EXPERIMENTAL PERFORMANCE EVALUATION OF A CHARCOAL-FIRED FISH SMOKING KILN

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Abstract

Efficient fish preservation is important when quality, hygienic products and the highest possible profits are to be achieved in fish production. An effective-fired charcoal-fired fish smoking machine was designed and developed with a carrying capacity of 7.2 kg in which the smoking of fish was carried out. The temperatures of the air within the smoking chamber were raised to the smoking temperatures (343.15K, 363.15K and 383.15 K) at varying velocities of air and maintained for some time until the moisture contents of the fish were reduced to between 16 - 18%. The temperature of the air increased steadily until the smoking temperatures were achieved and these occurred between 20 – 27 min. The time taken for the fish to attain the smoking temperature was recorded to be between 120 – 160 min. The minimum time taken for expelling the moisture content was 155 min at a drying temperature of 383.15 K and velocity of 1.0 m/s and the maximum time was 225 min at a drying temperature of 343.15 K and velocity of 0.6 m/s. The computed fish drying rate was \( Rc = 0.005370(\% / s) \) hence, for effective fish smoking, the fish should be smoked at a temperature and velocity of 383.15 K and 1.0 m/s respectively at a drying rate of \( Rc = 0.005370(\% / s) \).

Keywords: Fish, Charcoal, Smoking Kiln, Drying Temperature, Smoking Temperature.

1.0 Introduction

Nigerians are large consumers of fish, and it remains one of the main products consumed in terms of animal protein. It is highly acceptable, with little or no religious bias, which gives it an advantage over pork or beef, however, the consumption depends mainly on income across the country (Lenis et al., 2021). It has been established that fishes are well-known for their various nutritional values and compositions, approximately it contains 70-84 % water, 15-24 % protein, 0.1-22% fat and 1-2%, minerals, 0.5% calcium, 0.25% phosphorus and 0.1% vitamins A, D, B and C (Bereket et al., 2018). The gap between the demand and supply of fish is widening due to increase in population, poor postharvest handling, lack of processing and storage facilities and utilization of unconventional fish species. Only about 50% of the demand for fish is currently being met locally and out this about 69% is being produced by artisan, 27% aquaculture and only 4% by industrial production (Kikiope, 2018).

An estimated 20 to 50% of the fish produced in the remote coastal centres and hinterlands of many tropical countries perish before they get to the consumers due to poor handling, preservation and processing practices adopted by the artisanal fishermen, fish farmers and fisheries entrepreneurs (Babagana and Mohammed, 2020). If fish is not sold fresh, preservation methods should be applied to
extend the shelf-life, these include freezing, smoking, drying and heat treatment (Doyle, 2017). Efficient preservation of fish is important when top quality, maximum yield and highest possible profits are to be achieved (Ibrahim et al., 2022). According to Katerina et al. (2019), fish smoking is a process of treating fish by exposing it to smoke from smouldering wood or plant materials. This process is usually characterized by a combination of salting, drying, heating, and smoking in a smoking chamber (Ayeloja et al., 2020). According to Bereket et al. (2018) dried salted fish with salt content of 10 - 15 %, can effectively inhibit fish spoilage, but may be a limiting factor to consumer acceptance. According to Sikoki and Aminigo (2002) and Bereket et al. (2018) the minimum acceptable smoking moisture content range between 7 - 19%. Sikoki and Aminigo (2002) further stated that smoke-dried fish having a moisture content exceeding 20% would spoil within 5 days. The process of fish smoking is the simplest preservation method as it does not require sophisticated equipment or highly skilled workers. However, the process varies depending on the species of fish to be dried and the type of product desired (Doyle, 2017). There are various types of smoking techniques that can be applied to reduce the water and hence attains the purpose of fish preservation. The most commonly used are cold smoking and hot smoking (Dipanjan et al., 2021).

Traditional fish smoking is burning wood or charcoal in an uncontrolled environment and this process have complex effects on the fish, this includes exposing the fish to germs, contamination, uneven smoking, and very low drying rate due to energy loss to the surrounding, thus increase in the cost of smoking the fish. Charcoal was used because when wood is burnt it gives the compound a mixture of chemicals in addition to main gas like CO₂ and traces of H₂O and CO. Aliphatic chemicals (alcohol, aldehyde, ketone and acids) are released at higher temperature (280°C - 350°C), if burnt they will release out phenolic compounds (Dipanjan et al., 2021). These chemicals are largely considered to be carcinogenic substances. Hence, these associated factors spurred the need to develop a controlled charcoal-fired fish smoking kiln to mitigate the formation of these carcinogens. Deceases would form the objective of this study, and the results of the experimental performance parameters were compared with the conventional ones.

2.0 Materials and methods

2.1 Description of Fish Smoking Kiln
The fired charcoal-fired fish smoking kiln is rectangular in shape with an inner lining made of Aluminium sheet. Sawdust was used as insulating material which conserves the heat energy from being lost and keeping the working environment conducive for the user. It is made of three compartments: a charcoal pot, fish tray and ash collector as shown in Figure 1.

![Figure 1: (a) Charcoal-fired fish smoking kiln, (b) charcoal pot, (c) fish tray and (d) ash collector](image)

The kiln was incorporated with blower, belt drive and rotating spindle which helps to improve the air and heat circulation within the smoking chamber and removal of moisture out of the chamber. The blower was attached to the smaller shaft of the pulley and the rotating...
spindle to the bigger pulley. The design specifications for the components parts of the smoking kiln are presented in Table 1.

Table 1: Design Specification and Assumptions Parameters Specifications

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Height of the kiln</td>
<td>0.7 m</td>
</tr>
<tr>
<td>Width of the kiln</td>
<td>0.6 m</td>
</tr>
<tr>
<td>Length of the kiln</td>
<td>0.6 m</td>
</tr>
<tr>
<td>Length of the fish tray</td>
<td>0.56 m</td>
</tr>
<tr>
<td>Width of fish tray</td>
<td>0.59 m</td>
</tr>
<tr>
<td>Height of fish tray</td>
<td>0.025 m</td>
</tr>
<tr>
<td>Length of the charcoal tray</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Width of charcoal tray</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Height of charcoal tray</td>
<td>0.12 m</td>
</tr>
<tr>
<td>Height of ash collector</td>
<td>0.1 m</td>
</tr>
<tr>
<td>Length of ash collector</td>
<td>0.3 m</td>
</tr>
<tr>
<td>Width of ash collector</td>
<td>0.3 m</td>
</tr>
<tr>
<td>Ambient Temperature</td>
<td>307.65 K</td>
</tr>
<tr>
<td>Maximum Smoking Temperature</td>
<td>383.15 K</td>
</tr>
<tr>
<td>The thickness of aluminum sheet</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>The thickness of mild steel sheet</td>
<td>2 mm</td>
</tr>
<tr>
<td>Distance between fish and charcoal tray</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Lagging material</td>
<td>Sawdust</td>
</tr>
<tr>
<td>Number of fish tray</td>
<td>One</td>
</tr>
<tr>
<td>Heat source</td>
<td>Charcoal</td>
</tr>
</tbody>
</table>

2.2 Design Analysis

The fish smoking kiln was analyzed with the following: the kiln capacity, air blowing mechanism, amount of moisture to be removed, the quantity of air required for effective smoking, quantity of heat required, heat transfer rate, rate of mass transfer and thermal efficiency of the kiln.

2.2.1 Kiln capacity \( (M_f) \)

The capacity of the kiln is the amount of fish in kilogram that can be smoked per batch of operation and was computed using equation (1) (Omotara and Adesoji, 2014).

\[
M_f = \rho_f \times V_f \quad \ldots (1)
\]

where: \( \rho_f \) density of the fish and \( V_f \) volume of the fish tray

The volume of the fish tray was obtained using equation (2)

\[
V_t = l_t \times b_t \times h_t \quad \ldots (2)
\]

where: \( b_t \) is the breadth of the fish tray, \( h_t \) is the height of the tray and \( l_t \) is the length of the tray.

The number of fish per tray was also computed using equation (3)

\[
n = \frac{M_f}{m_f} \quad \ldots (3)
\]

where: \( m_f \), is the mass of individual fishes and \( M_f \), is the total mass of the fish.

2.2.2 Mass of water removed \( (M_w) \)

The amount of water removed was computed using equation (4) (Omotara and Adesoji, 2014; Uzma et al., 2018)

\[
M_w = M_f \left( \frac{m_i - m_f}{100 - m_f} \right) \quad \ldots (4)
\]

The mass of the smoked fish was obtained by using equation (5)

\[
M_d = M_f - M_w \quad \ldots (5)
\]

where: \( m_i \) is the initial moisture content of the fish and \( m_f \), is the final moisture content of the fish.

2.2.3 Mass of air required for smoking \( (M_a) \)

The amount of air required for the entire smoking was computed using (6) as developed by Uzma et al. (2018) and Vanaparti (2016).

\[
M_a = \frac{M_w L}{c_p(T_a - T_{am})} \quad \text{or} \quad M_a = \frac{M_w L}{c_p(T_a - T_{am})} \quad \ldots (6)
\]
where: \( C_p_a \), is the specific heat capacity of air, \( L \), is the latent heat of water, \( M_w \), is the mass of water, \( T_a \), is the air temperature and \( T_{am} \), is the ambient temperature.

The mass flow rate of the air was computed using equation (7) Uzma et al. (2018).

\[ m = \frac{M_a}{t} \quad \ldots (7) \]

where: \( M_a \), is the mass of air and \( t \), is the smoking time.

### 2.2.4 Rate of drying (\( R_c \))

The rate at which the moisture of the fish was removed according to Isinkaye et al. (2022) is as shown in equation (8) and was used in computing the rate of drying.

\[ R_c = \frac{m_i - m_f}{t} \quad \ldots (8) \]

where: \( m_i \), is the initial moisture content of the fish, \( m_f \), is the final moisture content of the fish and \( t \), is the smoking time.

### 2.2.5 Quantity of heat required to effect smoking (\( q_f \))

The quantity of heat that is required to affect the smoking (\( q_f \)) of the fish was computed using equation (9) (Vanaparti, 2016 and Isinkaye et al., 2022).

\[ q_f = M_f C_p_f (T_2 - T_1) \quad \ldots (9) \]

where: \( T_2 \), is the final temperature of the fish, \( T_1 \), is the initial temperature of the fish, \( C_p_f \), is the specific heat capacity of the fish and \( M_f \) is the mass of the fish.

### 2.2.6 Heat dissipated by the charcoal box (\( q_{cp} \))

According to Omotara and Adesoji (2014) and Vanaparti (2016) the amount of heat loss by the charcoal pot can be computed using equation (10)

\[ q_{cp} = \frac{K A_{ch} (T_2 - T_1)}{X} \quad \ldots (10) \]

where: \( K \), is the thermal conductivity of mild steel, \( A_{cp} \), is the area of the charcoal pot, \( T_2 \), is the temperature of the charcoal in the combustion chamber, \( T_1 \) is the temperature of the outside wall of the combustion chamber and \( X \), is the thickness of the charcoal pot.

#### 2.2.7 Heat loss through the walls of the kiln (\( q_w \))

Heat flow across multiple walls of the smoking kiln was computed using equation (11) (Cengal and Ghaja, 2015)

\[ q_w = \frac{dF}{\sum R} = \frac{T_2 - T_1}{\sum R} \quad \ldots (11) \]

where: \( T_1 \), is the temperature on the outer surface, \( T_2 \), is the temperature on the inner surface and \( \sum R \), is the heat resistance through the wall.

But \( R \) can be computed using equation (12)

\[ \sum R = \frac{t_{alu}}{k_{alu} A_w} + \frac{t_{in}}{k_{sd} A_{in}} + \frac{t_{ow}}{k_{ms} A_{ow}} \quad \ldots (12) \]

where: \( A_w \), is the cross-sectional area of the inner wall, \( A_{in} \), is the cross-sectional area of the insulator, \( A_{ow} \), is the cross sectional area of the outer wall, \( t_{alu} \), \( t_{in} \) and \( t_{ow} \), are the thickness of the inner wall, insulating materials and outer wall respectively and \( k_{alu} \), \( k_{sd} \) and \( k_{ms} \) are conductive heat transfer coefficient for the inner wall, sawdust and outer wall respectively. But the area of the multiple walls can be computed using equation (13)

\[ A_{total} = (A_{top} - A_{chimney opening}) + A_{bottom} + A_{left} + A_{right} + A_{back} + A_{front} \quad \ldots (13) \]

#### 2.2.8 Fuel consumption rate (\( F_c \))

The amount of fuel consumed by the kiln per hour was also computed using equation (14) Uzma et al. (2018).

\[ F_c = \frac{M_{ch}}{t} \quad \ldots (14) \]

where: \( t \), is the time of smoking and \( M_{ch} \), is the mass of the charcoal.
2.3 Design of Belt Drive
A belt drive consists of two pulleys attached to each shaft and endless belt wrapped around them with some initial tension. Power was transmitted from the driver pulley to the belt and from the belt to the driven pulley with the help of friction.

2.3.1 Velocity ratio ($V_R$)
Velocity ratio (Khurmi and Gupta 2003) is the ratio of speeds of driver and driven pulley.

$$\frac{N_2}{N_1} = \frac{D_1}{D_2} = V_R \quad \ldots \ (15)$$

where: $N_1$ and $D_1 =$ speed (rpm) and the diameter of the driving pulley and $N_2$ and $D_2 =$ speed (rpm) and the diameter of the driven pulley, respectively.

The peripheral velocity ($m/s$) of the belt passing over the driving pulley was obtained using equation (16)

$$V_1 = \frac{\pi D_1 N_1}{60} \quad \ldots \ (16)$$

The peripheral velocity ($m/s$) of the belt passing over the driven pulley was also computed using equation (17)

$$V_2 = \frac{\pi D_2 N_2}{60} \quad \ldots \ (17)$$

2.3.2 Length of the belt (L)
If $D_2$ and $D_1$ are diameters of smaller and larger pulleys respectively with $C = 0.365m$ as the center distance between the axes of the pulleys, length of the belt was computed using equation (19) (Khurmi and Gupta 2003).

$$L = \pi (D_1 + D_2) + 2C + \frac{(D_1 - D_2)^2}{C} \quad \ldots \ (19)$$

2.3.3 Angle of Wrap ($\alpha$)
Angle of wrap on smaller ($\alpha_s$) and larger pulleys ($\alpha_l$) was obtained using equations (20) and (21) respectively (Khurmi and Gupta 2003).

$$\alpha_s = 180^\circ - 2 \sin^{-1} \left(\frac{D_1 - D_2}{2C}\right) \quad \ldots \ (20)$$

$$\alpha_l = 180^\circ + 2 \sin^{-1} \left(\frac{D_1 - D_2}{2C}\right) \quad \ldots \ (21)$$

2.4 Blower Design

2.4.1 Blades Diameters ($D$)
From the optimum performance specification, it is stated that the ratio of the internal diameter to the external diameter of blower blade is to fall between 0.4 - 0.7 as stated in the ASME code.

$$0.4 < \frac{D_1}{D_2} < 0.7 \, , \, \text{for this design the ratio} \, \frac{D_1}{D_2} = 0.4$$

2.4.2 Number of Blades ($B_n$)
From the ASME code, for optimum performance the number of blades was obtained using equation (22)

$$B_n = \frac{8.5 \sin \beta_2}{1 - \frac{D_1}{D_2}} \quad \ldots \ (22)$$

where: $\beta_2$ is the outlet vane angle which has a range of $20^\circ < \beta_2 < 90^\circ$

For this design $\beta_2$ were chosen to be $60^\circ$.

2.4.3 Blade Width ($B_w$)
It is given from the ASME code specification that, the blade width is given by the formula:

$$B_w = \frac{6(D_1/2)}{B_n + 1} \quad \ldots \ (23)$$

where: $B_n$ is the number of blades (Abubakar, 2018).

3.0 Experimental setup
According to Dipanjan et al. (2021), hot smoking is done within the range of 333 $K$ to 393 $K$

and temperature below that is consider as cold smoking while temperature above it is considered as barbecuing. The designed carrying capacity of the fish was 7.2 Kg and the kiln was tested at 343.15 $K$ smoking
temperature using 6 kg of the fish and 1 kg of charcoal as source of heat energy. This was done at three different air velocities: 0.6 m/s, 0.8 m/s and 1.0 m/s, respectively. Digital thermometer was used to measure the temperatures of the fish, kiln walls and air in the kiln. The entire process was repeated using 363.15 K and 382.15 K smoking temperatures at already stated air velocities above. The fish were reweighted so as to determine the rate of moisture removal at every twenty-minute intervals.

The experimental setup for the fish smoking process and the equipment used for the experimentation were presented in Plates I, II, III, IV, V and VI. The fish before and after smoking are presented in Plate I and II and the experimental set-up is presented in Plate III.

3.0 Result and Discussion
The experimental results of air temperature, fish temperature and moisture variation of the fish were plotted against drying time and are presented and discussed under these subheadings.

4.1 Air Temperature
Figure 2 (a, b and c) presents the profile of drying air temperature at various air velocities against time during smoking. It was observed that the temperature of the drying air reaches the smoking temperature (343.15K, 363.15K and 383.15K) steadily and subsequently maintained a constant temperature throughout the smoking process at all the working velocities of air of 1.0 m/s, 0.8 m/s and 0.6 m/s respectively. The increase in drying air temperatures is proportional to the air velocities. It was observed that the drying air temperature took more time before it reached the smoking temperature at 0.6 m/s when compared with those at 1.0 m/s and 0.8 m/s velocities. This is obvious due to the fact that, at a higher velocity of air, the radiative and convective heat transfer will increase thus higher temperature of the air. This was manifested in the temperature of the fish which spontaneously increases until it reaches the respective smoking temperatures. The air temperature for the three velocities and smoking temperatures reached their respective smoking temperatures (343.15 K, 363.15 K,
and 383.15 K) at 27 min, 23 min and 20 min respectively. This means that the rate at which the air temperature increases depend on the drying air velocity.

![Figure 2: Influence of drying air velocity on the variation of air temperature during smoking at (a) 343.15 K, (b) 363.15 K and (c) 383.15 K](image)

### 4.2 Fish Temperature

The fish temperature for the three levels of smoking temperatures and velocities were plotted against time and are presented in Figure 3 (a, b and c). The temperature of the fish uniformly increases as time increases, however, at velocity of air of 1.0 m/s, faster rate of heat transmission to the fish was noticed. This means that the higher the velocity of air the higher is the drying air temperature, consequently the faster will be rate of drying. The smoking temperatures (343.15 K, 363.15 K, and 383.15 K) were attained at 160 min, 150 min and 120 min respectively; this also indicate that a faster rate of temperature rises at higher drying temperature. It was observed that the temperature profile of drying at 383.15 K and 1.0 m/s air velocity has the highest rate of temperature rise. In general, it was found that the rate of fish drying was \( R_c = 0.005370 \% / \text{s} \).

![Figure 3: Influence of drying air velocity on the variation of fish temperature during drying at (a) 343.15 K, (b) 363.15 K and (c) 383.15 K](image)

### 4.3 Moisture Variation of the Fish

Figure 4 (a, b and c) shows the experimental results of moisture content variation against drying time at three levels of smoking temperatures and velocities. The moisture content of the fish continues to decrease over time and the rate of moisture evaporation was high at 1.0 m/s for smoking temperature of...
383.15 K due to enough hot air circulation within smoking chamber. The time taken for the fish to reach the smoked moisture content at velocity of 1 m/s was less when compared with that of 0.8 m/s and 0.6 m/s respectively. This is because as the temperature increases, the kinetic energy of the moisture increases making it easier for the moisture to diffuse out of the fish and be taken away by the moving air. When the hot dry air absorbs water from the surface of the fish, it needs to be quickly moved on so that another set of air can repeat the process. The time taken for the fish to reach a safe moisture content for the three smoking temperatures of the fish are approximately 200 min, 225 min and 230 min as shown in Figure 4 (a, b and c). These compared favorably with the works of Sikoki and Aminigo (2002) and Bereket et al. (2018) (360 min – 480 min). Figure 4c has the lowest drying time when compared with that of Figures 4a and 4b. It takes only 155 min, 175 min and 195 min for the fish to attain 18% moisture content at 1.0 m/s, 0.8 m/s and 0.6 m/s, respectively. For proper smoking all the fish were smoked to a moisture content between 16 – 18%, as this range falls within the acceptable smoking moisture content according to Sikoki and Aminigo (2002) and Bereket et al. (2018).

5.0 Conclusion
A charcoal fish smoking kiln was effectively designed with a carrying capacity of 7.2 kg and was tested experimentally. The smoking temperatures used were 343.15 K, 363.15 K, and 383.15 K and working velocities of air were varied between 1.0 m/s, 0.8 m/s and 0.6 m/s. It was observed that the temperature of the air increased steadily until the smoking temperatures were achieved and these occurred between 20 – 27 min. The time taken for the fish to attain the smoking temperature was between 120 – 160 min. It was also observed that at higher temperatures and air velocities, the moisture contents of the fish were expelled at a faster rate. The minimum time taken for expelling the moisture content was 155 min at drying temperature of 383.15 K and velocity of 1.0 m/s and the maximum time was 225 min at a drying temperature of 343.15 K and velocity of 0.6 m/s and it was found that the rate of fish drying was \( \dot{R}_c = 0.005370(\% / s) \). The fish were smoked to a moisture content between 16 - 18%, which falls within the acceptable smoking moisture content. It can be concluded that the ideal smoking temperature and velocity for this design are 383.15 K and 1.0 m/s, respectively.
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