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Analysis of the Propagation of Temperature and Thermal Conductivity of Sawdust Pyrolysis Process with Modeling Fea and Experiment

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***Abstract*—The study uses densified sawdust with heat propagation and thermal conductivity to achieve better pyrolysis and gasification processes. Analysis of sawdust's heat propagation and thermal conductivity during pyrolysis was developed with Finite Element Analysis (FEA). The thermal conductivity values of sawdust (k) obtained from FEA are 1.49, 1.3, 1.1, and 0.7 W/m C considering the sawdust heated with a triggering temperature (T0) 535 ºC and reaches a constant temperature of T1 = 265 ºC, T2 = 165 ºC, T3 = 115, and T4 = 95 ºC respectively after 20 minutes. The temperature distribution of sawdust heated shows between the experimental and FEA results is quite the same; however, differences on graph T1 show the experimental thermal conductivity (k) value is distinct from the simulated thermal conductivity (k) value due to a significant change that occurred as sawdust transformed into charcoal at minute 70, where the distance between point T1 and the trigger point (T0) is 40mm and after 180 minutes the sawdust had turned into charcoal completely. Furthermore, 31 grams (6.46%) of sawdust underwent pyrolysis in this experiment. The findings can aid future research and development in this field and provide valuable insight into the duration of time a bio stove utilizing compacted sawdust can produce a sustainable flame and be used as a reference for future experiments.**

***Keywords*— Thermal conductivity; sawdust; charcoal; pyrolysis; heat propagation; FEA.**

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I. INTRODUCTION

Wood Biomass is a renewable energy source as a substitute for fossil fuels (petroleum) because of some beneficial properties that can be utilized sustainably. The potential for developing biomass energy is estimated at 50 GWe, while Indonesia's installed biomass energy capacity is around 1600 MW [1]. Wood biomass utilization in Indonesia has been a significant focus due to the country's abundant resources and the potential for renewable energy sources [1], [2], [3]. Teak wood is frequently used as a raw material for furniture production[4]. Teak wood sawdust is readily available, but its utilization as a material to aid in brick burning and its subsequent disposal can lead to environmental pollution [5], [6]. Wood biomass resources can be converted through various thermochemical processes such as gasification, pyrolysis, and combustion [7], [8], [9].

Process gasification occurs in several stages, drying at 100–200 °C and then pyrolysis at 200–500 °C. This results in the decomposition of biomass components into charcoal and gas (H_2, CO, CO_2, and CH_4)[10], [11], [12].

The heat propagation of sawdust during the pyrolysis process can significantly influence the quality and outcome of the obtained syngas, as demonstrated in various research studies. For instance, the first research projects found that pyrolysis temperature can impact the distribution and properties of the resulting products, with higher temperatures causing an enhancement of gas and liquid yields whereas detract in charcoal yield [13], [14]. The second research project discovered that pretreatment of sawdust with microwave before pyrolysis can enhance the degree of semi-aromatic tar produced [15], [16], [17]. The third research project reported that the primary process of pyrolysis (residence time, heating rate, and heat) impacted the results and product properties of sawdust[18], [19]. The fourth research project suggested that the thermal resistance of sawdust blocks can slow down the propagation rate of the pyrolysis process [20]. The fifth research project demonstrated that the devolatilization kinetics of sawdust during pyrolysis can be studied using thermogravimetric analyzers to understand the process and obtain global kinetic parameters [21], [22]. The sixth research project highlighted that high sawdust density in the bio stove produces a larger heat propagation area and a faster heating rate [23]. The seventh research project investigated the flame duration shown in Fig. 1, which varies based on the density of sawdust used in bio stoves. The density of sawdust directly impacts heat propagation, which can be observed through the production of syngas [24].

(a) (b)

Fig. 1 (a) Syngas is produced by heating sawdust in the center of compacted sawdust on a bio stove (b) Saw dust in bio stove[24]

Based on the available research, we can conclude that a comprehensive analysis of sawdust's heat propagation and thermal conductivity during the pyrolysis process with Finite Element Analysis (FEA) and experiment is yet to be conducted. Moreover, critical analysis of the sawdust conductivity is subjected to process pyrolysis until it turns charcoal. Therefore, this research aims to provide valuable insights into the pyrolysis process that produces optimal syngas in sawdust by determining the conductivity value, time, and temperature of propagation in the sawdust. Furthermore, it may be used as a reference to determine how long a Bio stove with sawdust can produce the flame.

II. MATERIALS AND METHOD

A. Materials

The researcher obtained sawdust from one of the reputable processing of wood stored in Yogyakarta, and all experiments were conducted in a well-equipped materials laboratory at Yogyakarta State University. The sawdust sample was carefully screened with a tolerance level of +/- 2mm, weighed accurately at 165 grams, and then compressed into a tube of the specified dimensions in Table 1.

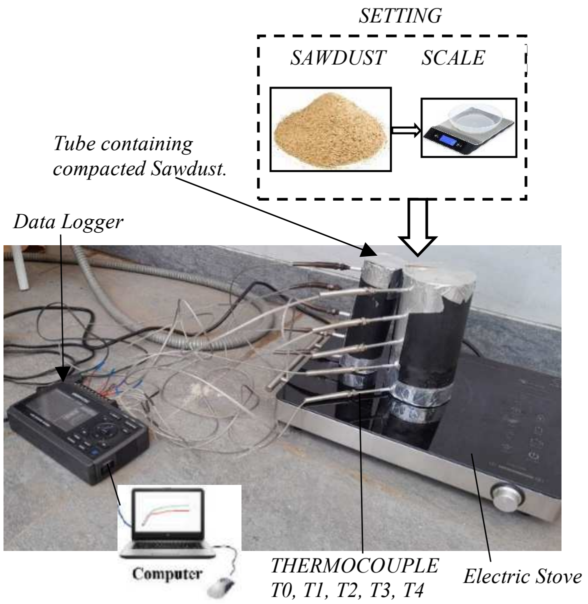
TABLE I
EXPERIMENT CONDITION

Conditions	Nomenclature	Values	Unity
Trigger Temperature	T0	35 - 535	ºC
Working Time	Ts	1 - 180	Min.
Inside Diameter of Tube	ID	54	mm
Tube Height	H	170	mm
Weight Sawdust before heating	m_i	470	gram
Weight sawdust after heating	m_a	439	gram
Sawdust Weight	m_s	165	gram
Sawdust Specific Gravity	ρ_s	0.004	gram/mm³
Distance between thermocouples	X	@40	mm

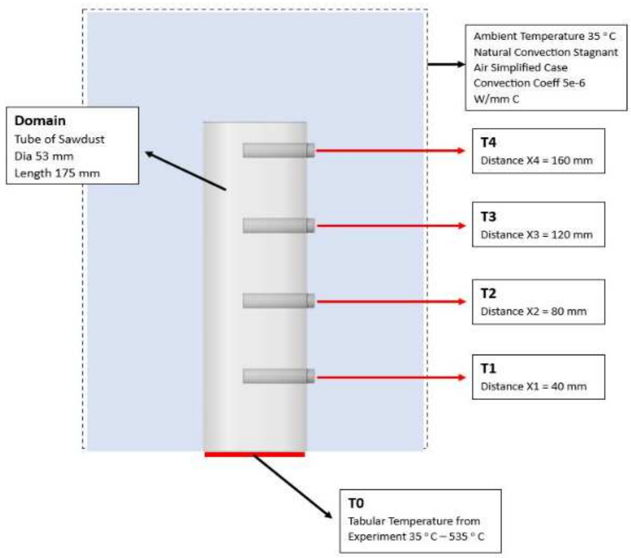
Afterward, the compacted sawdust was heated using an electric stove, with a trigger temperature range of 35-535 ºC and 1-180 minutes, as illustrated in Fig. 1. (a). Five thermocouples were installed at different distances to record the sawdust's temperature readings using a mini logger. These readings were plotted against time to generate a comprehensive sawdust's heat propagation and thermal conductivity graph.

B. Experiment Procedure

The compacted sawdust was subjected to heat using an electric stove, with a trigger temperature range of 35-535 ºC and a duration of 1-180 minutes, as illustrated in Fig. 2. (a) This technique is called the hot disk method [25], [26]. The five thermocouples were installed at different distances using a mini logger to record the sawdust's temperature readings. These readings were plotted against time to generate a comprehensive sawdust's heat propagation and thermal conductivity graph.



(a)



(b)

Fig. 2 (a) Experimental equipment to measure thermal effects during the pyrolysis process installed five thermocouples to measure compacted sawdust (b) FEA boundary conditions on compacted sawdust.

C. *Material Properties*

The experiment used the material properties based on Table 2. Sawdust was heated gradually from 35 to 533 °C.

TABLE II
TEAK WOOD SAWDUST PROPERTIES

Condition	Nomenclature	Values	Unity
Cellulose	S	34.5	%
Hemicellulose	H	28.6	%
Lignin	L	22.7	%
Water Content	Ka	9.26	%

D. *Finite Element Analysis (FEA)*

FEA models were conducted with boundary conditions as illustrated in Fig. 2 (b) by using ANSYS software to determine the heat propagation and thermal conductivity of the sawdust pyrolysis, which was done by previous project research [27], [28]. This research focuses on different temperature sensor points, T0-T4. Based on some of the research projects conducted, it was assumed a sawdust conductivity value of 1.49 W/m.C [29], [30].

III. RESULTS AND DISCUSSION

FEA modeling results are presented in Table 3 above, which shows the Thermal Conductivity at a certain temperature of sawdust on each point.

TABLE III
MAXIMUM AND MINIMUM TEMPERATURE VALUES AT A CERTAIN TIME AT EACH SENSOR POINT FROM THE FEA RESULTS

Position	Temp Min. (°C)	Time (Min.)	Temp. Max. (°C)	Time (Min.)	Thermal Conductivity (W/m C)
T0 (Trigger)	31.4	1	535	180	N/A
T1	31.2	1	265	180	0.7
T2	31.1	1	165	180	1.1
T3	31.1	1	115	180	1.3
T4	31.1	1	95	180	1.49

According to Table 3 above, the temperature and time graph are depicted in Fig. 3 below. The FEA simulation results illustrated in graphic Fig. 3 above show that the sawdust heated with a triggering temperature (T0) of 35-535 °C on points T1, T2, T3, and T4 reaches a constant temperature of T1 = 250 - 265 °C, T2 = 155 - 165 °C, T3 = 105 - 115, and T4 = 60 - 95 °C respectively after 20 minutes.

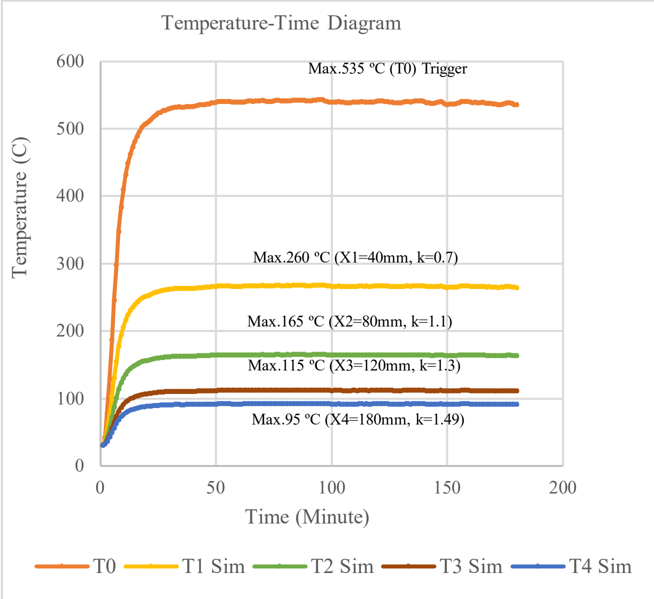


Fig. 3 Temperature, time graph, and Snapshot of FEA results

Each point's thermal conductivity values (k) have been adjusted to reflect the different constant temperature values obtained from experiments. It is worth noting that the value of (k) for sawdust decreases shown in Table 3 above (1.49, 1.3, 1.1, and 0.7 W/m C) as it transforms into charcoal due to the increase in temperature and the pyrolysis process that occurs. This information can help understand the behavior of sawdust under different heating conditions.

The temperature and time graph in Fig.3 shows that the value k changed linearly against time before a constant temperature of sawdust. It can be expressed as a linear equation (1) below.

$$K = (1 - x)\ Ksawdust + K\ charcoal \qquad (1)$$

The FEA simulation results show that conductivity, k, the heat transfer rate of sawdust, is calculated using equation (2) per heat conduction formula (Fourier's law)[31], [32], [33].

$$Q = k.A\ \frac{T0 - TX}{L} \qquad (2)$$

TABLE IV
HEAT TRANSFER RATE OF SAWDUST

Position	(T0) Temp. Min. (°C)	(TX)TempMax. (°C)	(K) Thermal Cond.(W/m C)	(L) Trigger point distance (m)	(A) Area Sawdust (m²)	(Q) Heat Transfer Rate (Watt)
T0 (Trigger)	31.4	535	-	-	-	-
T1	31.185	265	0.7	0.04	0.0023	10.816
T2	31.105	165	1.1	0.08	0.0023	11.646
T3	31.064	115	1.3	0.12	0.0023	10.415
T4	31.048	95	1.49	0.16	0.0023	9.379

The Heat transfer rate of sawdust illustrated in Table 4 above shows that as the value of k increases, the rate at which is transferred also increases, resulting in a faster transfer of heat in sawdust. Accordingly, it revealed that the value Q corresponded to syngas production sawdust. It will increase when the sawdust turns into charcoal/syngas production. To further enhance the accuracy of FEA results, the Experiment result is presented in Table 5, which shows the Temperature against the time of sawdust during the experiment. According to Table 5, the temperature and time graph are depicted in Fig. 4.

TABLE V

MAXIMUM AND MINIMUM TEMPERATURE VALUES AT A CERTAIN TIME AT EACH SENSOR POINT FROM EXPERIMENTAL RESULTS

Position	Temp. Min. (°C)	Time(Min.)	Temp. Max. (°C)	Time.(Min.)
T0 (Trigger)	31.4	1	535	180
T1	31.4	1	260	180
T2	31.8	1	170	180
T3	31.8	1	115	180
T4	31.5	1	95	180

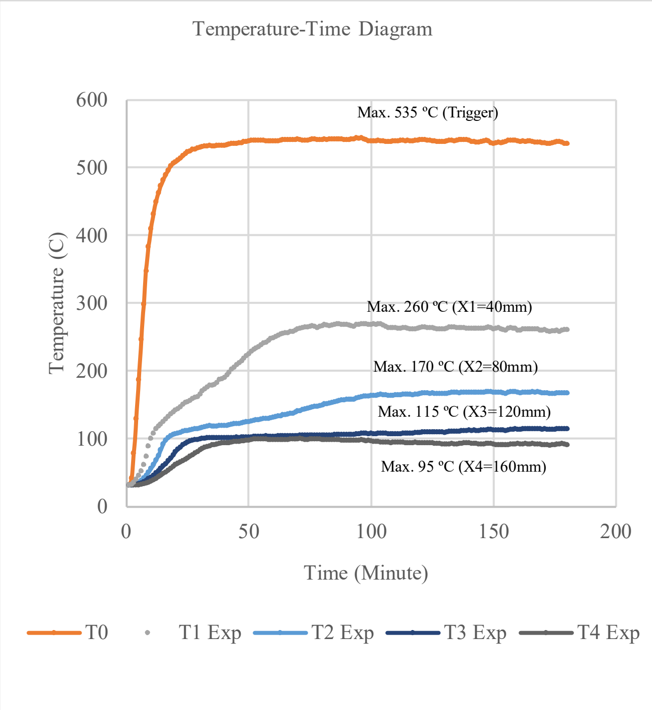


Fig. 4 Temperature, time graph, and illustration of experimental results

The experimental results illustrated in Fig. 4 show that the temperature distribution of sawdust heated with a trigger temperature (T0) of 35-535 °C on points T1, T2, T3, and T4 is quite interesting. The temperature at point T1 reaches a constant temperature of 250-260 °C after 60 minutes, indicating that the sawdust has turned into charcoal or the pyrolysis process has already occurred entirely. This is because the distance between T1 and the trigger point (40mm) is very close. At point T2, the temperature reaches a constant temperature of 150-170 °C at 80 minutes, indicating that only some sawdust will turn into charcoal. Meanwhile, points T3 and T4 reach a continual temperature of 90-115 °C at 25 minutes, indicating that the sawdust has not yet turned into charcoal. Based on Table 1, we can see that the weight of the tube containing the sawdust before being heated is 470 grams, and the weight of the tube containing the sawdust after being heated for 180 minutes is 439 grams. This means that 31 grams (6.46%) of sawdust underwent pyrolysis. This information is valuable as it can help us better understand the behavior of sawdust when heated to different temperatures.

Based on the presented Fig. 3 and 4, it can be observed that the experimental and simulated points, T1, reach a maximum or constant temperature of approximately 260-265 °C. This temperature indicates the average thermal conductivity (k) of sawdust and charcoal, which was found to be 0.7 W/m C. The difference between the experimental and simulated graphs for T1 shows that the experimental thermal conductivity (k) value is distinct from the simulated thermal conductivity (k) value. During the experiment, a significant change occurred as sawdust transformed into charcoal at minute 70, where the distance between point T1 and the trigger point (T0) was only 40mm. The experimental results at minute 180 demonstrated that the sawdust had turned into charcoal (complete pyrolysis) or had produced syngas at that point (distance between point T0 and T1 = 40mm).

Similarly, the experimental and simulated T2 points reach a maximum or constant temperature of about 165-170 °C. This temperature shows an average thermal conductivity (k) value of sawdust and charcoal of 1.1 W/m C. The difference between the experimental and simulated graphs for T2 reveals that the experimental thermal conductivity (k) value is dissimilar from the simulated thermal conductivity (k) value. At minute 100, some sawdust transformed into charcoal, where the distance between point T2 and the trigger point (T0) was 80mm. At minute 180, the experimental results indicated that some of the sawdust had turned into charcoal (complete pyrolysis), while the rest did not turn into charcoal at that point (distance between point T0 and T2 = 80mm).

Furthermore, the experimental points T3 and T4 and simulated points T3 and T4 reach a maximum or constant temperature of around 115 °C and 95 °C, respectively. This temperature signifies a thermal conductivity (k) value of sawdust of 1.3 W/m C on point T3 and 1.49 W/m C on point T4. The slight difference between the experimental and simulated graphs for T3 and T4 indicates that sawdust at those points did not turn into charcoal or produce syngas after 180 minutes (3 hours) of the experiment. This was due to the distance from the trigger temperature (T0), where T0 - T3 = 120mm and T0-T4 = 160mm.

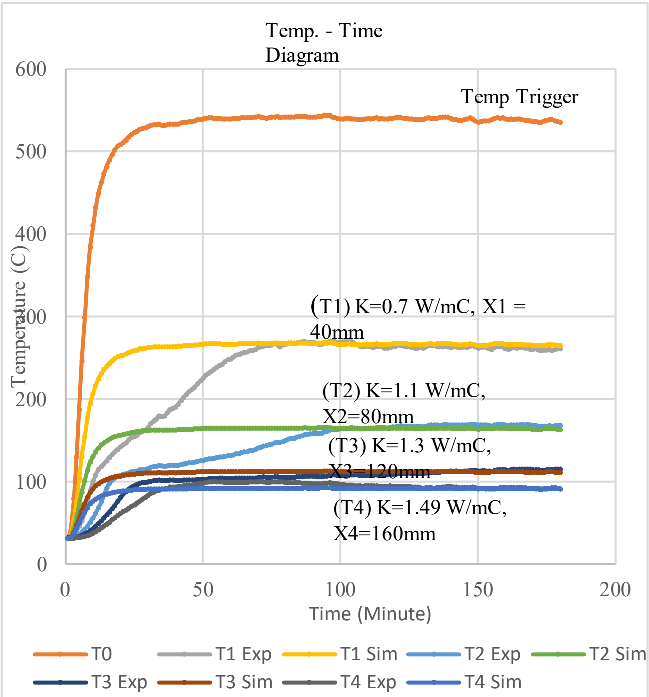


Fig. 5 Combined graph of experimental results and FEA simulation

The graph in Figure 5 displays the experimental and FEA simulation results. It is worth noting that the assumed value (k) was adjusted to fit the experimental graph, which led to a close approximation between the assumed value and experimental results. However, the difference between the experimental and FEA simulation results is that as the value of (k) decreases, some of the sawdust becomes charcoal or undergoes a pyrolysis process, which is not accounted for in the FEA simulation.

Furthermore, it was mentioned above that the Temperature–Time Graphic for simulation and experiment mentioned the same trend of the graphic, which is the initial sawdust changed to charcoal or up to come on the constant temperature in a linear line.

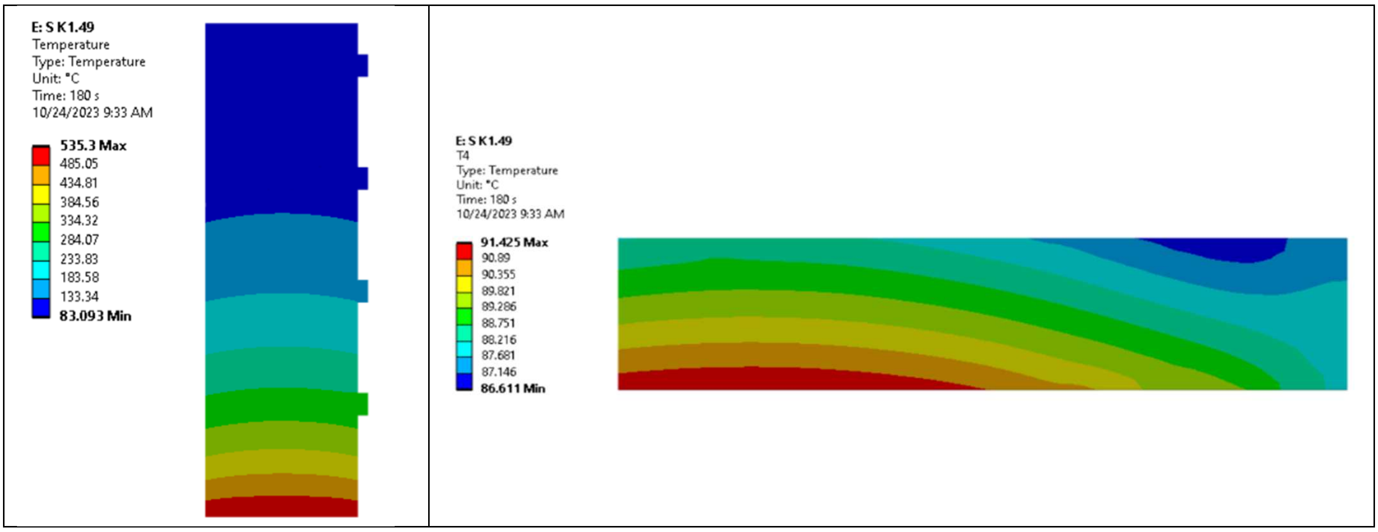


Fig. 6 Snapshot temperature distribution at each value k = 1.49 of sawdust conductivity

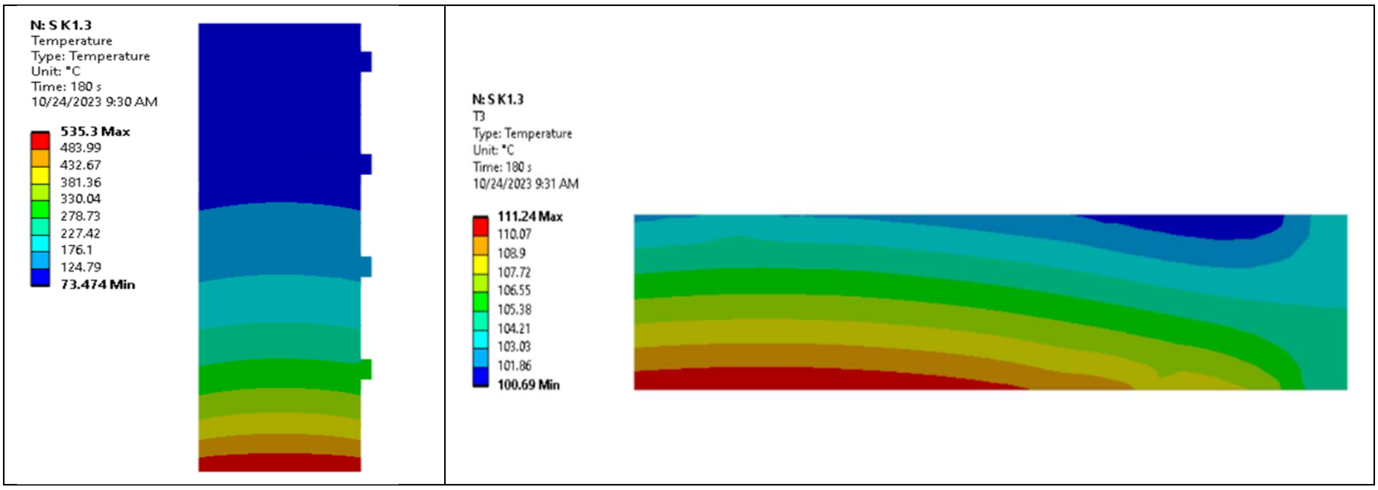


Fig. 7 Snapshot temperature distribution at each value k = 1.3 of sawdust conductivity.

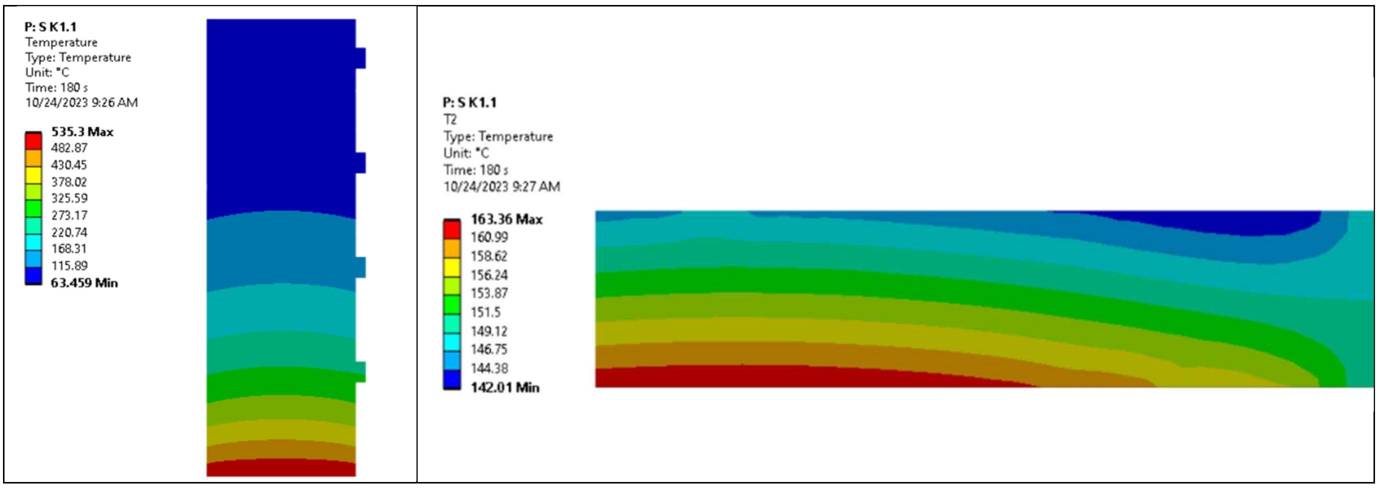


Fig. 8 Snapshot temperature distribution at each value k = 1.1 of sawdust conductivity.

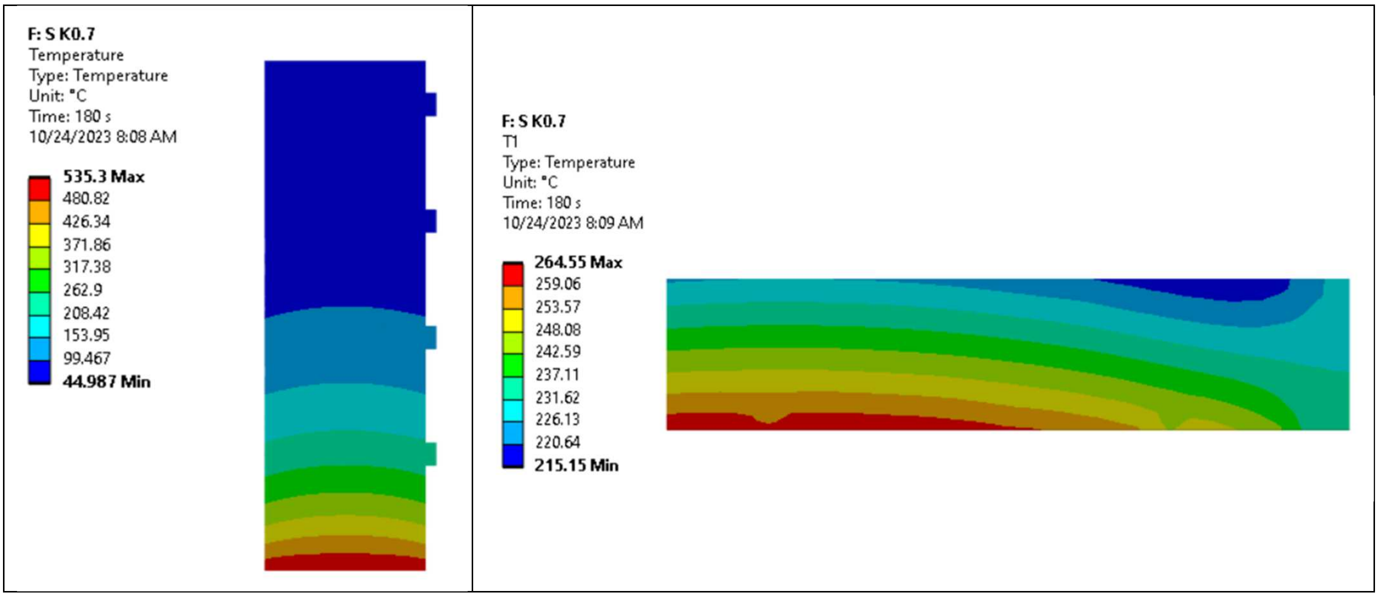


Fig. 9 Snapshot temperature distribution at each value k = 0.7 of sawdust conductivity.

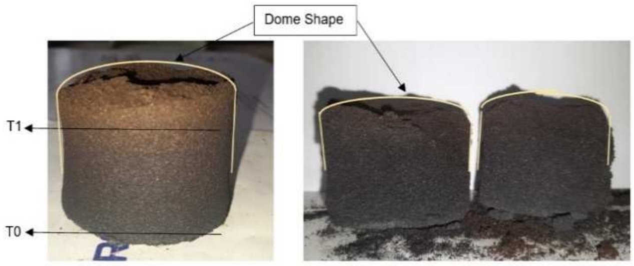


Fig. 10 Photo Sawdust Experiment Results after heating for 180 minutes.

Moreover, the simulation results of FEA findings in Figures 6, 7, 8, and 9 agree, demonstrating that the sawdust turning into charcoal displays a dome-shaped contour. This is because the sawdust at the center has a high temperature, which is not influenced by the temperature outside the tube. On the other hand, the sawdust near the tube is affected by the temperature outside the tube.

The experiment results presented in Fig. 10 agree that the sawdust turning into charcoal displays a dome-shaped contour, especially in point T1, near T0 as the trigger temperature. This is because the sawdust at the center has a high temperature, which is not influenced by the temperature outside the tube. On the other hand, the sawdust near the tube is affected by the temperature outside the tube.

Accordingly, it was clearly shown that the conversion of compacted sawdust to charcoal has concluded, thereby eliminating syngas production. This phenomenon can be better understood by examining the conductivity values observed during the experimental result using FEA simulation, as depicted above. Additionally, the conductivity value of sawdust provides a valuable time indicator for producing syngas.

IV. Conclusion

Based on the research results, FEA obtained the thermal conductivity value for teak wood sawdust (k = 1.49, 1.3, 1.1 dan 0.7 w/m C) that corresponded with the experimental findings, as the values decreased when the sawdust turned into charcoal. Similarly, the simulation and experiment results matched that the sawdust turning into charcoal displays a dome-shaped contour. Furthermore, the research established that 31 grams (6.46%) of sawdust underwent pyrolysis within 180 minutes.

The study concluded that it may be used to predict the k value of sawdust changes against the time of the pyrolysis process. This observation provides valuable insight into the duration of time a bio stove utilizing compacted sawdust can produce a sustainable flame and be used as a reference for future experiments.

Nomenclature

Q	heat transfer rate	Watt
L	length trigger point distance	m
A	cross-sectional area of sawdust	m^2
T0	trigger temperature	°C
TX	maximum temperature of each sensor	°C
k	conductivity thermal of sawdust	W/m C
L	length trigger point distance	m

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