Proceedings for the 5th International Fire Behavior and Fuels Conference
April 11-15, 2016, Portland, Oregon, USA
Published by the International Association of Wildland Fire, Missoula, Montana, USA

Experimental Study on the Surface Spread of Smoldering Peat Fires

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Introduction

Smoldering wildfires in peatlands are the largest combustion phenomena on Earth, and contribute considerably to annual greenhouse gas emissions [1]. Peatlands cover 2-3% of the Earth's land surface, and are most abundant in boreal and tropical regions. They are important ecosystems for a wide range of wildlife habitats supporting biological diversity, hydrological integrity and carbon storage, storing 25% of the world's soil carbon. Annually, peat fires release huge amounts of ancient carbon roughly equivalent to 15% of the man-made emissions [2, 3], and result in the widespread destruction of ecosystems and regional haze events, *e.g.* recent megafires in Southeast Asia, North America, and Northeast Europe [1, 2]. Moreover, recent global warming dries the peatlands and increases the depth of belowground soil combustion, creating a positive feedback to the climate system [4].

Peat, as a typical organic soil, is a porous and charring natural fuel, thus prone to smoldering [1, 5]. Smoldering combustion is the slow, low-temperature, flameless burning of porous fuels, and the most persistent type of combustion phenomena [5]. Once ignited, smoldering peat fires can burn for velong periods of time (*e.g.*, months and years) despite rains, weather changes, or fire-fighting attempts [1]. Two mechanisms control the spread of smoldering combustion: oxygen supply and heat losses [5-7]. Most smoldering peat fires are initiated on the ground surface by flaming fires, lightning strikes or hot particles. Afterwards, smoldering fire spread laterally along the free surface and vertically to peat layers in-depth, dominated by forward smoldering [8], as shown in Fig. 1.

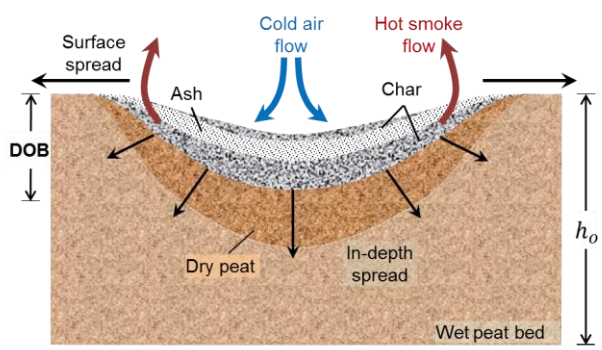

Figure 1: Schematic diagram of the smoldering fire spread along the peat surface and in-depth [8].

Compared to flaming wildfires, the fundamental chemistry and dynamics of smoldering wildfires so far are not well understood with only limited number of studies found in the literature. Ohlemiller studied the two-dimensional (2D) profiles for smoldering of dry wood-based fibres [9]. Frandsen [10] experimentally studied the ignition threshold for various bench-scale peat and other soil samples, and found a correlation between critical MC and IC, recently verified computationally in [11]. Hadden *et al.* performed a small-scale experiment with boreal moss peat, and revealed the competing pyrolysis and oxidation reactions in the char formation [12]. The depth of burn (DOB) and critical MC for extinction at the in-depth spread of peat fires have been investigated by various experiments [13] and numerical simulation [14]. The surface peat fire is found not to spread on the free surface but at a depth below ("overhang" phenomenon) [15-17], which has not been well explained or studied until now.

Experimental method

Figure 2(a) shows the schematic diagram of the experimental setup. A fire reactor with an inner dimension of 20×20×10 cm^3 and a 1.27 cm thick insulation fibre board was used to contain the peat sample. Some additional tests were also conducted with a taller (20×20×20 cm^3) fire reactor. A 20-cm coil heater was attached to one side 5 cm below the top free surface, and used to initiate a uniform smoldering front spreading in the lateral and vertical directions. The ignition protocol was fixed to be 100 W for 30 min, which is strong enough to ignite a peat sample of MC < 150%.

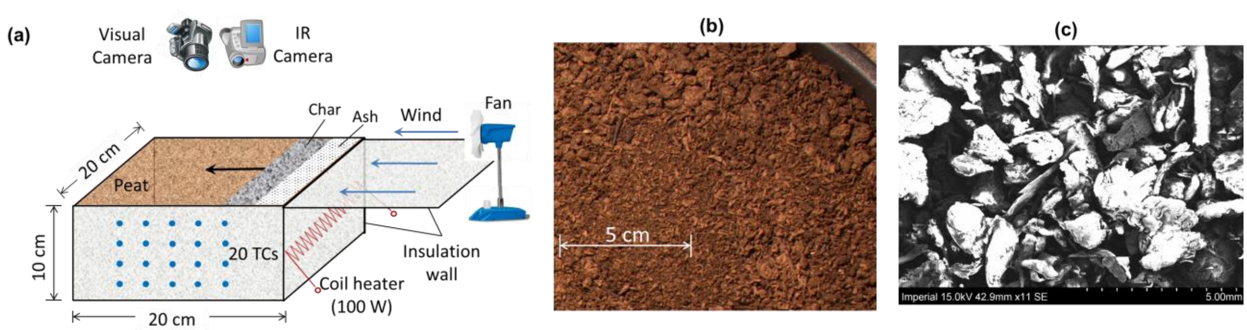

Figure 2. (a) Diagram of the experimental setup and the arrangement of thermocouples array; (b) visual image of the moss peat; and (c) scanning electron microscopy imaging of peat sample.

The peat used in the experiment is a commercial Irish moss peat (Shamrock Irish Moss Peat, Bord na Mona Horticulture Ltd.), as shown in Fig. 2(b) and (c). It is used instead of naturally sourced peat because it is readily available in large quantities, has relatively homogeneous properties and constant composition, and had been used in previous experiments in [12]. This moss peat has a dry density of 136 ± 5 kg/m^3 and a low mineral content (IC~2%). The element analysis for the organic matter shows 53.8/5.5/38.4/1.9/0.5% mass fraction for C/H/O/N/S.

Targeted MC values for peat were 5%, 50%, 100%, 130%, and 150%. Both a visual camera and an infrared (IR) camera were placed above the sample to monitor the process on the top surface. A typical smoldering fire on peat of 20×20×10 cm^3 would last between 3 and 15 h. 20 thermocouples (TCs) were arranged as an array (4 rows × 5 columns) and inserted through one sidewall into the central plane of the peat bed to measure the temperature evolution and distribution. At least three experiments were conducted at each condition for repeatability.

Experimental results

Imaging and overhangs

Figure 3(a) shows the visual and IR images for smoldering spread over peat samples with 50% MC. The IR camera was used to track the movement of the smoldering front (high irradiation region) on the top surface. Once the coil heater was on, the peat nearby was degraded into black char, and the char would be further oxidized into white ash (mainly minerals). During the 0.5 h ignition time, a uniform smoldering front was generated near a side without clear fire spread on the top surface. Afterwards, this burning smoldering front expanded out both laterally (*x* direction) and vertically (*z* direction).

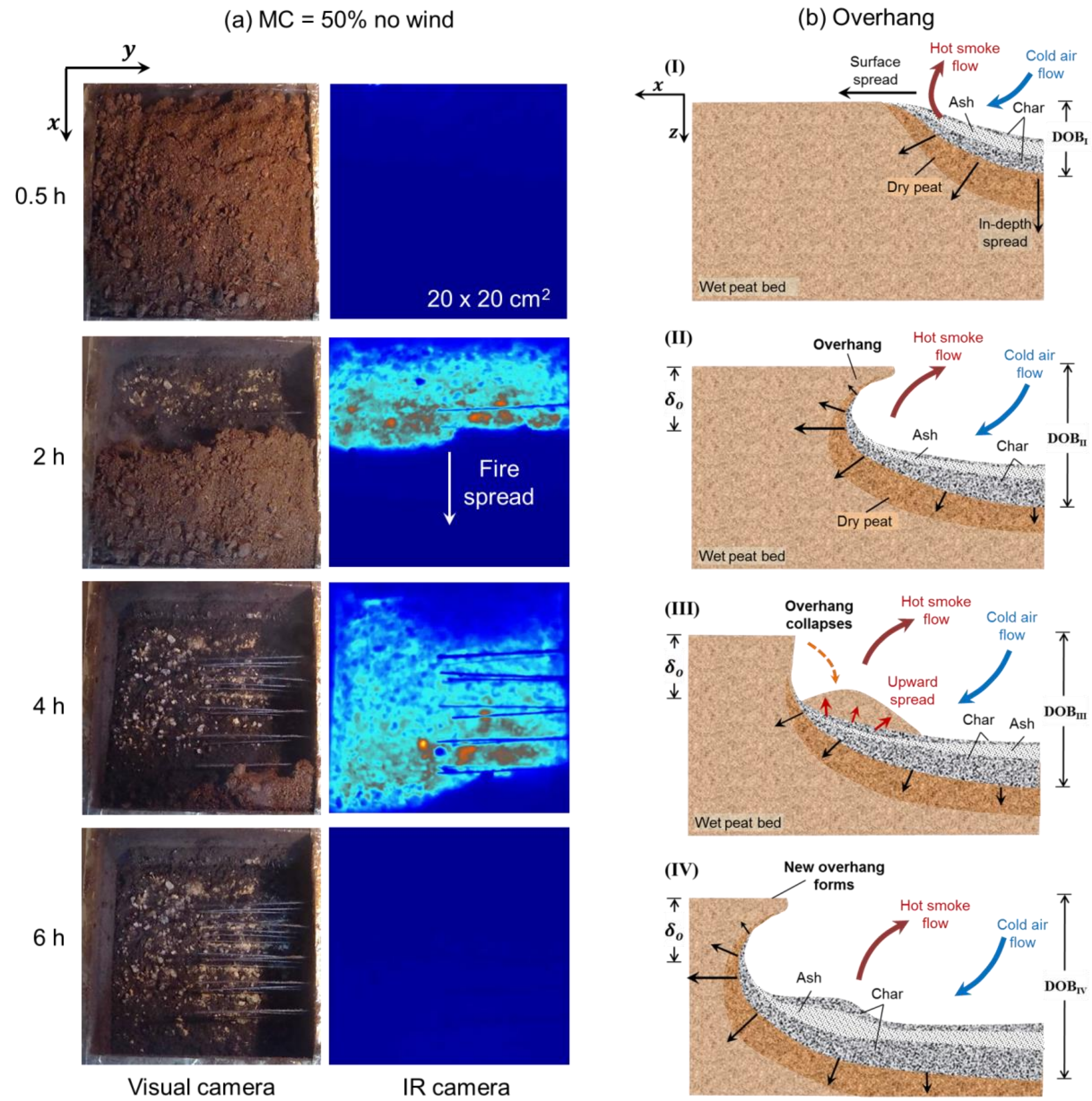

Figure 3: (a) Imaging by visual and IR camera from top for smoldering fire spread in peat sample with MC = 50% without wind, and (b) Schematic diagram for the periodic formation and collapse of overhang in smoldering spread over wet peat.

For wet peat samples (MC ≥ 50%), during the surface fire spread, a clear "overhang" could be visually observed: the smoldering fire tended to spread at a depth (i.e. overhang thickness, δ_o) below the top surface, as illustrated in Fig. 3b(II). Peat within the overhang was seen to be unburnt because it did not degrade into black char, while, for peat below the overhang, clear charring burning process was observed.

In the experiment, this overhang state was unstable because as more peat was burnt underneath, the char and ash yielded were not strong enough to support the unburnt peat above. Therefore, the overhang collapsed before it could be ignited by the burning layer below. The collapsed overhang covered the burning char back stream and evened out the leading edge, as illustrated in Fig. 3b(III). Note that the collapsed overhang was not able to extinguish the fire because it was below the critical MC [10, 11] and was even partially dried. Therefore, it would be further ignited and consumed through the upward spread. Afterwards, fire continued to spread vertically, increasing the depth of burn (DOB), and laterally, generating a new overhang shown in Fig. 3b(IV). Thus, a cycle of overhang formation and collapse was created until peat was entirely consumed.

Spread rate profile

Using visual and IR imaging at the top view (see Fig. 3a), the lateral spread rate on the free surface was measured. Note that due to the formation and collapse of overhang, peat on the free surface does not burn locally (see Fig. 3b(II)), so the visual and IR cameras actually recorded the rate of disappear (collapse) on the free surface and the spread rate of high-temperature region in a shallow layer, respectively.

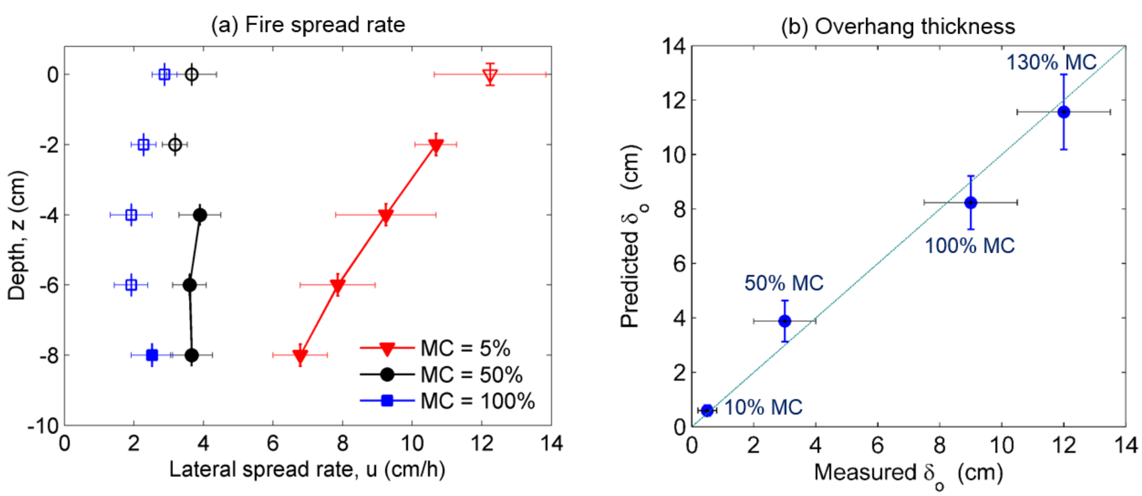

Figure 4: (a) Depth profile of the mean lateral spread rate for different moisture contents (MCs) without wind where solid symbols are found by tracking the peak temperature below overhang; hollow symbols by tracking 100°C within overhang. (b) Comparison between experimental and predicted overhang thickness (δ_o) at various moisture content (MC).

In addition, the lateral spread rate below the free surface can be estimated by tracking the thermocouple measurements [7]. Data processing showed that tracking the peak temperature and drying front (100°C) gave similar values for the spread rate. The lateral spread rate was found to be relatively constant within 10 cm over 5 thermocouples at each measured depth. Therefore, if all thermocouples in that row are below the no overhang region, their peak temperatures were tracked to estimate the mean lateral spread rate. Within the overhang layer, the drying front (100°C) was tracked. Figure 4(a) shows the depth profile of the mean lateral spread rate changing with MC without wind, where the hollow points mean that overhang occurred at that depth.

As expected, the overall spread rate profile reduces remarkably as the MC increases, indicating that moisture has a strong influence on the spread rate of peat fires. For dry peat (5% MC), the spread rate reduces significantly from 12 to 7 cm/h with increasing depth. Similar measurement was found in the experiment of smouldering dry wood-based fibres [9]. It is because as the depth increases, the ambient oxygen supply is reduced and the more ash is accumulated below the free surface. On the other hand, for wet peat samples, the lateral spread rate shows small sensitivity to the depth, implying that it is the moisture controlling the spread rate.

According to the definition of overhang thickness (δ_o): the optimal depth at which the fastest burning is achieved, the non-dimensional analysis is used to estimate the overhang thickness. The overhang thickness should relate to the spread rate difference between top and lower layers, and the thermal property of the peat bed as, $\delta_o \sim \alpha_p / \Delta u$, where the α_p is the thermal diffusivity of dry peat (~4.5×10^{-7} m^2/s [11]); Δu is the difference between the highest spread rate at the overhang thickness ($u_{\max} = u_{z=\delta_0}$) and the spread rate at the top surface ($u_{z=0} \to 0$) where burning ceases due to the large heat loss to environment. Here, $u_{\max}$ is measured as the first solid point in Fig. 4(a).

Figure 4(b) compares the predicted overhang thickness with the experimental measurement without wind in Fig. 8. In general, a good agreement is shown, supporting the critical role of spread-rate depth profile in the overhang formation.

5. Conclusions

In this work, for the first time the overhang phenomenon, peat fire spreading below the free surface, is observed with bench-scale tests using homogeneous peat samples in the laboratory. In addition, the formation and collapse of overhang is found to be periodical, and the thickness of overhang is found to increase with peat moisture. The depth profile of lateral spread rate is successfully measured by visual and infrared imaging as well as by thermocouple array. Results show that the lateral spread rate decreases with moisture content. For dry peat samples, the spread rate significantly decreases with depth because the oxygen supply is the dominant mechanism, and it decreases with depth. As the moisture content increased, the spread rate became less sensitive to the depth, suggesting moisture content became the dominant mechanism in the spread of peat fire. This experimental study provides a physical understanding of the surface spread and overhang phenomenon in peat wildfires, and explains the role of moisture and oxygen supply in peat smoldering, thus helping to understand this important natural and widespread phenomenon.

Acknowledgements

The authors thank the support from EPSRC, and the travel grant from Imperial College Trust, International Association of Wildland Fire (IAWF), and Association for Fire Ecology (AFE).

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