

EXPERIMENTAL STUDY OF 1-D DOWNWARD-OPPOSED SMOLDERING COMBUSTION OF TROPICAL PEAT AND EFFECT OF EXCESS AIR ON THE TRANSITION FROM SMOLDERING TO FLAMING

by

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This research is conducted to study the effect of air-flow rate to the smoldering combustion dynamics and transition flaming. Test is done using peat extracted from Papua Provinces, Indonesia. The combustion is conducted on natural, 1.33 cm/s, 3.98 cm/s, and 6.63 cm/s of air-flow, respectively, representing the oxidation with lack and excess of air as calculated by stoichiometric equilibrium. Test result show that smoldering spread rate tends to increase with increasing the air supply. Differences in physical properties yield the different of the smoldering dynamic behavior. In general, the higher the air-flow velocity leads to a higher smoldering temperature, spread rate, and mass loss rate. Combustion with natural air and lack of oxygen will result in smoldering whereas in excess air led to transition flaming.

Key words: *peat, fuel oxidation, char oxidation, smoldering spread rate, transition flaming*

Introduction

Peatland fires continue to be a point of concern for the environment issue because they have a significant impact on GHG emissions. Smoldering peat and biomass can last for a long time in the form of smoldering incomplete combustion and emit dense smoke and particulates. The large amount of fuel burned on land will result in thick smoke and extensive environmental damage, which can be attributed to transboundary haze pollution. Low visibility caused by peatland fires hampered sea, land, and air transportation.

Fire on the surface of dry peatland ignites a smoldering combustion in the peat layer, where the embers can spread widely and to a certain depth where conditions permit burning. Previous researchers have conducted a number of studies on smoldering combustion on peatland. Smoldering is a type of combustion without a flame, a slow reaction at a low temperature, and a heterogeneous oxidation reaction in which oxygen attacks the solid fuel's surface [1, 2]. Smoldering can persist for extended periods of time and spread through and into the fuel, resulting in a temperature of 500-700 °C and propagation rates ranging from of 1-10 cm/h [3, 4]. This temperature range is lower than that of flaming combustion, which can reach up to 1500-1800 °C [5]. Moisture and organic content are the most influential physical properties in smoldering combustion. The ignition of peat smoldering can only occur at a critical moisture content of 125% in dry base [3]. The presence of oxygen has a significant impact on fire activity

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as it can be greatly suppressed below 18.5% O₂, completely switched off below 16% O₂, and rapidly increased between 19-22% O₂ [6].

Smoldering fires are typically low temperature fires, and sufficient heat must be present to support sustained combustion. The concentration of oxygen is critical here because it plays a key role in char oxidation, which supplies a rapid boost in heat to support the transition flame. Char oxidation is typically a second phase oxidation that occurs after partial combustion of the starting fuel. According to the *fire triangle*, three conditions must be met in order to transition from smoldering to flaming combustion: the rate of release of combustible vapors must be sufficient to support flame, and the system's air (oxidant-containing medium) and heat ratio can support flame combustion.

As fuels are typically somewhat porous, solid fuel combustion produces an air-flow that influences heat dissipation and oxygen supply. The gas-flow is initiated by convections generated by smoldering. This may indicate that the air-flow pushes heat, volatile fuels, and oxygen into an area where combustion can occur. Frequently, the directions of travel are contradictory and therefore, can be in opposition. Air/gas-flows can disperse heat and push volatiles away from the combustion zone. While the actual trigger mechanism appears to be dependent on the fuel type, composition, and air-flow of the system, it is believed that a critical point is reached when the equilibrium between oxygen content, fuel levels, and temperature is reached. It appears that the concentration of oxygen is the crucial factor in this process.

Overhang has been observed in the field, which has been explained by a possible heterogeneous soil profile, *i.e.* moisture content or inorganic content of surface layer too high to support combustion, and as smoldering fire spreads below the top surface [7]. As the deeper peat layer is burned, the char and ash produced are not strong enough to support the peat above, causing the overhang to collapse. The collapsed overhang falling on the smolder will ignite and burn rapidly due to its hot and dry condition. This research studied smoldering combustion of Indonesian peat under natural air, lack, and excess air, including its transition from smoldering to flaming.

Materials and methods

Samples preparation

The peatland sample used in this study was collected from Bagaiserwar district of Papua province at the co-ordinates S: 01°55'14,11"; E: 138°6'17,35". The PVC pipe with nominal diameter of 15 cm and a length of 60 cm was used to extract the sample at a depth of 10-70 cm from the land surface. The sampling method used was undisturbed; both ends of the pipe containing the peat sample were covered with an epoxy-hardener glue mixture to retain sample characteristics and prevent contamination from microbe activity and other chemical reactions until the tests were performed. A portion of the sample that will be used for combustion testing is oven-dried for 24 hours at 105 °C.

Experimental set-up

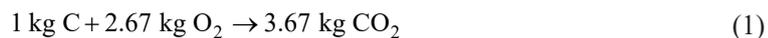
This experiment investigated the behavior of smoldering peat combustion with and without air-flow. The combustion reactor used for the air-flow experiment is a cylindrical chrome tube with an inner diameter of 4 cm and a height of 27 cm. The base of the cylindrical tube is equipped with an air-flow pathway to ensure uniform quality of the inlet air before blowing into the peat sample, and a coil heater is placed 1 cm from the surface of the tube to act as an ignition source when electrically heated. Temperature is measured using six units of *K*-type thermocouples spaced four centimeters apart along the cylindrical vertical axis.

Figure 1 depicts the apparatus scheme for the experiment. A similar set-up is used for the experiment without air-flow (natural flow), though the reactor is different. As a combustion reactor, a wire-mesh cylindrical tube with a mesh number of 81 (≈ 0.018 cm) is used. The cylindrical tube containing peat samples is placed on top of a digital measuring scale, which records mass data in real time. Thermogravimetric analysis (TGA) and differential thermal analysis (DTA) analysis, as well as the evolution temperature and mass loss real time measurement, were used to examine the smoldering propagation and mass loss rate.

Before filling the reactor tube with peat, the digital measuring scale is set to 0 (zero) to determine the initial mass of peat. The flow of air is controlled to the desired rate (1.33 cm/s, 3.98 cm/s, and 6.63 cm/s), whereas natural flow is achieved using a cylindrical tube made of wire mesh. The exhaust fan and measurement equipment have been activated. Even though previous experiments required 30 minutes before ignition, an electrically heated coil of nickel wire delivered 100 W electrical power for 5 minutes, enabling a sustained smoldering combustion. Experiments were replicated three times for each air-flow rate. The air supply rate in this test is determined in accordance with the calculation of the chemical reaction of combustion based on the ultimate analysis of the peat samples, tab. 1. The following is an analysis of air requirement based on the oxidation reactions that can take place (Stoichiometric chemical reactions):

For 1 kg of peat, then:

Combustion reactions between C and O:



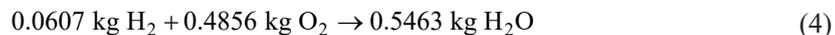
Since peat contain 50.62% of C then the reaction equation becomes:



Combustion reaction between H and O:



Since peat contains 6.07% of H than the reaction equation becomes:



Reaction between S and O, where peat contains 0.25% of S, then the reaction equation becomes:



Then the amount of oxygen requires as from eqs. (2), (4), and (5) become:

$$= 1.3516 + 0.4856 + 0.0025 = 1.8401 \text{ kg.}$$

As the peat contain 36.24% oxygen, the oxygen required for burning 1 kg peat is $1.8401 - 0.3624 = 1.4759$ kg. As a result, the theoretical air mass required for the oxidation reaction becomes $1.4759 \times 4.31 = 6.36$ kg. Based on the prediction of the reaction rate (spread

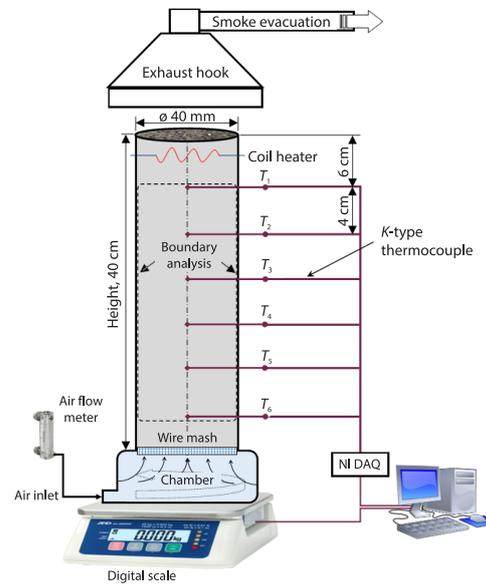


Figure 1. Experimental set-up

rate) of 4.5-4.75 cm/h [8] and the air density of 1.2 kg/m³, the required air supply equals $2.37 \cdot 10^{-5}$ kg/s or 1.18 Lpm or 1.56 cm/s. However, an increasing supply of air is predicted to result in an increasing combustion reaction rate. To examine the occurrence, air supply rate of 1, 3, and 5 Lpm (equivalent to 1.33, 3.98, and 6.63 cm/s) were applied to this test.

Smoldering combustion is an oxygen-limited oxidation because air must penetrate through the abundant porous fuel before reaching the reaction site, which is a slow process. However, because a smoldering reaction requires little oxygen to continue itself, it is particularly difficult to extinguish. Aside from combustion with natural air-flow, tests with varying air-flow velocity were performed in this study at 1.33 cm/s, 3.98 cm/s, and 6.63 cm/s, respectively. These air-flow rates are significantly lower than the prior [7], which used wind speeds of 0.5 m/s and 1.2 m/s to investigate the creation and collapse of an overhang during the lateral spread of smoldering peat fires. As an ignition protocol, a coil heater is heated with 100 W of electrical power for 5 minutes until combustion occurs evenly and sustainably. As illustrated in fig. 1, the combustion test model employs downward-opposed smoldering combustion. The initial mass of the sample is determined to be 85 g, and mass changes are recorded in real time during the combustion process. The ash and organic material content of the combustion residue are also measured.

Results and discussion

Peat sample characterization

In terms of peat as a solid fuel, before beginning this experiment, proximate and ultimate analysis were performed to determine the requisite peat sample properties, as given in tab. 1.

Table 1. Proximate and ultimate analysis

Analysis	Value [%]
Proximate analysis	
Total moisture (ar) ^a	88.65
Moisture in air dry based (% adb) ^b	10.44
Ash (% adb)	4.23
Volatile matter (% adb)	62.06
Fixed carbon (% adb)	27.20
Gross calorific value (kJ/kg adb)	21131
Ultimate analysis	
% C (adb)	50.62
% H (adb)	6.07
% N (adb)	1.69
Total sulfur (% adb)	0.25
% O (adb)	36.42
Bulk density [kgm ⁻³]	181.2 ±6.4

^aar = as received, ^badb = air dried base

The parameters derived from proximate and final analysis would indirectly reveal combustion properties such as volatile matter, fixed carbon, ash, bulk density, and calorific value. Other characteristics, such as a high percentage of volatile matter and oxygen, as well as a

low bulk density, would lead to a faster smoldering propagation rate. The results of oven drying indicate that the sample used in the experiment has a MC of 7.74% (wet base).

Thermogravimetric and differential thermal analysis

A TGA curves show the percentage of mass loss during the pyrolysis and combustion process. The TGA testing was performed at a rate of 20 °C per minute from ambient temperature to 600 °C to determine the limits of evaporation, pyrolysis, and char oxidation in both types of peat. The TGA testing was performed using Shimadzu DTG-60 test equipment at 20 °C, the 60%, using N₂ with a temperature increase of 20 °C per minute, then held at 105 °C for 5 minutes before using compressed air (O₂) with a temperature increase of 20 °C per minute. A DTA curves show the magnitude of the voltage on the thermocouple, which correlates with the rate of heat release during combustion. Water evaporation (*i.e.*, bounded water in the sample that is difficult to remove throughout the drying process), pyrolysis, and combustion are the three types of mass loss in the process. In this test, the pyrolysis and combustion reactions are referred to as fuel oxidation and char oxidation, respectively, where the fuel oxidation reaction occurs in peat samples with the outcome of charcoal and the char oxidation reaction occurs in charcoal with ash as combustion products. Endothermic reactions include evaporation and fuel oxidation, whereas exothermic reactions include char oxidation. The TGA and DTA curve of peat are shown in figs. 2. and 3, respectively.

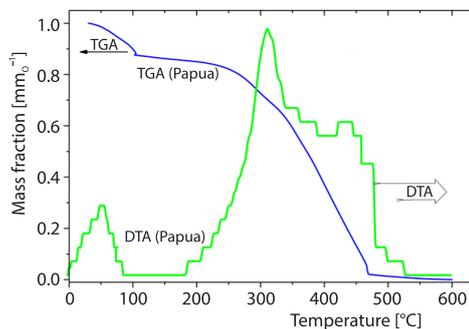


Figure 2. The TG-DTG of peat sample decomposition at 20 °C per minute

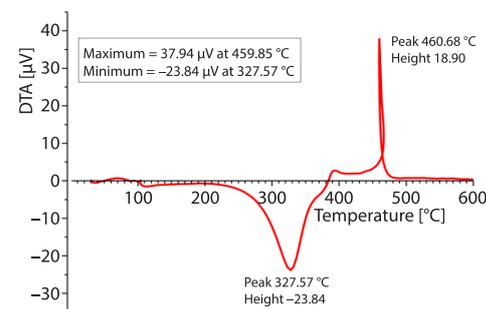


Figure 3. The DTA curves of peat sample

Based on the DTA curve, fig. 3, during the testing against the peat material, three phases' decompositions occurred: evaporation, pyrolysis (fuel oxidation), and char oxidation. The fuel oxidation phase occurs at 193.5-384 °C, with a peak temperature of 327 °C. The char oxidation phase will occur after the fuel oxidation phase until it is extinguished. These temperature limit values will be used as the temperature reference in performing the spread rate analysis based on time, which is directly related to the mass loss rate calculation based on temperature evolution, as shown in figs. 4 and 5. These values appropriate to Boreal peat ignition temperature at 210-270 °C represented in Ignition Handbook [9], while char oxidation occurred at 384 °C during secondary combustion. These values are in the same range with the ignition temperatures of lignin at 191-212 °C [10].

Temperature and smoldering propagation analysis

The tendency of smoldering combustion in both natural air-flow and forced air supply exhibits the same smoldering propagation pattern from the peat surface to the bottom, consisting of two-stages of combustion - fuel oxidation and char oxidation, including the occurrence

of smoldering combustion with downward-opposed, as shown in figs. 4 and 5. The smoldering combustion occurs quickly during the fuel oxidation phase because temperatures above 300 °C result in volatile matter, which is the component with the highest percentage being released from the sample material. At this stage, the sample being oxidized shrinks in volume and mass, creating a cavity between sample particles and allowing for more oxygen availability and faster convection heat transfer. As a result, oxidation will occur with faster propagation the smoldering front. In the bottom of the reactor, where there is no more available fuel, the smolder (*i.e.*, fuel oxidation) stops propagating and continues with the char oxidation phase (upward-forward) and collides with the propagation of char oxidation which also occurs from above (following the fuel oxidation), resulting in burning with high heat accumulation, thus smoldering temperature would increase until it reached its maximum temperature and smoldering combustion would continue and This is the second phase of combustion, char oxidation. These phenomena occur in either natural or forced air supply.

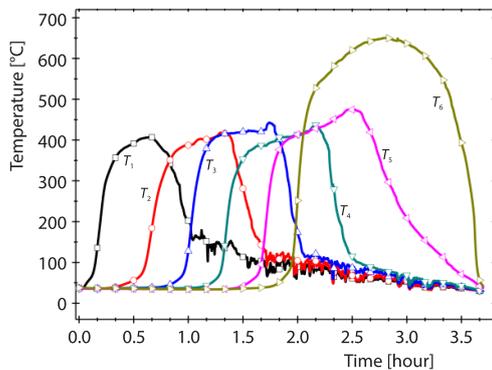


Figure 4. Smoldering temperature by natural air-flow

In natural air, fuel oxidation reaches 436.07 °C and 8.98 cm/h. The fuel oxidation temperature is slightly higher than the DTA test temperature, fig. 3, indicating that the oxidation reaction has continued to char oxidation while fuel oxidation propagates to the underlying layer. Fuel oxidation spreads faster than char oxidation. In char oxidation, maximum temperature and smoldering spread rate average 650.28 °C and 4.75 cm/h. The smoldering temperature of peat is higher than smoldering combustion temperatures in general, such as 600 °C, and 500-600 °C [5], 400-600 °C [11, 12] while Nuria Prat achieved 400 °C [13] in a horizontal propagation experiment, compared to 500-700 °C [3].

Smoldering peat combustion inside a tube with a constant supply of air, fig. 5, results in a high initial fuel oxidation rate and a high propagation rate from the surface to the bottom of the peat. Fuel oxidation occurred rapidly downwards to the reactor's base in the reaction zone, followed by significant mass loss. A portion of the mass (moisture and volatile matter) is released at this stage, and the particles are shrinking, resulting in higher density.

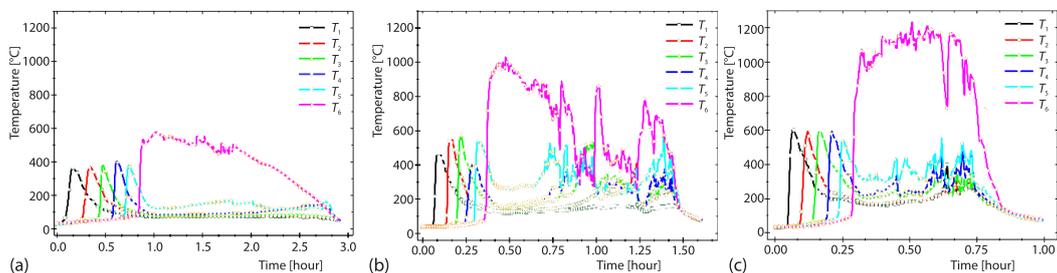


Figure 5. Smoldering temperature for 1.33 cm/s (a), 3.98 cm/s (b), and 6.63 cm/s (c) air-flow

At this stage, smoldering combustion would consume peat in the same direction as the air-flow (upward-forward combustion) with a lower velocity than fuel oxidation. In char oxidation, the rate of consumption of peat would exceed its propagation rate, and the cavities

will start to develop at the bottom of the reactor. Insufficient structural integrity and ash volume causes the char to collapse and fill the voids, triggering to smoldering combustion at a higher temperature due to the accumulation of heat from the burning collapsed overhanging char in close proximity to an oxygen source. According to Huang's research this phenomenon occurs in many peat fires. Consequently, the maximum temperature during the char oxidation phase will always be at the location of thermocouple Number 1, as depicted in figs. 4. and 5. The addition of the air-flow rate increased the maximum temperature, spread rate, and mass loss rate in the experiment with air supply. This is due to the low density and large porosity of the peat, which leads to rapid heat transfer from the burning material into the air through the slit surface of the peat material at high air velocity. In general, the oxidation rate of fuel and char increases as the air-flow velocity.

These smoldering propagation rates were significantly higher than previous experiments, such as Wein's experiment, which discovered a propagation rate of 4.2 cm/h for Australia Peat but appropriate within 2.8-6.0 cm/h for numerous moisture content arrangements [13, 14], whereas, for other experimental results, the finding propagation rates are relatively higher or lower, *i.e.* 1-3 cm/h [3, 5, 15-17], 3.83 cm/h [9], and 9.8-10 cm/h [13]. Except for the parameters of spread rate and mass loss rate, the profile temperature at combustion with 1.33 m/s air supply is not significantly different from the natural flow. This demonstrates the effect of air velocity on convection heat transfer, where heat released from burning peat is rapidly transferred to unburned samples via the air-flow, allowing the combustion process to proceed more quickly. The tendency of increasing smoldering temperature by adding air-flow velocity can be seen in the curves, which shows a significant increase in combustion temperature at char oxidation phases, indicating a transition from smoldering to flaming.

Figure 7 is the result of the spread rate in both the fuel oxidation and oxidation stages. The graph also shows an increase in the rate of combustion propagation as the air-flow rate increases. This implies that a large air supply (in this case, oxygen as a reactant) of up to 6.63 cm/s provides enough oxygen intake to promote a combustion reaction sufficient for the air-fuel ratio, resulting in a more complete reaction and then a higher smoldering spread rate. Fuel oxidation spread quickly in response to the increase in air-flow velocity. Compared to combustion in natural air conditions, increasing the air velocity to 1.33 cm/s, 3.98 cm/s, and 6.63 cm/s increases the spread rate by 3.0, 8.2, and 9.7 times, respectively. The maximum temperature and propagation rate are slower in the test with an air supply of 1.33 cm/s (lack

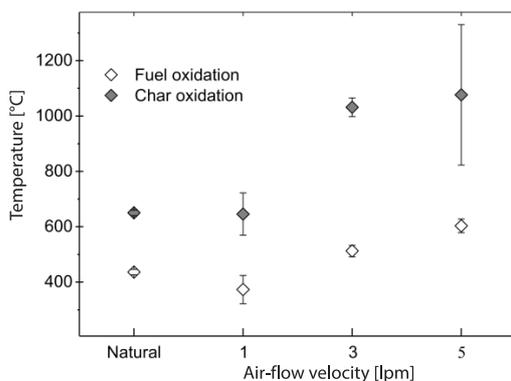


Figure 6. Maximum smoldering temperature

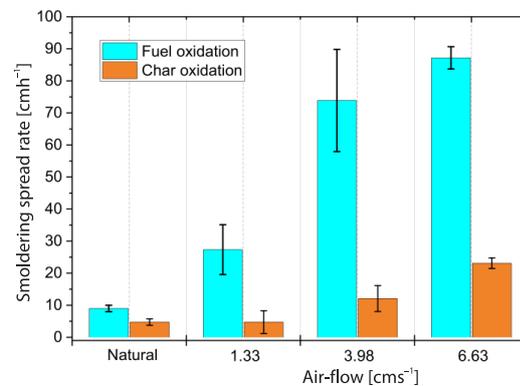


Figure 7. Comparison of spread rates of fuel oxidation and char oxidation

of air 15%) than with air supplies of 3 (20% excess air) and 5 Lpm (60% excess air). This is because the fuel still lacks enough oxygen to complete the oxidation reaction. Low temperatures also cause heat transfer to be slower, resulting in a slower process of volatilization and oxidation.

During the char oxidation phase, the smoldering propagation rates increase to 1.00 cm/h, 2.55 cm/h, and 4.87 cm/h for air supply accordingly and increase the combustion temperature where the maximum temperature can reach 1330.19 °C at the air supply of 6.63 cm/s. As shown in fig. 11., air-flow velocities of 3.98 and 6.63 cm/s induced the transition from smoldering to flaming, as indicated by the emergence of flame at the tube's surface. The smoldering propagation rate for char oxidation was consistent with previous experiments. Nonetheless, with air-flows of 3.98 cm/s and 6.63 cm/s, a transition from smoldering to flaming occurred, resulting in a high temperature, which is consistent with previous experiments [3, 5, 18]. Figure 6 depicts the maximum temperature ratio attained during combustion with various air velocities.

The phenomenon of rapidly smoldering spread rate behavior on fuel oxidation has been visually evaluated using a high heat resistance glass tube as shown in figs. 8(a) and 8(b) with the product of fuel oxidation in the form of charcoal shown fig. 8(c).

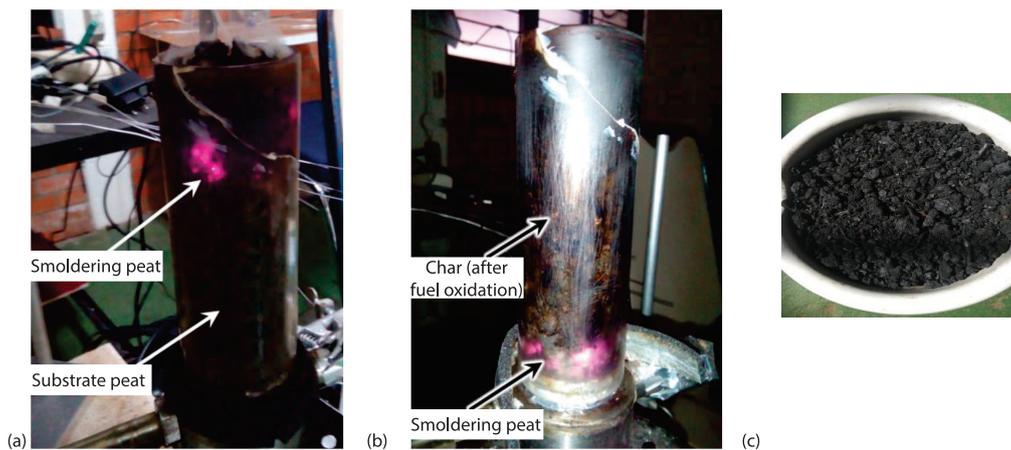


Figure 8. Smoldering front visualization of fuel oxidation, with smolder spreading from top (a), to the bottom (b), and charcoal as product (c)

Figure 8(a) show the position of smoldering front shortly after the fuel oxidation occurs at the surface while fig. 8 (b) shows the end position (at the bottom of the reactor) of smolder which is the beginning of char oxidation phase will take place. In this phase, mass loss and spread rate is ridiculously huge. The spread rate of fuel oxidation occurred for 1.333 m/s, 3.983 m/s, and 6.63 m/s air supply were 27.34 ± 7.77 cm/h, 73.88 ± 15.95 cm/h, and 87.18 ± 3.47 cm/h, respectively.

The combustion reaction during the fuel oxidation phase consumes a certain amount of peat mass and causes the volume of charcoal in the reactor, which will be burned in the next phase (*i.e.*, in char oxidation), is reduced. Due to the fuel oxidation, the density of the charcoal is reduced and not measured in real time except by measuring the deflation of the level of the charcoal surface in the reactor. In this experiment, there was a mean surface deflation of 2.5 cm, 5 cm, and 7 cm for the air-flow velocity of 1.33 cm/s, 3.98 cm/s, and 6.63 cm/s, respectively. The measured height of charcoal in this reactor becomes a reference to calculate the spread rate

of char oxidation based on the time to consume the char until it is suppressed. This experiment demonstrates that the rate of smoldering spread is highly dependent on the burning temperature, which is affected by air velocity. In this experiment, it is also observed that an increase in the rate of air supply will increase the rate of reaction, despite the fact that the reaction rate appears to be faster than the oxygen supply, indicating that the air supply is sufficient to sustain the reaction.

Mass loss rate

Refers to the DTA analysis, fig. 3, the time at which the temperature reaches the start and end of the fuel oxidation and char oxidation process becomes the reference to calculate the mass loss rate based on the corresponding time.

Based on fig. 9, the average fuel oxidation phase spread rate is 1.93 ± 0.9 greater times than the char oxidation phase spread rate under natural air conditions. By increasing the air supply velocity, the average rate of fuel oxidation spread increased from 3.07 ± 1.40 to 4.10 ± 1.81 times that of the char oxidation phase.

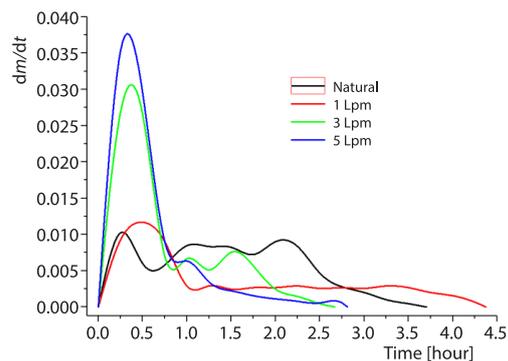


Figure 9. Mass loss vs. time during smoldering combustion

The mass loss calculation is divided into two parts based on the oxidation phases that occur during combustion: mass loss in the fuel oxidation phase and mass loss in the char oxidation phase. The calculation of mass loss in both oxidation phases refers to the TGA/DTA analysis, in which the mass loss from the start of the fuel oxidation phase and the end of the char oxidation phase are determined when the temperature reaches around 200 °C. The process that occurs after the temperature of the burning sample drops below 200 °C is considered an extinguish phase and is not included in the mass loss rate calculation. The transition from the fuel oxidation phase to the char oxidation phase was timed to coincide with the temperature of the oxidation reaching 384 °C. The mass loss curve plotted as a function of air-flow velocity, fig. 10, reveals a linear relationship, indicating that an increase in reaction rate is proportional to an increase in air velocity. The elevation for the trendline of the char oxidation curve is smaller than that of the fuel oxidation curve, indicating that the smoldering combustion rate in the char oxidation phase is relatively slow. This is due to the fact that the reaction in the fuel oxidation phase proceeds quickly by releasing amounts of volatile matter and pyrolyze, while in the char oxidation phase it only consumes flammable material of charcoal with a slower reaction.

The addition of air velocity from 1.33-3.98 cm/s and then 6.63 cm/s leads to an increase in mass loss with the slope of 23.55 for fuel oxidation and 6.76 for char oxidation, as shown in fig. 10.

In general, an increase in air-flow to 6.63 cm/s would accelerate the rate of smolder-

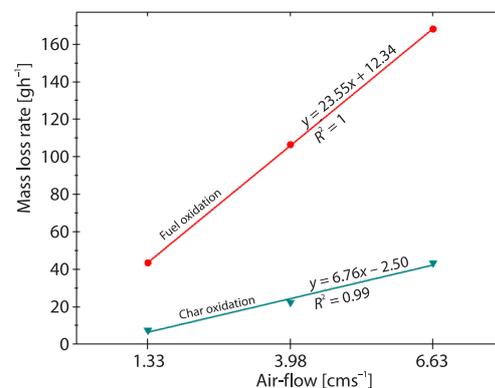


Figure 10. The relation of the total mass loss rate to the increase of the air-flow rate shows the tendency of linear trendline

ing propagation and increase peat consumption. This result is consistent with the findings of the proximate and ultimate analyses presented in tab. 1 which indicate that a low bulk density suggests a quicker combustion process.

Transition from smoldering to flaming

Transition from smoldering to flaming is caused by fast exothermic gas-phase reactions that can occur when pyrolysis gas mixes with oxygen in the air reaches flammability limits and there is enough heat to ignite it. In tests with natural, fig. 4 and 1.33 cm/s air-flow, fig. 5, no transition from smoldering to flaming was observed whereas the phenomenon occurs at 3.98 cm/s and 6.63 cm/s air-flow rates. This demonstrates that the rate of air supply (which contains oxygen) has a significant impact on the rate of reaction, combustion temperature, and transition flaming. When smoldering occurs and sufficient air is available, this results in more complete oxidation and the release of a large amount of heat, giving rise to high temperatures. Such high temperatures can start a fire on the peat surface. Furthermore, the amount of flammable substance, *i.e.*, methane (as in part of this series of studies), has a significant impact on the occurrence of such flame. Flames have even appeared on the reactor surface shortly

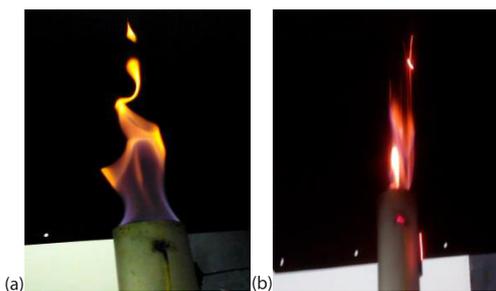


Figure 11. Photo capture of flaming occurred at (a) at fuel oxidation and (b) char oxidation

after fuel oxidation in some experiments, as shown in fig. 11(a), the high temperature indicates the occurrence of a flame or the transition from smoldering to flaming. Flaming in char oxidation occurs in the bottom of reactor (thermocouple position No. 6) where the heat loss becomes smaller and appears out on the surface of the reactor as in fig. 11(b). There is a fusion flame in this flaming, which can last for a long time until the amount of flammable substance decreases and the mixture with air becomes poor.

Another phenomenon that also observed during the combustion process is the occurrence of collapse resulting in changes of the denser structures become tenuous so that the surface of burning char and cavity becomes wider and making it easier to air access for the ongoing oxidation reaction and produce higher heat energy. The high energy production combined with a porous char with easy access for oxygen will in some cases result in transition from smoldering to flaming as can be observed in some peat fire where the burning of ruins material result in a larger flame. This phenomenon is common in peat fires and is one of the major obstacles to extinguish it.

Note that the measured temperature (± 1200 °C) occurs at the bottom layer (thermocouple position No. 6) where at the top side (thermocouple position No 2-6) there still charcoal layer of previous fuel oxidation products, according to the graph in fig. 5, which indicates the flaming occurs at the bottom of the reactor.

Conclusion

With natural air-flow, a smoldering front develops gradually and eventually consumes all of the fuel (organic content), leaving ash behind, whereas with supplied air-flow, fuel oxidation occurs with a higher spread rate towards the source of the air-flow, where higher air-flow rates result in faster fuel oxidation rates. The second phase that continues is the char oxidation phase, also known as the smoldering combustion phase. During this stage of the process, smol-

dering combustion with a feverish temperature and rate of spread occurs. Between air-flow rates of 3.98 cm/s and 6.63 cm/s, there is a transition from smoldering to flaming, which is caused by the presence of remnants of litter that has not been properly decomposed in the peat.

Thermal analysis, smoldering spread rate, and mass loss rate characteristics are matched with TGA-DTA, proximate-ultimate, and mass-temperature results. This experiment showed that air flux velocity and smoldering temperature have a significant influence on smoldering spread rate. It is also revealed in this experiment that increasing the rate of air supply enhances the reaction rate. Because the char oxidation phase generates more heat per unit mass of peat than the fuel oxidation phase, it has a higher smoldering temperature. The availability of air flux is one of the main factors which results to the transition from smoldering to flaming, which also results in high temperatures. Furthermore, porosity allows oxygen to easily react with char as well as convection heat loss to the air. Collapses also results in a hollow with a burnt surface area and increased volatile production, which may result in a lit reaction (flaming).

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