# Heat Transfer Modelling of Biomass Torrefaction

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**Abstract.** The depletion of coal reserves and the increase of environmental problems urge the use of renewable energy sources. Biomass is a renewable energy source and is also used as one of the feeds for co-firing, a promising energy generation technology. However, the shortcomings of biomass, such as low calorific value, hygroscopic, and low grindability, limit its usage. Torrefaction is a mild form of pyrolysis of biomass that results in better solid fuel properties. This study aims to model a simple heat transfer numerical equation to predict the torrefaction of biomass in various operating conditions. The temperature distribution in biomass during the torrefaction process is also predicted, as well as the mass yield, energy yield, and HHV behaviour of the torrefied biomass. The modelling was conducted based on Calliandra wood biomass. The pellet biomass diameter was modelled to vary within a range of 1-3 cm and a length of 10 cm. The operating conditions used for this modelling were the temperature of torrefaction with a range of 230-270 °C. Heat transfer modelling was carried out by using MATLAB. The modelling produces a numerical equation of transient heat transfer with a radial axis base with the kinetic model used as TPR (Three Parallel Reaction). The modelling produces an error of 1.424% compared to the experimental data by Felfli *et al*. The simulation shows that torrefaction that makes a higher and more uniform temperature distribution will result in a higher HHV value. Based on the simulation, the recommendation of torrefaction operating conditions for Calliandra wood with a diameter of 1-3 cm is at a torrefaction temperature of 270°C and residence time of 1.5 hours. This will result in a calorific value of approximately 5300 kcal/kg.

## 1 Introduction

Biomass is an alternative source of energy that is environmentally friendly and can be a substitute for coal. This is in line with Sustainable Development Goal (SDGs) where the global carbon emission needs to achieve net zero emission by 2050, and Indonesia committed to achieving net zero emission by 2060. The power generation from biomass energy in Indonesia reaches 32.6 GW [1]. This resource comes from energy plantation forests that spread in the Indonesian archipelago.

However, biomass has unfavourable properties if compared with coal, such as a low calorific value, low grindability, high moisture content, and low bulk density. Drying and densification (pelletizing, and briquetting) as well as pyrolysis, are some ways to improve the biomass properties for the utilization of the subsequent conversion process [2]. Torrefaction is a mild form of pyrolysis process occurring between 200 and 300°C at a residence time of up to hours which results in partial devolatilization (0-60% by weight of the original feedstock, or even retained up to 90% of its original energy [3]. The overall process can be represented by the following reaction:

*Raw biomass →Torrefied Biomass + Condensable Volatiles + Gases*

There are many studies that discuss the development of torrefaction technology in the last four decades [3-5]. Developments of biomass torrefaction have included kinetics, particle and reactor scale models, and reactor designs [2]. In the past year, many studies were focused on reaction modelling, index of torrefaction, wet torrefaction, extended applications, and moving towards commercialization.

In the torrefaction process, there are two influencing events, namely chemical kinetic reaction, and heat transfer. Heat transfer is thought to be more dominant than chemical kinetic reactions. Modelling of the torrefaction process allows us to predict the phenomena and determine the optimum condition of the process. Basu *et al* [4] presented experimental data of biomass torrefaction and it was concluded that mass and energy yield increase with particle length but contradictive with particle diameter. Al Haddad *et al*

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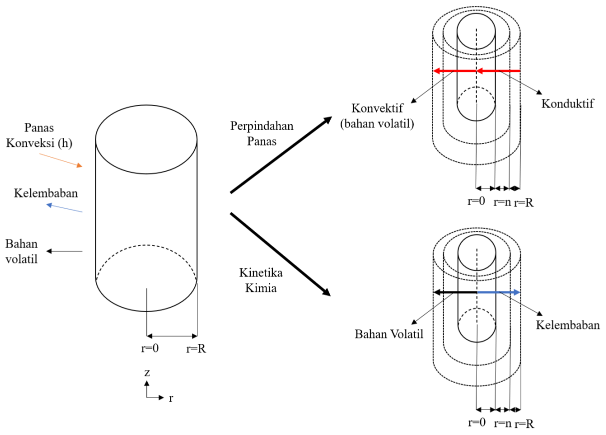
[6] modelled the biomass torrefaction and compared it to heat flux-controlled experiments. The comparison between the experimental data and simulated results shows that the kinetic parameters need to be further optimized to accurately represent the final product yields.

This study aims to model the heat transfer phenomena of biomass torrefaction. Calliandra Woods was used for the biomass model (HHV: 4720 kcal/kg), and an adaption of the mathematical model applied by Felfli *et al* [7] was used in this study.

## 2 Methodology

Torrefaction is modelled as depicted in Figure 1. The biomass pellet has cylindrical shape, with length *l* is assumed much longer compared to the diameter (*d*), so that the heat transfer occurred radially.



Heat transfer modelling started from the heat balance of the phenomena:

$$\left\{\begin{matrix} heat\ accumulation \\ rate \end{matrix}\right\} + \{\text{convection}\} =$$

$$\{\text{conduction}\} + \{\text{heat of reaction}\} \qquad (1)$$

The heat transfer is modelled as follows:

$$\frac{\partial T}{\partial t}\left(\rho_B Cp_B + \rho_c Cp_c + \varepsilon\rho_g Cp_g\right) = \frac{1}{r}\frac{\partial}{\partial r}\left(r\lambda_{eff}\frac{\partial T}{\partial r}\right)(2)$$

with $\lambda_{eff}$ is effective thermal diffusivity/
Initial value:

$$t = 0;\ T(r,0) = T_0 \quad (3)$$

The boundary conditions are as follows:

$$r = 0; \frac{\partial T}{\partial r} = 0. \qquad (4)$$

$$r = R;\ -\lambda_{eff}\frac{\partial T}{\partial r} = h(T - T_f) \ \ (5)$$

The effective conductivity is defined as :

$$\lambda_{eff} = \frac{\lambda_B\rho_B + \lambda_c\rho_c}{\rho_0} + \varepsilon\lambda_g\rho_g \qquad (6)$$

From the integration of the differential equation, biomass temperature profile will be predicted. This temperature is used for calculation of mass loss as follows:

$$\frac{\partial m_{BM}}{\partial t} = -\left(k_g + k_c + k_t\right)m_{BM} \qquad (7)$$

Where $k_g$, $k_c$, and $k_t$ is the kinetic rate constant for gas,char, tar, and the respective data taken Sasongko *et al* [9]. Remaining mass percentage is defined as 100% - percentage of mass loss.

The physical properties of pinewood that is used for model validation is presented in Table 1, while Table 2 shows the physical properties of Calliandra wood.

Table 1. Physical properties of pinewood for validation

| Parameter | Data | References |
|---|---|---|
| Density (kg/m³) | 370 | [7] |
| Porosity | 0.6971 | |
| Moisture | 0,12 | [8] |
| Heat Conductivity (W/m.K) | 0.0983 | [7] |
| Heat Capacity (J.kg/K) | 1500 + T | |

Table 2. Physical properties of Calliandra Wood

| T | 230°C | 250°C | 270°C | Ref |
|---|---|---|---|---|
| ρ (kg/m³) | 580 | 580 | 580 | [10] |
| Porosity | 0.26 | 0.26 | 0,26 | |
| Moisture | 0.105 | 0.105 | 0,105 | [11] |
| k (W/m.K) | 0.14 | 0.14<br>(2) | 0.14 | |
| h (W/m².K) | 9322 | 9.472 | 9.605 | |
| Cp (J/kg.K) | 1500+ T | 1500+T | 1500+T | |
| HHV (kkal/kg) | 4720 | 4720 | 4720 | |

(3)

Energy retention or energy yield is defined as follows:

$$\eta E = 100{,}59 \times (1 - 0{,}008\Delta m_{BM}) \qquad \textbf{(8)}$$

HHV of torrefied biomass is defined as follow (dry basis):

$$HHV = \frac{\eta E \times HHV_{init}}{\eta m} \qquad (9)$$

## 3 Results and Discussions

### 3.1 Effect of Torrefaction Temperature

The heat transfer model that has been developed was validated with Felfli's experimental data. The torrefaction experiment used Pinus cylinders (20 mm in diameter and 40 mm in length). During experiments, the temperature of each sample was measured as a function of time.

Figure 1 shows a validation of the current model with experimental data. It is obtained that the error between the model and experimental data is 1.424%. The developed model agrees with experimental data; thus, the model may be applied to explore different operating conditions.

In all simulated temperatures, the centre of biomass temperature reaches the operating torrefaction temperature after 12 minutes.

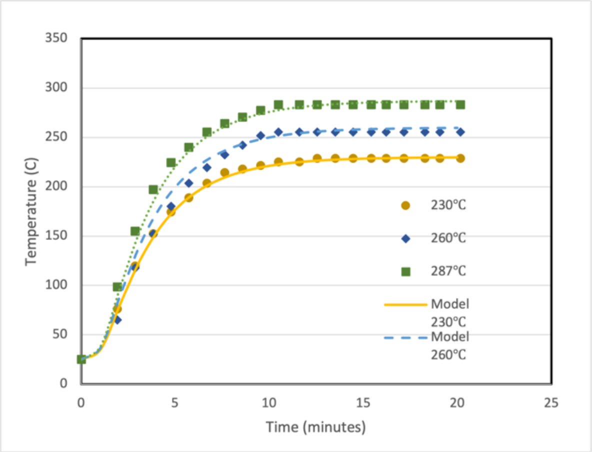


**Fig. 1.** Predicted biomass temperature at the center (line) compared with Felfli's experimental data (line)

The temperature profile obtained in Figure 1 is used to calculate the mass loss during torrefaction. Figure 2 shows the predicted remaining mass (or mass yield) during torrefaction at operating temperatures of 230, 250, and 270°C, respectively. In the first 10 minutes, the mass slightly decreases due to the temperature still increasing. After 10 minutes, there are decreases in torrefied biomass due to volatilization. The sharp decrease is found at the temperature of 270°C due to a higher kinetic rate of devolatilization.

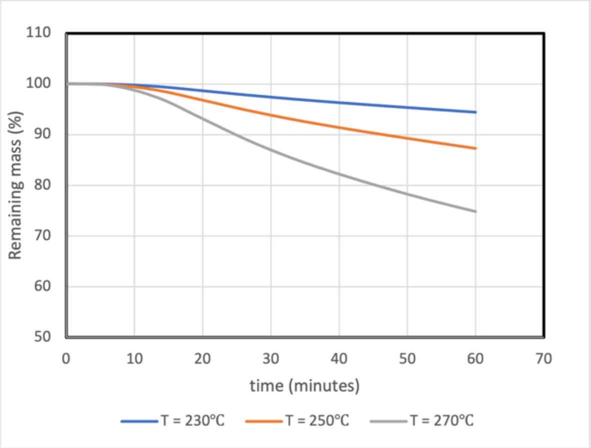


**Fig. 2.** Predicted Torrefied Biomass at Different Operating Temperature

### 3.2 Temperature distribution of pellet

To examine the distribution of temperature inside a single pellet, the simulation was conducted at the centre of the pellet (d=0), a radius of 0.5 cm (d=1/3 D), radius of 1 cm (d=2/3 D) and at the surface of the pellet (d=D). Figure 3 shows the predicted temperature of the pellet for operating temperature of 250°C. The surface temperature of the pellet sharply increases to 200°C in the first 2 minutes and gradually increases to 250°C. The temperature at different positions shows a significant difference in the first 20 minutes. At 10 minutes, the temperature of the surface is 240°C, while the centre temperature is 170°C.

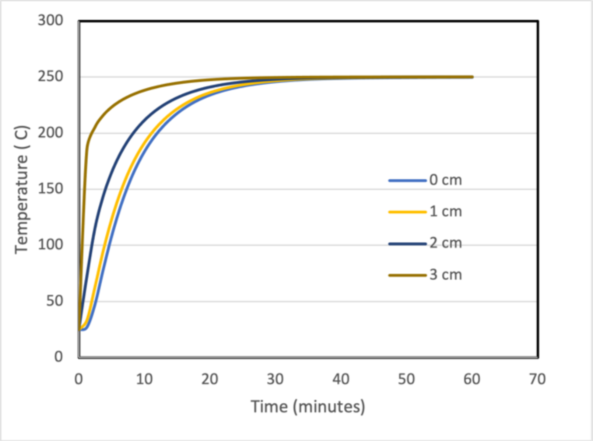


**Fig. 3.** Predicted temperature of pellet at d= 0; 1/3D, 2/3D, and D (with D= 3 cm). Operating temperature: 250°C

### 3.3 Retained Energy and HHV

One of the important parameters for the torrefaction process is the remaining mass percentage (mass yield), retained energy (energy yield), and Heavy Heating Value (HHV). HHV is an important energy density property of the resulting torrefied biomass.

Figure 4 shows the predicted remaining mass and its retained energy at a torrefaction temperature of 270°C while Figure 5 shows the comparison of the predicted remaining mass and its retained energy at temperatures 230°C, 250°C, and 270°C. In Figure 4, After 20 minutes, the mass percentage begins to decrease. As the retained energy correlates to the remaining mass, the retained energy also decreases with higher torrefaction temperature.

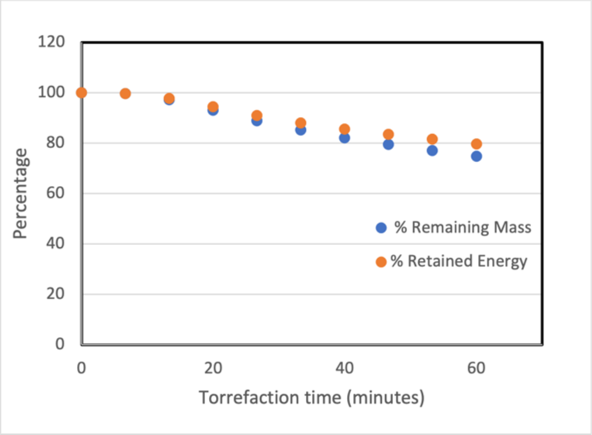


**Fig. 4.** Predicted remaining mass and retained energy at operating temperature of 270°C.

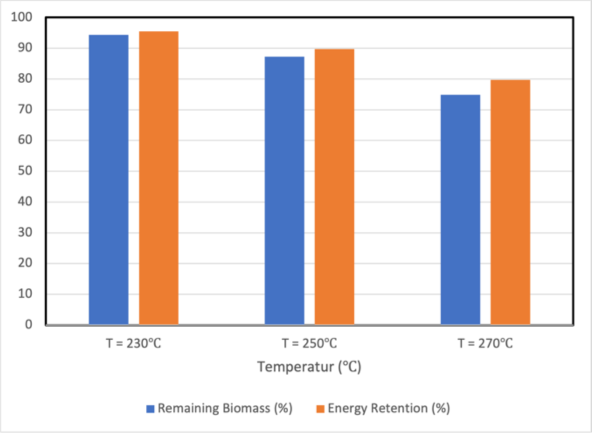


**Fig. 5.** Comparison of remaining biomass and retained energy at different torrefaction temperatures at 1 hour residence time

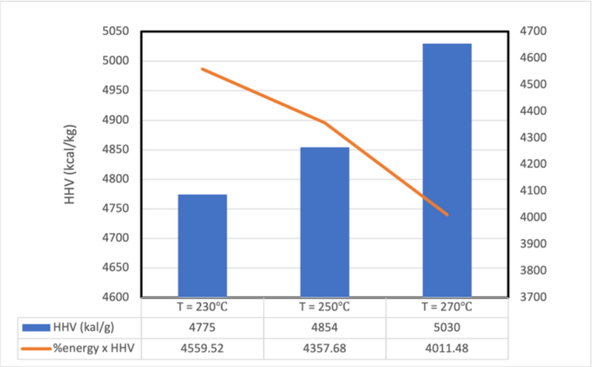


**Fig. 6.** Predicted HHV of torrefied biomass per kg product and kg biomass.

Figure 6 shows the predicted HHV of torrefied biomass at different torrefaction temperatures. Decreasing remaining mass and retention energy will increase the HHV in kcal per kg torrefied biomass product. This is because mass loss is caused by the volatilization of moisture followed by the devolatilization of volatile matter. However, when the calorific value is multiplied by its retained energy percentage from the feedstock basis, it is found that a torrefaction temperature of 230°C retains higher energy compared to 270°C.

The retained energy for torrefaction of 230°C is predicted to 4559 kcal/kg-raw material, while the retained energy for torrefaction of 270°C is 4011 kcal/kg-raw material, as there is significant amount of compound has volatilized at higher temperature.

### 3.4 Effect of Pellet Size to HHV

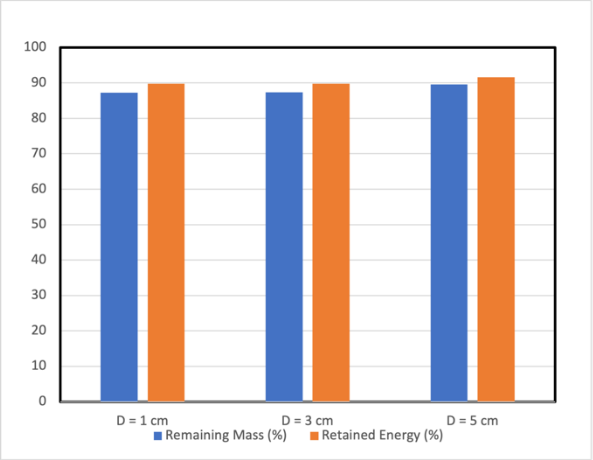


**Fig. 6.** Effect of Pellet Size to HHV of Torrefied Biomass at 250°C

Figure 6 shows the results of remaining mass and retained energy of biomass torrefaction at 250°C and 1 hour with different pellet diameters, i.e., 1 cm, 3 cm, and 5 cm. Increasing pellet size results in increasing remaining mass and retained energy, since the heat transfer rate in higher diameter is slower.

The heat transfer modelling confirms several aspects that agree with other studies [5]. The remaining mass and retained energy decrease as the diameter for a fixed length is kept constant.

This model has a limitation that has not been able to break the de-volatilized compound, such as moisture and volatile matter.

## 4 Conclusions

Modelling of heat transfer numerical equation has been developed to predict the torrefaction of Calliandra wood in cylindrical pellets in torrefaction ranges 230 to 270°C. The modelling produces an error of 1.424% compared to the experimental data by Felfli *et al* for a case of pine wood torrefaction. The simulation shows that increasing torrefaction will result in more uniform temperature distribution and result in a higher HHV value. The heat distribution in biomass during the torrefaction process can be predicted, as well as the remaining mass, retained energy, and HHV behaviour of the torrefied biomass. Based on the simulation, the recommendation of torrefaction operating conditions for Calliandra wood with a diameter of 1 to 3 cm is at a torrefaction temperature of 270°C or more for a maximum of 1.5 hours. This will result in a calorific value of 5300 kcal/kg. A validation of this model to Calliandra wood torrefaction is needed for further refinement of the model.

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