Journal of Engineering Physics and Thermophysics, Vol. 82, No. 6, 2009

REVIEWS

ON PHYSICAL AND MATHEMATICAL MODELING OF THE INITIATION AND PROPAGATION OF PEAT FIRES

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UDC 531.534:536.245.022

Works devoted to experimental and theoretical investigations of peat fires under laboratory and natural conditions have been reviewed. Evaluations show that the smoldering of surface combustible materials in peatlands involves half the biomass burnt during natural (forest, steppe, and peat) fires. These fires are of first importance in emission of combustion products into the atmosphere, destruction of the soil structure, and damage to the environment. Many investigations have been carried out on the problem of peat-fire behavior, and they have been published in various journals and materials of conferences.

Keywords: *peat, peatlands, moisture content, heat of combustion, physicomathematical modeling.*

Introduction. No flame tongue is observed in smoldering of ground vegetable combustible materials; nonetheless, smoldering is an important factor of peat fires and a severe hazard to different ecosystems. When an organic-soil layer ignites, it burns stably without a flame and the fire front gradually penetrates into the soil. Large smoldering fires are rare events on a local scale but occur regularly on a global scale. As soon as they are initiated, it is particularly difficult to extinguish them despite extensive rains or the effort to control the fire. These fires are capable of lasting for long periods of time (from a week to a few years) [1, 2] and of propagating to vast areas. Penetrating deep into the peatland, smoldering fires can give rise to flame combustion, which is initiated at unexpected sites by the soil layer breaking under a peat fire. These fires lead to mass emissions of harmful substances into the atmosphere, destruction of carbon reserves in the soil, and damage to the natural environment [1, 3]. Subsoil fires often occur in the organic material accumulated in surface forest layers (e.g., in the forest floor or humus) and in deeper layers, e.g., in peat and even in coal beds. It has been reported [3] that up to 50% of the total amount of biomass burnt in peatland fires can burn as a result of the smoldering of surface combustible materials and peat fires in countries with moderate and northern climates predominantly [3] and in the tropical woodland [4], e.g., near the River Amazonka. These fires are responsible for the high percentage of pollutants emitted into the atmosphere during natural fires [1, 3].

The review covers both experimental and theoretical investigations and gives an idea of today's level of physical and mathematical modeling of peat fires.

Peat and Peatlands. Peat is a half-decayed vegetable substance which has been accumulated and has partially decomposed in marshy lands. Peat layers may have a very high moisture content that is several times higher that that of organic components, and their thickness changes from a few centimeters to tens of meters. Peatlands are marshy lands with peat-forming vegetation [5]. Peatlands cover more than $4 \cdot 10^6$ km^2 (3% of the surface of the Earth's dry land) and are part of the Earth's ecosystem. Of all peatlands in the world, nearly 80% are located in northern moderate regions, 15–20% are located in tropical or subtropical regions, and only a few percent are in southern moderate regions [6]. These ecosystems contain one-third of the soil carbon and one-tenth of global sweet-water reserves [7]. The total amount of carbon in peat exceeds the amount of carbon in the world's forests.

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Factors usually used for classification of different peat types are as follows [8–12]: 1) botanical composition of peat; 2) concentration of inorganic substance and chemical composition; 3) microbic activity; 4) moisture content; 5) drainage and water-retention properties; 6) high combustion temperature; 7) age; 8) decomposition state; 9) volume density; 10) content of gas (porosity); 11) content of fibers; 12) color; 13) structure (e.g., fibrous or amorphous); 14) heat of combustion, which changes with the botanical composition, degree of decomposition, moisture content, and volume density of peat.

The heat of combustion and chemistry of peat are close to the corresponding characteristics of wood and coal [12]. They change as a result of variation of the composition of peat in vertical and horizontal directions in any peatland; however, there are not enough accessible data on this change.

The moisture content of peat W is critical (W_*), if the peat does not ignite and burn for $W > W_*$. There are a few characteristics and processes in the peatland hydrology that may be considered as important for initiation and propagation of a peat fire: humidity of a combustible material (peat), deposition, percolation (filtration) of water through the peat, and total evaporation [13].

Peat Fires. Fires in peatlands occur in tropical, moderate, and northern forests. They are particularly frequent in the case of droughts. Peat fires strongly influence the cycle of substances, biodiversity, the erosion of soil, and the quality of drinking water. On a global scale, they make a significant contribution to the emission of carbon gases (CO and CO_2) into the atmosphere [1]. Smoldering fires have a strong effect on the soil structure, since their action produces the combustion of a combustible material (organic matters in soil), with the result that high temperatures are preserved in the source of fire for long periods of times. The burnt peat layer (ashes) is removed under the action of wind, and then a new peat layer burns. The removal of ashes leads to the erosion of combustion products. Fires in peatlands are observed in different countries, e.g., in Indonesia [14], Russia [15], and Great Britain [16]. Peat fires exert a strong influence on the structure of soil and heat it, damaging the roots of plants.

The soil's organic part, i.e., peat, is a natural combustible material (fuel) that represents a permeable porous medium consisting of macroparticles, grains, and fibers, which contributes to the development of heterogeneous reactions of the organic matter with oxygen and ensures a large combustion-surface area per unit volume of the porous medium. It is precisely this structure of a combustible material that ensures lengthy and extensive combustion in the Earth's space. Also, the porous medium (peat) acts as that insulation that diminishes the heat loss, but at the same time, owing to the porosity of this medium, oxygen is transferred to combustion zones.

Smoldering peat fires propagate in both surface and deep peat layers. Each front has a different propagation velocity. The surface combustion front borders the atmosphere, with the result that oxygen arrives with a high velocity; simultaneously we have convective heat loss. Therefore, this type of fire is called a surface peat fire. A deep subsurface peat fire occurs many meters below the Earth's surface. In this case oxygen supply from the atmosphere is limited and the atmospheric heat loss is much smaller than that for a surface peat fire.

Changes in the soil that are produced by smoldering fires in peat are induced by two factors: high temperatures and a high mass loss by the soil due to the peat combustion. Removal of the layers of soil on its surface causes the soil erosion to increase, and the destruction of deeper layers can lead to a destruction of the peatland structure. Heating of the soil by natural fires tends to change the chemical composition (carbon, nitrogen, and organic-phosphorus loss) and the biological structure (changes in the feeding, microbic dynamics, and varieties of plants). It should be noted that fairly high temperatures (up to 1500 K) above the Earth's surface are attained in flaming peat fires but only during short periods of time (seconds and minutes). In smoldering peat fires, heat is transferred to the surface soil layer over a longer period of time — of the order of an hour, which can lead to a sterilization of the soil [17–19]. Heat release from peat fires is an important factor of increase in the human mortality in the fire zone; allowance for this factor is no less important than allowance for the crown damage from flaming peat fires [20].

Surface Fires. Such fires occur in peat as a result of the heating of soil and the burnout of the organic layer in it due to smoldering [21].

There are three directions of propagation of smoldering subsurface fires: downward, in the direction opposite to the z axis, and in the horizontal plane along the x and y directions (Fig. 1).

In organic soil layers, there is a combustible material (peat). The combustion front (Fig. 1) moves owing to the oxygen diffusion from the free surface, from which oxygen from the atmosphere propagates to deeper peat layers where the heat loss is diminished. Thus, the reaction zone moves deeper in the same direction as the oxygen flow

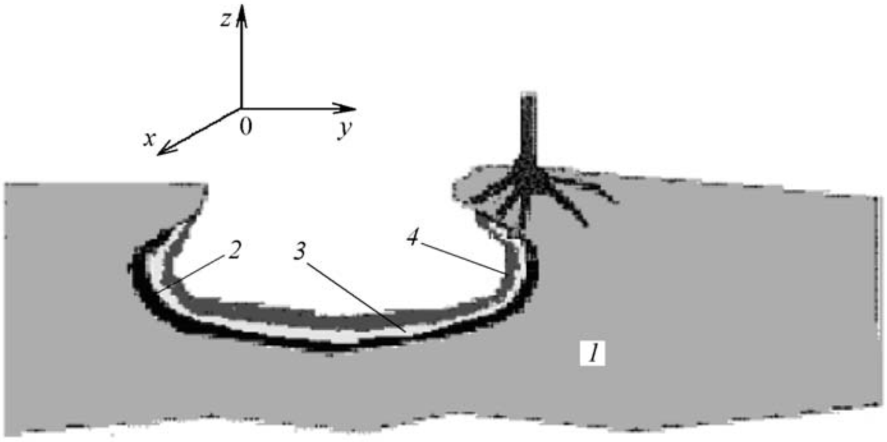

Fig. 1. Propagation of a smoldering peat fire over the Earth's surface [22] and deep into the soil: 1) organic soil layer; 2) drying zone; 3) pyrolysis zone; 4) oxidation zone.

(which is called a diffusion flux) [23]. The resulting structure of the combustion front is such that the drying and pyrolysis zones are ahead of the oxidation zone which remains in contact with the atmosphere. The downward propagation of the fire gives rise to overhangs (protrusions) (Fig. 1), which occur when the front moves toward the lower layers of the combustible material, leaving the unburned layer of peat and ground on top. Subsoil layers smolder particularly intensely, when the front propagates along the root system of a tree, with the result that combustion areas represent nearly circular portions of ground around the roots. The main parameters influencing the ignition of a smoldering source of biomass are the contents of water and organic matter.

Figure 2 shows photographs of neighboring forest areas after a peat fire during which the source of combustion scorched the trees up to a height of 1 m from the base and burned part of the grass, and a smoldering fire burned the peat to a depth of 0.5–1 m, destroying an enormous amount of soil. The root systems and tree bases turned out to be most affected by the smoldering zone. Many smoldering hollows in the form of pits were noticed around forests and individual trees. They formed as a result of burning of large portions of peat soil approximately in rounded areas with radii from 0.5 to 3 m around the bases of the trees and with protruding mineral layers of soil (see the right-hand Fig. 2). The dependence of burnt peat samples on distances from tree bases in several areas of the forest (see Fig. 2) has been investigated in [24–26]. Near the tree bases, where the action of their crowns decreases the amount of precipitation (shower) and the roots absorb water, there was observed a much higher rate of peat combustion and of propagation of fire over the tree roots.

The peat fire was accompanied by tongues of flame during three days and smoldered for six weeks. The left-hand Fig. 2 shows a forest undamaged by a peat fire; it shows trees and a peat layer, and the right-hand figure shows a forest with tree trunks that are scorched by fire and soil damaged by a smoldering fire.

Subsurface Fires. Underground peat fires are dangerous for personnel who fight the fire since the relatively thin layer of soil, separating the source of fire from the surface layer of the atmosphere, can be destroyed under the weight of a man or heavy machines and expose a hot source below. Underground fires (Fig. 3) in peatlands are rare events, but when they are active, they can smolder for a very long time, releasing huge amounts of combustion products into the atmosphere, worsening the quality of the air, and causing health problems in humans [27]. These fires are substained by additional supply of small portions of air continuously passing through gaps, cracks, and the matrix (crystal lattice) of a porous combustible material that allows the oxidizer to circulate under the surface. The reduced heat loss and the high thermal inertia of the process of peat combustion underground together with the abundance of combustible material and the low influx of oxidizer contribute to sustained smoldering combustion of peat and allow slowly moving but extensive propagation of the fire front deep into the soil and over the surface of the ground. These fires, it turns out, are difficult to detect, which makes extinguishing them difficult.

Underground smoldering of peat was the main cause of the widespread peat fires in peatlands of Indonesia in 1997. Those fires caused a thick fog that enveloped most of South-East Asia. There occurred a lot of peat fires that

Fig. 2. Photographs of forest areas adjacent to the peat fire in Scotland (July 2006, Great Britain [18, 26]).

got out of control and spread, releasing carbon particles whose mass was equivalent to 10% of the annual global emission of carbon caused by the combustion of coal combustible materials [1]. This contributed, to a great extent, to the greatest annual growth in the concentration of carbon dioxide (CO_2) in the atmosphere. Various intense peat fires similar to the above-said, occurred again in 1998, 2002, and 2006.

There was observed spontaneous combustion of peat both in a fractured state [28] and in peatlands containing natural sources of methane [29].

Experimental Investigations of the Combustion of Peat. *Combustion Dynamics.* Frandsen [30] has conducted laboratory experiments on ignition of peat in a box of volume 500 cm^3 to evaluate the influence of the moisture content of peat on the propagation of a smoldering fire. Ignition was effected on that side where a 10-mm-thick peat plate was cut and replaced by dry peat. The dry peat was ignited with a spiral heated by an electric current. The results of experimental investigations were presented on the plot of [30] as the ignition probability versus the peat humidity and showed that ignition is possible if the moisture content of peat is lower than 110%. The influence of the mineral content was checked by artificial addition of clay. Frandsen has stated [30] that peat ignites if the moisture content W varies within $80\% < W < 110\%$. This experimental setup was modified [18] to study the change in the peat temperature and the propagation of the smoldering front and to compare smoldering fires in peat and humus [19].

Heat generated by a smoldering porous combustible material was measured by a calorimeter developed specially for this purpose [31], since the traditional methods of determination of the heat flux from smoldering cannot give the correct value of the quantity of heat transferred to the mineral soil of the source of smoldering peat. These methods incorrectly allow for the heat and mass transfer of steam and for its condensation. The new method [31] has made it possible to measure the heat-flux density within the range 10–100 $J{\cdot}m^{-2}$. These results can be used as the boundary condition for mathematical models within whose framework the heat flux to an unburned combustible material and to the underlying (floor) mineral soil is determined.

In [32], the heat evolved from the smoldering of peat was measured by the calorimetry method with allowance for the oxygen consumption. Heat released per unit organic mass was almost independent of the volume density of the organic matter and the inorganic substance but diminished with growth in the moisture content.

The average quantity of heat for all 190 observations [33] was 14.2 $J{\cdot}kg^{-1}$ (error less than 4.5%). Peat was moistened or dried for attaining the selected values of moisture content. Sprayed quartz was added to the raw peat to obtain a higher concentration of inorganic substances. It has turned out that the addition of inorganic materials strongly suppresses smoldering combustion, influencing the concentrations of CO and CO_2 and the rates of their formation [33].

Simple mathematical correlations for prediction of the physical and chemical properties of such a complex organic material as peat using thermogravimetry data have been evaluated in [34]. Persson et al. [34] used peat as a complex organic material, analyzing eight types of Swedish peat. Thermogravitograms were obtained in the temperature range 368–873 K with a rate of heating of 15 K per minute.

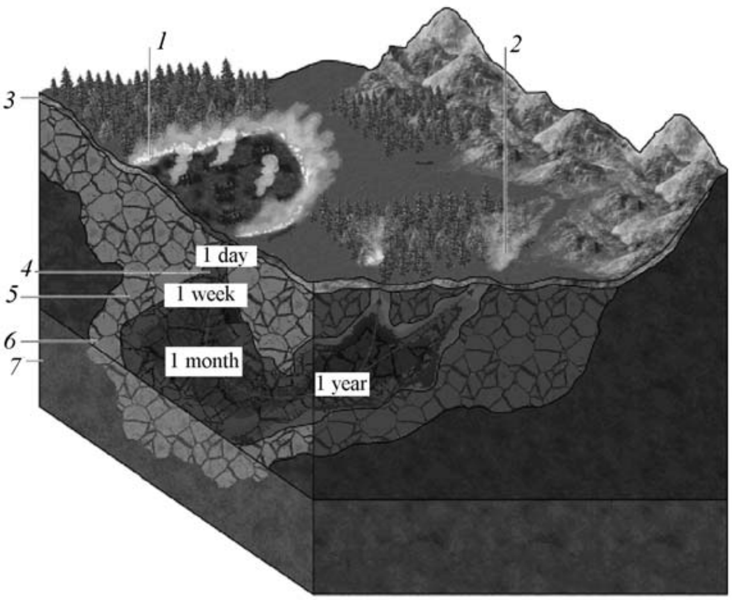

Fig. 3. Illustration of the peat fire initiated on the surface, which propagated in the soil and lasted several months [9]: 1) initial forest fire; 2) forest fire initiated by a subsurface fire; 3) boundary; 4) zones of subsurface peat fire in a day, a week, a month, and a year; 5) peat; 6) natural network of pore channels; 7) level of subsoil waters.

Atmospheric Emissions. The combustion reaction occurring in smoldering of peat is characterized by the fact that peat burns up incompletely; therefore, the emission of toxic gaseous compounds into the atmosphere is more intense than that for forest fires in open space.

The emission of pollutants from peat fires includes CO, CO_2, unburned hydrocarbons, and small particles of carbon, ashes, and gases that are usually present in smoke.

Bertschi et al. [3] have investigated emissions from the smoldering of peat-biomass combustibles and have computed emission from actual natural fires. A comparison of these results yields that in tropical fires in savannah, 130% more CO, 670% more hydrocarbons, and 15% less CO_2 is released in smoldering of peat to the total exclusion of NO. Compared to the emissions of harmful substances from northern fires, 30% more CO and 20% more hydrocarbons but 13% less CO_2 is produced in smoldering of peat, and the total exclusion of NO is observed. Many fire-related problems of control of smoke emissions in the USA included the emission of smoldering [35]. Bertschi et al. [3] used the term *residual smoldering combustion,* defined as the combustion of biomass in the absence of strong fire-induced free convection. They found that the low humidity of a combustible material in organic soils and the decomposition of wood combustible materials contributed to an easier ignition of the combustible materials under study in low-temperature pyrolysis that occurred at $473 \text{ K} < T < 873 \text{ K}$. A white smoke which represented a complex inflammable mixture including oxygen-saturated organic compounds with a low molecular weight and water was released. As the temperature grew from 673 to 873 K, the produced low-temperature charcoal was subjected to high-temperature pyrolysis with the resulting formation of such gas-phase products as alkanes and a solid intermediate product, the so-called "high-temperature charcoal," with a high aromatic content. The reactions of gasification and high-temperature pyrolysis formed a weak bluish-white smoke. Nilson [36] has given the value of the coefficient of CO_2 emission for burning peat of $k = 105–108 \text{ gCO}_2/\text{MJ}$. This value will, apparently, be lower (nearly 20%) in the case of smoldering peat.

Chand et al. [37] have measured the optical properties of aerosols generated by smoldering peat. Aerosols generated by a peat fire can strongly influence the radiative properties of the atmosphere which in turn cause climate change. These aerosols absorb water, with the result that the scattering coefficient increases, which changes the value of the heat flux from the sun.

Meharg and Killham [38] have proved that the burning of coastal peat in Scotland became a substantial source of dioxins long before the industrial revolution of 1800. Their results are based on an analysis of the ash samples of soil and peat dug up near the house on the island of Hirta (Scotland, Great Britain) that was abandoned by its residents in 1930. Quite a substantial amount of dioxins is released as a result of the burning of coastal peat due to the presence of chlorine from the sea and the low temperature typical of smoldering.

The results of investigations of surface and smoldering fronts of combustion of peatlands in the north of Scotland have been given in [39]. The peat samples smoldered in a cone calorimeter apparatus, which made it possible to study CO and CO_2 emissions. Two variable quantities — humidity and external heat flux — were varied so as to obtain different rates of combustion and front thicknesses. The results have shown that peat with a high moisture content smolders with a larger CO_2 yield than drier peat but with the same CO yield.

Review of Results of Mathematical Modeling. All mathematical models existing in scientific literature can be subdivided into two categories: fundamental mathematical models and approximate analytical ones. Mathematical modeling is currently the most difficult variant of investigation of peatlands, since first one must determine, from experimental data, the transfer coefficients and the rates of drying, pyrolysis, and combustion of peat as functions of the parameters of state of the medium (peat) under study.

The first fundamental mathematical model of peat fires has been proposed in [40] and [41]. It represented the set of partial equations expressing the laws of conservation of mass, momentum, and energy. It was assumed that the temperatures of the gas and condensed phases differed; peat was modeled by a multicomponent two-temperature porous reacting medium. The warmup, drying, and pyrolysis of peat and the combustion of gaseous and condensed pyrolysis products were allowed for. To determine the coefficients of transfer of thermokinetic constants (activation energies and pre-exponential factors) experimental investigations of the processes of ignition and combustion of peat were carried out [42] and then the corresponding inverse problems of the mechanics of reacting media were solved [43]. With this mathematical model and the iteration-interpolation method [44], the problem on ignition of a horizontal peat layer has been solved in [45, 46].

Analytical models are more simple in solution. Good evaluation of the order of magnitude of the sought variables, particularly of the total characteristic combustion temperature and the velocity of propagation, in the process of combustion of peat is ensured. These models are basically used in analyzing results of experimental investigations. Empirical constants are used in most of them. For example, several analytical models of heating of soil and ignition of peat can be found in [47]. These models of warmup of soil make it possible to evaluate only the average consumption of heat by heating a forest floor. The most significant propagation models [48, 49] are stationary (steady-state) modelings of a smoldering front propagating in a one-dimensional porous combustible material.

The fronts of drying, pyrolysis, and oxidation with heat transfer by heat conduction, convection, and radiation have been included into the Costa and Sandberg models [49]. The results of [48] were compared qualitatively to experiments. However, the smoldering temperature and the velocity of propagation were not determined independently, and the results were dependent on experimental measurement of at least one of these variables. More reliable is the analytical model of Dosanjh et al. [50] which was subsequently refined by Bar-Ilan et al. [51]. However, this model has thus far been used only for mathematical description of combustion of industrial combustible materials. It encompasses, on the basis of heat balance, the most important mechanisms in self-sustained propagation of smoldering. A comparison to experimental results leads to a marked correlation with tests, and the model can be used for checking theoretical solutions. Models in the first group (fundamental models) model ignition and propagation in a porous solid body and usually explain the conservation of mass, momentum, energy, and chemical kinetics of a combustible material.

One-dimensional models [51–54] were used for modeling of different combustible materials and configurations with different chemical mechanisms. Only a few models have been compared to experimental results [52, 53], and they, apparently, encompass the most important features of this process.

The two-dimensional propagation of smoldering in a cellulose bed in stationary air has been studied by Di Blasi [55]. The predicted smoldering-front structure was investigated. It has been established that the pyrolysis of the starting intact combustible material penetrates deep into the layer of combustible material at a distance from the free surface. Charcoal oxidation is bounded by the external part of the propagation front, which is close to the free surface with access for oxygen. It has been proved that the heat loss in the external environment and the transfer of oxygen from it to the combustion zone control the intensity and rate of the smoldering. Furthermore, in this work, certain quantitative comparisons to experimental observations have been presented.

Conclusions. From the review of the publications. we can state that substantial gaps in the knowledge and understanding of the process of combustion of peat still exist and there are possibilities for further investigation [9, 45, 46]. Most works deal with laboratory investigations of the peat recovered from bogs and of garden peat rather than the peat widespread in bogs. Therefore, the necessity exists of solving primal and inverse problems of mathematical physics for creation of peat-fire theory. The topicality of studying peat fires is beyond doubt, since most countries of the world will have a warmer and more arid summer in the future, as climate experts predict. This can lead to a growth in the number of fires in peatlands and to negative environmental effects.

NOTATION

k, coefficient of carbon-dioxide emission for burning peat; T, temperature, K; W, moisture content; x, y, z, coordinates of the Cartesian coordinate system.

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