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Design and Assessment of Heat Exchanger Parameters for Thermal Efficiency in Fish Smoking Kiln

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Abstract

Efficient thermal management in fish smoking kilns is essential for enhancing product quality, optimizing fuel consumption, and promoting operational sustainability. Conventional kiln systems frequently suffer from inconsistent heat retention and poor energy utilization due to suboptimal heat exchanger configurations. This study evaluates the influence of three key parameters—blower speed (650, 725, and 800 rpm), number of open pipe inlets (5, 10, and 15), and insulation material (sawdust, clay, and fiber) on the thermal performance of a locally fabricated heat exchanger integrated into a fish smoking kiln. A Response Surface Methodology (RSM)-based central composite design was employed to structure a 20-run experimental matrix, allowing for systematic interaction analysis between design variables. Airflow rate measurements were taken at the exhaust outlet of the heat exchanger to ensure consistent thermal load evaluation. Statistical analysis using ANOVA revealed significant effects ($p < 0.01$) of blower speed and insulation type on outlet air temperature, with the maximum temperature of 96°C achieved at 800 rpm, 15 open pipes, and fiber insulation. Additionally, airflow rate was strongly influenced by both linear and quadratic terms of blower speed and pipe configuration, with adjusted $R^2 = 0.995$ and Adequate Precision = 79.48, indicating model robustness. This work distinguishes itself from previous studies by integrating cost-effective materials, a scalable exchanger design, and a quantitative optimization framework for kiln retrofitting. Its adaptability to diverse kiln geometries and biomass fuel types underscores its potential for widespread application across artisanal and semi-industrial fish processing facilities. These findings offer a replicable pathway for transitioning traditional fish smoking systems toward higher thermal efficiency and environmental compliance.

Keywords: System, integration, robustness, fuel, environmental.

INTRODUCTION

The processing and preservation of fresh fish remain a critical challenge in regions with limited cold chain infrastructure. Due to its high moisture content, fresh fish is highly perishable and susceptible to microbial spoilage shortly after harvest. To mitigate these losses and extend shelf life, drying, particularly through smoking has been widely adopted in developing regions, especially in sub-Saharan Africa (Oduntan et al., 2019). Smoking not only dehydrates the fish, reducing water activity (aw < 0.6), but also enhances its flavor, color, and microbial safety due to the deposition of antimicrobial compounds present in wood smoke (Jimoh, 2022; Swastawita et al., 2022).

While traditional methods of fish smoking using open fires or rudimentary drum kilns are still prevalent, they are often inefficient, labor-intensive, and yield inconsistent product quality. Limitations such as poor temperature control, uneven heat distribution, and exposure to environmental contaminants result in high post-harvest losses, increased fuel consumption, and compromised food safety (Adeyeye et al., 2017). Moreover, Nigeria's smoking industry is largely dominated by artisanal operations lacking technical enhancements, which further constrains commercialization and quality assurance (Ogbadu, 2014).

To improve drying efficiency and product integrity, artificial smoke dryers and improved smoking kilns have been introduced. However, most existing kilns still suffer from low thermal efficiency due to poor heat conservation design, particularly in the configuration of the heat exchanger system. The uncontrolled release of combustion heat directly into the drying chamber causes temperature spikes that negatively impact both fuel efficiency and product quality. This uncontrolled thermal delivery leads to higher fuel consumption and risks overexposing fish to excessive heat, resulting in uneven drying, nutritional degradation, and undesirable texture or flavor (Nguimdo & Valdo, 2020).

The heat exchanger plays a pivotal role in regulating energy transfer from the combustion zone to the drying chamber. Its performance depends on several interrelated design and operational parameters including blower speed, air distribution system, heat retention mechanisms (insulation), and surface area of contact. Insufficient control over these factors can lead to rapid heat dissipation and thermal instability during the drying cycle.

To address these limitations, this study focuses on the design and assessment of heat exchanger parameters within a fish smoking kiln, with the goal of enhancing thermal efficiency. Specifically, the influence of blower speed, the number of open pipe inlets, and insulation type (fiber, clay, sawdust) on heat transfer performance were systematically investigated. By evaluating their combined effects on outlet air temperature and flow rate, the study aims to identify configurations that optimize energy retention and drying uniformity, thereby improving kiln performance.

The outcome of this research is expected to offer practical insights for upgrading artisanal smoking kilns using accessible materials and design improvements, ultimately promoting sustainable fish processing, reducing fuel usage, and improving product quality.

MATERIALS AND METHODS

Description of the heat exchanger

The combustion chamber, constructed from galvanized steel (thickness of 0.0015m) for improved corrosion resistance and longevity, measures 0.50 m in height, 0.35 m in length, and 0.35 m in width. This chamber houses a coal pot with dimensions of 0.15 m × 0.33 m × 0.33 m, designed to hold an optimal quantity of charcoal for sustained combustion. Integrated within the chamber are 15 galvanized steel (thickness of 0.002m) duct pipes, each measuring 0.03 m in diameter and 0.35 m in length, which function to guide the heated air through the exchanger efficiently. A mild steel chimney, measuring 0.025 m in diameter, thickness of 0.002m and 0.1 m in height, is installed for smoke venting and safe discharge of combustion by-products.

The blower section comprises blower housing, propeller, electric motor, and engine seat. The housing is fabricated from mild steel (thickness of 0.0015m), featuring a circular frame with a 0.19 m diameter, thickness of 0.0015m and includes a rectangular air outlet of 0.25 m × 0.25 m and a circular air inlet with a diameter of 0.2 m. This configuration ensures a directed and controlled flow of heated air into the drying chamber, thereby improving thermal distribution.

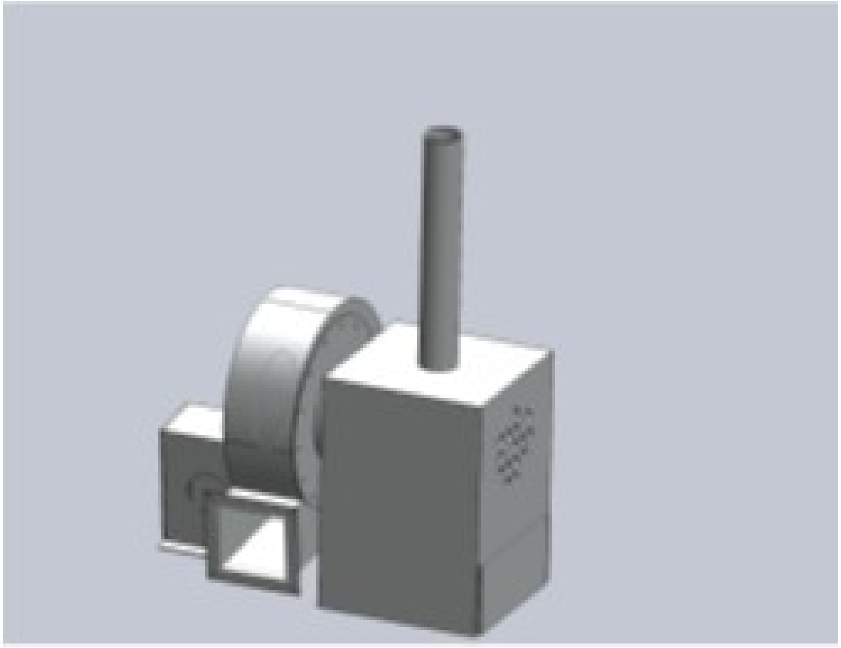

Figure 1: Orthographic technical drawing shows top, front, and side views of the system

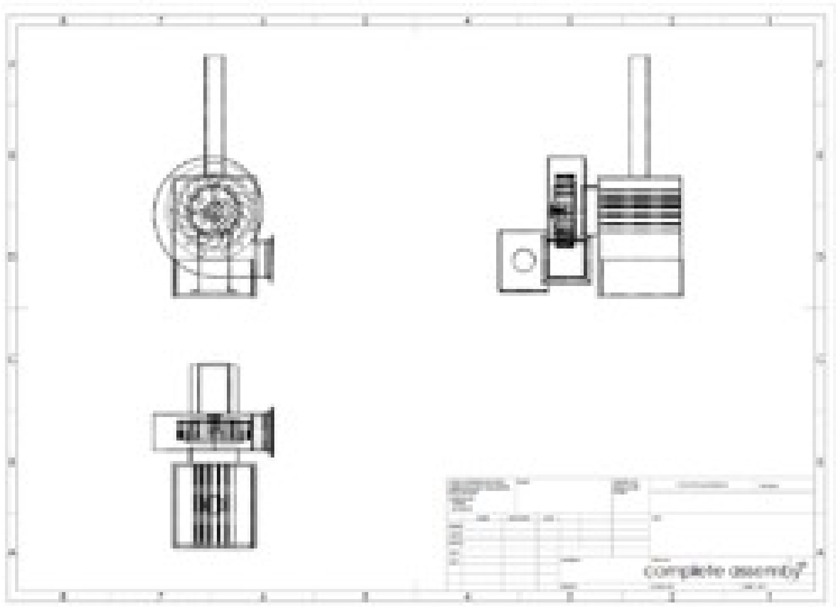

Figure 2: 3D CAD rendering of the complete heat exchanger assembly

Choice of Materials

The heat exchanger was constructed using carefully selected materials chosen for their mechanical properties, thermal characteristics, and local availability. Galvanized sheet metal was employed for the fabrication of the heat exchanger due to its excellent thermal conductivity and durability under high-temperature conditions. This material ensures efficient heat absorption and radiation, which are critical for sustaining thermal consistency within the system. Mild steel was selected for constructing the blower housing. Its high tensile strength, weldability, and structural stability make it ideal for withstanding operational stress while maintaining airtight integrity. For the air duct system, galvanized steel pipes were utilized, as they provide corrosion resistance and structural rigidity essential for directing hot airflow effectively through the exchanger.

The structural framework was supported by an angle iron, chosen for its mechanical robustness and ease of fabrication. Powering the centrifugal blower is a 0.38 horsepower electric motor, which was matched to the operational load requirement for efficient air propulsion. A variable frequency drive (VFD) was incorporated to modulate the motor speed dynamically, enabling controlled airflow based on process demands.

To support data acquisition and thermal monitoring, a thermometer was positioned at strategic points within the ductwork to measure both internal and outlet air temperatures. In addition, a tachometer was used to measure the motor's angular speed, providing precise feedback for process control. In designing the heat exchanger, several practical factors were considered. Material type was prioritized based on functional compatibility with different sections of the design, ensuring optimal heat resistance, mechanical strength, and corrosion protection. Material availability was also a critical consideration to support cost-effective and timely fabrication using locally sourced components.

The heat exchanger was engineered to handle the necessary fuel volume required to complete a full drying cycle, ensuring uninterrupted operation. Portability was another key design goal; the system was kept compact to facilitate mobility between different workspaces or processing sites. Finally, the design incorporated elements that would ensure low maintenance costs, such as modular components and accessible maintenance points, supporting long-term operational sustainability with minimal downtime.

Design calculation

Batch capacity of the kiln was obtained to be an average of 52kg of fish. Average temperature range for smoking fish 80oC – 150oC. Amount of moisture to be removed according to Sunmonu and Kehinde (2019); Oduntan et al. (2019).

$$\text{MR} = \text{M}\left(\frac{Q_1 - Q_2}{100 - Q_2}\right) 1$$

where Q_1 is the initial moisture content,
Q_2 is the final moisture content, and
M is the dryer mass capacity.

$$\text{dr} = \left(\frac{MR}{t_d}\right) 2$$

where
MR is the amount of water to be removed and
t_d is the maximum drying time (hr).

$$\text{m}_a = \left(\frac{dr}{w_f - w_i}\right) 3$$

where
w_i is the initial humidity ratio
and
w_f is the final humidity ratio.

$$\text{v}_a = m_a \times v 4$$

$where v_a$ is the specific volume of air.

Experimental procedure

The fabricated heat exchanger coal pot was loaded with charcoal and sawdust and allowed to combust before it was taken to the combustion chamber. The inlet pipes temperature was recorded using a thermometer until a stable temperature was noted after heating the pipes for 1 hour. The blower was then operated, and the outlet temperature and air flow rate were recorded. The process was carried out for 20 runs at varying parameters of the heat exchanger as presented in Table1, such as blower speed, number of open pipes at air inlet, and insulator. 2.6 Optimization for temperature and air flowrate The experimental study explored the impact of three (3) independent variables, namely blower speed, number of open pipes, and insulators, on two response variables: outlet air temperature and outlet air flowrate. A total of 20 experimental runs were carried out, systematically adjusting the levels of the independent variables in each run. The analysis of the collected data aimed to provide a comprehensive understanding of the relationships between the independent variables and discover optimal operating conditions as well as potential enhancements for the heat exchanger

Statistical Analysis

Design experiments were carried out using the statistical software Design-Expert 13.0. A regression analysis of the experimental data was performed to estimate the response of the independent variables. The quality of fit of the second-order equations was expressed by the coefficient of determination (R^2), and P $<$ 0.05 was considered statistically significant for all analyses. Design-Expert 13.0 is a statistical software package from Stat-Ease Inc. specifically designed to determine the significance of these factors using analysis of variance (ANOVA). Projects with an optimal mix were used if the response varied depending on the relative components of the combination. Table 2 shows the 20 experimental trials and the different factor combinations.

Table 1: Independent variables

Factor	**Name (Variable)**	**Units**	**Type**	**SubType**	**Minimum**	**Maximum**
x_1	Fan Speed	RPM	Numeric	Discrete	650.00	800.00
x_2	No. of Pipes		Numeric	Discrete	5.00	15.00
x_3	Insulator		Categoric	Nominal	Fibre	Clay

RESULTS AND DISCUSSION

Effect of Heat Exchanger Parameters on Outlet Air Temperature

Table 3 summarizes how outlet air temperature varies with key factors. The maximum temperature (96°C) occurred at 800rpm blower speed, 15 open pipe inlets, and fiber insulation. Conversely, the minimum temperature (31°C) was recorded at 650rpm, 5 open pipes, and sawdust insulation. This confirms that increased blower speed and pipe count enhance convective heat transfer (per Bernoulli's principle governing pressure–velocity relationships), while lower-conductivity insulation, such as fiber, reduces heat loss and bolsters outlet temperature.

A reduced quadratic model was fitted to the temperature data using ANOVA. The model was statistically significant, as indicated by an F-value of 566.74 and a p-value $<$ 0.0001, signifying that the predictor variables meaningfully influenced the response. Additionally, an Adequate Precision ratio of 79.482 far exceeding the acceptable threshold of 4 validated the model's strong signal-to-noise ratio, ensuring the reliability of the experimental design. The model's coefficient of determination (R^2 = 0.9976) indicates that 99.76% of the variability in outlet temperature could be explained by the selected input parameters. The predicted R^2 (0.9976) closely aligned with the adjusted R^2 (0.9958), confirming the model's robustness and predictive capability. The final regression equation representing the relationship between outlet air temperature and the coded independent variables is:

$$\text{Y}_{temp} = 58.34 + 10.80x_1 + 18.75x_2 + 5.32x_3 + 4.85x_3 + 6.22x_1x - 2 + 2.94x_2x_3 - 3.42x_2x - 3 - 4.52x_2$$

This equation indicates that temperature increases linearly with blower speed

Table 2: Experimental runs to be carried out

Run	**Factor 1** (x_1) (RPM)	**Factor 2** (x_2) (No. of Pipes)	**Factor 3** (x_3) (Insulator)
1	800	15	Sawdust
2	650	10	Sawdust
3	725	15	Fibre
4	650	15	Clay
5	725	10	Clay
6	650	10	Sawdust
7	650	15	Fibre
8	800	5	Fibre
9	725	10	Clay
10	725	5	Fibre
11	800	5	Clay
12	650	5	Clay
13	800	5	Sawdust
14	725	10	Clay
15	725	10	Fibre
16	650	5	Sawdust
17	800	10	Fibre
18	800	15	Fibre
19	800	15	Clay
20	650	10	Fibre

(x_1), $numberofpipes(x_2), insulator(x_3),$ [illegible]
$asfanspeedandnumberofpipesincrease,$ [illegible]

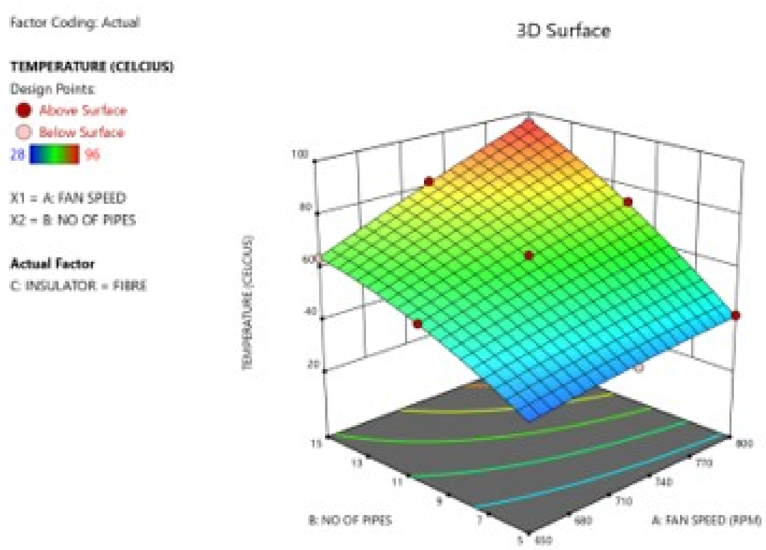

Figure 3: Effect of blower speed and number of open pipes on outlet temperature

Table 3: Experimental results

Run	Temperature (°C)	Flowrate (m^3/s)
1	82	0.27
2	42	0.15
3	82	0.25
4	55	0.22
5	58	0.17
6	42	0.15
7	64	0.22
8	42	0.09
9	58	0.17
10	37	0.08
11	40	0.09
12	28	0.07
13	37	0.09
14	58	0.17
15	65	0.17
16	31	0.07
17	74	0.18
18	96	0.27
19	90	0.27
20	53	0.15

Effect of Heat Exchanger Parameters on Air Flow Rate

The impact of design parameters on air flow rate is presented in Table 3. Flow rate values ranged from 0.08 to 0.27m³/min. Statistical analysis revealed that blower speed and number of open pipes had significant linear and quadratic effects on the airflow. The model F-value of 9254.83 ($p < 0.0001$) confirms a strong and reliable model with minimal chance of error due to random variation.

The model exhibited exceptional statistical fit, with an R^2 value of 0.9997, indicating that nearly all variability in flow rate was accounted for by the model. The predicted R^2 (0.9993) and adjusted R^2 (0.9996) were in close agreement, further validating model consistency. A remarkably high Adequate Precision value of 262.381 substantiates the strength of the signal relative to noise, affirming the model's utility for guiding process optimization. The polynomial regression model for flow rate is given as:

$$\mathrm{Y}_{flowrate} = 0.1696 + 0.017x_1 + 0.0829x_2 + 0.0074x_1x_2 - 0.0033x_{12} - 0.0039x_{22}$$

This equation indicates a positive influence of blower speed (x_1) and number of open pipes (x_2) on airflow, with diminishing returns at higher levels due to quadratic effects. These results are consistent with the findings of Etim *et al.* (2019), who demonstrated that increasing the air inlet area in solar dryers significantly increased airflow and reduced drag, emphasizing the importance of pipe size and count in air distribution systems.

This 3D surface plot (Fig. 4) visualizes the interaction effect of fan speed (RPM) and number of open pipes on air flowrate (in cubic meters per second) in the heat exchanger system, with fiber used as the insulator. The surface curve is smooth and upward-sloping, suggesting a positive linear relationship between the variables and airflow, within the experimental range. This trend can be explained by convective flow principles and Bernoulli's theorem that increasing the fan speed raises the air velocity, reducing static pressure and increasing kinetic energy, which improves forced convection through the ducts (Rizwan, 2020). More open pipes increase the cross-sectional area available for airflow, thereby reducing flow resistance and enabling greater volumetric throughput (Al-Obaidi and Alhamid, 2021.). Together, these changes enhance the air circulation rate, crucial for maintaining consistent drying conditions inside the kiln and preventing temperature drops during long smoking sessions.

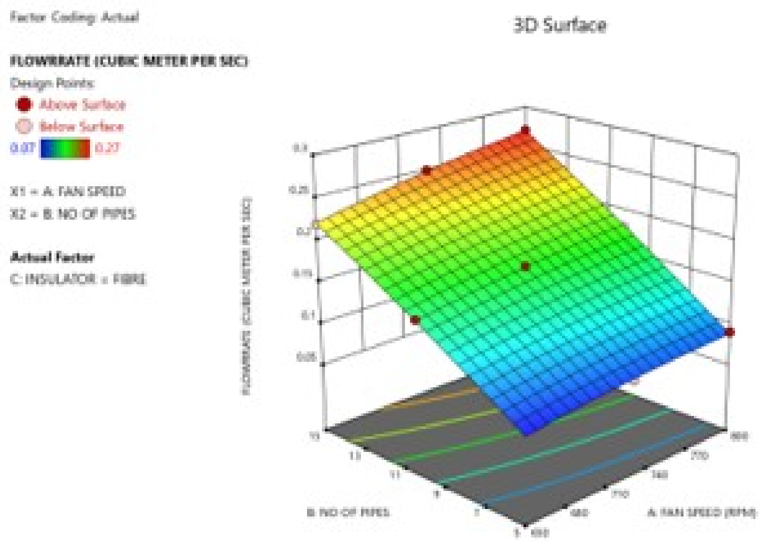

Figure 4: Effect of blower speed and number of open pipes on outlet air flowrate

Expand model validation with additional blower speeds to cover all insulation materials, include residual analyses for robustness, and assess practical benefits such as reduced fuel consumption and processing time. Future studies should also evaluate smoke composition and fish sensory quality under varying thermal regimes bridging engineering innovation with food safety and consumer acceptance.

CONCLUSION

This study evaluated the influence of key heat exchanger parameters are blower speed, number of open pipes, and insulation type on the thermal performance of a fish smoking kiln. The experimental design, supported by statistical modeling, revealed that all three variables significantly affected both the outlet air temperature and the airflow rate. The results demonstrated that higher blower speeds, a greater number of open pipe inlets, and the use of fiber insulation contributed to improved heat retention and elevated airflow. The optimal configuration yielded an outlet temperature of 96°C and a maximum airflow rate of 0.27m³/min, confirming the system's efficiency under specific parameter settings. The statistical models exhibited high predictive accuracy with R^2 values exceeding 0.99, and adequate precision values well above the acceptable threshold, confirming model reliability.

These findings highlight the importance of systematic parameter tuning in the design of efficient heat exchanger units for fish smoking kilns. By leveraging accessible materials and simple design modifications, significant improvements in energy efficiency and drying performance can be achieved.

The integration of such optimized systems in artisanal and semi-commercial smoking operations can reduce fuel consumption, enhance product quality, and support the development of sustainable fish processing technologies in resource-constrained regions.
Future work may explore long-term performance under real-world smoking conditions, cost-benefit analysis of insulation types, and integration with renewable energy systems for enhanced environmental sustainability.

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