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Design of organic waste processing equipment for liquid smoke production

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ABSTRACT

This study presents the design of an organic waste processing device that produces liquid smoke through a combination of combustion, particle separation, and condensation processes. The system consists of a combustion chamber, a cyclone separator, and a condensation tube, which were designed and analysed numerically with software. Dry organic waste, such as coconut shells, rice husks, and leaves, was used as raw material with a capacity of 15 kg per cycle. Simulation results indicate that the combustion chamber reached a maximum temperature of approximately 333°C. The cyclone separator achieved flow velocities of 4.72–7.48 m/s, resulting in effective particle separation. Additionally, the condensation tube reduced the smoke temperature to approximately 27°C, allowing for the formation of liquid smoke. This device offers potential as a solution for organic waste management, while producing valuable by-products, including natural pesticides and organic preservatives. This could be one solution for future waste processing, thus creating a healthy environment.

Keywords: liquid smoke, organic waste, smoke, waste processing.

INTRODUCTION

Waste management is one of the significant challenges faced by almost all countries worldwide, including Indonesia. According to data from the Ministry of Environment and Forestry (KLHK), Indonesia generates more than 67 million tons of waste annually, with around 37% originating from household activities (KLHK, 2020). Among this amount, organic waste constitutes the most significant portion, consisting mainly of food scraps, leaves, and agricultural residues. If not properly managed, the accumulation of organic waste can lead to serious problems, including environmental pollution, greenhouse gas emissions, and public health risks (Azizah, 2021).

In general, various efforts have been made to address the issue of organic waste, including composting, biogas production, and incineration (Wartojo, 2018). However, these methods have certain limitations. Composting requires a relatively long period (Ningrum et al., 2022). Biogas production demands a more complex management system (Suntoyo, 2016). While incineration has the potential to cause air pollution if not equipped with adequate emission control (Lasmana et al., 2021). Therefore, an alternative method of organic waste treatment is needed that is practical, efficient, and economically viable.

One promising approach is controlled combustion of organic waste, which produces smoke as a by-product (Hayatun et al., 2024). This smoke can then be captured and further processed through condensation into liquid smoke (Yunus, 2011). Liquid smoke has high added value, as it can be used as a natural pesticide, food preservative, tanning agent, and an antimicrobial agent against fungi and bacteria (Ayudiarti et al., 2010). Thus, this technology not only helps reduce waste volume but also generates products with significant economic potential (Istiqomah et al., 2019).

Nevertheless, direct combustion of organic waste may lead to severe air pollution due to uncontrolled gas emissions (Wahyudi, 2019). Hence, there is a need for a processing device capable of controlling emissions while maximising condensation efficiency—the cyclone separator functions to separate solid particles from flue gas (Supriyadi et al., 2023). The condensation tube facilitates the conversion of smoke into liquid smoke through cooling (Fathussalam et al., 2019).

Haryanto et al (2020) demonstrated that lowering the condenser temperature from 27 °C to 15 °C significantly increased the yield, suggesting 15 °C as an optimal condition for effective condensation. Similarly, Ayudiarti and Sari (2010) and Istiqomah and Kusumawati (2019) emphasised the importance of product characterisation, particularly in terms of chemical composition, pH, and phenolic content, to ensure the liquid smoke meets functional and safety standards. However, despite these advances, most of the reported studies are predominantly experimental in nature and do not provide detailed insight into the underlying flow dynamics, heat transfer behaviour, and particle separation efficiency of the cyclone-condenser system.

Moreover, there is limited exploration of CFD as a predictive and design tool for optimising biomass-based liquid smoke production systems. The existing literature rarely addresses how variations in operating conditions, such as further reducing condensation temperature below 15 °C, could influence system performance in terms of yield, efficiency and product selectivity. In addition, while the potential of liquid smoke as a sustainable waste-to-value product is widely recognised, there is still a lack of systematic frameworks that integrate numerical modelling, performance evaluation, and considerations of appropriate technology for small and medium-scale applications.

Therefore, this research aims to fill the gap by employing CFD simulation to investigate the performance of a cycle condenser system at a lower condensation temperature (8°C). By doing so, it not only extends the understanding of condensation thermodynamics beyond the commonly studied 15 °C benchmark but also contributes a methodological framework that combines numerical prediction with design metrics relevant to sustainable waste management technology.

Based on this background, this research aims to develop a design for an organic waste processing device that not only reduces waste accumulation but also produces a useful liquid smoke with a more effective cooling system compared to previous research, specifically at 8°C. Through design and simulation, this research is expected to contribute to the development of a more sustainable waste processing system.

METHOD

This research began with a literature study to obtain references related to organic waste processing, combustion principles, particle separation, and the condensation process of smoke into liquid smoke. The next stage involved designing the device using software to create a 3D model of the main components, specifically the combustion chamber, cyclone separator, and condensation tube. Numerical simulations were then carried out using software to analyse flow phenomena and heat transfer in the designed device. The simulation focused on three main components: temperature distribution in the combustion chamber, flow velocity and particle separation in the cyclone separator, and the cooling process in the condensation tube to produce liquid smoke. This research is limited to design and simulation results, as the findings still require the creation of a real prototype to ensure the design functions as intended.

The simulation results were then analysed to evaluate the performance of the device and its conformity with the initial design. With this approach, the research method not only produced a theoretical design for the organic waste processing device but also provided numerical validation through simulation, ensuring that the resulting design can serve as a reference for future prototype development.

The research process flow is summarised and presented in a flowchart/diagram as a guide for conducting the study, as follows:

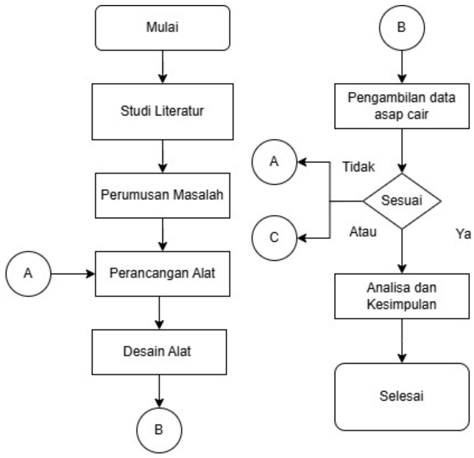

Figure 1. Flowchart

Research Implementation Steps

1. Modelling

Modelling was conducted based on observations and calculations made regarding the overall structure of the liquid smoke production device.

2. Simulation of the device’s performance

Simulations were performed to analyse the performance of the liquid smoke production device.

3. Validation of the design results.

The simulation parameters set for each component are as follows:

1. Combustion Chamber

In the combustion chamber simulation, the approach used was to apply a heat flux directly to the waste surface. A heat flux value of 366.344 W/m² was used in the simulation.

Therefore, this value was entered into the setup when running ANSYS Fluent simulations, along with additional configuration details: an Air Inlet Velocity inlet, an air temperature of 30 °C, and an air velocity of 0.04 m/s. Wall thermal condition set to *Specified Heat Flux* with a value of 366.344 W/m².

2. Cyclone Separator

In the cyclone separator simulation, the approach used was to apply a direct fluid flow velocity. A flow velocity of 7.6 m/s was applied in the simulation based on the blower specifications. The velocity value was entered into the ANSYS Fluent setup, along with additional configurations. Air Inlet Velocity inlet, air temperature of 30 °C, air velocity of 7.48 m/s. Discrete Phase Model (DPM): Ash particles were added in the *injection* section to simulate particle separation.

3. Condensation Tube

In the condensation tube simulation, the approach used was to apply an inlet velocity of 7.6 m/s and specify an external cooling fluid temperature. The setup included. Air Inlet velocity inlet, air temperature of 50 °C, air velocity of 7.48 m/s. Outside Fluid Cooling fluid temperature of 278.15 K (5 °C).

RESULT AND DISCUSSION

Design

Figure 2 illustrates the design results that have been calculated, with each component serving its own function to produce a high-quality product. The working process of the device begins in the combustion chamber, where organic waste is burned under limited-air conditions as designed. Due to the restricted air supply, the combustion produces a larger volume of smoke.

The second stage occurs in the cyclone separator, which separates ash particles from the smoke flow that is pushed through a blower fan. With this separation process, the resulting liquid smoke contains fewer ash particles compared to systems without a cyclone separator.

Finally, the process continues in the condensation tube, where the smoke that has passed through the cyclone separator is cooled using an ice-based cooling system. At this low temperature, the amount of liquid smoke produced becomes greater.

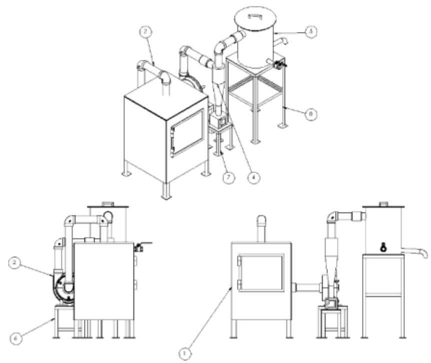

Figure 2. Hasil akhir perancangan

Component Specifications

The organic waste processing device for liquid smoke production comprises several main components designed to operate in an integrated system. The specifications are as follows:

1. Combustion Chamber

Quantity: 1 unit
Material: Steel plate
Dimensions: 800 × 500 × 500 mm
Function: Main chamber for burning organic waste.

2. Exhaust Pipe

Quantity: 1 unit
Material: Galvanised pipe
Size: Ø 2 inches

Function: Channelling combustion gas from the chamber to the cyclone separator and condenser.
3. Blower
Quantity: 1 unit
Material: Casting iron
Size: 2 inches
Function: Drives airflow to accelerate gas movement through the system.
4. Cyclone Separator
Quantity: 1 unit
Material: Steel plate
Dimensions: Ø 105 × 450 mm
Function: Separates solid particles (ash) from the gas stream using centrifugal force.
5. Condensation Tube
Quantity: 1 unit
Material: Steel plate
Dimensions: Ø 300 × 400 mm
Function: Cools the smoke to produce liquid smoke through condensation.
6. Blower Stand
Quantity: 1 unit
Material: Angle iron
Dimensions: 200 × 200 × 170 mm
Function: Supports the blower to maintain stability during operation.
7. Cyclone Separator Stand
Quantity: 1 unit
Material: Angle iron
Dimensions: 200 × 170 × 170 mm
Function: Holds the cyclone separator in place and ensures stable operation.
8. Condenser Stand
Quantity: 1 unit
Material: Angle Dimensions: 350 × 350 × 500 mm
Function: Supports the condenser tube and maintains its balance.

Simulation results in the combustion chamber

Based on the simulation results shown in Figure 3, the temperature distribution in the fluid domain of the combustion chamber was obtained using Fluent simulation. The visualisation indicates that the hot air inside the chamber reaches a combustion temperature of approximately 539 K (266 °C), as seen from the colour differences around the combustion area. This result is desirable, as the combustion process can generate more smoke, thereby optimising the production of liquid smoke. The analysis of heat transfer in this study focuses on convection and conduction, based on the research conducted by Ma et al. (2022), Ma'a et al. (2023), and Ma'a et al. (2024).

From Figure 3, it can be observed that the temperature variation caused by the combustion process (with combustion assumed as a box in the centre of the chamber) is represented by the green-coloured region surrounding the box. Meanwhile, the blue areas at the bottom represent cooler air entering from the inlet. The simulation results can thus be assumed to resemble the actual combustion process.

The findings also indicate that the upper region of the combustion chamber receives the highest temperature exposure. Therefore, the plate thickness in this area should be increased to minimise deformation due to excessive heat during combustion.

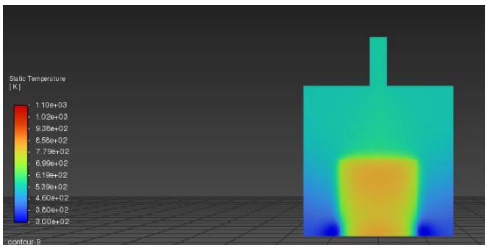

Figure 3. Static temperature result

Simulation results of the cyclone separator

Based on the simulation results shown in Figure 4, the movement of ash particles within the fluid domain of the cyclone was simulated using Fluent. The visualisation shows that the ash particles flow along the cyclone wall and gradually move downward to the bottom section of the cyclone. The longest time required for ash to settle in the ash collector is indicated in red, which is 4.135 seconds. Based on this simulation approach, it can be concluded that the device is capable of effectively separating ash particles from the smoke flow.

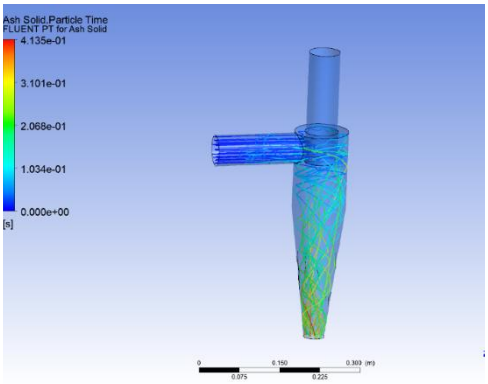

Figure 4. Particle Ash Time

From Figure 5, the phenomena observed through the simulation are visible. The colour gradient differences indicate that the initially stable incoming airflow experiences a decrease in velocity within the conical section, as shown by the change in colour from orange to blue. This is influenced by the change in airflow direction, which initially moves through a straight pipe and then undergoes deflection in the conical part. As a result of this deflection, the airflow circulates along the cyclone wall.

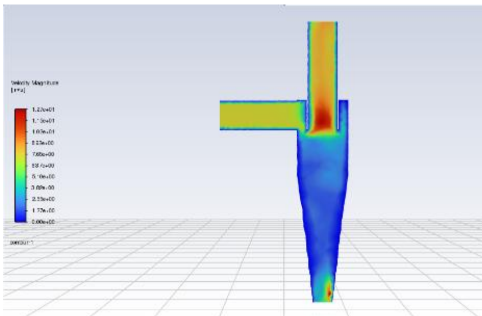

Figure 5 Cyclone separator velocity result

Simulation result of the condensation tube

In Figures 6, 7, and 8, the velocity contours of fluid flow inside the condensation tube are presented. In Figure 6, the inlet flow velocity is 7.48 m/s, and the colour variation at the outlet indicates a change in outlet velocity. In Figure 7, the inlet velocity is 5.54 m/s, which also shows colour changes at the outlet. Meanwhile, in Figure 8, the inlet velocity is 4.72 m/s, and the outlet likewise exhibits colour variation.

From Figures 6, 7, and 8, it can be observed that the fluid flow phenomena are relatively similar, despite the differences in inlet velocity. The contour visualisations show that the decrease in flow velocity occurs in the smaller inner tube, as indicated by the shift in contour colour to blue, which signifies a reduction in velocity due to the difference in cross-sectional area. Conversely, at the pipe's end section, the red contour indicates a sharp increase in flow velocity. This phenomenon occurs due to changes in cross-sectional area: the airflow slows down as the diameter increases from 60 mm to 150 mm and then rises drastically when the air passes through the 26 mm diameter section due to the narrowing of the cross-sectional area.

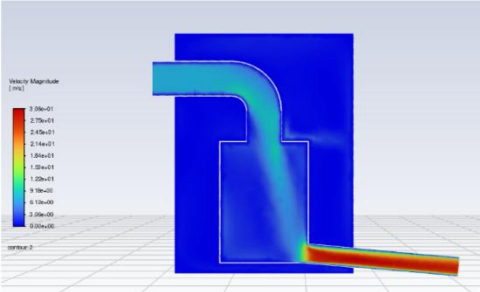

Figure 6 Velocity result for 7,48m/s

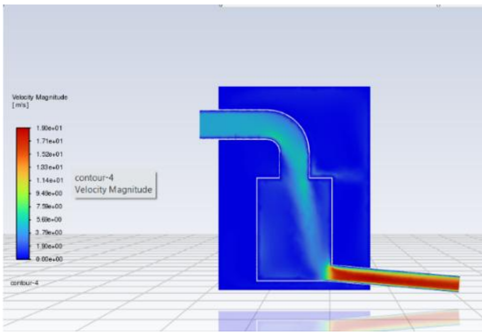

Figure 7 Velocity result for 5,54m/s

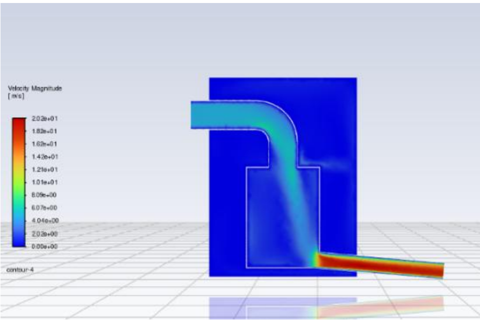

Figure 8 Velocity result for 4,72m/s

Based on the simulation results shown in Figure 6, the temperature distribution in the fluid domain inside the condensation tube was obtained using Fluent simulation. The visualisation indicates that the hot air entering the tube has a maximum temperature of approximately 328 K (55 °C, red) and gradually decreases as it flows toward the outlet, with a minimum temperature of about 313 K (40 °C, orange). The apparent temperature gradient between the inlet and outlet demonstrates significant heat transfer from the hot air to the tube wall, and subsequently to the ice water outside the tube. Cooling with ice was able to reach a temperature of 281 K (8 °C).

In this simulation approach, the cooling temperature achieved in the condensation tube was 8 °C. In experimental testing conducted by Haryanto et al., the optimal cooling temperature required to produce liquid smoke was reported to be 15 °C (among tested values of 15, 18, 22, and 27 °C). Their findings concluded that the lower the cooling temperature, the more optimal the liquid smoke yield (Haryanto et al., 2020). Thus, based on the conducted simulations, which achieved a cooling temperature of 8 °C, the required cooling conditions as indicated by Haryanto et al. have been met. From a thermophysical perspective, a lower condensation temperature increases the saturation of volatile organic compounds. Thereby enhancing the fraction of vapours that condense into liquid smoke. At lower temperatures, the temperature gradient between the hot gas and the condenser surface becomes higher. This results in more efficient heat transfer and faster condensation kinetics. Consequently, under simulated flow conditions, cooling to 8 °C is expected to produce a higher liquid smoke yield than cooling to 15 °C. Therefore, the design of the organic waste processing device for liquid smoke production can be further developed for fabrication.

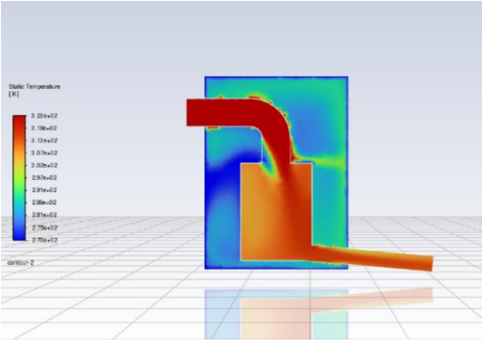

Figure 9 Condensate tube static temperature result

CONCLUSION

Based on the design and simulation results, the organic waste processing device for liquid smoke production was successfully designed with three main components: the combustion chamber, cyclone separator, and condensation tube. The design was developed using 3D modelling software and validated through numerical simulations based on Computational Fluid Dynamics (CFD).

The simulation results showed that the combustion chamber was able to reach a maximum temperature of approximately 539 K (±266 °C) with uniform heat distribution and produced a gas flow velocity of 5.087 m/s at the outlet. In the cyclone separator, the airflow velocity ranged between 4.72 and 7.48 m/s depending on the inlet condition, while the outlet velocity reached 5.53 m/s. These results indicate that the cyclone separator effectively separates solid particles through the application of centrifugal force. In the condensation tube, the simulation showed a significant temperature drop from 323 K to 313 K (approximately 10 °C) with external wall cooling using water and ice. Further cooling reached as low as 8 °C, which is below the minimum requirement of 15 °C for liquid smoke formation, thus enabling optimal condensation.

The fluid flow simulation also confirmed that the velocity and temperature distribution throughout the system aligned with the design objectives. With a capacity of 15 kg of organic waste per cycle, the device has proven to be a viable alternative solution for managing organic waste, while simultaneously producing liquid smoke with added value as a natural pesticide, organic preservative, and industrial support material. Therefore, this design can be a good solution for organic waste processing. Furthermore, this design can serve as a reference for future organic waste processing developments aimed at achieving sustainable results.

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