Smouldering combustion of peat with various permeability at natural convection of oxidizer

Zaichenko A.Yu., Podlesniy D.N., Salganskaya M.V., Tsvetkov M.V., Salgansky E.A., Malinouski A.I.

1 Institute of Problems of Chemical Physics, Russian Academy of Sciences, Chernogolovka 142432, Russia
2 M.V. Lomonosov Moscow State University, Moscow, 119991, Russia
3 State Scientific Institution «A.V. Luikov Heat and Mass Transfer Institute of the National Academy of Sciences of Belarus», Minsk, 220072, Republic of Belarus

*dim1990@mail.ru

Abstract. The regularities of smouldering combustion of peat with different permeability under conditions of natural oxidant convection were experimentally investigated. It is shown that as the permeability of peat samples increases, the peak temperature increases from 500 to 900 °C, and the spread rate increases from 8 to 80 mm/h, and oxygen is consumed more fully with increasing concentration of monoxide and carbon dioxide in gaseous products.

1. Introduction

In Russia, more than 65,000 peat deposits with a total area of 80.5 million hectares with reserves of about 235 billion tons or 47% of the world's peat reserves are taken into account and partially explored. It makes peat a strategically important raw material, especially given the limited nature of stocks of traditional combustible minerals (oil, gas, coal) [1].

In general, the technology of using peat, from its extraction to the final product, can be represented in the form of a scheme: drainage of the deposit, extraction, storage of seized peat, transportation, storage of a final product, and use as fuel. When using peat for any purpose, there are a number of general operations, mainly related to the extraction of raw materials and their preparation for use, which are characterized by increased fire danger, because moisture is extracted from the peat. It should be noted that the degree of fire hazard of peat is much higher than that of coal [2]. It is a combustible material that can ignite from a small heat source [3-5]. When storing peat its self-ignition might occur [6]. The ignition can occur in two ways: from an external thermal source on the surface of peat or from a source of heat released into the layer as a result of the biochemical, physical and chemical processes.

The burning of peat, and in particular peatlands, is accompanied by a large release of greenhouse gases, leading to local ecosystem destruction and air pollution by combustion products. During the 1997 there was the largest ignition of peatlands in Indonesia, which was accompanied by the release of greenhouse gases in the amount of approximately 13-40% of the annual emissions due to human activities [7]. The estimates in [8] have shown that the annual release of greenhouse gases from peatlands burning is 15% of the annual emission due to human activity. In addition, air pollution by products of peat burning significantly increases the risk of cardiopulmonary diseases [9].
To simulate the combustion and smoldering of peat, chemical schemes of various complexities were worked out. As a general scheme for any smoldering fuels, a chemical scheme consisting of three reactions, including one pyrolysis reaction and two oxidation reactions was proposed in [10]. In [11] after generalization of the literature data, a chemical scheme for the smoldering combustion of peat from five reactions - one drying reaction and four decomposition and oxidation reactions - was proposed. At the same time they concluded that none of the developed schemes can fully and quantitatively describe all the regimes of smoldering and burning of peat. As a rule, all the proposed chemical schemes do not describe the composition of gaseous products, assuming that this gas has constant averaged characteristics. However, the composition of the gaseous products, which depends mainly on the process temperature, affects the spread rate [12-14]. A distinctive feature of the combustion of porous materials with natural convection is that the flow of air passing through the porous object is unknown beforehand, and only the gas pressure at the boundaries of the object is known. In case of the self-heating object self-regulation of the flow of the gas passing through it takes place, which determines the temperature and the spread rate. The air flow rate in case of the natural convection will primarily depend on the permeability of the porous object [15, 16].

In the literature there is few data on the composition of gaseous products from the smoldering and burning of peat. The measurements of the composition of gaseous products upon heating of small samples of peat in a closed beaker [17] and smoldering of peat in the open air [18] showed approximately the same result. In both cases, the main products were carbon monoxide and dioxide, the yield of the remaining gases did not exceed 1% for any substance (for dry gas) from the mass of the sample. The yield of CO was 3-7.5%, and CO2 30-36% of mass in the first work and 9.5% and 77% in the second work, respectively. Similar results were obtained in [19] in investigating the smoldering of peat with its different humidity and ignition conditions. Average CO yields were 20% and CO2 40-50% in the volume of gaseous products.

In the present work, the regularities of peat smouldering combustion with different permeability of the samples under the conditions of natural convection of a gaseous oxidant were investigated.

2. Experimental set-up
A sample of peat was placed in a reactor with open ends (upper and lower), which ensured the occurrence of natural convection of a gaseous oxidant. In our case, to simulate the ignition of peat from a source of heat release inside the layer, the ignition of the samples was carried out from the lower boundary. Experiments on ignition of porous objects were carried out in a vertical quartz tube reactor with an internal diameter of 66 mm and a length of 500 mm (fig. 1). The wall thickness of the reactor (3) was 3 mm. To reduce lateral heat loss along the outer wall of the reactor, a mirror screen (6) was installed, which reduces the level of heat losses due to radiation. The lower part of the reactor was filled with a Raschig rings (7) with a high porosity (porosity = 0.6) and characteristic size of 5 × 10 mm. In order to avoid spilling inert rings from the reactor and providing a free air supply, the lower end of the reactor was closed with a metal mesh (4). Through the outer wall of the reactor the inert rings was heated by means of an electric heater (8) until the entire volume was uniformly heated to the ignition temperature of the 450 °C, after which the peat sample was load (5). As an object of research, the extruded peat of the Tver region was used. An analysis of air-dry peat on the yield of volatile substances and coke was carried out, moisture and ash content was determined. Based on the working mass, the volatiles yield was 54.2 wt. %, non-volatile carbon 23.8 wt. %, humidity 5.8 wt. %, ash content 16.2 wt. %. Elemental analysis of the dried peat was carried out on a CHNS/O element analyzer «Vario Micro cube». The elemental composition of peat on a dry ashless mass was determined by burning in oxygen, it showed the following results: C – 46.8 wt. %, H – 5.2 wt. %, N – 1.7 wt. %, O – 46.3 wt. % (by difference).

The mass of peat samples in all the experiments was constant and amounted to 191 g. The height of the filling was 100, 120, 130, 140 ± 5 mm for particle size fractions 2-3, 3-5, 5-7 and 7-10 mm, respectively. The characteristics of peat samples of different fractions are given in Table 1.
Measurements of permeability coefficients were carried out in a vertical reactor using a manometric method — the differential pressure of the gas was recorded when the gas flowed through the charge layer at a given flow rate. The formula for calculating the permeability coefficient follows from Darcy's law.

**Figure 1.** Schematic of the laboratory setup: 1 – PC; 2 – ADC; 3 quartz tubereactor; 4 – metal mesh; 5 – peat sample; 6 – mirror screen; 7 – inert material (Raschig rings); 8 – electric heater; TC1-TC4 – chromel-alumel thermocouples.

Chromel-Alumel thermocouples (TC1-TC4) were used to measure the temperature in the peat layer and further to determine the combustion rate, the junctions of which were located in the center of the reactor. Thermocouple measurements via the ADC (2) were output to the computer (1) in real time. The spacing between the thermocouples TC2, TC3 and TC4 was 15 mm. The first thermocouple in the peat layer (TC2) was located at a distance of 10 mm from the upper boundary of the inert charge. The position of the upper thermocouple in the peat layer (TC4) was chosen in such a way that the height of the ash residue after burning of peat above it did not exceed 5 mm, this made it possible to additionally control the end of the experiment.

| Particle size, mm | 2-3 | 3-5 | 5-7 | 7-10 |
|-------------------|-----|-----|-----|------|
| Permeability, m²  | 1.3*10e-8 | 2*10e-8 | 2.6*10e-8 | 5.3*10e-8 |
| Density, kg/m³    | 560 | 470 | 430 | 400 |

**3. Results and discussion**

The duration of the experiments for various peat samples was 5-10 hours. Figure 2 shows the temperature profiles of peat smouldering combustion under natural oxidizer convection for a peat particle size of 5-7 mm. The initial time corresponds to the start of the heating of the inert charge.
After heating the inert charge to the ignition temperature the peat was loaded (the loading time is denoted by a vertical solid line - 0) and the heater was turned off. Then the combustion front spread along the length of the reactor - in Fig. 2 curves 2, 3, 4, which correspond to the indications of thermocouples TC2-TC4. As can be seen from the figure an increase in the spread rate was observed - the time to reach the maximum value between thermocouples decreased almost twofold from $t_1 = 136$ to $t_2 = 74$ minutes, the spread rate in these sections was 17 mm/h and 32 mm/h, respectively. This is due to a decrease in the height of the sample during its burnout and an increase in the permeability of the layer. An increase in the spread rate leads to an increase in the heat release resulting in an increase in the peak temperature from $\sim 590^\circ C$ to $\sim 720^\circ C$.

![Figure 2. Profiles of the temperature versus time. Peat particles size 5-7 mm. 1-4 – thermocouples TC1-TC4. Vertical solid line (0) - time of loading of peat.](image)

In some experiments additional thermocouple was used to measure the temperature gradient across the reactor section. Thermocouple measure the temperature of solid phase [20-22]. In Fig. 3 presents the temperature profiles of peat combustion with natural oxidizer convection for peat particle size 2-3 mm. Small fluctuations in temperature on the graph correspond to fuel drop as a result of burnout. Despite the fact that the reactor has a heat-reflecting screen in the experiments there was a significant difference in the temperatures on the inner wall of the reactor (curve 2) and in the center (curve 3), which reached value of 250°C. However, even with such significant gradients of the temperature across the reactor section, after the experiment of unburned organic matter in the ash residue was not detected.
Figure 3. Profiles of the temperature versus time. Peat particles size 2-3 mm. 1 – thermocouple TC1 in the Raschig rings, 2 – thermocouple on the inner wall (across from the TC3), 3 – thermocouple TC3 in the center. Vertical solid line (0) - the moment of loading of peat, vertical discontinuous lines - the moments of sampling of gaseous products.

In the experiments gaseous products were periodically sampled (in Figure 3 the sampling times are indicated by vertical dashed lines) into a glass ampoule-trap from the top of reactor. The analysis of the selected gaseous products was carried out on a chromatograph Chromatek GC-CRYSTAL 5000, which allows analyzing products that are in the gaseous phase under normal conditions. The methodical error in measuring gaseous product concentrations did not exceed 2%.

Figure 4 shows the composition of gaseous products in the experiment on the combustion of peat, the particle size of which was 2-3 mm. Gas sampling times are the same for Figures 2 and 3. Hydrogen, methane and other hydrocarbons were present in small amounts in gaseous products (less than 1%), so they are not represented in the figure. As can be seen from the figure the concentrations of CO, CO2 and O2 remains practically unchanged throughout the entire experiment.
Figure 4. Composition of gaseous products versus time. Peat particles size 2-3 mm.

Table 2 shows the composition of the gaseous combustion products of various peat fractions, as well as the peak temperature and the average spread rate. As can be seen from the table as the particle size increases, the peak temperature increases from about 500 to 900 °C and the spread rate from 8 to 81 mm/h. Increasing the particle size results in an increase in the permeability of the layer, thereby increasing the air flow rate. The increase in air flow rate leads to an increase in the temperature and the spread rate. The measured peat spread rate is of the same order of magnitude as in the experimental work [23], and also in the computational work [11] on the investigation of peat smoldering. The spread rate in these works is about 6 mm/h. Its value is somewhat smaller because of the consumption of oxygen in the gaseous phase above the combustion front in case of propagation of the combustion front from top to bottom.

Table 2. The average values of the concentrations of gaseous products and the spread rate, the peak temperature for various peat size fractions.

| Particle size, mm | Composition of gaseous products, vol.% | \( T_{\text{max}}, \degree \text{C} \) | \( V_{\text{comb}}, \text{mm/h} \) |
|------------------|---------------------------------------|------------------|------------------|
| 2-3              | CO\(_2\) 4.1 O\(_2\) 16.1 CO 7.8 CH\(_4\) 0.1 H\(_2\) 0.2 | 509 | 8 |
| 3-5              | CO\(_2\) 6.1 O\(_2\) 13.9 CO 8.6 CH\(_4\) 0.2 H\(_2\) 0.5 | 604 | 18 |
| 5-7              | CO\(_2\) 8.8 O\(_2\) 10.1 CO 9.9 CH\(_4\) 0.3 H\(_2\) 1.0 | 733 | 23 |
| 7-10             | CO\(_2\) 10.4 O\(_2\) 5.8 CO 14.7 CH\(_4\) 0.5 H\(_2\) 2.2 | 886 | 81 |

Table 2 shows that the main gaseous products are CO, CO\(_2\), and O\(_2\). An increasing peat particle size from 2-3 to 7-10 mm (the permeability of the peat layer changed from 1.3*10\(-8\) to 5.3*10\(-8\) m\(^2\))
CO2 content increases from 4 to 10%, CO increases from 8 to 15%, O2 decreases from 16 to 6% by volume, the methane content increases from 0.1 to 0.5% and hydrogen from 0.2 to 2.2% by volume. The smouldering combustion of peat with natural convection is characterized by low temperatures (less than 900 °C), which causes incomplete consumption of oxygen. As was shown earlier in [17-19], when peat was smoldered the predominant substance in gaseous products was carbon dioxide. In the present work the content of carbon monoxide was greater than that of dioxide. The difference in the results of the composition of gaseous products is explained by the different regimes of peat combustion. In our work the ignition of the peat layer occurred from the bottom. In this case the gaseous products left the combustion zone and entered the upper colder layers of peat, where chemical reactions were negligible. In works [17-19] ignition of the peat layer occurred from the top. The gaseous products left the combustion zone and were filtered through a high-temperature ash where oxidation of carbon monoxide with oxygen could occur.

4. Conclusions
An experimental study of the regularities of smouldering combustion of air-dried peat with different permeability under conditions of natural oxidant convection was carried out. A sample of peat was placed in a reactor with open top and bottom, which ensured the occurrence of natural convection of a gaseous oxidant. The ignition of peat samples from the heat source was carried out from the bottom.

It is shown that the increase in the size of peat particles (the permeability of the peat layer increased from 1.3*10^-8 to 5.3*10^-8 m2) increases the peak temperature from about 500 to 900 °C and the spread rate from 8 to 81 mm/h. An increase in the permeability of the peat layer leads to a decrease in the resistance of the filling, as a result to increase the air flow. The increase in air flow rate leads to an increase in the temperature and the spread rate of peat smouldering combustion.

The main gaseous products of peat smouldering combustion under conditions of natural air convection are CO, CO2. With an increase in the permeability of the peat layer from 1.3*10^-8 to 5.3*10^-8 m2, the CO2 content increases from 4 to 10%, CO increases from 8 to 15%, O2 decreases from 16 to 6%, methane content increases from 0.1 to 0.5% and hydrogen from 0.2 to 2.2% by volume. The smouldering combustion of peat with natural convection is characterized by low temperatures (less than 900 °C), which causes incomplete consumption of oxygen.

References
[1] Kulesh RN, Orlova KY. Field research of firing stored peat critical conditions. MATEC Web of Conferences 2016;72:01055. DOI: 10.1051/matecconf/20167201055
[2] Epshtein SA, Kossovich EL, Kaminskii VA, Durov NM, Dobryakova NN. Solid fossil fuels thermal decomposition features in air and argon. Fuel 2017;199:145-156. DOI: 10.1016/j.fuel.2017.02.084
[3] Grishin AM, Yakimov AS. Mathematical simulation of the process of peat ignition. JEPT 2008;81:1:204-212. DOI: 10.1007/s10891-008-0016-5
[4] Thompson DK, Wotton BM, Waddington JM. Estimating the heat transfer to an organic soil surface during crown fire. Int. J. Wildland Fire 2015;24:1:120-129. DOI: 10.1071/WF12121
[5] Lutsenko NA. Modeling of Heterogeneous Combustion in Porous Media under Free Convection. Proceedings of the Combustion Institute 2013;34:2:2289-2294. DOI: 10.1016/j.proci.2012.06.147
[6] Restuccia F, Huang XY, Rein G. Self-ignition of natural fuels: Can wildfires of carbon-rich soil start by self-heating? Fire Safety Journal 2017;91:828-834. DOI: 10.1016/j.firesaf.2017.03.052
[7] Page SE, Siegent F, Rieley JO, Boehm HDV, Jaya A, Limin S. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature 2002;420:61-65. DOI: 10.1038/NATURE01131
[8] Poulter B, Christensen J, Norman L, Halpin PN. Carbon emissions from a temperature peat fire and its relevance to inter annual variability of trace atmospheric greenhouse gases. Journal of
Geophysical Research, D, Atmospheres 2006;111:D06301. DOI: 10.1029/2005JD006455

[9] Kim YH, Tong H, Daniels M, Boykin E, Krantz QT, McGee J, Hays M, Kovalkic K, Dye AJ, Gilmour MI. Cardiopulmonary toxicity of peat wildfire particulate matter and the predictive utility of precision cut lung slices. Particle & Fiber Toxicology 2014;11:29-45. DOI: 10.1186/1743-8977-11-29

[10] Ohlemiller TJ. Modeling of smoldering combustion propagation. Progress in Energy and Combustion Science 1985;11:277-310. DOI: 10.1016/0360-1285(85)90004-8

[11] Huang X, Rein G. Smoldering combustion of peat in wildfires: Inverse modeling of the drying and the thermal and oxidative decomposition kinetics. Combustion and flame 2014;161:1633-1644. DOI: 10.1016/j.combustflame.2013.12.013

[12] Salganskaya MV, Glazov SV, Salganskii EA, Kislov VM, Zhuludev AF, Manelis GB. Filtration combustion of humid fuels. Russian Journal of Physical Chemistry B 2008;2:1:71-76. DOI: 10.1007/s11826-008-1011-5

[13] Salgansky EA, Zaichenko AYu, Podlesniy DN, Salganskaya MV, Tsvetkov MV. Gasification of powdered coal in filtration regime with a fuel continuous injection. Fuel 2017;210:491-496. DOI: 10.1016/j.fuel.2017.08.103

[14] Amelin II, Salgansky EA, Volkova NN, Zhuludev AF, Alekseev AP, Polianchik EV, Manelis GB. Region of the stationary filtration combustion wave in the charge with a low carbon content. Russian Chemical Bulletin, International Edition 2011;60:6:1150-1157. DOI: 10.1007/s11722-011-0180-1

[15] Lutsenko NA. Numerical model of two-dimensional heterogeneous combustion in porous media under natural convection or forced filtration. Combustion Theory and Modelling 2018;22:2:359-377. DOI: 10.1080/13647830.2017.1406617

[16] Lutsenko NA, Levin VA. Effect of Gravity Field and Pressure Difference on Heterogeneous Combustion in Porous Media. Combustion Science and Technology 2014;186:10-11:1410-1421. DOI: 10.1080/00102202.2014.934611

[17] Christian TJ, Kleiss B, Yokelson RJ, Holzinger R, Crutzen PJ, Hao WM, Saharjo BH, Ward DE. Comprehensive laboratory measurements of biomass-burning emissions: 1. Emissions from Indonesian, African, and other fuels. J. Geophys. Res. 2003;108:4719. DOI: 10.1029/2003JD003704

[18] Rein G, Cohen S, Simeoni A. Carbon emissions from smoldering peat in shallow and strong fronts. Proceedings of the Combustion Institute 2009;32:2489-2496. DOI: 10.1016/j.proci.2008.07.008

Acknowledgments
The study was partially supported by the Russian Foundation for Basic Research (project 17-53-04091 bel_mol_a) and State task #0089-2019-0018.