# Optimizing Heat Flow for Sustainable Smoking: Dual-Heating System to Reduce Mangrove Consumption and Control PAH Contamination

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Mangrove overharvesting for firewood threatens the Irrawaddy dolphins' habitat. Recently, automated smoking machines have been proven to reduce mangrove consumption. However, they are not user-friendly. Therefore, we proposed a modular smoking machine with dual heating sources based on practical considerations suggested by traditional smoked shrimp experts. This study showcases the optimization of heat flow in the design contributed by the two direct heating sources configured in an "L"-shape, i.e., one from the heater installed at the wall, and one from the smoking tray at the bottom of the insulated smoking chamber. Other notable modifications include the blower and chimney placement to that of the rotating tray and wall heater. Our work extensively discusses the evaluation of heat flow distributions, and particle movements to track the pathway of vapor and plausible Polycyclic Aromatic Hydrocarbons (PAH) contaminants. Computational fluid dynamic (CFD) outcomes corresponded positively with the experimental study. In the experiment, the smoker is fed hourly with 1 kg of mangrove firewood. After 5 hours, the drying and smoking process of smoke shrimps was completed when the moisture reduction reached 90% compared to the previous model, 70%, which saved up to 80% of mangrove consumption. Before the intervention, the traditional method consumed 20.79 kg per cycle. The optimized dual heating sourced smoking machine only needed 4 kg. CFD simulation demonstrated the uniform distribution of steam and heat flow contributed to this improvement. It is implicated that the well-controlled environment within the insulated smoking chamber stimulated firewood to form embers that radiate substantial consistent heat above 400°C resulting to the generation of PAH. Tests confirmed that the smoked shrimp samples contained an average of 0.2 mcg/kg PAH, which is lower than, and adhere to the value of the European Commission standards at 2.0-12.0 mcg/kg.

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# Optimizing Heat Flow for Sustainable Smoking: Dual-Heating System to Reduce Mangrove Consumption and Control PAH Contamination


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***Abstract*— Mangrove overharvesting for firewood threatens the Irrawaddy dolphins' habitat. Recently, automated smoking machines have been proven to reduce mangrove consumption. However, they are not user-friendly. Therefore, we proposed a modular smoking machine with dual heating sources based on practical considerations suggested by traditional smoked shrimp experts. This study showcases the optimization of heat flow in the design contributed by the two direct heating sources configured in an "L"-shape, i.e., one from the heater installed at the wall, and one from the smoking tray at the bottom of the insulated smoking chamber. Other notable modifications include the blower and chimney placement to that of the rotating tray and wall heater. Our work extensively discusses the evaluation of heat flow distributions, and particle movements to track the pathway of vapor and plausible Polycyclic Aromatic Hydrocarbons (PAH) contaminants. Computational fluid dynamic (CFD) outcomes corresponded positively with the experimental study. In the experiment, the smoker is fed hourly with 1 kg of mangrove firewood. After 5 hours, the drying and smoking process of smoke shrimps was completed when the moisture reduction reached 90% compared to the previous model, 70%, which saved up to 80% of mangrove consumption. Before the intervention, the traditional method consumed 20.79 kg per cycle. The optimized dual heating sourced smoking machine only needed 4 kg. CFD simulation demonstrated the uniform distribution of steam and heat flow contributed to this improvement. It is implicated that the well-controlled environment within the insulated smoking chamber stimulated firewood to form embers that radiate substantial consistent heat above 400℃ resulting to the generation of PAH. Tests confirmed that the smoked shrimp samples contained an average of 0.2 mcg/ kg PAH, which is lower than, and adhere to the value of the European Commission standards at 2.0-12.0 mcg/kg.**



***Keywords—smoking machine, optimization, dual-heating, mangrove consumption, PAH.***


## I. Introduction

Mangroves play a vital role in protecting coastlines by creating a calm and clear water environment. This environment is abundant in organic matter and tiny organisms that form the food web for crustaceans, molluscs, and various fish species. Therefore, it has become an ideal breeding habitat for the Irrawaddy dolphins. However, the Irrawaddy dolphins' habitat overlaps with areas of intensive human activities threatening their survival to the point that their recorded population in Sarawak has declined below 200 [1].

The coastal communities harvest mangroves as firewood for fisheries preservation processes [2]. Mangrove wood is favored due to the delicate taste attributed to the aroma of the smoke. Smoked fisheries, especially the infamous sesar unjur (smoked shrimp) are sought-after local delicacies. From our extensive interviews with the coastal communities in Belawai, where the Irrawaddy dolphins can be spotted [1], 1 kg of smoked shrimp has an average market value of MYR160. Even though engineering interventions have led to automated drying machines, these machines do not retain the smoky fragrance [3]. Thus why, the traditional method is still preferred. However, the makeshift built environment of the traditional smoking chambers is problematic. They are shacks with trays made of bamboo or wires hung over uncontrolled open fires. Therefore, a substantial cost of mangrove wood is required. Eventually, this leads to overharvesting, endangering the Irrawaddy dolphins' habitat [1][2].

In recent years, hybrid-powered smoking machines to improve sustainability alongside the productivity and hygiene aspects of the cottage industry are trending. Solar-hybrid smoking machines can heat up to about 60℃ in 4.0 hours with 75% moisture reduction [3]. Hybrid smoking kilns using propane gas from biomasses can reach 120℃ in two hours [4]. These reviewed designs are either stationary or complicated – wnot travel-friendly. Couriering machinery with elaborate designs to interior coastal areas is not cost-effective.

We proposed a robust modular smoking machine with dual heating sourced as a potential solution. The design reduces the moisture content to 70% in five hours which significantly saves mangrove consumption. The smoked products tested negative for Coliform and E. Coli [5]. Howeverm compared to bacterial infestations, Polycyclic Aromatic Hydrocarbons (PAH) particularly benzo[a]pyrene contamination in hybrid-powered smoking machines are rarely investigated. This concern cannot be overlooked as Kpoclou et. al., [6] reported high levels of carcinogenic PAH contamination in shrimp smoked with acacia wood. Alas, it is inevitable to prevent PAH contamination due to the intense temperature from burning biomass firewood [7]. For this reason, the European Commission (EC) has standardized the acceptable amount of benzo[a]pyrene per kg in smoked fisheries to be 5.0 mcg, and the overall PAH amount per kg at 2.0-12.0 mcg.

To tackle wood consumption problems and concerns on PAH, this work explores the optimization of our design based on real-life feedback from communities' experience of utilizing the dual heating sourced smoking machine by improving the interior heat flow to further reduce mangrove firewood. In regards to food safety issues, we tested the product for PAH contents and compared it to the EC standard.

## II. Material and Method

### A. Design Description

The redesign of the dual heating sourced considered the practically of the smoking labour while expected to reduce mangrove wood consumption. Figure 1 shows the schematic for the redesigned smoking machine with two heat sources configured in "L"-shape. Heat source 1 (Q1) is the main heat source for the smoking machine. The community in Tebelu, Sarawak preferred tapping electric source as the area has a three-phase transformer connected to the state's grid. Meanwhile, community in Belawai, Sarawak chose liquefied petroleum gas as it is readily accessible in their area. Heat source two (Q2) is the direct smoking chamber, the smoker tray is shown in figure 1(b). The machine functions as an oven with one hot air blower which is a mounted fan inlet and one chimney outlet. Previous study [5] proved that the motor automated rotating tray aided uniform drying and smoking, hence the design was retained.

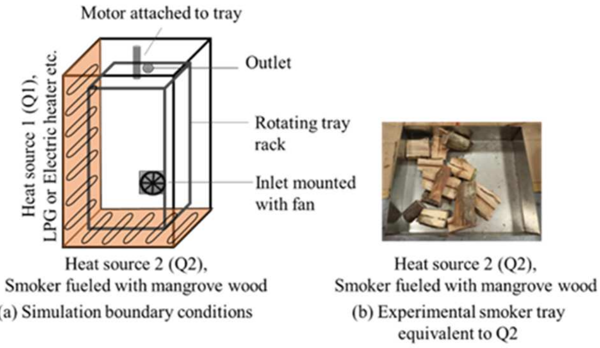



Fig. 1. Schematic diagram of smoking machine including the (a) simulation boundary conditions. The source of heat source 2 (Q2) for the experimental setting is shown in the smoker tray (b).

Table 1 is the ranges for fish smoking technique temperature which are light, medium, and intense smoking [8]. The machine was intended to work in the intense smoking machine range, about 100 ℃ to 150 ℃ (423.15 K). This temperature was adopted for the computational fluid dynamics (CFD) simulation of the smoked shrimp.

TABLE 1. FISH SMOKING TECHNIQUE TEMPERATURE [8]

| | | |
|---|---|---|
| **Light Smoking** | 270-340 °F / 130-180 °C | Under 1 Hour |
| **Medium Smoking** | 210 – 284 °F / 100 – 140 °C | 1-2 Hours |
| **Intense Smoking** | 180 – 250 °F / 80 – 120 °C | 2-5 Hours |

Traditionally, smoked shrimps are made from small salt water red shrimp. Their weight per tray is approximately 3.0-5.0 kg/tray due to the size variant. In the experiment, the interior temperature was controlled at 100 °C. The recipe specified that the drying and smoking process was completed when the moisture content of the shrimps was reduced about 90% from the initial weight. Equation (Eq.) 1 shows the calculation for the percentage of weight loss due to the evaporation of water content from the shrimp samples.

$$Percentage\ of\ W_r = \frac{W_i - W_f}{W_i} \times 100\% \qquad (1)$$

The machine took an average of 3 to 4 hours, with mangrove wood chip totaling 4.0 kg per one cycle. Figure 2 exhibits the before and after drying and smoking.

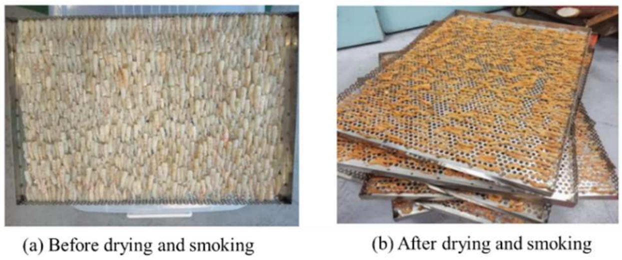



Fig. 2. Comparison of the before, (a), and after, (b) drying and smoking process of smoked shrimps.

### B. CFD Boundary Conditions

In the simulation setting, the interior of the machine was defined as an open area with adequate natural ventilation. This set-up required that air velocities, v to be 0.5 m/s $< v <$ 2.0 m/s [9]. Here, it is assumed that the smoking machine utilized industrial centrifugal fan. The regular power of the blower is 1250 W, 3200 $m^3$/h air volume, 142.42 m/s speed, and 480 Pa pressure. This assumption was similar with the previous machine [5]. Combining these two condition boundaries, heat loss must be considered due to pressure difference between the high-speed blower and the chimney. Hence, in the simulation, the heat source for Q1 and Q2 as depicted in Figure 1 (a) is defined at 150 ℃. The simulation was conducted in ANSYS Fluent©. Grid independence test was run, and the data showed that simulation runs optimally with 95522 mesh nodes, time step 3600 s, number step 250 at 5000 iterations. Subsequently the contamination of PAH granules was recreated using particle movement simulation. The inert particles were defined as water vapor and carbon dioxide. For this component, the time step size was integrated to 0.01 s with number step 1000.

## III. Results and Data Analysis

### A. Experimental Test

Based on the interview with local experts, 14 days operation using the traditional method requires more or less 11 $m^3$ of wood. Coastal area in Malaysia main mangrove species is assumed to be Sonneratia caseolaris and Ceriops tagal [10]. These mangrove wood density ranges from 330 kg/$m^3$ to 640 kg/$m^3$. From the calculation in Eq. 2, the cottage industry in Belawai consumed 3630 kg of wood in two weeks. Therefore, the estimated amount of wood per day i.e., one cycle of drying and smoking can process on average 100 to 200 kg of shrimp, burns 259 kg (Eq. 3). $\rho = \frac{m}{V}$ whereby, $\rho$ is density, $m$ is mass and $V$ is volume.

$$m = \rho \times V = 330\ kgm^{-3} \times 11m^3 = 3630\ kg \qquad (2)$$

Therefore, kg wood per 14 days is:

$$\frac{3630\ kg\ wood}{14\ day} = 259\ kg\ wood\ /\ day \qquad (3)$$

Consider 200 kg shrimp is processed in 1 day. Therefore,

$$\frac{259\ kg\ wood}{200\ kg\ shrimp} = 1.295\ kg\ wood/kg\ shrimp \quad (4)$$

For 16 kg of shrimps, the traditional method consumes:

$$16\ kg\ shrimp\ \times 1.295\ kg\ wood/kg\ shrimp$$
$$= 20.72\ kg\ wood \quad (5)$$

Meanwhile, the smoking machine required 4.0 kg per cycle for 16 kg shrimp if one cycle processed 4.0 trays. This meant that the machine has cut down the consumption of mangrove wood by 80% (Eq. 4 to 5), which is a significant result as the World Wildlife Federation Sarawak aimed to reduce 50% of mangrove use per cycle.

### B. PAH Test

The samples were sent for PAH testing using the In House Method 0537 based on U.S. Environmental Protection Agency |(USEPA) 3540C in combination with the House Method 0534 based on USEPA 8270C, December 1996. Table 2 lists down the results of the test.

TABLE 2. PAH TEST RESULTS

| Polycyclic Aromatic Hydrocarbon (PAH) | PAH in sample (mcg/kg) | |
|---|---|---|
| | Belawai | UNIMAS |
| | Traditional method | Dual-heating source smoking machine method |
| Acenaphthene | Not Detected (<0.1) | 0.1 |
| Acenaphtylen | Not Detected (<0.1) | Not Detected (<0.1) |
| Anthracene | 0.3 | 0.2 |
| Benza(a)anthracene | 0.2 | 0.3 |
| Benzo(a)pyrene | 0.1 | 0.2 |
| Benza(b)fluoranthene | 0.1 | 0.2 |
| Benzo(g,h,i)perylene | Not Detected (<0.1) | Not Detected (<0.1) |
| Benzo(k)fluoranthene | 0.1 | Not Detected (<0.1) |
| Chrysene | 0.2 | Not Detected (<0.1) |
| Dibenza(a,h)anthracene | 0.1 | 0.2 |
| Fluoranthene | 0.2 | Not Detected (<0.1) |
| Fluorene | Not Detected (<0.1) | 0.2 |
| Indeno(1,2,3-cd)pyrene | Not Detected (<0.1) | Not Detected (<0.1) |
| Naphthalene | 0.2 | 0.2 |
| Phenanthrene | 0.3 | 0.1 |
| Pyrene | 0.2 | Not Detected (<0.1) |

The results were consistent with the study of PAH contamination in smoked fish and smoked shrimp [6]. It was confirmed that the smoked shrimp adhere to the PAH restriction by the EC. The tests clarified that there are lesser PAH types detected in the smoked shrimps processed by the smoking machine. The PAH content on average is 0.2 mcg/kg.

From the mathematical perspective, the results demonstrated that with 4.0 kg wood per cycle, the dual heating sourced smoking machine can smoke the shrimps with more or less the same smoking intensity of using 20.72 kg wood per cycle of the traditional method. This was deduced from aforementioned wood chip consumption. The ability of the machine to produce marketable quality smoked shrimp at 20% of the amount of the firewood and 6 times faster than the traditional method showed that the heat flow within the insulated chambers were well-controlled. The next section displays the relation between smoking efficiency and PAH contamination through fluid dynamics visualization.

### C. CFD Simulation

The wind generated by the blower into the smoking chamber distributed the heat flow, which means it represents the plausible movement of PAH granules. Here, red represents the maximum value, 150 ℃, which also indicates the value of boundary condition input. Meanwhile, blue is the minimum value, which indicates the gradual spread of ambient temperature, with the lowest value registering at 26 ℃. It can be observed in the cross-section view that the walls of the smoking chamber are constant at 150 ℃ while the interior part stabilized around 80 ℃ to 100 ℃. As expected the lowest temperature can be observed near the blower vicinity.

The new design of the smoking machine demonstrated a significant improvement in heat flow uniformity compared to the last model [5]. The "L"-shaped heat sources enhanced the drying and smoking performances of the design. This was due to the advantage of the steel walls' material properties. Steel is a good heat conductor, resulting in maximum interior temperature, and uniform radiation of ambient temperature as shown in figure 4(a).

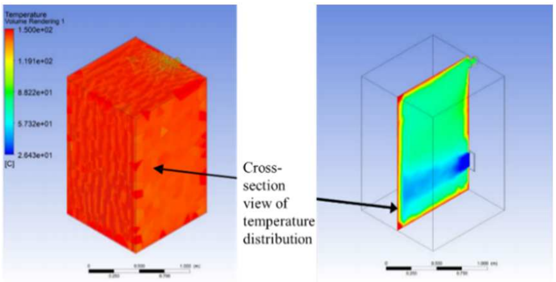
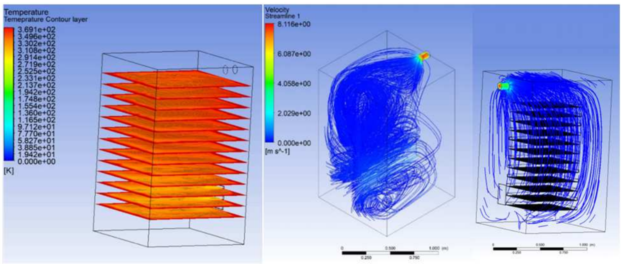



Fig. 3. Cross section view of the temperature distribution in the dual-heating smoke machchine.

Similarly, the particle movement simulation of carbon dioxide's and water vapor's streamlines also spread almost evenly inside the chamber. Figure 4(b) verified the discussion on PAH testing, whereby, the CFD assessment clarified that the aerosol pathway of the smoke flowed almost uniformly in figure 4(c).



(a) Temperature distribution of trays (b) Heat flow streamline (c) Particle movement streamline

Fig. 4. Demonstration of temperature (a), heat flow streamline, (b), and, particle movement uniformity , (c).

### D. Correlation with Past Performance

The simulation presented reliable coherency with the experiment. Note that PAH exists due to incomplete combustion that occurs at above 400 ℃ and the smoking machine was set between 100℃ to 150℃. PAH still existed in the machine due to the uniform and constant distribution of heat flow. The consistent incomplete burning of firewood forms ember which can produce ambient temperature above 400 ℃ . Hence, releasing PAH granules, consequently, contaminates the smoked shrimps. Through CFD assessment, figure 5 establishes the correlation of simulation and experiment study.

Figure 5(a) confirmed the high consistency of temperature integration versus the streamline time within 200 s in the new design compared to the plot of the original design in 5(b) [5].

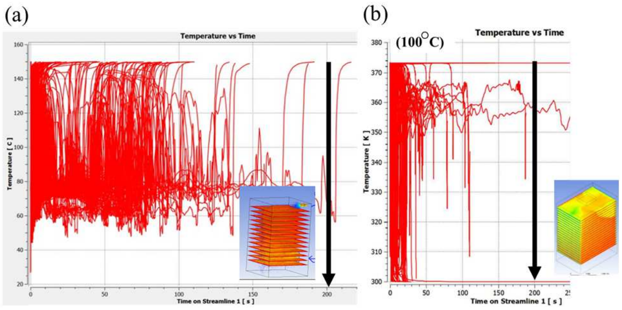



Fig. 5. Comparison between (a) optimized model of the dual-heating sourced smoking machine, and (b) original model [11].

## IV. CONCLUSION

The design of the dual heating sourced smoking machine was revisited and optimized. CFD assessment confirmed that modification of the heating sources to "L"-shaped configuration in the insulated chamber controlled the drying and smoking processes at a consistent temperature with uniform heat distribution. The new design saved up to 80% of mangrove wood consumption and could reduce 90% of moisture in five hours. However, a well-controlled burning environment formed ember from the mangrove firewood chips which released PAH and contaminated the smoked shrimp samples. The amount of PAH adhere to EC standards.

## V. ACKNOWLEDGEMENT

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