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*Research article*

# Analyzing temperature distribution in pyrolysis systems using an atomic model

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**Abstract:** Pyrolysis is a complex energy conversion reaction due to the multiple stages of the process, the interaction of kinetics, mass and heat transfer and thermodynamics. The feedstock, temperature, heating rate, residence time, and reactor design are only a few factors that might impact the final product during the pyrolysis process. This study focuses on the temperature analysis of pyrolysis with sheep manure as feedstock, which includes reactor, pipes and condenser. The examination of the temperature distribution within a pyrolysis system can contribute to the preservation of product quality, the maintenance of heat balance, and the enhancement of energy efficiency. Based on the analysis, the degradation temperature of sheep manure is between 210–500 °C. Consequently, it is crucial to control the reactor temperature at a desirable temperature that aligns with the degradation temperature of sheep manure. To ensure optimal condensation and maximize bio-oil yield, it is also necessary to control the condenser temperature. This study aims to determine the characteristics of temperature changes in pyrolysis systems using atomic models. The atomic model was built in OpenModelica using the Modelica language. The atomic model was validated with experiment, and it was found that there was a significant difference in reactor temperature. Complex processes occur in the reactor where pyrolysis occurs and various factors can impact the temperature of the reaction. The temperature in the multistage condenser gradually decreases by 1–3 °C. In the principle of condensation, this temperature drop is considered less than optimal because the cooling fluid in the pyrolysis condensation system is air coolant, which is entirely reliant on ambient temperature. The accuracy of the atomic model is evaluated using error analysis and the mean absolute percentage error (MAPE). A value of 13.6% was calculated using the MAPE. The atomic model can be applied because this value is still within the tolerance range.

**Keywords:** atomic model; pyrolysis; temperature distribution; OpenModelica

## 1. Introduction

Climate change is a major worldwide issue. Growing industrial activity and human population have sped up climate change, including an annual increase in average surface temperatures [1]. Climate change happens as the concentration of carbon dioxide and other gases in the atmosphere rises, causing the greenhouse gas effect. Based on the International Renewable Energy Agency (IRENA) in the Indonesia Energy Transition Outlook report released in October 2022, renewable energy can only ever reach 0.3% of Indonesia's energy. One of the renewable energy sources that is still underutilized is biomass. Indonesia has 43.3 GW of biomass potential, but only 1.9 GW (4.38% of total existing potential) has been exploited. As of 2020, biomass was still a small part of renewable energy at 11% [2]. For this reason, our work studies the utilization of biomass as renewable energy capable of reducing carbon gas emissions.

Animal manure is considered a promising renewable energy source and contributes to carbon emissions, accounting for approximately 10% of total emissions, including $CO_2$, $CH_4$ and $N_2O$ [3]. Among various animal manure, sheep manure is of particular interest. Each sheep weighing 20–40 kg produces around 0.32–0.62 kg of manure daily, equivalent to 0.3 tons per year [4]. The population of small sheep in Indonesia has been steadily increasing, reaching 18.7 million in 2020, with a growth rate of 1.23% from the previous year [5]. Population growth indicates a growing potential for renewable energy from biomass sources as the livestock population continues to rise. Compared to other animal manures, such as cow, pig and poultry manure, sheep manure has a higher volatile content (58–64%) and a greater hydrogen and oxygen content [6]. It also exhibits lower nitrogen, sulfur and chlorine content. Past research has shown that cow and pig manure are more suitable for biochar production, while sheep manure is better suited for producing bio-oil and syngas [6]. Sheep and poultry manure contain a higher fixed carbon composition (13% and 12%, respectively) than other manures, indicating the potential for a higher calorific value. Particularly, sheep manure stands out with its higher carbon content (51%) than other manures. Sheep manure is a promising biomass resource for bio-oil production and further research aims to enhance the characteristics of the bio-oil derived from sheep manure [4].

Some methods for converting biomass into more valuable energy are combustion, gasification and pyrolysis. The combustion process only produces 10% efficiency and causes environmental pollution, whereas gasification occurs in the partial oxidation process and converts solid fuel [4]. Pyrolysis is recognized as a highly effective and popular technology for generating biofuels, among various methods developed for converting biomass. Its simplicity, ability to produce a wide range of products, operation under relatively mild conditions, cost-effectiveness and potential industrial applications make it a favorable choice [7]. However, a significant disadvantage of the pyrolysis process is the loss of heat during operation [8]. In the pyrolysis process, heat loss can lower energy efficiency. If the heat required for the pyrolysis reaction is lost to the environment, most of the energy provided to the system is not used optimally to support the pyrolysis reaction. Therefore, the desired results, require a greater energy source. In addition, heat loss can disrupt the pyrolysis reaction process, change the temperature profile in the reactor and produce inconsistent products.

Pyrolysis is a complex thermal process in which organic matter is decomposed into valuable products under conditions without oxygen or a limited reactive environment [9]. Pyrolysis involves an intricate sequence of reactions, making it challenging to acquire a comprehensive understanding [10]. In the case of pyrolysis of animal manures, most research has focused on the kinetics and or characterization of the pyrolysis products (biochar, bio-oil and biogas) [11–17] and limited information is available on improving the process of heat transfer in the pyrolysis reactor so that the desired reaction temperature can be achieved. The temperature distribution of the pyrolysis components substantially impacts the yield and quality of the products. Atomic modeling can identify areas in the system that require thermal optimization to improve process efficiency. This can assist in designing and optimizing operational conditions to achieve the desired product yield. Heat balance estimation can identify potential thermal problems in a pyrolysis system, such as hot spots or uneven temperature differences, which can cause system degradation or instability. Using atomic modeling, computer simulations can be carried out to understand the thermal characteristics of pyrolysis systems without needing expensive and time-consuming physical experiments.

Without conducting experiments, the heat balance of the pyrolysis can be calculated using three methods [18,19]. In the first method, the total heat requirement for pyrolysis of biomass is calculated as the sum of sensible heat ($\Delta$Hs) and reaction heat ($\Delta$Hr). Sensible heat is the heat required to raise the temperature of the biomass until it reaches the reaction temperature, while the heat of the pyrolysis reaction is released or absorbed. In the second method, the heat balance is based on empirical correlation between the effects of moisture and ash content. The third method is based on enthalpy calculations. There is still not much research on pyrolysis heat balance calculations. Khan et al. optimized and calculated heat loss in pyrolysis reactors [8]. Atsonios calculates the energy balance in fast pyrolysis using an enthalpy calculation [18]. Amita et al. analyzed low-density polyethylene pyrolysis's mass and energy balance [20]. However, no one has investigated the heat balance by examining the temperature distribution of each component in the pyrolysis system.

In previous studies, atomic modeling based on fluid catalytic cracking (FCC) systems has been carried out [21]. Similar trends may be seen in the experiment result and the estimation result from the atomic model. This suggests that the atomic model can be used to calculate the impact of the different opening valve variations on the hydrodynamic properties, particularly the flow distribution, in the FCC system. The novelty of this research is in the atomic modeling of pyrolysis systems to determine the characteristics of temperature changes so that heat balance can be analyzed. It is envisaged that this research will lead to chances for the development and improvement of pyrolysis systems' efficiency. A pyrolysis-specific atomic model was developed in this study due to the atomic model's success when used for hydrodynamics modeling with FCC. The temperature distribution in each pyrolysis system component is carefully examined using atomic modeling. The atomic model enables microscopic heat distribution analysis, which can be used to identify hot spots that may develop in the pyrolysis system. Atomic modeling calculates the heat balance involved in reactions and phase changes.

## 2. Materials and methods

### *2.1. Pyrolysis system*

Pyrolysis is a thermal decomposition process carried out without oxygen [22]. The main advantage of the pyrolysis process is that it can be adjusted according to the desired products. Slow pyrolysis is used to improve bio-char yield, while fast pyrolysis is used to increase bio-oil yield [23]. Bio-oil yield depends on the feedstock, temperature and type of reactor. Various kinds of reactor types are used in pyrolysis and some of the types of pyrolysis reactors used are fixed bed and some are moving bed. The moving bed consists of a fluidized bed reactor, an entrained flow reactor, a rotary bed reactor, ablative pyrolysis and vacuum pyrolysis. The heating source for pyrolysis can be obtained from steam, furnace, heating tape, or microwave, where each heating source has a different heating rate and heat transfer values. Therefore, the reactor must be designed based on heat resources to maximize efficiency [24].

In this work, a fixed bed reactor was used. Compared to other reactors, fixed bed reactors can offer a more consistent temperature distribution within the bed. This is because the bed functions as a thermal mass, which can assist in balancing temperature gradients and preventing the formation of hot spots [25]. The fixed bed reactor uses fire-resistant materials and maintains the feedstock in a fixed position throughout the entire pyrolysis process. Fixed bed reactors have advantages, such as wide temperature distribution, melting ash and producing clean gas with minimal tar content. Additionally, these reactors exhibit high carbon efficiency [24]. Furthermore, the size of the feedstock particle can interact with pyrolysis temperature [26]. Therefore, it significantly impacts the pyrolysis products. The feedstock particle is reduced to smaller sizes to prevent uneven heating with large thermal gradients. Larger particle sizes are prone to experiencing conduction, which can lead to temperature variations during the pyrolysis process. The pyrolysis process can be categorized into flash, fast and slow pyrolysis [27]. In pyrolysis, large hydrocarbon molecules from biomass are broken down into smaller hydrocarbon molecules. The pyrolysis reaction is shown in Figure 1.

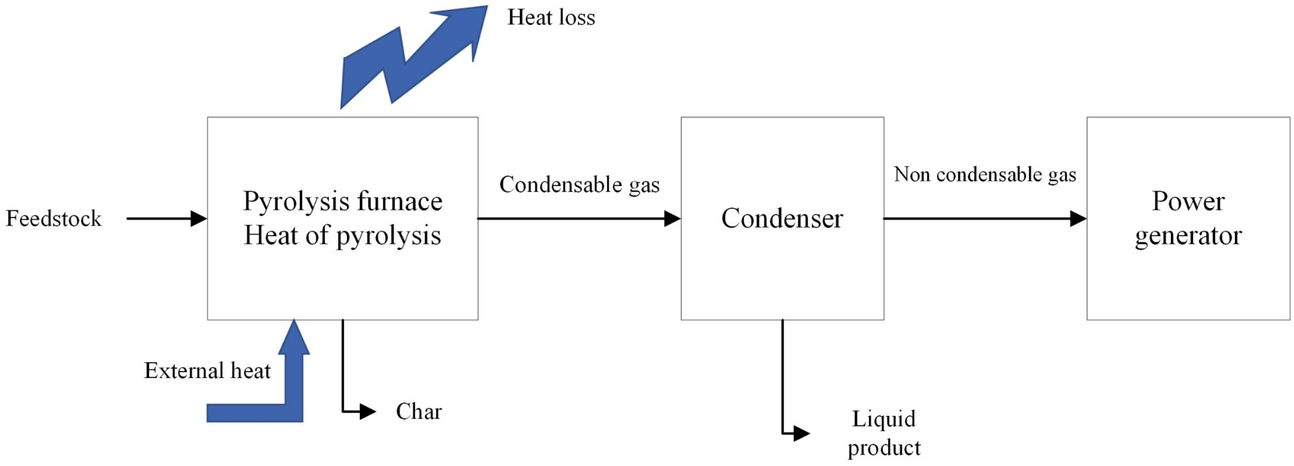


**Figure 1**. Pyrolysis system [28].

Figure 1 depicts the pyrolysis process flow. The pyrolysis system starts from the feedstock put into the reactor and is heated until it reaches the pyrolysis temperature. Inside the reactor, mass decomposition process occurs to form condensable gas and char. Char is collected in a storage tank, while the condensable gas is transferred to the condenser to be condensed to produce bio-oil. In the context of pyrolysis, condensable gasses include $H_2$, CO, $CO_2$, $H_2O$, $CH_4$, $C_2H_4$ and $CH_PO_Q$, whereas non-condensable gasses include $H_2$, CO, $CO_2$, $CH_4$, $C_2H_4$ [28]. The yields of bio-oil, biochar and biogas can be calculated using Eqs (1–3) [29].

$$Bio-\ oil\ yield, wt.\% = \frac{mass\ of\ bio-oil(g)}{mass\ of\ feed(g)} x100 \tag{1}$$

$$Biochar\ yield, wt.\% = \frac{mass\ of\ bio-char(g)}{mass\ of\ feed(g)} x100 \tag{2}$$

$$Biogas\ yield, wt.\% = 100\% - (Bio-\ oil\ yield +\ Biochar\ yield) \tag{3}$$

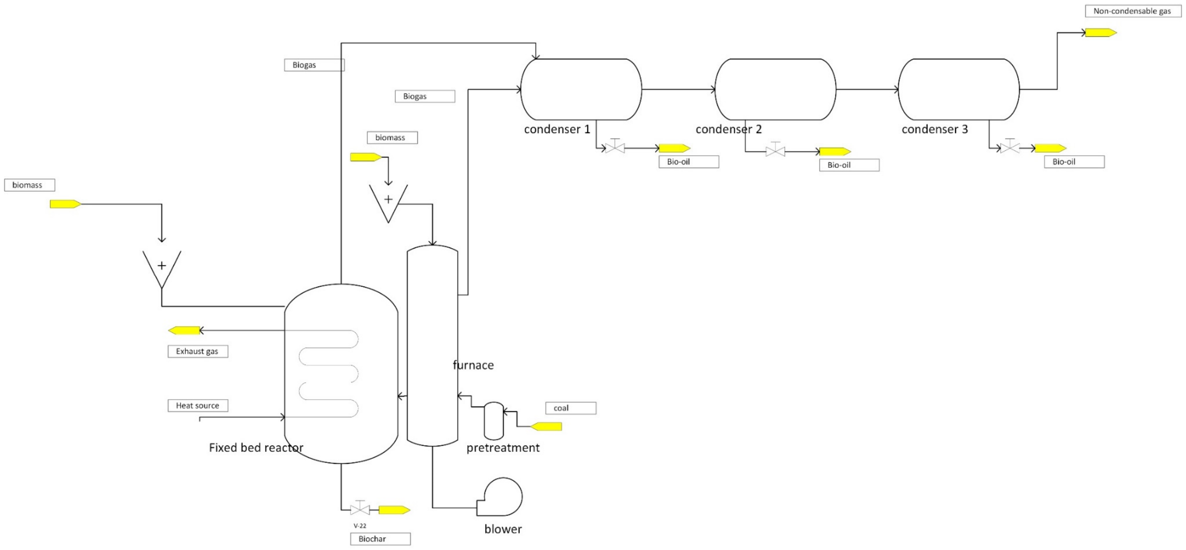


**Figure 2**. Schematic diagram of pyrolysis.

Slow pyrolysis was employed in this study and its schematic diagram is depicted in Figure 2. The slow pyrolysis experiment of sheep manure was conducted using a fixed-bed reactor, with internal combustion engine (ICE) exhaust gas serving as the energy source. The reactor has a capacity of 2 kg, operates at a heating rate of less than 20 °C/min and allows a maximum residence time of 150 minutes at different pyrolysis temperatures. Before the pyrolysis reaction, the raw material is dried until the moisture content reaches less than 10% and pulverized. This system implements multilevel condensation, which enables the separation and screening of pyrolysis products based on their condensing temperatures. Consequently, purer and higher-quality pyrolysis products can be obtained and the amount of flue gas released into the atmosphere during the pyrolysis process is reduced. Through condensing the pyrolysis gas into liquid form, any toxic or hazardous products can be separated and further processed, mitigating negative environmental impacts. The pyrolysis system has several temperature sensors strategically installed in various locations. The volatile matter is condensed in the condenser and the resulting bio-oil yield combines the condensate collected from each condenser. All condensers efficiently condense biogas at room temperature.

## *2.2. Heat balance modeling*

The heat balance modeling is based on an atomic model. To validate the predictive atomic model, the model must be compared with the experiment. The experimental procedures are explained in the following sub-section. It is crucial to evaluate the predictive atomic model accuracy since predictive models are being used more frequently across various conditions and predictive accuracy affects the quality of the predictions made as a result. Therefore, mean absolute percentage error (MAPE) is used to calculate model accuracy.

### 2.2.1. Atomic model

The heat balance of a pyrolysis system is estimated using an atomic model. The atomic model is a modeling concept based on the atomic scale, that describes each component of the system [30]. This modeling is based on atomic models created with OpenModelica. OpenModelica is a free software program that makes use of the Modelica language. Modelica is a declarative, object-oriented, multi-domain modeling language for “component-oriented” modeling of complex systems, i.e., systems with mechanical, electrical, electronic, hydraulic, thermal, control or process-oriented subcomponents [31]. In the same way that classes and class instances operate in C and Python, OpenModelica is an example of object-oriented programming that allows system models and components to be defined and reused [32]. Modelica can model a complex system through a hierarchy of several components. On an atomic scale, the behavior or characteristics of each of the components that make up the system can be described [33]. Two types of modeling approaches can be used in Modelica: equation-based approach and component-based approach. Through equation-based approaches, a system is described through the equations that describe the whole of the system. For simple systems, equation-based approaches can be effectively used. However, such approaches are ineffective to apply to highly complex system modeling. Therefore, the component-based approach can be used to model a complex system. Using a component-based approach, each component in a system will be properly modeled. Then, using connectors, models of any such component can be coupled in various ways. The key to component-based modeling is using a free body diagram of each component model. Each component will then be connected to form a system.

This study aims to determine heat transfer characteristics in the pyrolysis system, especially in each component. This pyrolysis system atomic model uses several “class” objects. Therefore, the characteristics of each component can be modeled more simply. First, each component will be represented by a subclass in the atomic model. Then, the subclasses of each component will be linked using the subclass connectors provided in OpenModelica. Using this connector subclass, each component class will create a “system” that fulfills the conservation principle [30]. The object “class” that builds this pyrolysis system model consists of pipes, condensers and elbows as shown in Figure 3. Each object of this class can be used to define more than one component with different parameters, such as length, diameter, material and so on. With this approach, this study will provide a profile of the heat transfer characteristics. This will assist in understanding and optimizing the performance of the pyrolysis system and designing components according to the system's needs. Figure 3 depicts a pyrolysis system that modeled the biogas flow from the process of pyrolysis of sheep manure. The atomic model consist of condensers, pipes and elbows.

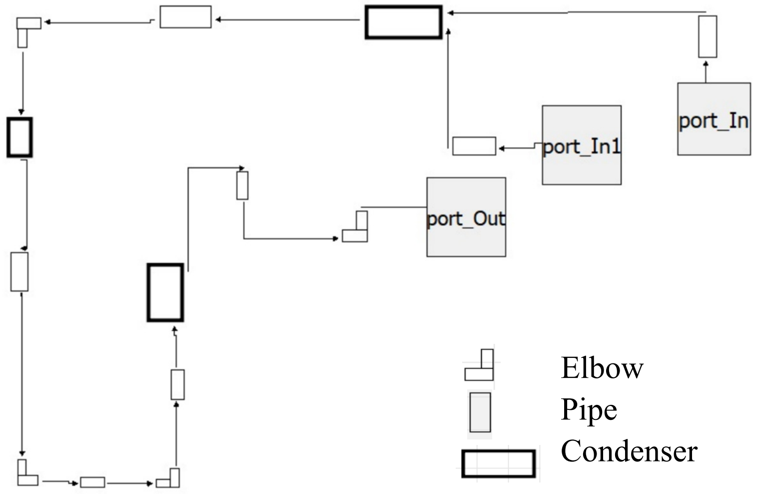


**Figure 3.** Atomic model of pyrolysis.

### 2.2.2. Heat balance calculation based on atomic model

Heat balance modeling is a mathematical approach used to describe heat transfer within a system or object. This modeling relies on the laws of thermodynamics and physical principles governing heat transfer from one place to another. The primary objective of heat balance modeling is to comprehend and analyze how heat distribution changes within a system over time or under specific conditions.

The conservation concept is used in the Modelica-based pyrolysis system's heat balance modeling. To achieve heat balance in Modelica-based heat modeling, the energy entering the system must be equal to the energy leaving the system. It is essential to ensure that the code and algorithm in the atomic model of the pyrolysis system coincide when constructing the model. This includes ensuring that the number of variables and equations in the model are the same. Before the atomic model is executed, it is necessary to "check the model" through the existing features in the software. If there is a discrepancy between the number of variables and the equation, this feature can warn about syntax errors in the code. The same number of variables and equations indicates that the code and algorithm in the atomic model of the pyrolysis system have been stated correctly and mathematically. In this atomic model, there are 176 equations and 176 variables, so it can be concluded that the atomic model of the pyrolysis system is appropriate. The algorithm of the atomic model is shown in Figure 4.

The atomic model begins with biogas generated from a pyrolysis reactor. Subsequently, the biogas flows through a series of pipes and a condenser. The enthalpy calculation for the pipes and condenser employs the following equation [34]. According to the Reynold number equation, the biogas flow leaving the pyrolysis reactor is classified as turbulent flow. The enthalpy calculation is based on the principles of internal forced convection, which applies to the gaseous fluid flow within the pipe. The heat transfer in the pipes is determined using Eqs (4–8).

$$\dot{Q} = \dot{m}\, c\, (T_e - T_i), \tag{4}$$

$$Q = h\, A\, \Delta T, \tag{5}$$

$$Re = \frac{\rho\, v\, D}{\mu}, \tag{6}$$

$$Nu = 0{,}125\, f\, Re\, Pr^{1/3,} \tag{7}$$

for fully developed turbulent flow with smooth surfaces.

$$Nu = \frac{h\, D}{k} = 3.36, \tag{8}$$

where: $\dot{Q}$ = heat (kJ/s), $\dot{m}$ = mass flow rate (kg/s), $T_e$ = temperature output (°C), $T_i$ = temperature input (°C), $h$ = heat transfer coefficient (Watt/m$^2$.°C), A = area (m$^2$), $Re$ = Reynolds number, Nu = Nusselt number, f = friction factor and Pr = Prandtl number.

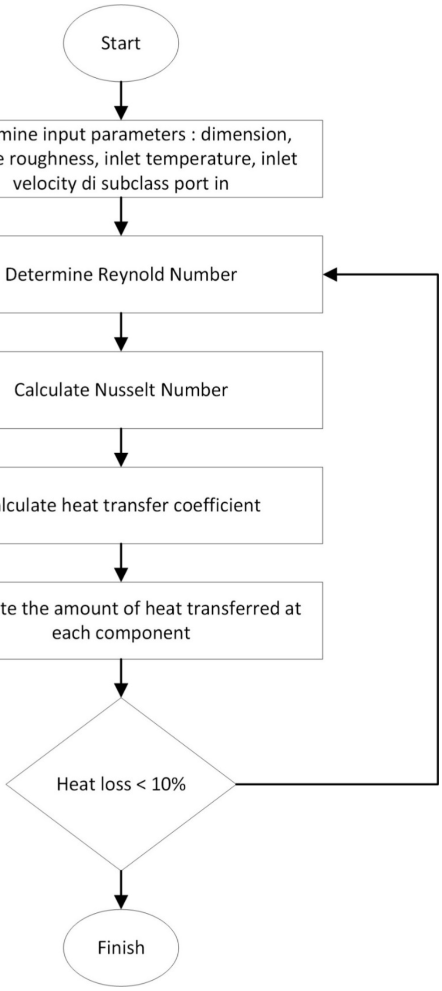


**Figure 4**. Atomic model algorithm of heat loss calculation of pyrolysis.

In calculating the outlet temperature at the condenser, it is assumed that the surface temperature corresponds to room temperature, which is 27 °C. The condenser utilizes unrestricted airflow to cool the gas fluid, making it isothermal at 27 °C. Therefore, Eqs (9–11) is used to calculation the condenser temperature:

$$\Delta T_{ln} = \frac{T_i - T_e}{\ln\frac{T_s - T_e}{T_s - T_i}}, \tag{9}$$

$$Q = h\, A_s\, \Delta T_{ln}, \tag{10}$$

$$A_s = \pi\, D\, L, \tag{11}$$

where $T_s$ = surface temperature (°C).

### *2.3. Experiment*

This experiment aims to measure and understand how energy enters and exits a pyrolysis system. Experimental data from various schemes in Table 1 will be compared with the predictions from atomic models. Here are some steps in the experiment methodology:

a. Preparation of feedstock. The moisture content and particle size of ground sheep manure are reduced to less than 10% and less than 5 mm, respectively.
b. Set up data acquisition and several measurement systems as shown in the Tables 1 and 2.
c. Continuously feed the feedstock into the pyrolysis reactor according to the test scheme shown in Tables 1 and 2.
d. Carry out heating by connecting the gas hose through the helical pipe in the reactor according to Tables 1 and 2.
e. Record data using a data logger in the data acquisition system.
f. The pyrolysis test is performed for no more than two hours or until the temperature for the decomposition of sheep manure is attained.
g. Experimental data is used to verify the atomic model predictions.

**Table 1.** Test scheme.

| No. | Feedstock (kg) | Mass flowrate of heat source (kg/min) | Scheme |
|---|---|---|---|
| 1 | 0.5 | 0.0167 | A |
| 2 | 0.75 | 0.0167 | B |
| 3 | 1 | 0.0167 | C |
| 4 | 0.5 | 0.0133 | D |
| 5 | 0.75 | 0.0133 | E |
| 6 | 1 | 0.0133 | F |

**Table 2.** Experimental variables.

| No. | Component | Variable |
|---|---|---|
| 1 | Reactor and condenser | Temperature (T1, T2, T3, T4, T5, T6) |
| 2 | Helical pipe as a heating gas channel | Input pressure<br>Output pressure |
| 3 | Helical pipe as a heating gas channel | Velocity of heat source (gas) |
| 4 | Sheep manure as feedstock | Mass |

# 3. Results

## 3.1. Multi stage condensation

There are several types of condensation pyrolysis systems, namely single condensation with a single product, multistage condensation with a single product and multistage condensation with multiple products [35]. Khan et al. [36], Erdogdu, et al. [4], Poddar et al. [37] have used multiple condensation in different pyrolysis systems. In this study, we used multi condenser with multiple liquid products. The condenser used is an air-cooled condenser that uses natural convection. Multiple condensation systems in pyrolysis can improve product quality. By using graded condensation, the different product fractions can be better collected, reducing the content of unwanted compounds and improving the quality of end products such as biofuels or high value chemical products [35].

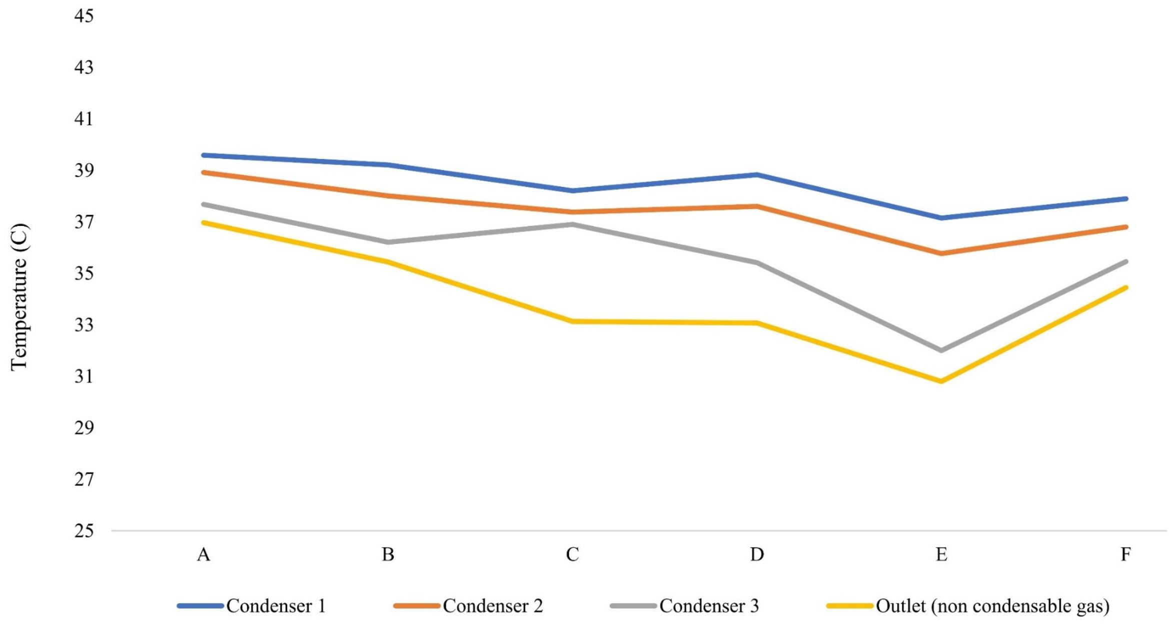
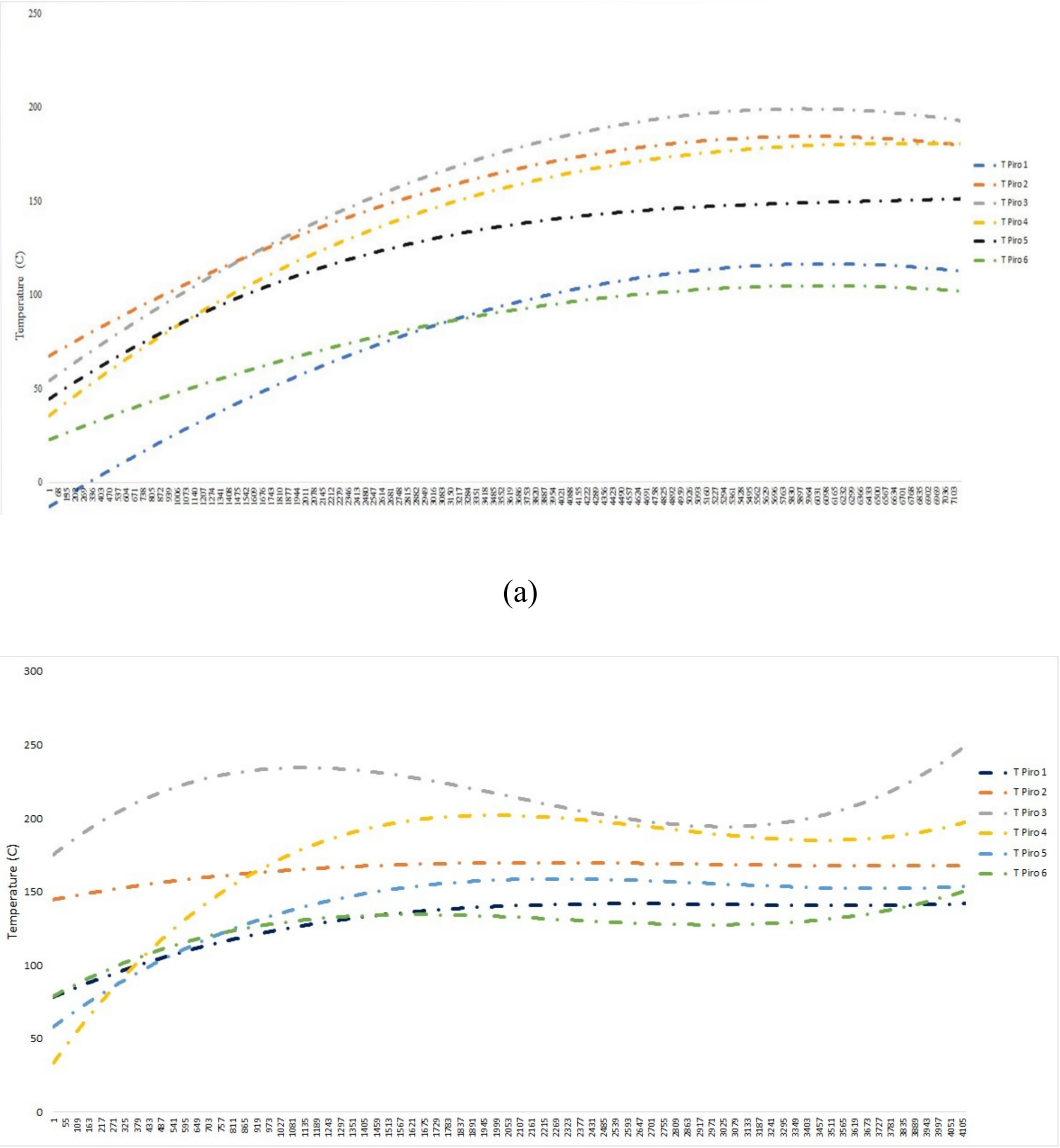


**Figure 5**. Comparison of the mean temperature in the condenser.

Figure 5 depicts the temperature comparison in a multistage condenser. In all experimental schemes, it is evident that the temperature reduction in all condensers is relatively modest. The data presentation in Figure 5 is the average data during the pyrolysis process. The decreasing temperature trend in the condenser is linear, with the temperature drop in every condenser approximately 1–3 ℃. The temperature ranges for condenser 1, 2, 3 and the non-condensable gas are 48.5–43.5 ℃, 45.2–39.8 ℃, 42.8–39 ℃, 40–36 ℃ respectively. This insignificant decrease in temperature is due to the type of condenser used using natural convection, namely ambient air. Some of the advantages of this type of condenser are that it does not require additional devices such as fans or pumps to drive air flow, thereby reducing operational costs and maintenance requirements and it is more environmentally friendly because there is no additional energy consumption. However, there are some limitations to air-cooled condensers with natural convection, which depend on environmental conditions, especially temperature, humidity, wind speed and low efficiency. Compared with forced convection condensers, natural convection condensers may have slightly lower cooling efficiency. When compared with other studies, the decrease in temperature in the study was not significant, unlike in the studies conducted by Chen et al. and Kim et.al although the trend in the temperature of both is downward. Research conducted by Chen et al. [38] using a multistage 4 condensers with coolant water showed a less significant decrease. The temperature in each condenser 1, 2, 3 and 4 was 32–44 °C, 25–27 °C, 22–25 °C and 22–25 °C, respectively. In addition, Kim et al. used 3 multistage condensers where in each condenser there was a significant decrease in temperature respectively 121–132 °C, 107–116 °C and <25 °C. Bio-oil was produced in the lower temperature-controlled condenser with a high water content and light oxygenated components [39]. The temperature drop in the condenser is influenced by several factors, including coolant, differences in ambient air temperature and working fluid. In the future, it will be necessary to design an effective condensation system to increase the yield of bio-oil produced in each condenser.

### *3.2. Reactor temperature distribution*

Temperature sensors are strategically installed at various positions within the reactor to monitor the temperature profile. Figure 6 depicts the temperature change in test schemes B and E. In scheme B there is a heating rate of 0.99 °C/min, whereas in scheme E the heating rate is 2.24 °C/min. This is due to differences in the mass flow rate of exhaust gas as a source of heat energy in this pyrolysis. The higher the mass flow rate of the heat source, the higher the heating rate, so that the pyrolysis temperature is reached more quickly. The thermogravimetric analysis (TGA) results reveal that the most significant mass degradation of sheep manure occurs within the temperature range of 210–500 °C, corresponding to the decomposition of hemicellulose and cellulose. Above 500 °C, the mass degradation decreases until reaching 900 °C, indicating the disappearance of most volatile compounds. To maintain the reactor at the optimal temperature for the pyrolysis reaction, a uniform temperature distribution is essential. According to the Tables 3 and 4, the temperature distribution in this study is relatively even, though the heating rate for slow pyrolysis remains relatively low. The temperature trend observed in Figure 6a is gradual increase at all measurement points. The highest average temperature is recorded at T Piro 3, as it is situated close to the heat source. Conversely, the lowest temperatures are found at the top of the reactor, specifically at points 5 and 6. This area is in close proximity to the biogas pathway that enters condenser 1. In this test scheme, temperatures of 200 °C are observed starting from the 5th minute.



(a)

(b)

**Figure 6.** Temperature profiles of pyrolysis reactor on (a) scheme B and (b) scheme E.

**Table 3.** Descriptive statistics for the temperature distribution in scheme B.

| | T Piro 1 | T Piro 2 | T Piro 3 | T Piro 4 | T Piro 5 | T Piro 6 |
|---|---|---|---|---|---|---|
| Mean | 79.29 | 151.29 | 158.48 | 140.45 | 123.53 | 81.30 |
| Standard error | 0.46 | 0.41 | 0.51 | 0.49 | 0.36 | 0.29 |
| Standard deviation | 38.66 | 34.96 | 42.99 | 41.85 | 30.26 | 24.31 |
| Sample variance | 1494.92 | 1222.42 | 1848.43 | 1751.48 | 915.83 | 591.18 |
| Kurtosis | –0.58 | 0.29 | –0.19 | –0.44 | –0.38 | –0.85 |
| Skewness | –0.87 | –1.10 | –1.00 | –0.91 | –0.99 | –0.81 |
| Range | 123.75 | 142.50 | 157.00 | 144.25 | 120.50 | 73.00 |
| Confidence level (95%) | 0.90 | 0.81 | 1.00 | 0.97 | 0.70 | 0.56 |

**Table 4.** Descriptive statistics for the temperature distribution in scheme E.

| | T Piro 1 | T Piro 2 | T Piro 3 | T Piro 4 | T Piro 5 | T Piro 6 |
|---|---|---|---|---|---|---|
| Mean | 130.27 | 165.25 | 214.11 | 173.05 | 140.83 | 126.79 |
| Standard error | 0.26 | 0.11 | 0.28 | 0.63 | 0.39 | 0.21 |
| Standard deviation | 16.83 | 7.35 | 18.22 | 40.23 | 25.33 | 13.28 |
| Sample variance | 283.31 | 53.96 | 332.06 | 1618.16 | 641.58 | 176.29 |
| Kurtosis | 0.79 | 1.72 | –0.36 | 1.02 | 0.78 | 3.94 |
| Skewness | –1.43 | –1.49 | –0.27 | –1.56 | –1.45 | –1.88 |
| Range | 68.25 | 34.75 | 86.75 | 148.00 | 101.75 | 71.25 |
| Confidence level (95%) | 0.51 | 0.22 | 0.56 | 1.23 | 0.77 | 0.41 |

The temperature distribution in a pyrolysis reactor can vary significantly based on factors such as reactor design, feedstock and operational conditions [40]. In a pyrolysis reactor, feedstock is heated at high temperatures in an oxygen-free environment to produce pyrolysis products, e.g., biochar, bio-oil, and biogas. Pyrolysis reactor design plays a crucial role in determining temperature distribution. Pyrolysis reactors with well-designed flow configurations ensure efficient contact between the feedstock and the heat source, leading to a more uniform temperature distribution. Conversely, poor design or enclosed areas can result in hot spots or uneven temperature distribution. Additionally, the type of heat energy source used also has an impact. Direct heating methods, such as heating with a heating element or flame, heavily rely on the design and position of the heat source, leading to varying temperature distributions. In contrast, indirect heating, like heating by radiant heat from the reactor wall, can produce a more even temperature distribution. Various heat sources, such as steam, furnace, microwave and heating tape, can be employed in pyrolysis [24]. The composition and physical properties of the feedstock also influence the temperature distribution. Additionally, the flow rate of the feedstock into the reactor can have an impact on temperature distribution. Slower flow rates may result in heat buildup in particular regions, whereas faster flow rates can contribute to a more even temperature distribution.

Achieving an even temperature distribution within the pyrolysis reactor is crucial for producing uniform and high-quality pyrolysis products. For this reason, it is necessary to carry out careful reactor design, selection of appropriate heat sources and control heat flow and feedstock. Hot spots or areas with high temperatures in the pyrolysis reactor can be located in specific regions, depending on the reactor design, heat source and feedstock type. Typically, high-temperature points tend to occur in several areas within the reactor. The first is at the center of the reactor, where the highest temperature is experienced due to the introduction of heat energy. The second area is the reaction zone where the pyrolysis reaction occurs, surrounding the material undergoing pyrolysis. This results in high temperatures due to the energy required for the pyrolysis reaction to proceed.

### *3.3. Analysis of atomic modeling result: Temperature distribution on each component*

Thermal equilibrium atomic modeling in pyrolysis systems has been developed. This pyrolysis system consists of several components: the reactor, pipes for connection and condenser. This modeling is designed for gas channels (pyrolysis products in the reactor). The gas fluid flows through a series of pipe connections to the multistage condenser. This modeling is designed to estimate temperature changes in each component based on the principle of heat conservation. This basic principle is used to estimate heat transfer distribution in pyrolysis systems. Changes in temperature between the inlet and outlet are significant in the components, affecting the heat loss value. The higher the heat loss number, the more inefficient the system, which will have a negative impact on processes, operations and costs.

To validate the model, conditions similar to schemes B and E are simulated in the atomic model. The gas fluid flow from the pyrolysis reactor is used as an input variable for the atomic model, especially the velocity and temperature of the gas fluid. The results of the estimation of the atomic model are then compared with the results of experimental measurements. Knowing the temperature value, the pyrolysis system's heat balance can be calculated. Based on the comparison between the experiment depicted in Figure 7 and the estimation findings of the atomic model, the biggest discrepancy between the findings of the measurements and the atomic model estimation is the reactor temperature. A reactor is a pyrolysis place where complex reactions occur so that many factors can affect the decomposition process.

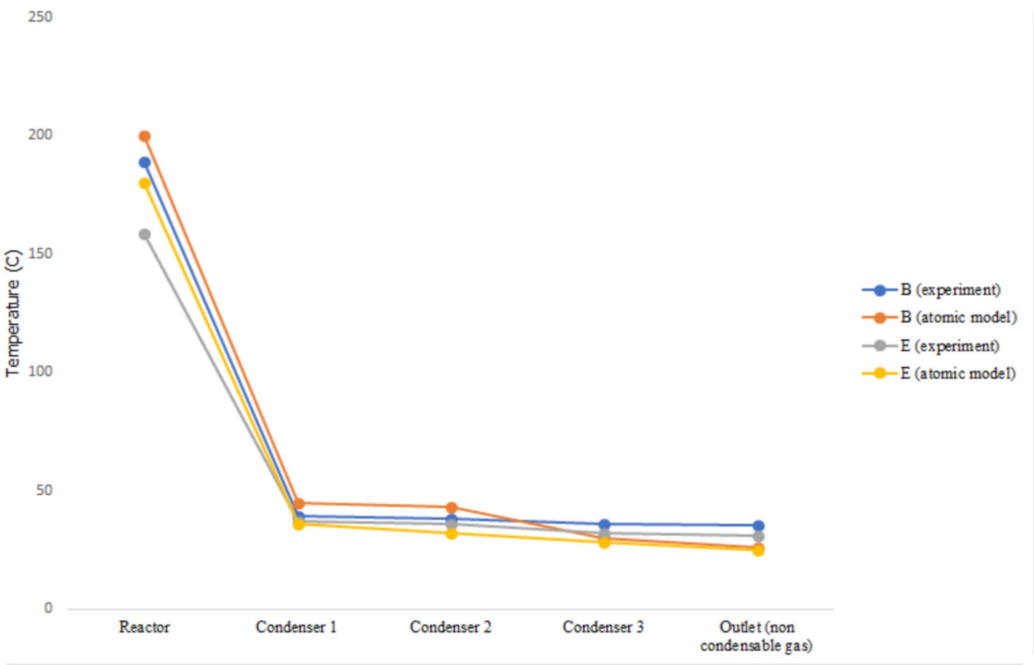


**Figure 7**. Comparison of atomic models and experiments on schemes B and E.

In error analysis, the mean absolute percentage error (MAPE) is used to determine the prediction outcomes of the atomic model with the experimental data. MAPE is a well-known predictor of performance [41]. MAPE is a measure used to calculate the percentage difference between expected and actual results [42]. Because it implies a decreased prediction error, the lower the MAPE number, the better the model performance. MAPE calculations using the atomic model and measurement findings provide 13.6%. This is still a small enough value to accept and use the atomic model.

After the pyrolysis reaction occurs in the reactor, the pyrolysis gas and char are formed. The char flows through a path different from that of the gas product. The gas resulting from the pyrolysis reaction is a condensable gas that contains water vapor, tar and other volatile components. This pyrolysis gas has a high temperature because it is the result of a chemical reaction that takes place in the reactor. In this pyrolysis atomic modeling, convection is applied. Convection heat transfer occurs in the gas stream flowing from the reactor to the condenser through the pipes in the pyrolysis system.

Meanwhile, the conduction is small, thus it is ignored in atomic modeling. This is because the pipe wall has a lower thermal conductivity than the pyrolysis gas and therefore, conduction heat transfer in the pipe wall does not play a significant role in pyrolysis. This pyrolysis is slow pyrolysis because it has a heating rate <20 °C. In addition, the pipe wall generally has a higher thermal conductivity than the pyrolysis gas, so conduction heat transfer in the pipe wall can increase the pipe wall temperature, but this conduction value is usually smaller than the convection value in the gas. Thus, in the atomic model of this pyrolysis system, only heat transfer by convection is calculated.

Based on Figure 7, there is a decrease in temperature at each stage of the condenser, but the decrease in temperature is not significant, so the yield of bio-oil produced is still not optimal. The average temperature decrease is only 10–30 °C. The average reduction between the atomic model estimates and the measurement results is almost the same. Ambient air cooling is usually less efficient than cooling with water or other liquids, especially when the ambient air temperature is high. Air has a lower heat capacity than water, so air cooling may not remove heat as efficiently as liquid-based cooling. Besides, using ambient air as a coolant is challenging to reduce the temperature of the condenser. Therefore, it can reduce the efficiency of the condenser. This research still has many shortcomings and needs to be improved, especially in pyrolysis system configuration.

## 4. Conclusions

In this work, atomic modeling has been successfully developed. This atomic model determines the temperature distribution characteristics in a pyrolysis system. The pyrolysis system uses sheep manure as a feedstock with a heat source from ICE exhaust gas. The atomic model is founded on the principle of heat balance conservation, which states that the heat entering a system equals the heat exiting the system. This atomic model is based on the gas channel produced by the pyrolysis reactor, which subsequently flows into a multistage condenser. This multistage condenser's temperature steadily drops by 10–30 °C. In the principle of condensation, this temperature drop value is considered less than optimal. This is because in the pyrolysis condensation system, water coolant is used as the cooling fluid, which only relies on ambient temperature. To determine the model's accuracy level, the temperature values resulting from the estimation of the atomic model are compared with the results of experimental measurements, especially the experimental schemes B and E. The largest difference between the estimated data from the atomic model and the measurement results is the temperature of the reactor. This is because the reactor is a place of pyrolysis where complex reactions occur, thus many factors can affect the pyrolysis temperature. According to MAPE calculation, a value of 13.6% was obtained. Therefore, the atomic model can be used.

## Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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## Conflict of interest

The authors declare no conflict of interest.

## Author contributions

Conceptualization, Ahmad Indra Siswantara; methodology, Illa Rizianiza, M.Hilman Gumelar Syafei; analysis, Illa Rizianiza, Adi Syuriadi, Tanwir Ahmad Farhan; writing, review and editing: Illa Rizianiza, Candra Damis Widiawaty. All authors have read and agreed to the published version of the manuscript.

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