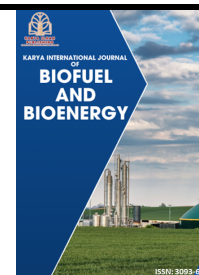




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AGRI-OIL: An Energy-Aware Smart Electric Pyrolysis System for Agricultural Waste-to-Bio-Oil Conversion

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ABSTRACT

Agricultural waste accumulates almost every harvest season, and most of it ends up being burned in the field or decomposed without further processing. In fact, the biomass pile stores energy that can be taken through thermochemical conversion, one of which is pyrolysis, which is the process of thermally decomposing biomass under limited oxygen conditions that produces bio-oil, biochar, and non-condensing gas. Problems that often arise in small-scale pyrolysis equipment are process temperatures that are difficult to maintain stable and the lack of records on how much electrical energy is used compared to the bio-oil produced. Departing from that, this study developed AGRI-OIL, an electric pyrolysis system equipped with a thermal energy monitoring and control unit throughout the process. Physically, the system consists of a pyrolysis reactor, heating elements, electrical system, sensor and temperature control units, copper pipe condensers, bio-oil storage containers, and an integrated energy monitoring system. The development phase reported here is still at the computer simulation level, pursued through two tracks: structural analysis of the frame and vessel using the Finite Element Method (FEM) using SolidWorks Simulation software to check whether the construction is able to safely withstand the load of components, and simulation of the process of separation-steam cooling of pyrolysis products using a mixture of five compounds (water, acetic acid, phenol, furfural, n-heptane) as the initial model of the bio-oil composition. The results of the structural analysis show a maximum von Mises stress of $1,000.121 \times 10^5 \text{ N/m}^2$, well below the material yield stress of $2.039 \times 10^8 \text{ N/m}^2$, with a minimum safety factor of about 3.0 and a maximum deflection of only $8.25 \times 10^{-4} \text{ mm}$, so that the frame can be said to be safe to proceed to the fabrication stage. The process simulation shows an operating temperature range of 298.1-417.1 K with a condenser cooling load of 0.152 kW, as well as an estimated cost of installed equipment of approximately USD 317,380 for the separator and condenser subsystems. These two simulations provide a reasonable initial basis for proceeding with AGRI-OIL to the physical prototyping and experimental testing stages, including testing pyrolysis temperature variations on bio-oil yields and specific energy consumption planned at the next stage.

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1. Introduction

The harvest season in Indonesia almost always leaves a large amount of straw, husks, corn cobs, or cassava stalks, with different thermal decomposition characteristics between types of waste [6]. Some farmers burn it directly on the land because this method is the fastest and does not require additional costs, although this practice contributes to the emission of carbon dioxide, carbon monoxide, and a considerable amount of other air pollutants every year [1]. On the other hand, the biomass left over from the harvest actually still retains a caloric value that can be used if processed in the appropriate way [2].

One of the treatment pathways that has been studied quite a lot is pyrolysis, which is the heating of biomass without oxygen or with very limited oxygen, so that the cellulose, hemicellulose, and lignin structures in it decompose into three fractions: solids (biochar), liquids (bio-oil), and non-condensed gases [3]. A comparison between slow and fast pyrolysis shows that the heating rate and the final temperature of the process greatly determine the proportion of the three products [4]. In agricultural waste such as rice husks or bagasse, the bio-oil that is formed is generally dominated by phenolic compounds and sugar derivatives such as furfural, with a fairly high content of water and acetic acid [5]. The higher the temperature of pyrolysis, the bio-oil yield in many types of biomass tends to rise to a certain point before finally decreasing again due to secondary cracking in the condensate vapor [7].

The problem is that most laboratory-scale pyrolysis research reports focus more on product results, while process temperatures are often not explained at what point and how stable the conditions are throughout the reaction time [8]. Some research groups have begun to address this problem by installing PID-based automatic temperature control in electric pyrolysis reactors, and as a result temperature fluctuations can be suppressed far compared to manual settings that can be missed by tens of degrees Celsius [9], [10]. Simulations of temperature profiles in electric heating furnaces also show that the thermal behavior of the reactor can be predicted quite close to the actual measurement data [11]. Unfortunately, information about the electrical energy used to achieve and maintain these temperatures is rarely reported along with product yield data, even though both determine whether an electric pyrolysis unit is feasible to be developed further on a larger scale.

Energy monitoring based on the Internet of Things itself is quite commonly used in the agricultural sector, for example to monitor the power consumption of solar panels or automatic irrigation systems [14], [15], but its application to agricultural waste treatment units such as pyrolysis reactors is still rarely specifically discussed. The combination of stable temperature control and energy recording that is integrated in one system is the gap that this study tries to fill. Based on this, this study aims to design and simulate AGRI-OIL, an electric pyrolysis system for agricultural waste that not only produces bio-oil, but also records how much energy is used to produce it, with the initial stage being in the form of verifying the strength of the frame structure and simulating the mass-energy balance in the separation and condensation subsystems.

2. Methodology

2.1 AGRI-OIL System Configuration

In general, AGRI-OIL consists of six main parts: a pyrolysis reactor where biomass is heated, an electric heating element as a heat source, a sensor and temperature control unit to keep the process conditions within a specified range, a copper pipe condenser to condense the steam from pyrolysis, a bio-oil storage container, and an energy monitoring system that records the consumption of electrical power during the process. These six parts are designed to be integrated in a single frame

so that they can be operated as a relatively compact unit, in line with AGRI-OIL's goal as a small-scale agricultural waste valorization technology.

Development at the stage reported here is focused on two things that can be examined through computer simulations before entering the physical prototype, namely the strength of the frame structure and reactor vessels, and the initial picture of the mass-energy balance in the steam separation and condensation subsystems.

2.2 Structural Analysis with Finite Element Method (FEM)

The strength of the frame and the AGRI-OIL vessel was examined through static structural simulation using SolidWorks Simulation. The three-dimensional assembly model that includes the reactor vessel, the steam line to the condenser, the condenser unit, and the mounting frame is subjected to a fixed support condition on the legs of the frame in contact with the floor, while the working load is the weight of the component itself which is applied as a vertical force on the top of the reactor vessel and along the support frame. The material used in this study has a yield strength of 2.039×10^8 N/m². The failure criterion used is the maximum von Mises stress, with the safety factor calculated from the ratio of the yield stress to the maximum von Mises stress that occurs in the model, as in Equation (1).

$$FOS = \frac{\sigma_y}{\sigma_{vM,max.}} \quad (1)$$

with σ_y is the material yield stress and $\sigma_{vM,max}$ is the maximum von Mises stress of the simulation result. The minimum FOS values that are commonly used as a reference for the framework of such mechanical equipment are in the range of 2 to 3 [16].

2.3 Simulation of Separation and Cooling Process with DWSIM

The mass and energy balance of the AGRI-OIL condensation subsystem was simulated using DWSIM, an open-source process simulation software that has been extensively tested for reliability for separation and bioprocess cases [12]. Given that the composition of bio-oil from biomass pyrolysis is in fact a mixture of hundreds of complex organic compounds, in this initial simulation the vapor of the pyrolysis product is approached with a mixture of five representative compounds in an equivalent mole fraction, 0.2 each, namely water, acetic acid, phenol, furfural, and n-heptane. These five compounds were chosen because they represent the group of compounds commonly found in lignocellulose biomass bio-oils: water as a decomposition product, organic acids, lignin-derived phenolic compounds, sugar-derived furan compounds, and light hydrocarbons [5], [7].

This mixed feed is fed to the ComponentSeparator unit (CS-1) which represents the separation of the steam fraction from the heavier fraction, then the resulting separation stream is cooled to the Cooler unit (CL-1) which represents the copper pipe condenser to an output temperature of about 30°C, close to the liquid bio-oil holding condition.

2.4 Estimated Equipment Cost

In addition to the mass-energy balance, DWSIM also provides an estimate of the purchase and installation costs for each operating unit based on the modular Guthrie/Turton correlation with the CEPPI cost index and the Lang factor of 3.5 [13]. This estimate is used as a rough approximation, with

an accuracy of about $\pm 30\text{-}50\%$, regarding the scale of investment required if the condensation-separation subsystem is developed at a larger size than the laboratory prototype.

3. Results

3.1 Structural Integration of the AGRI-OIL Framework

Figure 1 shows the von Mises voltage distribution in the AGRI-OIL model. The highest voltage is seen around the connection area of the reactor vessel with the support frame, with a maximum value of $1.121 \times 10^5 \text{ N/m}^2$. This value is well below the material's yield stress of $2.039 \times 10^8 \text{ N/m}^2$, or only about 0.05% of its yield limit.

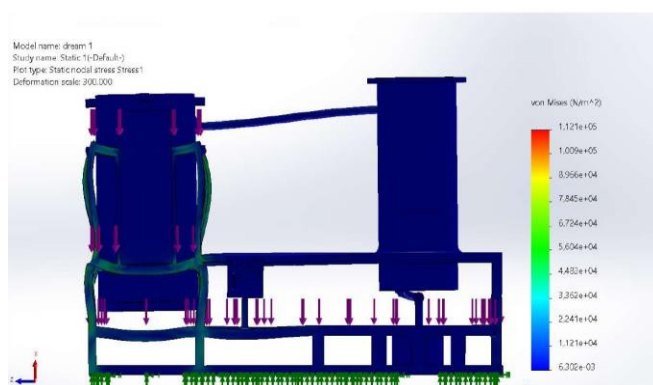


Fig 1. Von Mises voltage distribution in the AGRI-OIL model

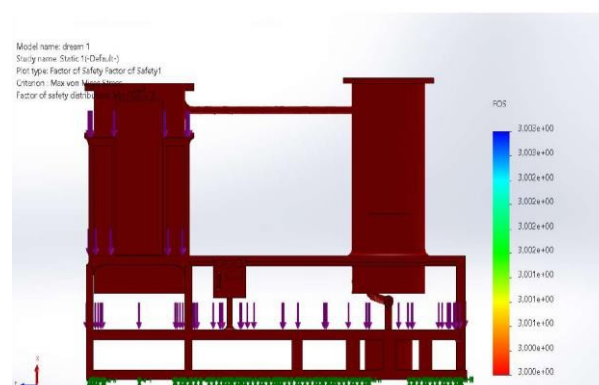


Fig 2. Distribution of safety factors in the AGRI-OIL model

The safety factor of the simulation is in the range of 3,000 to 3,003 in all parts of the model (**Fig 2**), with a minimum value of 3,000. This figure is consistent with the FOS range that is usually used as a reference for mechanical equipment frames, which is 2 to 3 [16], even at the upper limit. The maximum displacement recorded is $8.249 \times 10^{-4} \text{ mm}$ and the maximum strain is 3.053×10^{-7} , both of which are very small for the size of this type of reactor-scale metal structure.

From these three indicators, the AGRI-OIL frame and vessel can be declared safe to withstand the static load of its components, so that the current design can be continued to the fabrication stage without the need for the addition of reinforcement materials at the identified critical points. A summary of the structural simulation results is presented in Table 1.

Table 1

Summary of the Results of the Structural Analysis of AGRI-OIL

Parameter	Value
Maximum von Mises stress	$1.121 \times 10^5 \text{ N/m}^2$
Material yield stress	$2.039 \times 10^8 \text{ N/m}^2$
Minimum factor of safety	3.000
Maximum displacement	$8.249 \times 10^{-4} \text{ mm}$
Maximum strain	3.53×10^{-7}

3.2 Mass and Energy Balance of Separation-Condensation Subsystems

Fig 3 shows the DWSIM simulation flow scheme used for this subsystem. The five-component mixed feed is inlet with a mass flow rate of 0.01389 kg/s at 298.1 K and a pressure of 1.047×10^5 Pa. After passing through the separator unit, one of the outflows is a very small level of phenol vapor at 417.1 K and a density of 964.6 kg/m^3 , while the liquid flow is passed to the cooling unit and exits at 303.1 K, or about 30°C . The cooling load required in this unit is 0.1519 kW, with an overall system temperature range between 298.1 K to 417.1 K ($\Delta T = 119 \text{ K}$).

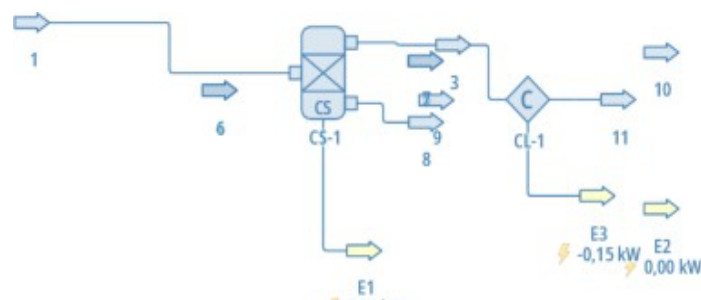


Fig. 3. DWSIM simulation flow scheme for subsystems separation and condensation of AGRI-OIL

It should be noted that this simulation is still an initial approach. The composition of five compounds with an equivalent mole fraction does not yet represent the actual composition of the pyrolysis bio-oil, which in practice depends on the type of biomass and the operating temperature conditions used [5], [7]. However, these results are sufficient to give an idea of the order of magnitude for the thermal loads that must be handled by the condenser unit as well as the temperature range that needs to be kept stable by the control system, before this data is later updated with experimental test results on physical prototypes. Testing of pyrolysis temperature variations on bio-oil yield, process duration, and specific energy consumption is on the agenda in the next stage of research.

A summary of the conditions on multiple key streams is shown in Table 2.

Table 2

Key flow conditions in a simulation of a separation-condensing subsystem

Flow	Temperature (K)	Pressure (Pa)	Mass Flow Rate (kg/s)
1 (bait)	298,1	$1,047 \times 10^5$	0,01389
8 (CS-1 steam)	417,1	$1,047 \times 10^5$	≈ 0
11 (CL-1 output)	303,1	$1,047 \times 10^5$	0,01389

3.3 Cost Estimation of Condensation Separation Subsystem

Table 3 summarizes the estimated equipment costs for the two operating units in this subsystem. The separation unit (CS-1) is estimated to require approximately USD 50,378 purchase cost and an installed cost of USD 176,322, while the refrigeration or condenser unit (CL-1) is estimated at USD 40,302 for purchase and USD 141,058 for installation. The total cost of installation (CAPEX) for these two units is approximately USD 317,380, with annual utility cost (OPEX) of approximately USD 109 and total annual cost (TAC) of approximately USD 105,903.

Table 3

Estimated cost of separation-condensing subsystem equipment

Unit	Purchase Fee (USD)	Installed Fee (USD)
CS-1 (Component Separator)	50.378	176.322
CL-1 (Cooler)	40.302	141.058

These figures cannot be directly compared to the real cost of making small-scale AGRI-OIL prototypes, because the Guthrie/Turton correlation used by DWSIM was basically developed for industrial-scale process equipment [13]. However, this estimate is quite useful as a starting point to compare the scale of investment between the option of developing a self-condensing separation unit and the option of using a simple condenser made of copper pipe that is more suitable for the scale of laboratories or small and medium-sized enterprises.

4. Conclusion

The static load of the components with a minimum safety factor of 3.0 and deflection is practically negligible, so the current structural design is feasible to proceed to the fabrication stage. Process simulations on the separation-condensing subsystem provide a preliminary picture of the operating temperature range of 298.1-417.1 K, cooling load of 0.1519 kW, and an estimated installed cost of approximately USD 317,380 for the two operating units. These results are still an approach based on a five-compound surrogate mixture, so the next step is to create a physical prototype of AGRI-OIL along with direct experimental testing, including testing pyrolysis temperature variations on bio-oil yield, process duration, and specific energy consumption, to validate and complement the simulation results obtained at this stage.

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Conflict of Interest Statement

The authors state that there is no conflict of interest related to the publication of this article. No financial support, grants, or other forms of compensation received could affect the results of this study. The research was conducted without the involvement of commercial or financial relationships that could be considered a potential conflict of interest.

Author Contributions Statement

Dhea Ananda Khusfita Sari designed the concept and directed the research, as well as reviewed the final manuscript. Ade Tafta Risqi conducted the structure and process simulation as well as data analysis. Aryo Adi Bhaskoro assisted in the concept design and drafting the initial draft of the manuscript. All authors contributed to the revision of the manuscript, as well as reading and approving the final version.

Data Availability Statement

All data generated or analyzed during this study are included in this published article. Additional data may be obtained from the authors of the correspondence upon reasonable request.

Ethics Statement

This research did not involve human or animal subjects. All data used came from computer simulations (SolidWorks Simulation and DWSIM) conducted by the research team, so no ethical approval from a special committee was required.

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