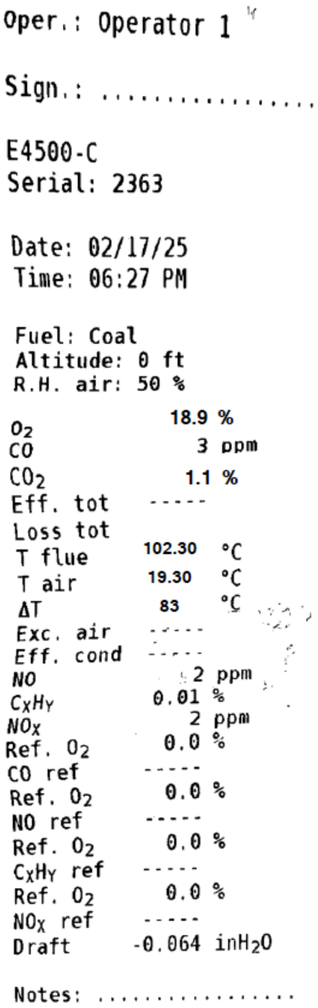
(*Biomass Energy Data Book*, 2011)

2. Emission factor of fuels

S.N.	Fuel	Emission factor in kg/TJ			
		CO_2	CO	PM_{10}	CH_4
1.	Coal	96,100	150	0.46	10
2.	Biomass	73,300	2,000	3.90	30
3.	Natural gas	56,100	2,000	0.04	1

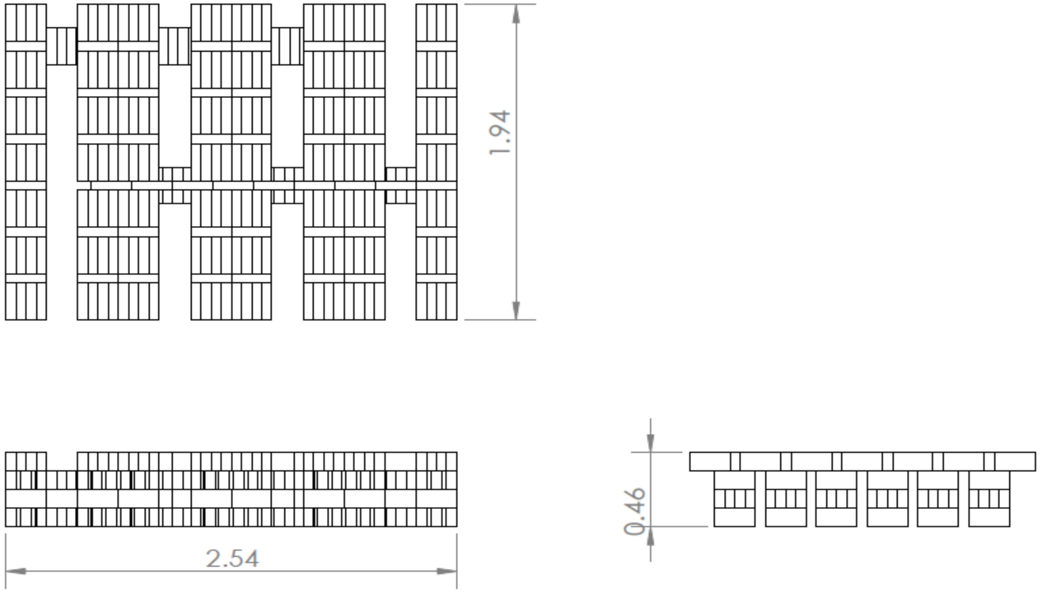
(Ram M. Shrestha et al., 2013)

Annex-2: Flue gas characteristics of the kiln



```
Oper.: Operator 1

Sign.: .................

E4500-C
Serial: 2363

Date: 02/17/25
Time: 06:27 PM

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

O2             18.9 %
CO                3 ppm
CO2             1.1 %
Eff. tot     -----
Loss tot
T flue       102.30  °C
T air         19.30  °C
ΔT              83   °C
Exc. air     -----
Eff. cond    -----
NO               2 ppm
CXHY          0.01 %
NOX              2 ppm
Ref. O2        0.0 %
CO ref       -----
Ref. O2        0.0 %
NO ref       -----
Ref. O2        0.0 %
CXHY ref     -----
Ref. O2        0.0 %
NOX ref      -----
Draft       -0.064 inH2O

Notes: .................
```

Annex-3: Drawing of brick stacks



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN METERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

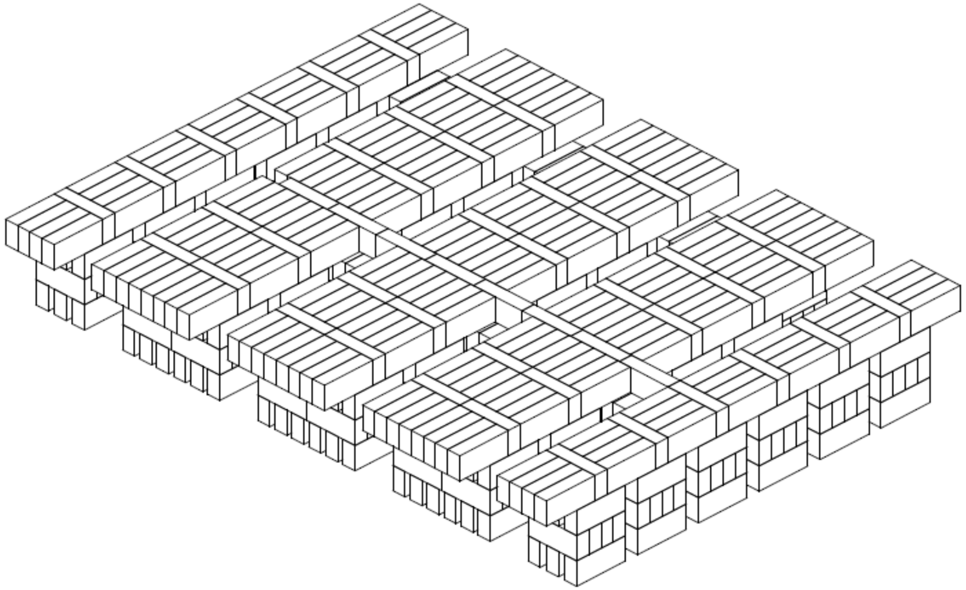
DWG NO.
Final brick stacking

A4

WEIGHT:

SCALE:1:33.3

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN IMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH:

DEBURR AND
BREAK SHARP
EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

MATERIAL:

DWG NO.

Final brick stacking

A4

WEIGHT:

SCALE:1:33.3

SHEET 1 OF 1

Annex-4: Efficiency calculation at different air velocity

Coal-biomass mixture at 0.0375 kg/s and air at 4.5 m/s

S.N.	Description	Value
1.	Heat loss due to dry flue gas	
	% of excess air (%)	394.51
	Theoretical air required (kg)	11.50
	Total amount of air supplied (kg / kg of fuel)	45.48
	Weight of the flue gas (kg / kg of fuel)	46.48
	Sensible heat loss (kCal / kg of fuel)	721.27
	Heat loss in flue gas (%)	14.05
2.	Heat loss due to moisture present in fuel	
	Moisture present in 1 kg of fuel (%)	10.80
	Heat loss (%)	1.26
3.	Heat loss due to hydrogen in fuel	
	kg of H_2 in 1 kg of coal (kg/kg of fuel)	0.04
	Heat loss (%)	2.32
4.	Heat loss due to openings	
	Shape of opening (D/X)	2.66
	Factor of radiation	0.79
	Black body radiation (kCal/cm^2/hr)	16.00
	Area of single opening (cm^2)	6358.50
	Area of total openings (cm^2)	127170.00
	Emissivity	0.80
	Total heat loss (kCal/hr)	64297.15
	Equivalent coal loss (kg/hr)	12.52
	Heat loss through openings (%)	9.28
5.	Heat loss through furnace body	
a.	Heat loss through roof and sidewalls	
	Average temperature of the surface (°C)	59.00
	Heat loss (kCal/m^2/hr)	350.00
	Total area of heating zone (m^2)	41.75
	Total heat loss (kCal/hr)	14612.50

S.N.	Description	Value
	Equivalent fuel loss (kg/hr)	2.85
b.	Total average surface temperature of the area other than heating zone (°C)	40.00
	Heat loss (kCal/m^2/hr)	150.00
	Total area (m^2)	36.25
	Total heat loss (Kcal/hr)	5437.50
	Equivalent fuel loss (kg/hr)	1.06
	Total loss of fuel (kg/hr)	3.91
	Total percentage loss (%)	2.89
Furnace efficiency (%)		70.20

Coal-biomass mixture at 0.0375 kg/s and air at 4.9 m/s

S.N.	Description	Value
1.	Heat loss due to dry flue gas	
	% of excess Air (%)	438.46
	Theoretical air required (kg)	11.50
	Total amount of air supplied (kg / kg of fuel)	50.54
	Weight of the flue gas (kg / kg of fuel)	51.54
	Sensible heat loss (kCal / kg of fuel)	799.69
	Heat loss in flue gas (%)	15.58
2.	Heat loss due to moisture present in fuel	
	Moisture present in 1 kg of fuel (%)	10.80
	Heat loss (%)	1.26
3.	Heat loss due to hydrogen in fuel	
	kg of H_2 in 1 kg of coal (kg/kg of fuel)	0.04
	Heat loss (%)	2.32
4.	Heat loss due to openings	
	Shape of opening (D/X)	2.66
	Factor of radiation	0.79
	Black body radiation (kCal/cm^2/hr)	16.00

S.N.	Description	Value
	Area of single opening (cm^2)	6,358.50
	Area of total openings (cm^2)	127,170
	Emissivity	0.80
	Total heat loss (kCal/hr)	64,297.15
	Equivalent coal loss (kg/hr)	12.52
	Heat loss through openings (%)	9.28
5.	Heat loss through furnace body	
a.	Heat loss through roof and sidewalls	
	Average temperature of the surface (°C)	59
	Heat loss (kCal/m^2/hr)	350
	Total area of heating zone (m^2)	41.75
	Total heat loss (kCal/hr)	14,612.50
	Equivalent fuel loss (kg/hr)	2.85
b.	Total average surface temperature of the area other than heating zone (°C)	40
	Heat loss (kCal/m^2/hr)	150
	Total area (m^2)	36.25
	Total heat loss (Kcal/hr)	5,437.50
	Equivalent fuel loss (kg/hr)	1.06
	Total loss of fuel (kg/hr)	3.91
	Total percentage loss (%)	2.89
Furnace efficiency (%)		68.67

Coal-biomass mixture at 0.0375 kg/s and air at 5.4 m/s

S.N.	Description	Value
1.	Heat loss due to dry flue gas	
	% of excess Air (%)	493.41
	Theoretical air required (kg)	11.50
	Total amount of air supplied (kg / kg of fuel)	56.86
	Weight of the flue gas (kg / kg of fuel)	57.86

S.N.	Description	Value
	Sensible heat loss (kCal / kg of fuel)	897.75
	Heat loss in flue gas (%)	17.49
2.	Heat loss due to moisture present in fuel	
	Moisture present in 1 kg of fuel (%)	10.80
	Heat loss (%)	1.26
3.	Heat loss due to hydrogen in fuel	
	kg of H_2 in 1 kg of coal (kg/kg of fuel)	0.04
	Heat loss (%)	2.32
4.	Heat loss due to openings	
	Shape of opening (D/X)	2.66
	Factor of radiation	0.79
	Black body radiation (kCal/cm^2/hr)	16.00
	Area of single opening (cm^2)	6,358.50
	Area of total openings (cm^2)	127,170
	Emissivity	0.80
	Total heat loss (kCal/hr)	64,297.15
	Equivalent coal loss (kg/hr)	12.52
	Heat loss through openings (%)	9.28
5.	Heat loss through furnace body	
a.	Heat loss through roof and sidewalls	
	Average temperature of the surface (°C)	59.00
	Heat loss (kCal/m^2/hr)	350.00
	Total area of heating zone (m^2)	41.75
	Total heat loss (kCal/hr)	14,612.50
	Equivalent fuel loss (kg/hr)	2.85
b.	Total average surface temperature of the area other than heating zone (°C)	40.00
	Heat loss (kCal/m^2/hr)	150.00
	Total area (m^2)	36.25
	Total heat loss (kCal/hr)	5,437.50
	Equivalent fuel loss (kg/hr)	1.06

S.N.	Description	Value
	Total loss of fuel (kg/hr)	3.91
	Total percentage loss (%)	2.89
Furnace efficiency (%)		66.76

Coal-biomass mixture at 0.0375 kg/s and air at 6.1 m/s

S.N.	Description	Value
1.	Heat loss due to dry flue gas	
	% of excess air (%)	570.33
	Theoretical air required (kg)	11.50
	Total amount of air supplied (kg / kg of fuel)	65.70
	Weight of the flue gas (kg / kg of fuel)	66.70
	Sensible heat loss (kCal / kg of fuel)	1,035
	Heat loss in flue gas (%)	20.16
2.	Heat loss due to moisture present in fuel	
	Moisture present in 1 kg of fuel (%)	10.80
	Heat loss (%)	1.26
3.	Heat loss due to hydrogen in fuel	
	kg of H_2 in 1 kg of coal (kg/kg of fuel)	0.04
	Heat loss (%)	2.32
4.	Heat loss due to openings	
	Shape of opening (D/X)	2.66
	Factor of radiation	0.79
	Black body radiation (kCal/cm^2/hr)	16
	Area of single opening (cm^2)	6,358.50
	Area of total openings (cm^2)	127,170
	Emissivity	0.80
	Total heat loss (kCal/hr)	64,297.15
	Equivalent coal loss (kg/hr)	12.52
	Heat loss through openings (%)	9.28
5.	Heat loss through furnace body	

S.N.	Description	Value
a.	Heat loss through roof and sidewalls	
	Average temperature of the surface (°C)	59
	Heat loss (kCal/m^2/hr)	350
	Total area of heating zone (m^2)	41.75
	Total heat loss (kCal/hr)	14,612.50
	Equivalent fuel loss (kg/hr)	2.85
b.	Total average surface temperature of the area other than heating zone (°C)	40
	Heat loss (kCal/m^2/hr)	150
	Total area (m^2)	36.25
	Total heat loss (Kcal/hr)	5,437.50
	Equivalent fuel loss (kg/hr)	1.06
	Total loss of fuel (kg/hr)	3.91
	Total percentage loss (%)	2.89
Furnace efficiency (%)		66.76

Natural gas at 0.017 kg/s and air at 4.9 m/s

S.N.	Description	Value
1.	Heat loss due to dry flue gas	
	% of excess air (%)	101.33
	Theoretical air required (kg)	11.50
	Total amount of air supplied (kg / kg of fuel)	11.77
	Weight of the flue gas (kg / kg of fuel)	12.77
	Sensible heat loss (kCal / kg of fuel)	198.12
	Heat loss in flue gas (%)	3.86
2.	Heat loss due to moisture present in fuel	
	Moisture present in 1 kg of fuel (%)	10.80
	Heat loss (%)	1.26
3.	Heat loss due to hydrogen in fuel	
	kg of H_2 in 1 kg of coal (kg/kg of fuel)	0.04

S.N.	Description	Value
	Heat loss (%)	2.32
4.	Heat loss due to openings	
	Shape of opening (D/X)	2.66
	Factor of radiation	0.79
	Black body radiation (kCal/cm^2/hr)	16
	Area of single opening (cm^2)	6358.50
	Area of total openings (cm^2)	127,170
	Emissivity	0.80
	Total heat loss (kCal/hr)	64,297.15
	Equivalent coal loss (kg/hr)	12.52
	Heat loss through openings (%)	9.28
5.	Heat loss through furnace body	
a.	Heat loss through roof and sidewalls	
	Average temperature of the surface (°C)	59.00
	Heat loss (kCal/m^2/hr)	350.00
	Total area of heating zone (m^2)	41.75
	Total heat loss (kCal/hr)	14612.50
	Equivalent fuel loss (kg/hr)	2.85
b.	Total average surface temperature of the area other than heating zone (°C)	40
	Heat loss (kCal/m^2/hr)	150
	Total area (m^2)	36.25
	Total heat loss (Kcal/hr)	5,437.50
	Equivalent fuel loss (kg/hr)	1.06
	Total loss of fuel (kg/hr)	3.91
	Total percentage loss (%)	2.89
Furnace efficiency (%)		80.39

Annex-5: Photographs

During field survey

Measurement of surface temperature

Measurement of firing zone temperature

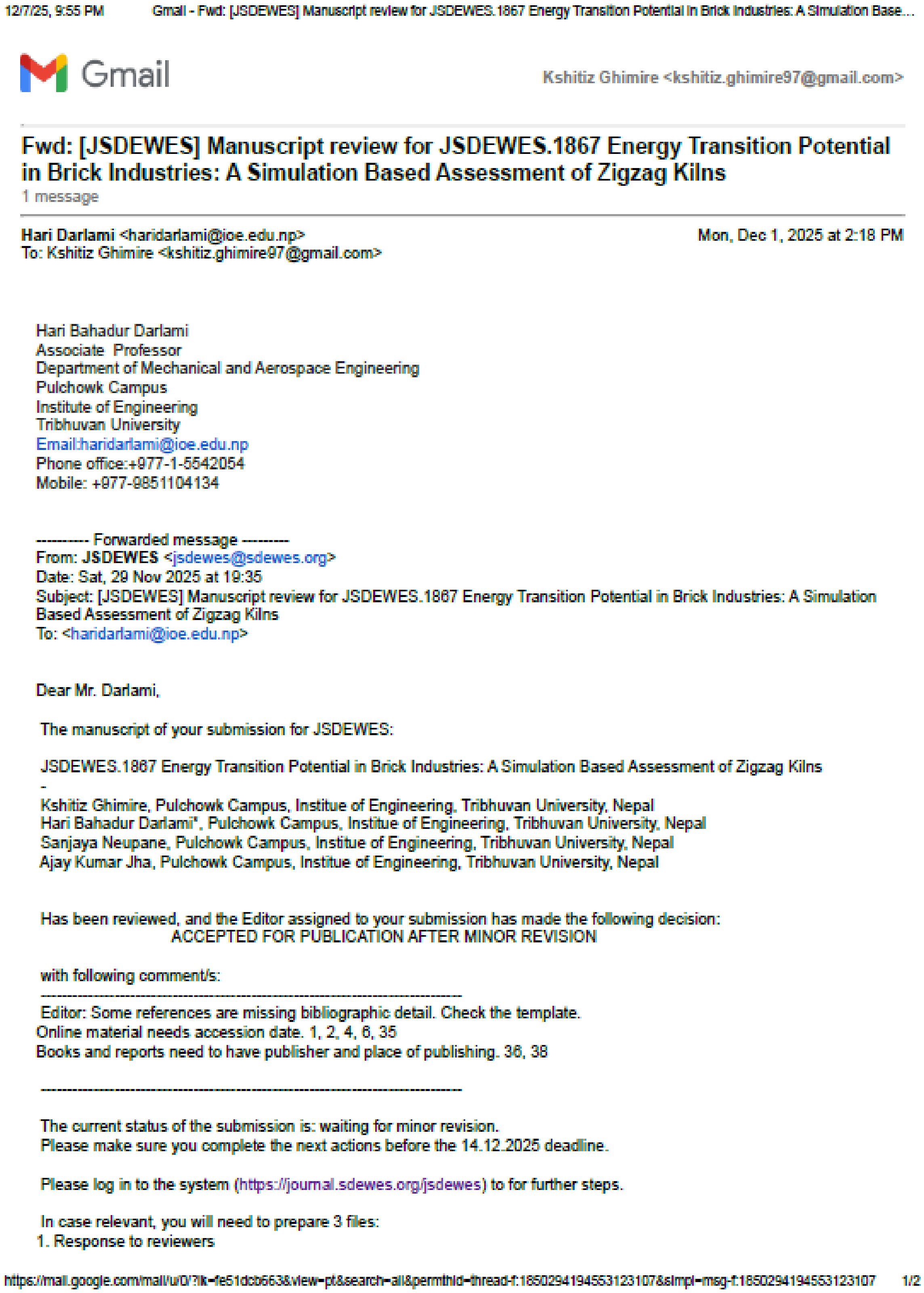
Flue gas analysis

Fuel used for firing

Sun-drying of bricks

Fired Bricks

Annex-6: Manuscript acceptance email



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Gmail Kshitiz Ghimire <kshitiz.ghimire97@gmail.com>

Fwd: [JSDEWES] Manuscript review for JSDEWES.1867 Energy Transition Potential in Brick Industries: A Simulation Based Assessment of Zigzag Kilns

1 message

Hari Darlami <haridarlami@ioe.edu.np> Mon, Dec 1, 2025 at 2:18 PM
To: Kshitiz Ghimire <kshitiz.ghimire97@gmail.com>

Hari Bahadur Darlami
Associate Professor
Department of Mechanical and Aerospace Engineering
Pulchowk Campus
Institute of Engineering
Tribhuvan University
Email:haridarlami@ioe.edu.np
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Date: Sat, 29 Nov 2025 at 19:35
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To: <haridarlami@ioe.edu.np>

Dear Mr. Darlami,

The manuscript of your submission for JSDEWES:

JSDEWES.1867 Energy Transition Potential in Brick Industries: A Simulation Based Assessment of Zigzag Kilns
-
Kshitiz Ghimire, Pulchowk Campus, Institue of Engineering, Tribhuvan University, Nepal
Hari Bahadur Darlami*, Pulchowk Campus, Institue of Engineering, Tribhuvan University, Nepal
Sanjaya Neupane, Pulchowk Campus, Institue of Engineering, Tribhuvan University, Nepal
Ajay Kumar Jha, Pulchowk Campus, Institue of Engineering, Tribhuvan University, Nepal

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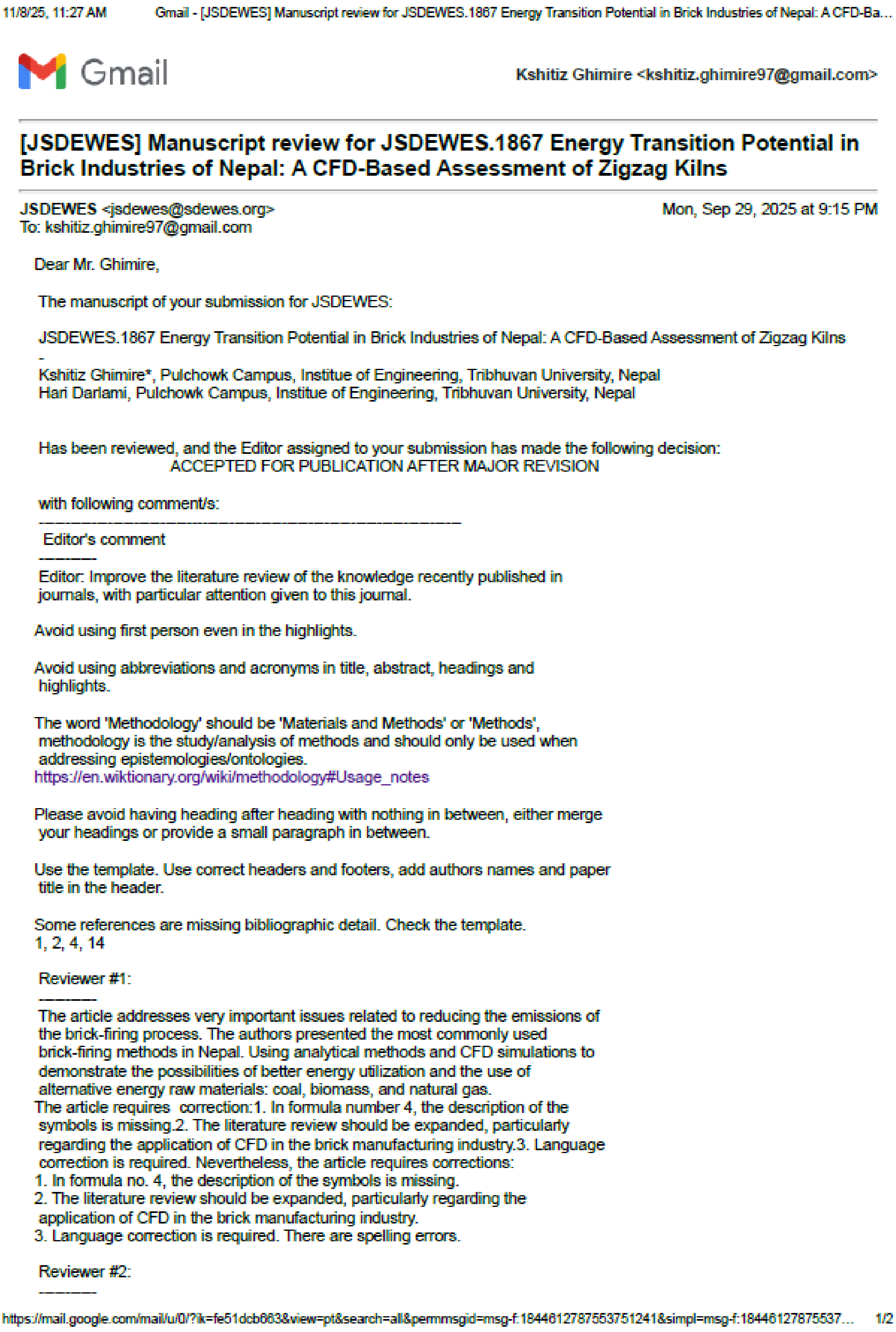

11/8/25, 11:27 AM Gmail - [JSDEWES] Manuscript review for JSDEWES.1867 Energy Transition Potential in Brick Industries of Nepal: A CFD-Ba…

Gmail **Kshitiz Ghimire <kshitiz.ghimire97@gmail.com>**

[JSDEWES] Manuscript review for JSDEWES.1867 Energy Transition Potential in Brick Industries of Nepal: A CFD-Based Assessment of Zigzag Kilns

JSDEWES <jsdewes@sdewes.org> Mon, Sep 29, 2025 at 9:15 PM
To: kshitiz.ghimire97@gmail.com

Dear Mr. Ghimire,

The manuscript of your submission for JSDEWES:

JSDEWES.1867 Energy Transition Potential in Brick Industries of Nepal: A CFD-Based Assessment of Zigzag Kilns
-
Kshitiz Ghimire*, Pulchowk Campus, Institue of Engineering, Tribhuvan University, Nepal
Hari Darlami, Pulchowk Campus, Institue of Engineering, Tribhuvan University, Nepal

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Reviewer #1:

The article addresses very important issues related to reducing the emissions of the brick-firing process. The authors presented the most commonly used brick-firing methods in Nepal. Using analytical methods and CFD simulations to demonstrate the possibilities of better energy utilization and the use of alternative energy raw materials: coal, biomass, and natural gas.
The article requires correction:1. In formula number 4, the description of the symbols is missing.2. The literature review should be expanded, particularly regarding the application of CFD in the brick manufacturing industry.3. Language correction is required. Nevertheless, the article requires corrections:
1. In formula no. 4, the description of the symbols is missing.
2. The literature review should be expanded, particularly regarding the application of CFD in the brick manufacturing industry.
3. Language correction is required. There are spelling errors.

Reviewer #2:
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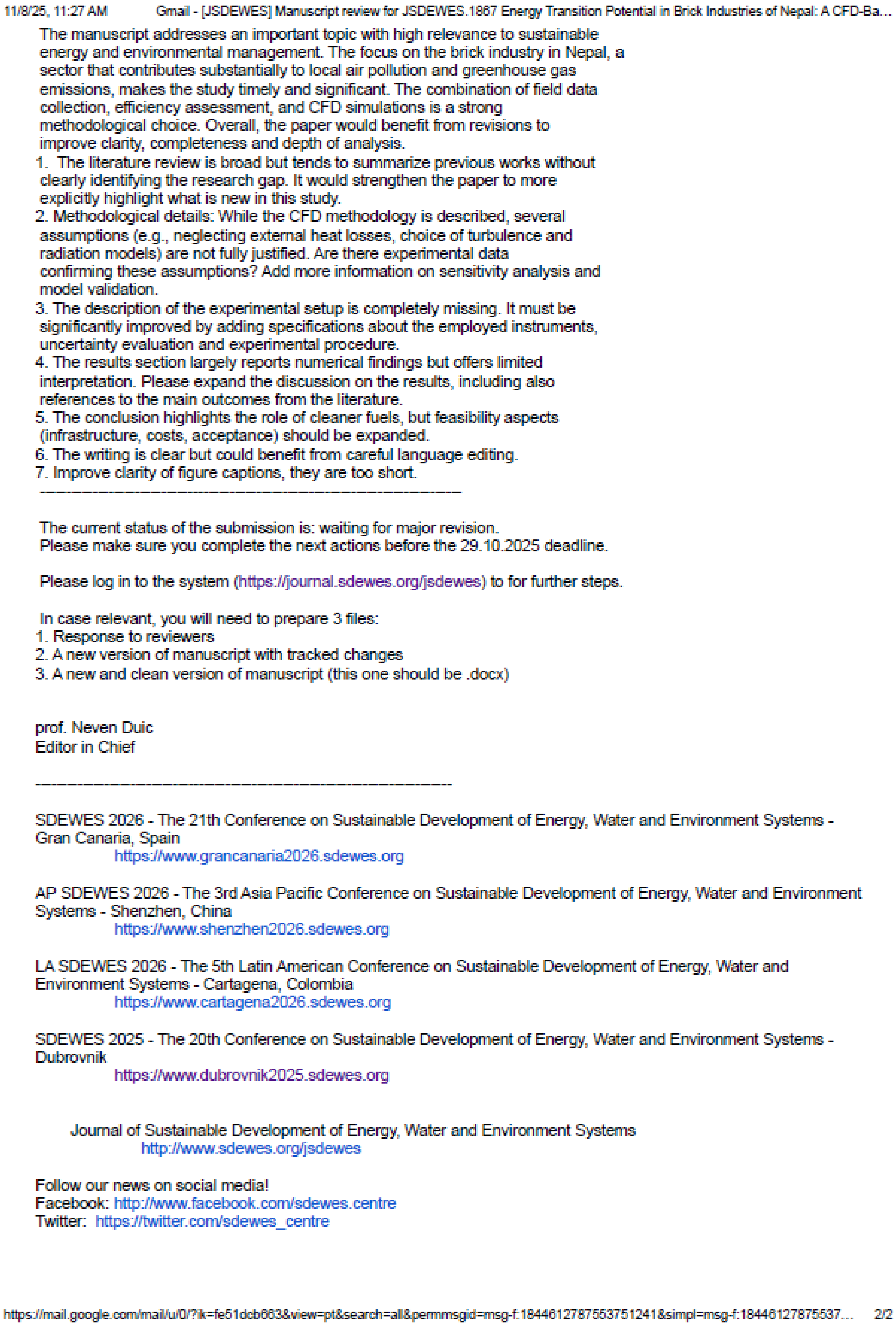

The manuscript addresses an important topic with high relevance to sustainable energy and environmental management. The focus on the brick industry in Nepal, a sector that contributes substantially to local air pollution and greenhouse gas emissions, makes the study timely and significant. The combination of field data collection, efficiency assessment, and CFD simulations is a strong methodological choice. Overall, the paper would benefit from revisions to improve clarity, completeness and depth of analysis.

1. The literature review is broad but tends to summarize previous works without clearly identifying the research gap. It would strengthen the paper to more explicitly highlight what is new in this study.
2. Methodological details: While the CFD methodology is described, several assumptions (e.g., neglecting external heat losses, choice of turbulence and radiation models) are not fully justified. Are there experimental data confirming these assumptions? Add more information on sensitivity analysis and model validation.
3. The description of the experimental setup is completely missing. It must be significantly improved by adding specifications about the employed instruments, uncertainty evaluation and experimental procedure.
4. The results section largely reports numerical findings but offers limited interpretation. Please expand the discussion on the results, including also references to the main outcomes from the literature.
5. The conclusion highlights the role of cleaner fuels, but feasibility aspects (infrastructure, costs, acceptance) should be expanded.
6. The writing is clear but could benefit from careful language editing.
7. Improve clarity of figure captions, they are too short.

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prof. Neven Duic
Editor in Chief

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Year XXXX, Volume X, Issue Y, xxxxxx

Original Research Article

Energy Transition Potential in Brick Industries: A Simulation Based Assessment of Zigzag Kilns

***Kshitiz Ghimire*[1], *Hari Bahadur Darlami**[1], *Sanjaya Neupane*[1], *Ajay Kumar Jha*[1]**
[1]Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Lalitpur, Nepal
e-mail: kshitiz.ghimire97@gmail.com

ABSTRACT

Brick manufacturing in Nepal relies heavily on coal and biomass mixtures, resulting in high energy use and significant air pollution. This study investigates the energy-saving potential and environmental implications of fuel substitution in brick kilns, focusing on coal, biomass, and natural gas. A combination of experimental data collection and steady-state computational fluid dynamics simulations was employed to analyse thermal performance, airflow characteristics, and pollutant formation along the kiln. The study evaluated the effect of varying inlet air velocities on fuel combustion, excess air, and kiln efficiency. For coal and biomass, inlet air velocities ranging from 4.5 to 6.1 m/s were analysed, while natural gas was studied as an alternative fuel for coal and biomass mixture under optimum condition. The results revealed that excess air in the combustion zone significantly influences the thermal efficiency, with coal and biomass showing higher excess air levels compared to natural gas. The kiln efficiency was determined using indirect method highlighting the potential for energy savings and emission reduction through optimized air supply and fuel transition. The findings provide quantitative insights into the benefits of energy transition in brick industries, demonstrating that adopting cleaner fuels and controlling excess air can improve efficiency and reduce environmental impact.

KEYWORDS

Brick kiln efficiency, thermal performance, excess air, Computational Fluid Dynamics

INTRODUCTION

Brick manufacturing is an energy-intensive industry and a major source of air pollution throughout the world. South Asia accounts for 21% of the global brick production, making it the second largest producer after China where traditional kiln technologies dominate. The technologies still remain unchanged over a longer time period [1]. A study done by International Centre for Integrated Mountain Development (ICIMOD) in 2019 estimated that the brick industries in Nepal are responsible for the emission of 5.1 Metric Tons of CO_2 emissions per year [2]. A total of 465,220 tons of coal equivalent per year is used as source of fuel for brick sector in Nepal producing total emission of 1,299,065 tons of CO_2 equivalent [3]. Traditional firing technologies in brick kilns are highly inefficient, leading to excessive fuel consumption and increased carbon emissions [4]. Improving kiln efficiency is therefore critical

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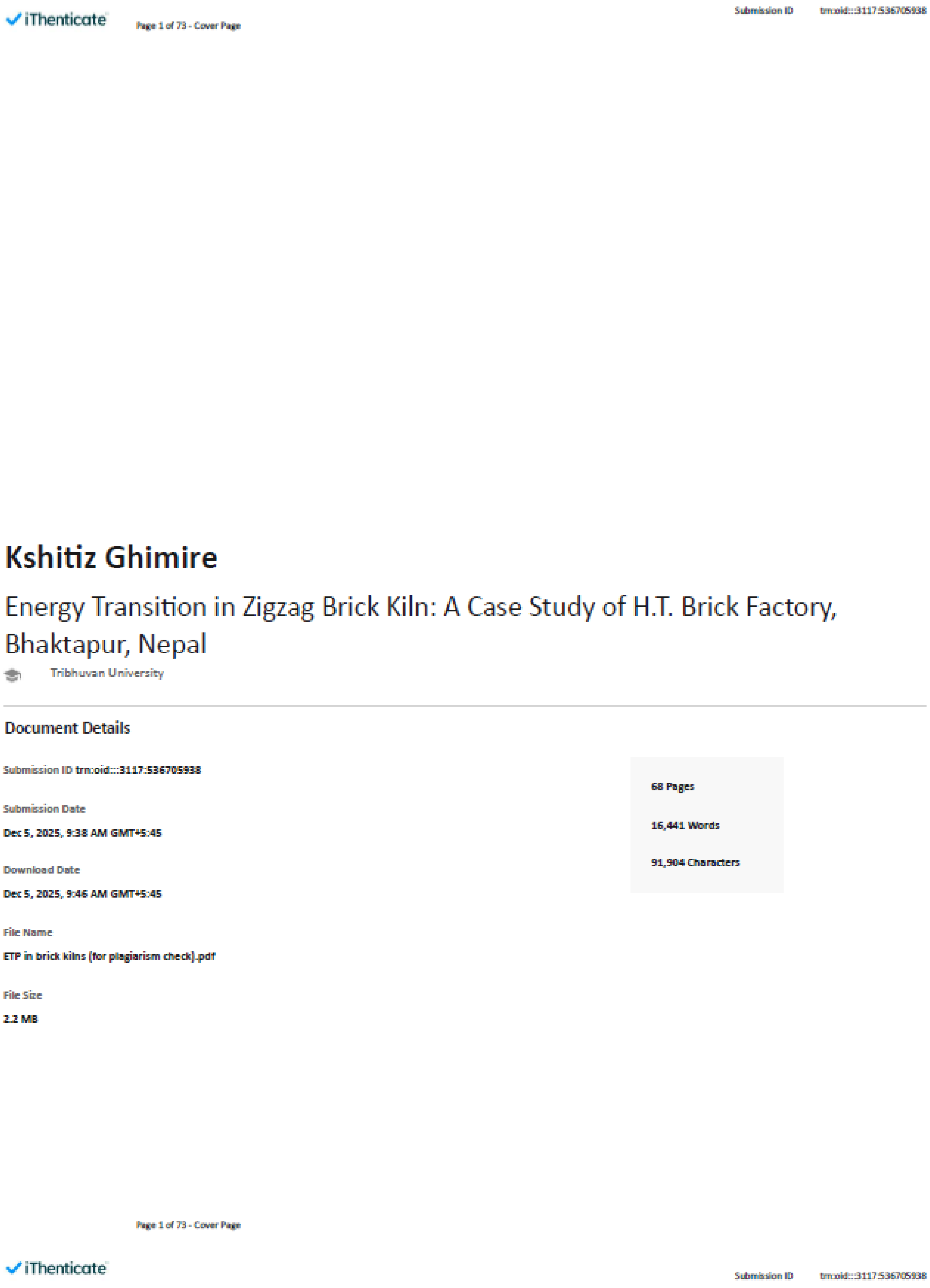

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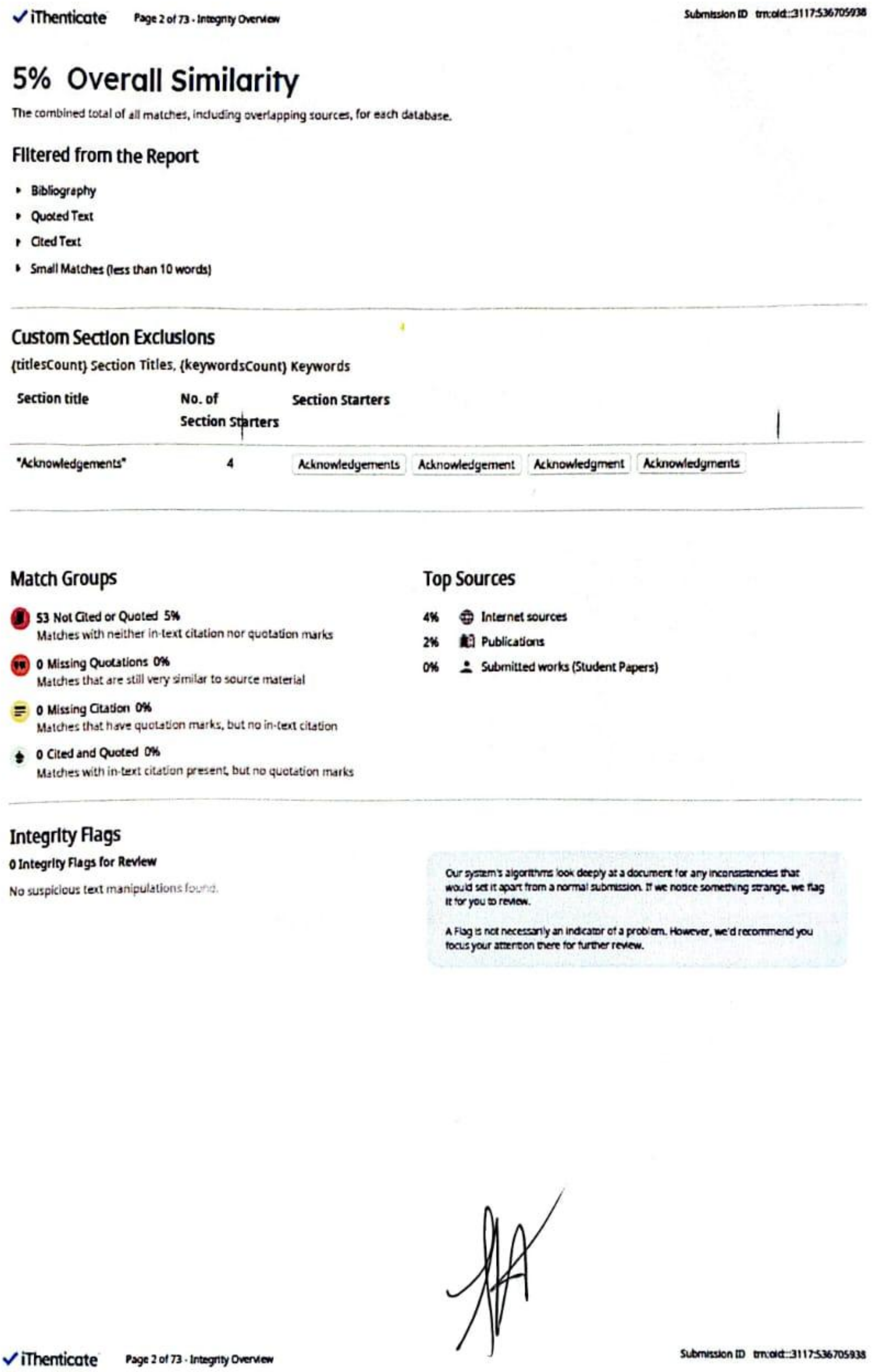

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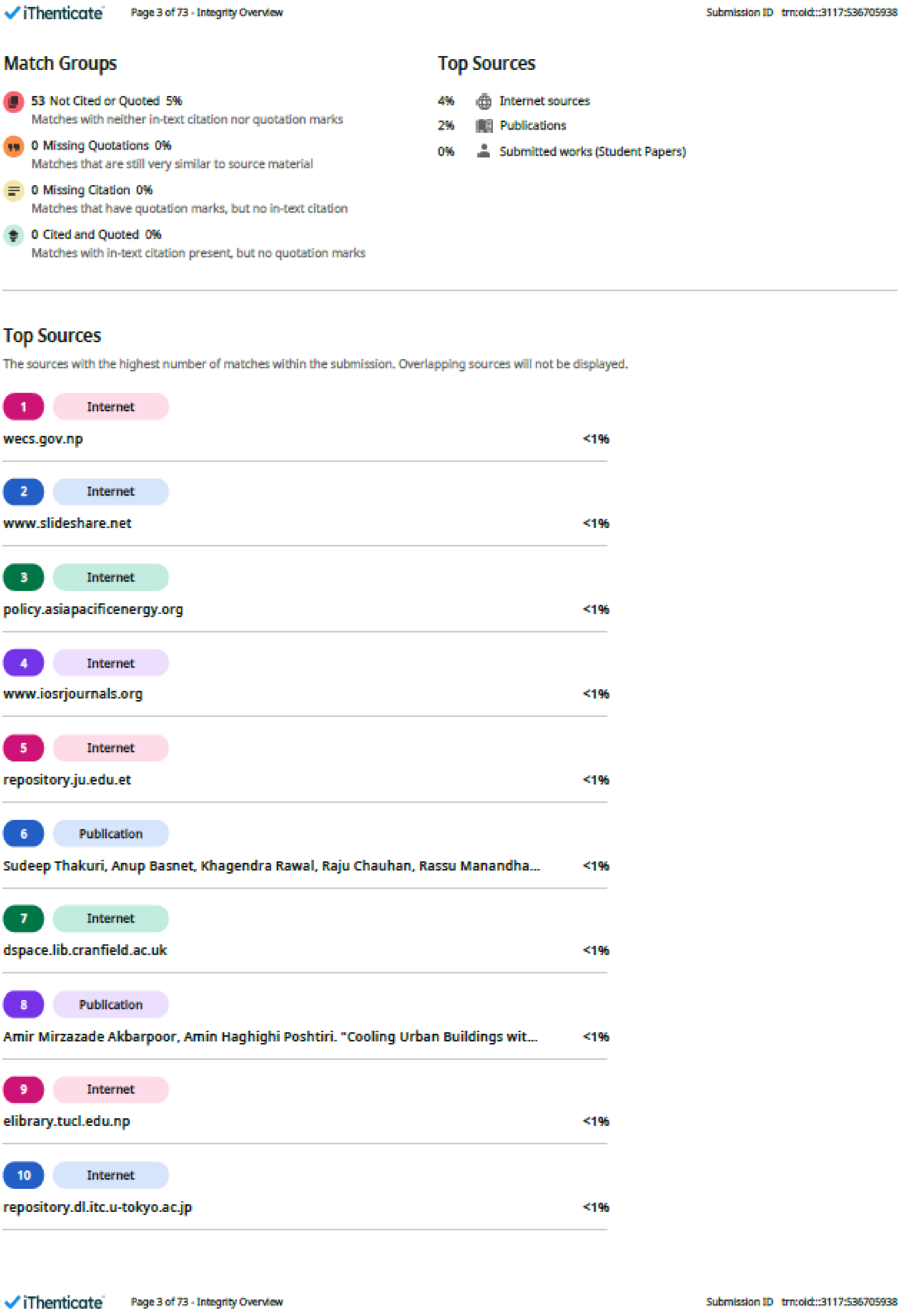

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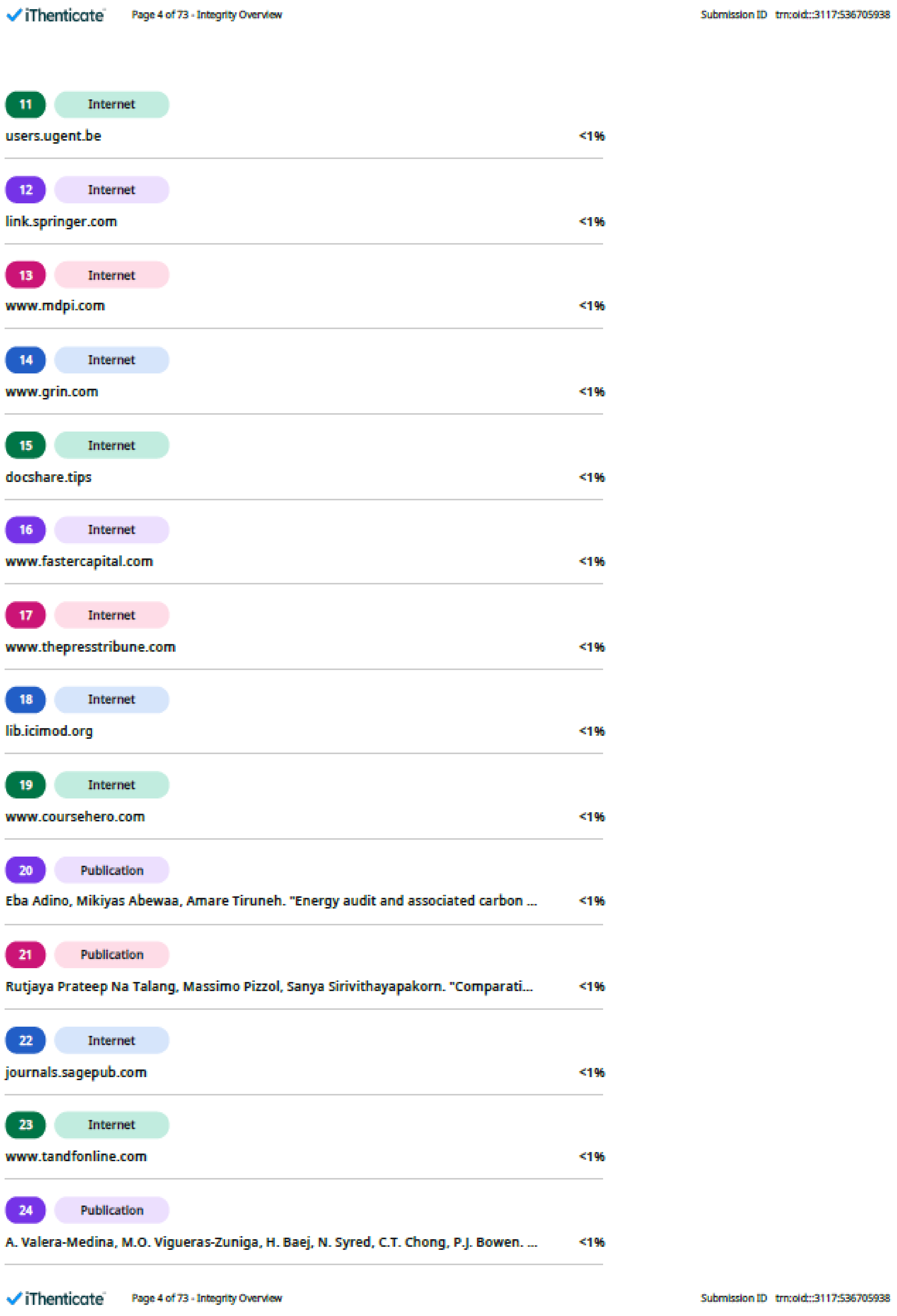

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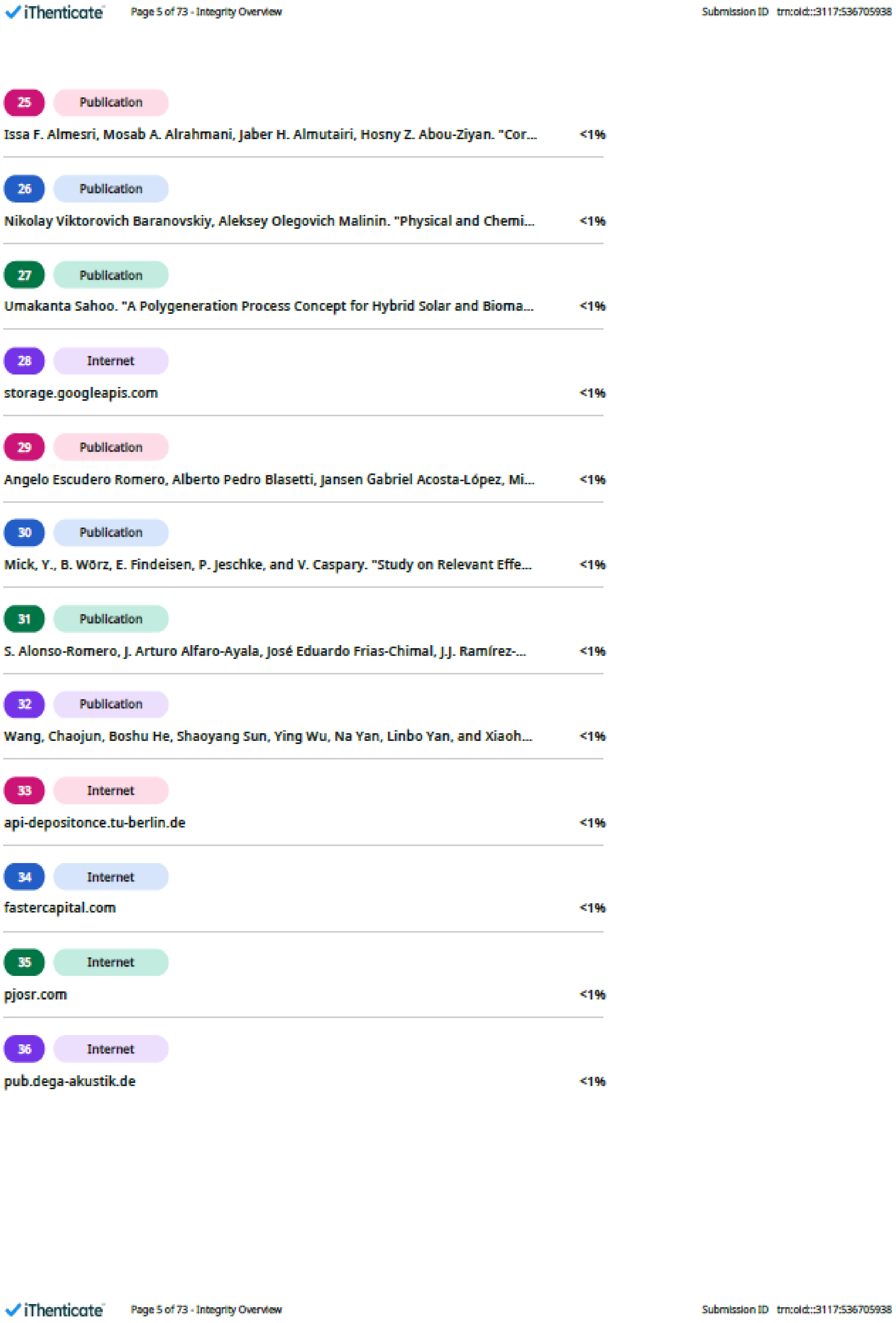

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