

Laboratory Experiments on the Effect of Moisture Content on Fire Propagation and Overhang Phenomenon in Burnt Tropical Peat Samples (Uji Laboratotium Pengaruh Kadar Air terhadap Penyebaran Api dan Fenomena Overhang pada Sampel Gambut Tropika Terbakar)

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Abstract

Peat fires are categorized as ground fires and are often accompanied by the formation of overhangs, which indicate deep peat fire occurrences. This study aims to examine how peat fires propagate under different moisture contents and how this affects the formation of overhangs at a laboratory scale. The parameters assessed include temperature changes over time, propagation rate, temperature distribution, and the visual presence of overhangs. Peat samples with 8%, 15%, and 23% moisture content were tested. The results showed that heat lasted the shortest in the 23% moisture content samples. Fire propagation was faster in the vertical direction than horizontally. Differences in temperature distribution at the start of combustion were caused by a shift in the coil heater. Notably, overhang structures were visually identified only in the 23% moisture content samples, while the 8% and 15% samples showed only the subsidences.

Keywords: Peat fires, combustion, subsidence

Abstrak

Kebakaran gambut dikategorikan sebagai kebakaran bawah permukaan (*ground fire*) dan sering disertai dengan terbentuknya *overhang* yang menunjukkan terjadinya pembakaran gambut dalam. Penelitian ini bertujuan untuk mengkaji bagaimana penyebaran api pada gambut dengan kadar air yang berbeda serta dampaknya terhadap pembentukan *overhang* pada skala laboratorium. Parameter yang diamati, meliputi perubahan suhu terhadap waktu, laju penjalaran api, distribusi suhu, dan keberadaan visual *overhang*. Sampel gambut dengan kadar air 8%, 15%, dan 23% digunakan dalam percobaan. Hasil penelitian menunjukkan bahwa panas paling cepat hilang pada sampel dengan kadar air 23%. Penyebaran api lebih cepat terjadi secara vertikal dibandingkan horizontal. Perbedaan distribusi suhu pada awal pembakaran disebabkan oleh pergeseran koil pemanas. Secara visual, struktur *overhang* hanya teridentifikasi pada sampel dengan kadar air 23%, sedangkan pada sampel 8% dan 15% hanya menunjukkan subsidensi.

Kata kunci: Kebakaran gambut, pembakaran, subsidensi

1. Introduction

Peatlands are vital ecosystems formed through the long-term accumulation of organic matter under waterlogged conditions. Indonesia's peatlands, covering approximately 13.43 million hectares, are predominantly found

in Sumatra (43.6%), Kalimantan (33.8%), Papua (22.4%), and Sulawesi (0.18%) (Anda et al., 2021). These ecosystems develop through paludification, a process in which plant biomass, particularly from trees, accumulates more rapidly than it decomposes, resulting in distinct soil

characteristics (Wahyunto & Suryadiputra, 2008; Noor et al., 2014). Peat ecosystems are fragile and prone to degradation because of their unique physical, chemical, and biological characteristics. Moreover, tropical peat soils are subject to irreversible drying, and have sensitivity to subsidence (Yuwati et al., 2021)

Degraded peatlands undergo a transformation from hydrophilic to hydrophobic properties, reducing their water retention capacity and increasing their vulnerability to fire (Noor et al., 2014; Perdana et al., 2018). Peat fires, which typically ignite at the surface and smolder beneath the ground, are notoriously challenging to extinguish. Lin et al. (2020) showed that the minimum rainfall intensity to extinguish the peat fire is roughly 4 mm/h, so that the persistent light rain cannot suppress such smoldering wildfire. These fires emit significant amounts of carbon dioxide (CO₂), exacerbating global warming and also lead to land subsidence and widespread ecological damage (Rein et al., 2008; Noor et al., 2014). A particularly destructive feature of these fires is the overhanging soil phenomenon, where unburnt surface layers remain suspended above the burnt sublayers, indicating deep peat fires (Huang et al., 2016). An overhang is formed because of the faster horizontal spread rate a few centimeters below the surface due to the reduced convective heat losses compared to the free surface of the organic soil fuel bed. The collapse of the peat overhang is because the char layer is gradually consumed and can no longer support the weight of the above soil (Santoso et. al.,

2019).

Although peat fires have been widely studied, the overhang soil phenomenon—especially in tropical peatlands—is still not well understood. Some studies have studied this phenomenon in tropical peat, such as research done by Usup et al. (2004), Santoso et al. (2022), and Palamba & Wardhani (2023). However, there has been no research specifically focused on overhang formation in tropical peat from previously burnt areas. This study aims to observe how peat fires spread under different moisture contents and how this affects the formation of overhangs at the laboratory scale. The results are expected to provide useful insights into fire behavior in tropical peat and help improve strategies for fire control and sustainable peatland management. To our knowledge, this is the first study that explores overhang characteristics in peat samples taken from post-burn areas.

2. Methodology

2.1. Location and equipment used

The peat soil samples used in this study were oven-dried to reach three targeted moisture content (MC) levels: 8%, 15%, and 23%. The samples were collected from a burnt peatland area located in Sinar Wajo Village, Tanjung Jabung Timur Regency, Jambi Province, Indonesia. Peat sampling was carried out using an intact soil sampling method to maintain the natural structure of the peat. The sampler used was a 60 cm PVC tube fitted with end caps (Fig. 1).



Fig. (Gambar) 1. A-60 cm PVS used to collect peat samples (*Paralon setinggi 60 cm yang digunakan untuk mengambil sampel gambut*)

The laboratory experiment was conducted at the Thermodynamics Laboratory, Department of Mechanical Engineering, Faculty of Engineering, University of Indonesia. The equipment used in this study includes a moisture analyzer, trash bags, aluminum foil, baking trays, an oven, an analytical balance, a coil heater (heating wire) with a length of 10 cm and 10 coils, plastic jars, a 10 x 10 x 10 cm reactor that constructed

by the Thermodynamics Laboratory, nine thermocouples (TC), a Graphtec data acquisition device surrounded by an insulator made of calcium silicate board, a power supply with a capacity of 42A, a webcam, mica sheets, OriginPro software, and a laptop. The nine thermocouples used were arranged in three rows indicating the depth of the peat sample, e.g. 2.5 cm, 5 cm and 7.5 cm. Each row consists of three thermocouples.

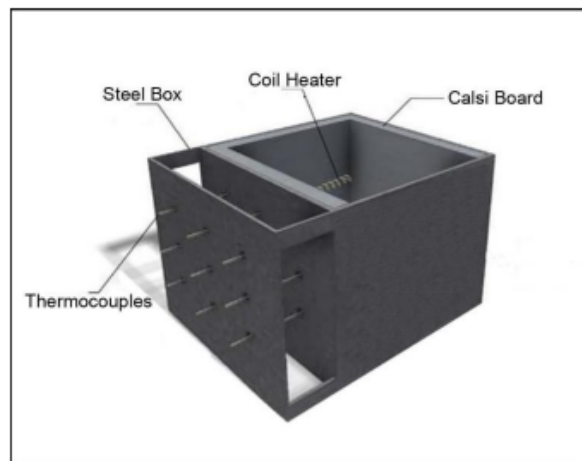


Fig. (Gambar) 2. The reactor design used (*Desain reaktor yang digunakan*)

2.2. Data Analysis Procedure

2.2.1. Temperature propagation testing

Soil samples were dried in an oven set at 100°C to reach moisture contents of 8%, 15%, and 23%, then placed in a reactor equipped with thermocouples (TCs) and a coil heater. A smoldering combustion test was carried out by connecting the coil heater to a power supply, which heated the sample for 60 minutes, allowing the peat around the coil to ignite and the fire to propagate.

2.2.2. Analysis of vertical and horizontal propagation directions

Vertical and horizontal fire propagation was analyzed by monitoring thermocouple readings until the temperature reached 300°C. At this temperature range (250–350°C), peat begins to convert into charcoal and volatile compounds (Martin et al., 2019; Usup et al., 2004). The propagation speed

(*v*) was calculated by dividing the distance between thermocouples (e.g., TC1 to TC2) by the time it took for the temperature at each point to reach 300°C. For vertical propagation, speeds (*v*₁, *v*₂, etc.) were measured between thermocouples placed at different depths. For horizontal propagation, speeds were calculated between thermocouples arranged laterally (e.g., TC1 to TC2 across the same depth).

$$v_1 = s_1 / \Delta t$$

Where:

*v*₁ : First propagation speed

*s*₁ : Distance between thermocouples

Δt : Time difference

The average combustion propagation speed is calculated by averaging all speeds.

$$v = (v_1 + v_2 + v_3 + v_4 + v_5 + v_6) / 6$$

Where:
 v : Average speed of heat peat propagation (cm/hour)

$v_1, \dots, 6$: Propagation speed between each thermocouple (cm/hour)

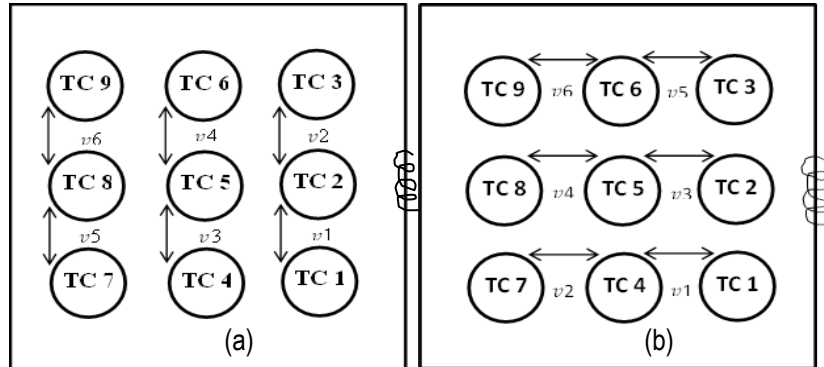


Fig. (Gambar) 3. (a) Vertical and (b) horizontal propagation diagram. TC1, TC2, etc refer to the thermocouple number. v_1, v_2 , etc refer to the propagation speed between successive thermocouples ((a) Diagram perambatan vertikal dan (b) horizontal). TC1, TC2, dan seterusnya menunjukkan nomor termokopel. v_1, v_2 , dan seterusnya merupakan kecepatan propagasi antara termokopel yang berdampingan.

2.2.3. Combustion testing

Peat samples were placed into the reactor, and the power supply was activated to initiate combustion. Temperature data was recorded using a Graphtec data acquisition system throughout the combustion process. After completion, the collected data was processed to analyze the effects of moisture content on combustion characteristics.

3. Results and Discussion

3.1. Results

3.1.1. Impact of moisture content on temperature dynamics

Temperature fluctuations were observed during combustion at different moisture content levels. Fig. 4 shows these fluctuations, with the highest temperature (408.1°C) recorded at TC4. Thermocouples placed at 5 cm depth recorded higher temperatures because they were closer to the heat source. Meanwhile, TCs at 2.5 cm depth cooled down to ambient temperature within 11 hours and 7 minutes. In comparison, deeper layers at 5 cm and 7.5 cm took longer—about 13 hours and 33 minutes—to cool, indicating slower heat dissipation at those depths.

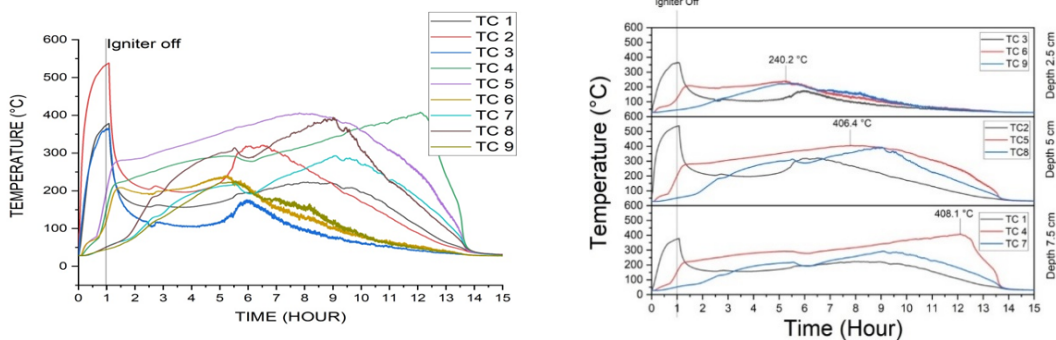


Fig. (Gambar) 4. Temperature changes over time (left) and per depth (right) at 8% water content (*Perubahan suhu seiring waktu (kiri) dan per kedalaman (kanan) pada kadar air 8%*)

We found the similar temperature fluctuations at 15% moisture content, with the highest temperature (460.6°C) at TC 5 (Fig. 5). TCs at 5 cm depth recorded the

highest average temperatures, while TCs at 2.5 cm cooled faster (within 8 hours and 13 minutes) compared to the 8% moisture.

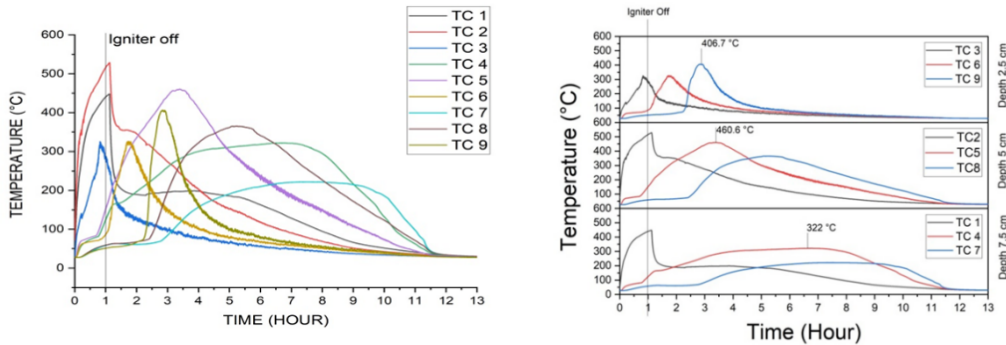


Fig. (Gambar) 5. Temperature changes over time (left) and per depth (right) at 15% water content (*Perubahan suhu dari waktu ke waktu (kiri) dan per kedalaman (kanan) pada kadar air 15%*)

Higher moisture content of 23% significantly inhibited combustion, with the highest temperature reaching only 180°C at TC 9 (Fig. 6). Thermocouple 1

which located at a depth of 7.5 cm, recorded a higher temperature compared to the other thermocouple.

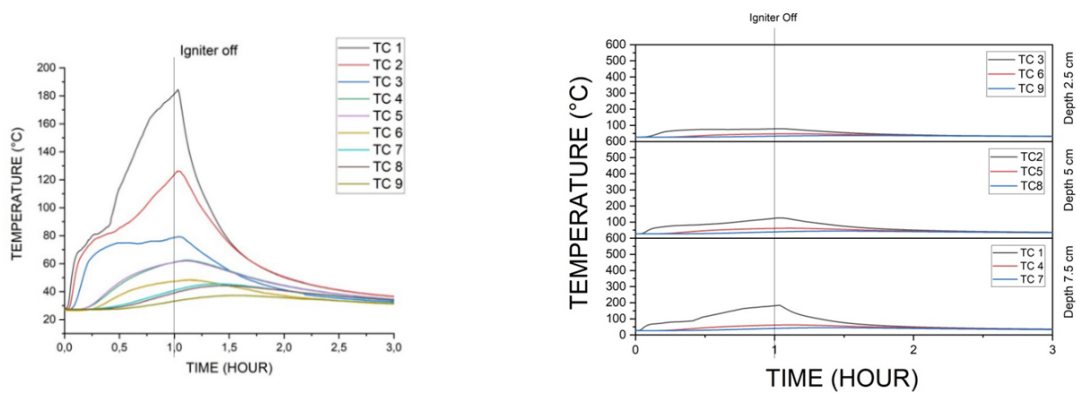


Fig. (Gambar) 6. Temperature changes over time (left) and per depth (right) at 23% water content (*Perubahan suhu dari waktu ke waktu (kiri) dan per kedalaman (kanan) pada kadar air 23%*)

3.1.2. Fire propagation in peat

Fire propagation is analyzed vertically and horizontally by dividing the distance between thermocouples with the

time difference when the temperature reaches 300°C. Table 1 presents the vertical heat propagation speeds for peat samples with moisture contents of 8%, 15%, and 23%.

Table (Tabel) 1. Vertical propagation analysis of burnt peat soil samples from Jambi (*Analisis perambatan vertikal sampel tanah gambut yang terbakar dari Jambi*)

Treatment (Perlakuan)	Propagation speed (<i>Kecepatan perambatan</i>)						
	<i>v1</i>	<i>v2</i>	<i>v3</i>	<i>v4</i>	<i>v5</i>	<i>v6</i>	\bar{v}
8%	7.58	6.57	0.58	0.00	0.00	0.00	2.46
15%	17.79	3.75	1.11	20.83	0.00	2.12	9.12
23%	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note (*Keterangan*): *v1* = first propagation speed, *v2* = second propagation speed, *v3* = third propagation speed, *v4* = fourth propagation speed, *v5* = fifth propagation speed, *v6* = sixth propagation speed, \bar{v} = average propagation speed (*v1* = *kecepatan perambatan pertama*, *v2* = *kecepatan perambatan kedua*, *v3* = *kecepatan perambatan ketiga*, *v4* = *kecepatan perambatan keempat*, *v5* = *kecepatan perambatan kelima*, *v6* = *kecepatan perambatan keenam*, \bar{v} = *rata-rata kecepatan perambatan*)

Table 1 showed that heat propagation speeds of *v4*, *v5*, and *v6* were zero for the 8% moisture content, indicating that heat could not propagate beyond certain thermocouple positions. . In the 23% moisture, no heat propagation was observed, likely due to the inability of the fire to sustain smoldering at that

moisture level.

Table 2 presents the vertical heat propagation speeds for peat samples with moisture contents of 8%, 15%, and 23%. The highest horizontal propagation speed (2.23 cm/hour) was observed at 15% moisture.

Table (Tabel) 2. Horizontal propagation analysis of burnt peat soil samples from Jambi (*Analisis perambatan horizontal sampel tanah gambut yang terbakar dari Jambi*)

Treatment (Perlakuan)	Propagation speed (<i>Kecepatan perambatan</i>)						
	<i>v1</i>	<i>v2</i>	<i>v3</i>	<i>v4</i>	<i>v5</i>	<i>v6</i>	\bar{v}
8%	0.45	0.00	1.15	1.33	0.00	0.00	0.98
15%	0.80	0.00	1.85	1.53	3.61	3.34	2.23
23%	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Note (*Keterangan*): *v1* = first propagation speed, *v2* = second propagation speed, *v3* = third propagation speed, *v4* = fourth propagation speed, *v5* = fifth propagation speed, *v6* = sixth propagation speed, \bar{v} = average propagation speed (*v1* = *kecepatan perambatan pertama*, *v2* = *kecepatan perambatan kedua*, *v3* = *kecepatan perambatan ketiga*, *v4* = *kecepatan perambatan keempat*, *v5* = *kecepatan perambatan kelima*, *v6* = *kecepatan perambatan keenam*, \bar{v} = *rata-rata kecepatan perambatan*)

Table 2 shows that the values of *v2*, *v5*, and *v6* in the 8% moisture content treatment are zero, indicating no horizontal heat propagation in those specific directions. For the 23% moisture content treatment, no horizontal or vertical propagation was observed, as the highest temperature recorded only reached 180°C (Fig. 4).

















3.1.3. Visual appearance of subsidence and overhanging in peat samples

Table 3 shows the visual analysis of subsidence and overhanging in peat

samples with 8%, 15%, and 23% moisture content when exposed to heat from the igniter. The visual appearance at the end of the combustion, shown in Fig. 5(a), demonstrates the subsidence in the 8% moisture sample.

For the 15% moisture sample, combustion continued until the sample turned to ash, as seen in Fig. 5(b), with the final appearance in Fig. 5(c) showing the burnt and charred layer. Overhanging occurred only in the 23% moisture sample, which indicates that higher moisture content promotes overhanging, as shown in Fig. 5(d).

Table (Tabel) 3. Visual appearance analysis of subsidence and overhanging in peat samples
 (Analisis penampakan visual penurunan dan tonjolan pada sampel gambut)

Treatment (Perlakuan)	Before (Sebelum)	After (Setelah)	Time (Waktu) (Hour/Jam)	Description (Keterangan)
8%			0.92	Subsidence
			1.52	Subsidence
			2.73	Subsidence
15%			0.22	Subsidence
			0.72	Subsidence
23%			0.79	Subsidence
			0.90	Overhanging
23%			1.13	Overhanging

Note (Keterangan): The section marked with a white circle indicates the presence of subsidence /overhanging (Bagian yang diberi tanda lingkaran putih menunjukkan adanya penurunan/tonjolan)

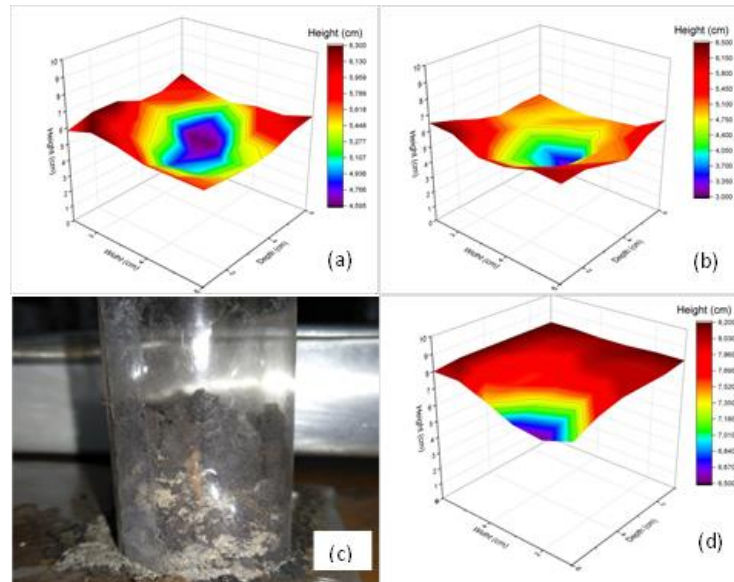


Fig. (Gambar) 7. (a) Subsidence at 8% moisture content, (b) Subsidence at 15% moisture content, (c) burnt layer in the peat sample with 15% moisture content, (d) Overhang at 23% moisture content ((a) *Penurunan muka tanah pada kadar air 8%*, (b) *Penurunan muka tanah pada kadar air 15%*, (c) *Lapisan terbakar pada sampel gambut dengan kadar air 15%*, (d) *Tonjolan pada kadar air 23%*)

3.2. Discussion

3.2.1. Impact of moisture content on temperature dynamics

Figs 4 and 5 show the temperature fluctuations recorded by the thermocouples during combustion of peat with 8% and 15% moisture content, respectively. For the 8% moisture content, the highest temperature was recorded by thermocouple 4, reaching 408.1°C. After reaching this peak, thermocouple 4 continued to record a gradual temperature drop until it returned to ambient levels. This may have occurred because the soil around the thermocouple had turned to ash and formed a cavity, causing the overlying soil to subside. According to Noor et al. (2014), subsidence refers to the lowering of the peat surface due to changes in peat maturity or its ability to retain water, often triggered by land clearing, intensive land use, fire, or prolonged drought.

We notice that thermocouple 3 in moisture content 15% exhibited a temperature decline during ignition due to depletion of combustible material, which is consistent with the subsidence observed in the 8% moisture. The highest temperature was recorded by

thermocouple 5, reaching 460.6°C. Similar to the experiment conducted at 8% moisture content, once the peak temperature was reached, the temperature readings from the thermocouples gradually decreased until returning to room temperature.

We observed that thermocouple 3 in the 15% moisture content treatment showed a temperature drop during ignition, likely due to the depletion of combustible material. This behavior is consistent with the subsidence observed in the 8% moisture content experiment. The highest temperature was recorded by thermocouple 5, reaching 460.6°C. Similar to the 8% moisture content case, once the peak temperature was reached, the thermocouple readings gradually declined until they returned to room temperature.

All thermocouples placed at a depth of 2.5 cm at moisture content 8% returned to room temperature at 11 hours and 7 minutes, indicating that smoldering had ceased at that level. Thermocouples at depths of 5 cm and 7.5 cm returned to room temperatures at 13 hours and 17 minutes, and 13 hours and 33 minutes, respectively.

TC 3 in moisture content 15% exhibit a temperature decline during ignition due to depletion of combustible material, which is consistent with the subsidence observed in the 8% moisture test. TCs at 5 cm depth recorded the highest average temperatures, while TCs at 2.5 cm cooled faster (within 8 hours and 13 minutes) compared to the 8% moisture test. This quicker cooling was attributed to the finer texture of the 15% moisture peat sample, which improved heat transfer. This result is contrary to Huang et al. (2016) that found higher moisture content led to shorter combustion duration, likely due to differences in peat structure. The 8% moisture sample consisted of coarse chunks retaining internal moisture, delaying combustion, whereas the finer 15% sample allowed faster heat transfer and combustion.

Fig. 6 shows no significant temperature fluctuations at 23% moisture content, indicating that the heat energy was insufficient to initiate smoldering combustion in the peat. Peat with higher moisture content is generally more difficult to ignite than drier peat. This is also evident in Fig. 4, where the temperature increase detected by the thermocouples only reached around 180°C. According to Palamba et al. (2020), smoldering combustion in high-moisture peat can only be sustained if enough heat is available to evaporate the water content within the peat. Thermocouple 1, located at a depth of 7.5 cm, recorded a higher temperature than the other thermocouples. This is likely due to the coil heater being placed at the same depth, causing the heat to be concentrated around thermocouple 1.

3.2.2. Fire propagation in peat

Zero vertical heat propagation speeds (v_4 , v_5 , and v_6) may indicate that heat could not propagate beyond certain thermocouple positions. Table 1 clearly shows that there was no vertical heat transfer from TC5 to TC6, TC8 to TC7, and TC8 to TC9. For the 15% moisture content, v_5 was also zero, indicating that heat did not propagate between TC8 and TC7. The highest vertical propagation speed was observed at 15% moisture, with a rate of 9.12 cm/hour. At 23% moisture,

there was no significant heat propagation, as the high moisture content prevented the peat from sustaining smoldering combustion.

Table 2 reveals that the highest horizontal propagation speed (2.23 cm/hour) was observed at 15% moisture. When comparing the vertical and horizontal heat propagation directions, it was found that the vertical propagation rate was faster for the 15% moisture treatment. This finding contrasts with the studies by Putra, et. al (2022) and Satyawan, et. al (2022), who reported an inverse relationship between moisture content and combustion propagation speed. The discrepancy can be attributed to differences in sample structure: the 8% moisture samples were coarser (chunky), while the 15% and 23% moisture samples were finer and more granular, allowing heat to transfer more efficiently. The presence of moisture in the coarser 8% samples likely slowed the propagation speed, as these chunks had to break down before heat could continue to propagate.

Similar findings were reported by Putra, et. al (2022), who observed faster vertical propagation compared to horizontal, while Satyawan (2022) found horizontal propagation to be faster. The differences may stem from variations in sample conditions, including peat combustion history and structural differences. Martin et al. (2019) also observed faster vertical propagation in certain regions, although this was not consistent across all areas of study, indicating that regional variations in peat composition and combustion characteristics can influence propagation patterns.

3.2.3. Visual appearance of subsidence and overhanging in peat samples

We observed the subsidence occurrences in the 8% and 15% moisture samples. For the 8% moisture sample, subsidence occurred at 0.23, 0.92, 1.52, and 2.73 hours, starting with subtle changes around the igniter, followed by more noticeable subsidence on the left side at 0.92 hours. By 1.52 hours, subsidence was observed at the reactor's center, and by 2.73 hours, it appeared on

the right side. Fig. 7a shows the visual appearance at the end of the combustion in the 8% moisture sample, demonstrates the subsidence occurrences..

For the 15% moisture sample, subsidence was noted at 0.22 and 0.72 hours. The first subsidence was clear around the igniter, and by 0.72 hours, the left side near the igniter experienced almost complete subsidence. Combustion continued until the sample turned to ash (Fig. 7b), Fig. 7(c) showing the burnt and charred layer as the final appearance of the 15% moisture content.

The 23% moisture sample exhibited subsidence at 0.79 hours, followed by overhanging at 0.9 and 1.13 hours. The first subsidence was visible at 0.79 hours around the igniter, while overhanging appeared at 0.9 hours, indicated by the hanging peat sample. By 1.13 hours, overhanging expanded further. Our results clearly shows that overhanging occurred only in the 23% moisture sample. This may indicates that higher moisture promotes overhanging (Fig. 5d). This finding is inline with Huang et al. (2016) that stated increasing moisture content enhances the visibility of overhanging.

As peat burns, the surface layer begins to burn downward and sideways, as noted by Usup et al. (2004). This leads to the overhanging phenomenon, where the unburnt surface peat remains suspended above the burnt interior. Table 7 supports this observation, showing that combustion spreads deeper into the peat while the surface remains intact, resulting in overhanging. High moisture content, as noted by Palamba et al. (2020), shortens the duration of smoldering fires because the available heat is insufficient to evaporate the moisture. This correlates with the observed decrease in burning of the peat and the formation of overhanging.

Huang et al. (2016) stated that overhanging peat does not degrade into charcoal, while the peat below it continues to burn. Eventually, this unstable overhang collapses once the lower layers turn to ash and can no longer support the weight above. Evidence of this can be seen in the surface subsidence shown in Table 3, which displays a parabolic depression at the end of combustion, as illustrated in

Fig.s 7a, 7b, and 7d. According to Wosten et al. (1997), subsidence follows the groundwater surface, turning a flat surface into a parabolic one. Zeitoun and Wakshal (2012) define subsidence as a gradual or sudden lowering of land due to soil movement. Noor et al. (2014) describe it as a decrease in peat surface height due to fire, land use changes, or prolonged dry seasons. As water content decreases, peat's pore space empties, causing surface subsidence (Hidayanti & Riwardi, 2011). Drainage and fire exacerbate this process by drying out the peat and contributing to subsidence, as noted by Turmudi et al. (2016). Therefore, while subsidence can occur due to several factors, fire plays a major role in accelerating its progression

4. Conclusions and Recommendations

4.1. Conclusions

The analysis indicated that heat propagation in peat samples with 8% and 15% moisture content occurred more rapidly in the vertical direction than in the horizontal direction. In contrast, no heat propagation was observed in the sample with 23% moisture content. Peat samples with higher moisture content, particularly at 23%, proved more difficult to ignite, as the heat available was insufficient to evaporate the water content, preventing sustained combustion. Furthermore, the overhanging phenomenon, observed exclusively in the 23% moisture content sample, suggests a relationship between moisture content and the likelihood of this occurrence. As moisture content increases, the probability of overhanging phenomenon occurrences also rises, accompanied by more pronounced visual effects.

4.2. Recommendations

A key recommendation of this research is for peat fire management strategies to place greater emphasis on monitoring and maintaining peat moisture levels, as higher moisture content was shown influencing fire behavior and the formation of overhang structures. It is recommended to explore the use of advanced detection tools such as sensors

or imaging technologies to identify overhangs and other subsurface fire patterns more efficiently. Further research under real-world conditions is also needed to better understand how these phenomena occur in natural peatlands. Improving knowledge and preparedness for overhang-related fire behavior will ultimately lead to better fire control, reduced risk of re-ignition, and more sustainable peatland management practices.

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