

# CFD-Based Energy and Thermal Performance Evaluation of a Coconut Shell–Fired Downdraft Kiln for Sustainable Brick Production

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**Abstract.** Enhancing energy efficiency and reducing environmental impact in energy-intensive industries are essential for sustainable energy systems. This study numerically evaluates the energy and thermal performance of a coconut shell–fired downdraft brick kiln as a renewable alternative to fossil-fuel-based firing. A three-dimensional kiln model was analyzed using Computational Fluid Dynamics (CFD) to examine combustion, airflow, and heat transfer. Fuel properties from proximate and ultimate analyses yielded an adiabatic flame temperature of 2242 K. Results indicate stable downdraft heat circulation, firing-zone temperatures above 1000 K, and a specific energy consumption of 2.7 MJ/kg while the experimental batch SEC was 3.5 MJ/kg, demonstrating improved efficiency and reduced carbon intensity compared with conventional kilns.

## 1 Introduction

### 1.1 Background and Motivation

The Philippines generates approximately 2.2 million tons of coconut shell waste annually, representing a high-calorific yet underutilized biomass resource for renewable energy applications [1]. Advances in biomass conversion have enabled coconut shells to be processed into solid biofuels and biochar with heating values comparable to conventional fuels [2]. When used as kiln fuel, coconut shells can provide a cleaner alternative to traditional biomass combustion, helping reduce emissions and fossil-fuel dependence while supporting circular bioeconomy goals through waste valorization in ceramic brick production [3], [4].

However, existing work on coconut shell–fired kilns largely emphasizes material characterization or qualitative thermal observations, with limited energy-oriented, CFD-based analyses of biomass-fired downdraft kiln systems. Quantitative studies linking airflow–heat transfer interaction and specific energy consumption (SEC) in small-scale brick

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production remain scarce. To address this gap, this study employs Computational Fluid Dynamics (CFD) to evaluate the thermal and energy performance of a coconut-shell-fired downdraft kiln by analyzing temperature distribution, airflow behavior, heat-transfer characteristics, and SEC relative to conventional kiln benchmarks.

## **2 Review of Related Studies**

### **2.1 Coconut Shells as a Biomass Energy Resource**

Coconut shells have been widely investigated as a biomass fuel due to their high lignocellulosic content, which enables efficient conversion into pellets, briquettes, and biochar [5], [6]. Pyrolysis-derived coconut shell biochar exhibits high carbon content and favorable heating values, supporting its application in industrial energy systems [7]. In coconut-producing regions, the low ash content and high calorific value of coconut shells make them suitable for reducing fossil-fuel dependence in energy-intensive processes [8], [9]. These characteristics align with circular economy strategies emphasizing waste utilization and sustainable bioenergy development [10].

### **2.2 Downdraft Kiln Technology for Brick Production**

Downdraft kiln systems are characterized by controlled airflow and relatively uniform temperature distribution, resulting in improved combustion efficiency and reduced emissions [11]. Previous studies report that coconut-shell-fired downdraft kilns can achieve lower specific energy consumption while maintaining acceptable brick quality, with additional benefits such as increased porosity and improved thermal insulation of fired bricks [12]. These findings demonstrate the suitability of downdraft kilns for biomass-based firing applications.

### **2.3 Application of Computational Fluid Dynamics in Kiln Energy Analysis**

Computational Fluid Dynamics (CFD) is widely applied in energy-intensive thermal systems, including biomass-fired kilns, due to its capability to model coupled combustion, fluid flow, and heat transfer under high-temperature conditions [13]. In ceramic kiln applications, CFD enables prediction of temperature and velocity fields that are difficult to obtain experimentally, supporting improved combustion efficiency and reduced energy losses [14]. By integrating fuel properties from proximate and ultimate analyses, CFD provides a cost-effective tool for energy-focused performance assessment and design optimization of renewable-energy-based kiln systems [15].

## **3 CFD Modeling and Simulation Framework**

### **3.1 Kiln Geometry and Numerical Model**

Computational Fluid Dynamics (CFD) was used to model the combustion process, airflow behavior, and heat transfer inside a downdraft brick kiln fueled by coconut shells. The kiln structure, including the combustion chamber, downdraft passages, and brick arrangement area, was created in ANSYS SpaceClaim to closely reflect the actual operating setup.

### 3.2 Simulation Setup and Governing Parameters

Simulations were performed in ANSYS Fluent using a steady-state, pressure-based solver with the RNG  $k-\epsilon$  turbulence model and enhanced near-wall treatment to model turbulence-combustion interactions. Fuel properties from proximate and ultimate analyses showed in Table 1 were incorporated into a global coconut-shell reaction model ( $\text{CH}_{1.39}\text{N}_{0.014}\text{S}_{0.0012}\text{O}_{0.44}$ ) based on biomass data reported by Suyambazhahan, enabling estimation of the adiabatic flame temperature and key combustion parameters. The adiabatic flame temperature was evaluated using MATLAB as a function of equivalence ratio, yielding a maximum value of 2242 K (Fig. 1), while the corresponding flue-gas viscosity ( $4.02 \times 10^{-5} \text{ m}^2/\text{s}$ ) informed the flue outlet design.

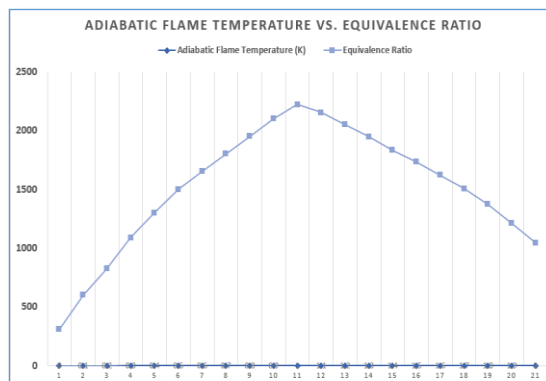
**Table 1.** Proximate Analysis and Ultimate Analysis of Coconut Shells

Proximate Analysis	As-Received wt. %	Element	As-Received wt. %
Fixed Carbon	19.58	Carbon (C)	54.03
Volatile Matter	73.03	Hydrogen (H)	6.25
Moisture	7.02	Nitrogen (N)	0.87
Ash	0.62	Oxygen (O)	38.55

A three-dimensional downdraft kiln geometry was developed in ANSYS SpaceClaim, with the chimney section excluded to reduce computational cost under academic license constraints. Temperature distribution within the kiln was obtained by solving the energy equation, accounting for enthalpy transport by convection, conduction, and combustion heat release. A non-uniform tetrahedral mesh with a maximum orthogonal quality of 0.99 was generated, and combustion was modeled using a species transport approach with non-premixed chemistry. The adiabatic flame temperature, used as a key boundary condition in the CFD simulation, was calculated using the energy balance formulation in Eq. (1) and represents the maximum theoretical temperature achievable under ideal combustion conditions for evaluating kiln thermal performance.

$$\sum n_i h_{f,i}^0 + \sum n_i \int_{T_{ref}}^{T_o} C_{p,i}(T) dT = \sum n_j h_{f,j}^0 + \sum n_i \int_{T_{ref}}^{T_o} C_{p,i}(T) dT \quad (1)$$

In Eq. (1),  $n_i$  denotes the molar quantity of each species,  $h_{f,i}^0$  is the standard enthalpy of formation at  $T_{ref} = 298 \text{ K}$ , and  $C_{p,i}(T)$  accounts for sensible enthalpy variations of reactants and products.



**Fig. 1.** Adiabatic Flame Temperature versus Equivalence Ratio

Temperature distribution within the kiln was obtained by solving the energy equation (Eq. 2) in ANSYS Fluent.

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\rho \vec{v} h) = \nabla \cdot (k \nabla T) + S_h \quad (2)$$

### 3.3 Energy Performance Evaluation

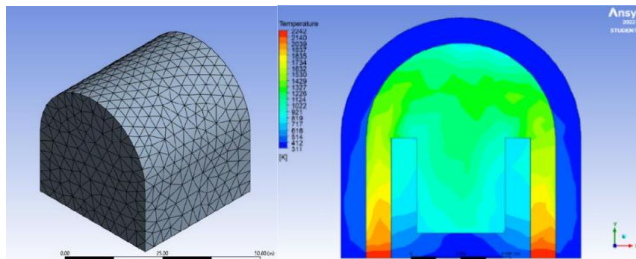
Specific energy consumption (SEC) analysis was used to compare energy performance. It is calculated by dividing the amount of energy used by the amount of product produced. In the context of brick kilns, SEC is defined as the Energy in MJ consumed for producing 1 kg of fired brick. The SEC of the kiln is computed through Eq. 3. Where  $H_{in}$  is the total energy input to the kiln for the duration of one firing cycle per batch. The total energy input includes all the energy input from the fuel, internal fuels added on the clay if present, and from the organic matter present in the brick soil. While  $M_{fbr}$  is the mass of fired bricks produced during one firing cycle per batch.

$$SEC = \frac{H_{in}}{M_{fbr}} \quad (3)$$

## 4 Results and Discussion

### 4.1 Computation Fluid Dynamics Results

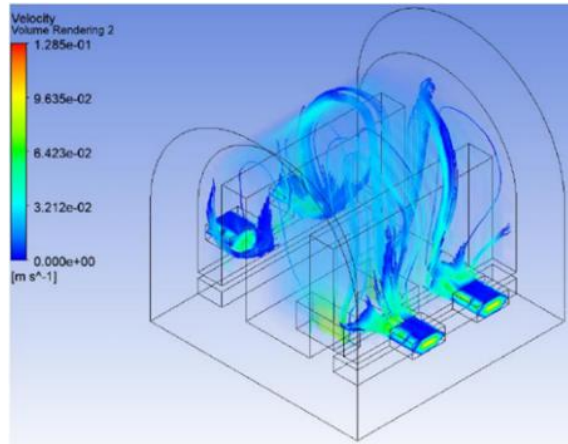
Figure 2 shows the non-uniform tetrahedral mesh and the predicted steady-state temperature field in the dome-type downdraft kiln. The simulation indicates that the highest temperatures are localized near the burner inlet regions and the lower side passages, where combustion intensity is greatest. Moving upward into the dome and toward the brick stack region, the temperature field becomes more moderate and spatially distributed, which is favorable for transferring heat into the stacked bricks rather than concentrating it in a single hotspot. The outer wall region remains significantly cooler due to heat losses to the surroundings, producing a clear thermal gradient from the hot interior core toward the kiln boundaries.



**Fig. 2.** A Non-Uniform Tetrahedral Mesh Domain Temperature Contour at Steady State in a Dome Type

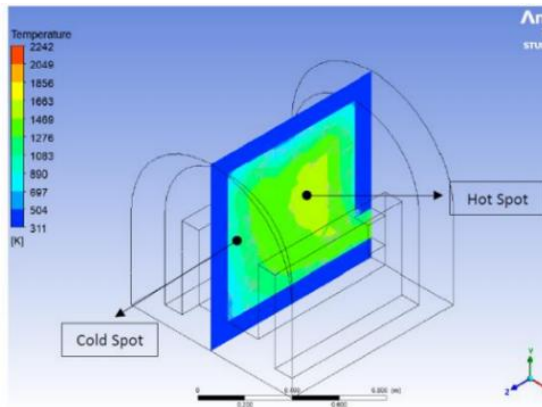
Velocity contours (Fig. 3) confirm the intended downdraft circulation pattern. Hot combustion gases rise toward the dome region and then recirculate downward through the brick stack before exiting toward the chimney. The predicted velocities decrease from approximately 0.13 m/s near the burner inlets to below 0.03 m/s near the walls, indicating reduced momentum and longer residence time in the interior zone. This lower-velocity recirculation is important because it increases gas–solid contact time, supporting convective

heat transfer to the brick surfaces and improving thermal utilization of the combustion gases before discharge.



**Fig. 3.** Velocity Profile Rendering

Figure 4 presents the temperature contour across the kiln center plane, highlighting spatial non-uniformities that influence firing uniformity. A localized high-temperature region, “hot spot”, is observed along the main internal flow path where combustion gases are concentrated before recirculating downward. In contrast, a “cold spot” is observed in regions closer to the wall and low-flow zones, where heat transfer is reduced by weaker circulation and boundary heat losses. The presence of these hot/cold regions suggests that brick stacking arrangement, air–fuel distribution, and sealing or insulation strongly affect firing uniformity. Maintaining sufficient circulation across the brick stack and minimizing leakage near openings are expected to reduce cold-spot formation and improve batch consistency.

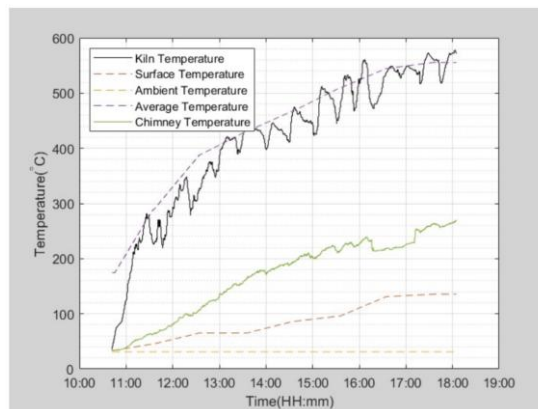


**Fig.4.** Temperature Contour Across the Center Plane

## 4.2 Simulation Results Validation

Figure 5 shows the measured temperature–time history during coconut shell firing, including kiln internal temperature, averaged kiln temperature, chimney temperature, surface temperature, and ambient temperature. The kiln temperature rises rapidly from near ambient

to about 250–300 °C, then increases more gradually as the kiln and load absorb heat and losses to the surroundings become more significant. Toward the latter portion of the run, the kiln reaches approximately 560 to 580 °C, with oscillations attributed to intermittent fuel feeding and draft/airflow variations. Since the CFD model is steady state, validation was performed by comparing the late-stage quasi-steady experimental temperature level with the simulated steady thermal field, supporting that the model captures the sustained firing regime achieved under coconut shell operation. Since the CFD steady-state temperature ranges from 921 to 1022 K, while the experimental late-stage quasi-steady average temperature reaches approximately 560 to 580 °C (833–853 K). The CFD prediction is therefore higher by approximately 70 to 190 K ( $\approx 8\text{--}23\%$ ), which is reasonable given the steady-state assumptions and idealized boundary conditions, whereas the experiment includes transient firing, intermittent fuel feeding, draft variability, and additional heat losses (e.g., door leakage and wall losses) that are not fully represented in the model.



**Fig.5.** Temperatures of the kiln's internal, external surfaces, and ambient as function of time

Specific energy consumption (SEC) was quantified using both the CFD steady-state solution and batch firing data. The integrated heat transfer rate delivered to the brick load was 21 KW. Over an 8-hour firing period, this corresponds to a total delivered energy of 604.8 MJ. For a fired batch mass of 225kg, the resulting CFD-based steady-regime SEC is approximately equal to 2.7MJ/g. Experimentally, a 225-kg batch of fired bricks consumed 23 kg of coconut shell fuel with HHV of 34.46 MJ/kg yielding an energy input of 792.12 MJ and an experimental SEC of 3.5205 MJ/kg. The higher experimental SEC is expected because it includes start-up heating and transient operational effects, as well as practical heat losses and fuel property variability that are not fully represented in the idealized steady-state CFD estimate.

## 5 Conclusion

This study evaluated the thermal and energy performance of a coconut-shell-fired downdraft kiln using combustion analysis and CFD. The simulation predicts localized high-temperature regions near the burner inlets and a more distributed thermal field through the brick-stack zone, while the downdraft recirculation and reduced velocities across the load suggest sufficient residence time for effective heat transfer. Experimental temperature–time data confirm sustained firing, with late-stage kiln temperatures of 560–580 °C (833–853 K) and comparatively low surface temperatures indicating wall heat losses. The CFD steady-state temperature range (921–1022 K) is of the same order as the late-stage measurements,

supporting that the model captures the sustained firing regime under coconut shell operation despite transient fluctuations from fuel feeding and draft variations. Energy performance was quantified using SEC, yielding a CFD steady-regime estimate of  $\sim 2.7$  MJ/kg and an experimental batch value of  $\sim 3.5$  MJ/kg, which has an error of  $\sim 22.8\%$ . The higher experimental SEC attributable to start-up energy, transient operation, and practical heat losses not fully represented in the steady-state model. Overall, the results demonstrate that coconut shells are a viable renewable fuel for ceramic brick production and highlight the importance of improved sealing/insulation and air–fuel/draft control to reduce losses and narrow the gap between modeled and as-operated performance.

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