DEVELOPMENT OF THE COMPUTER CODE FOR THE PREDICTION OF FOREST FIRE SPREAD

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ABSTRACT

The computer code for the prediction of forest fire spread is developed using the mathematical model of forest fire spreading process. The developed forest fire behavior model is derived on the physical level using the assumption that flame radiation is the dominating factor of the fire spread mechanism. The concept of interaction between outward and inward radiative heat fluxes from flame to natural fuel bed is considered to describe the fire spread mechanism. The developed computer code is arranged to be used in personal computer's software for practical activity of forest fire management.

KEYWORDS - forest fire spread, computer modeling, flame radiation, burning characteristics

NOMENCLATURE

A - Coefficient in Eq.(8);
C - Specific heat of fuel, J/kg·°K;
D - Width of the flame zone, m;
E - Emissivity of the "flame-fuel" system;
H - Flame height, m;
h - Thickness of fuel bed, m;
L - Flame length above the fuel bed, m;
l - Mean free path length of radiation in fuel bed, m;
M - Moisture content of fuel (kiln dried), %;
Q - Referential heat of gasification of fuel, J/kg;
q - Heat flux, W/m^2;
R - Rate of fire spread, m/s;
T - Temperature, °K;

U - Wind velocity, m/s;
V - Buoyancy velocity in flame, m/s;
W - Fuel loading (kiln dried weight), kg/m^2;

Greek

α - Angle between the directions of fire spread and wind;
γ - Flame angle to the fuel bed (Fig.1);
θ - Terrain slope angle;
ρ - Bulk density of fuel bed, kg/m^3;
σ - Stefan-Boltzmann constant, $5.67 \cdot 10^{-8}$ W/(m^2·K^4);
Φ - Factor of flame inclination to the fuel bed;

Subscripts

0 - Ambient;
i - Inward;
is - Isothermal;
o - Outward;
r - Radiative;
s - Surface;
sl - Slope;

INTRODUCTION

The general goal of present study has been focused on the development of the computer code for forest fire propagation that can be arranged to be used in practical activity of forest service management. Actually, no words are needed to describe the difficulties that are arisen in the implementation of such work which, in fact, is the quest for the compromise between the theoretical ideas of scientists and fire suppression tactics of fire fighters. First of all, the mathematical model has to be employed for the prediction of spread rate of forest fire. Concerning the aim of our study, such model claiming to be most suitable faces two highly contradictory requirements: it must be very comprehensive to be able to correspond to the complexity of natural fuel's combustion in fire as well as very simple to be included easily into the PC software.

A significant number of wildland fire spread models developed during the past decades have been reviewed in the recent comprehensive survey paper of Weber [1] who classified this models into three categories. Namely, there are statistical, empirical and physical models among which the models of first two groups only have been developed far enough to be able for operating in forest fire management. However, since no physical mechanism is involved to describe fire behavior, statistical and empirical models relate too close to the specific contidions under which they have been formulated and too many insoluble problems arise if such models are appplied in the conditions slightly altered. From this view-point the fire behavior model of physical level is used in further development of forest fire computer code which is intended to be suitable for a rather wide range of fire conditions. Apparently, the physical model also includes some amount of empirical coefficients and functions which have to be defined through the laboratory experiments or observations of real fires. This fact restricts the application of developed computer code to some types of natural fuels but this code is sufficiently general for the prediction of characteristics of some specific fire occured within the considered region. Furthermore, the most important requirement for the fire behavior model consists in the ability to predict correctly the fire spread rate while the other local characteristics such a temperature distribution, flame height and others are lateral and less important. Having the fire spread rate calculated with good accuracy, the forest fire perimeter can be estimated that provides a highly valuable information for forest service's fire fighting.

BACKGROUND

Probably the first attempt to describe the mathematical model of forest fire spread along the layers of forest fuels has been reported by Fons [2] who assumed that ignition of particles of the fuel bed is performed by heat transfer from flame gases enveloping the nearest particles of fuel. Later, Byram et al. [3] developed another version of the model based on the assumption that the fire spreads by repeating and permanent contact of fuel particles with the flame shifted by the wind. Emmons [4] described a physical model of intensive fire spread along a multy-store fuel beds as a process of radiative and convective heat transfer inside and outside the fuel bed from the flame zone to the fuel. This physical model became the basis for further mathematical modeling of forest fire spread performed by Thomas [5], Van Wagner [6], Telitsyn [7,8], Rothermel [9], Konev and Sukhinin [10]. These models have been analysed by Weber in his excellent review [1].

The model of Telytsyn [7], described briefly in the next section, has been used for the development of the computer code for forest fire spread. The physical basis for this model is the assumption that fuel particles are ignited by radiative heat flux from flame above the fuel bed (outward radiative flux) to the fuel surface. The penetration depth of radiative flux into the fuel bed is limited by the thickness of one thin surface particle of fuel bed, since all particles of forest fuels are not transparent for heat radiation. Following Thomas [5], the flame radiation flux in this model is considered as composition of two fluxes - inward and outward, and the contribution of each flux in fire spread rate is taken into account separately. These features make it possible to apply the model to thick fuel beds and to high-intensity forest fires.

FIRE SPREAD MODEL

The energy balance in the unit volume of fuel bed moving along the surface with the steady fire spread rate R (steady-state coordinate system is considered) is expressed as follows:

$$q_s = R\rho[C(T_s - T_0) + QM] \tag{1}$$

Since the radiation only is considered as a mechanism of fire spread the heat flux is described by the Stefan-Boltzmann law:

$$q_r = E\sigma(T_f^4 - T_0^4) \tag{2}$$

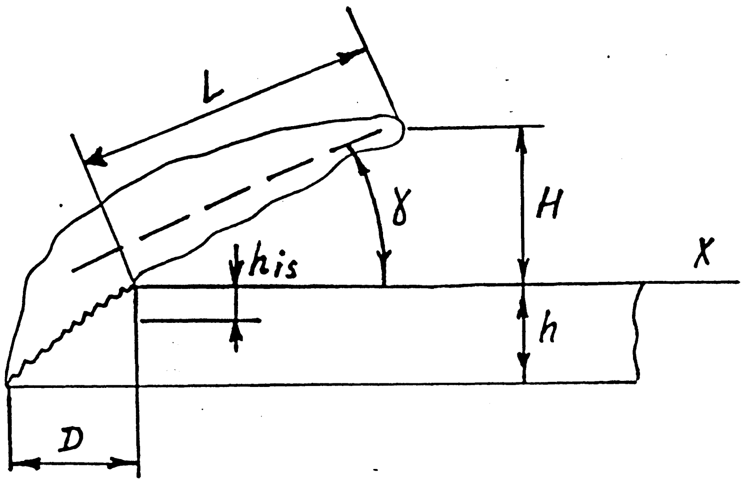

Fig.1 Fire Spread Model

Outward Radiative Heat Flux

In the case of fuel bed heated by external (outward) heat flux from flame that is non-uniform over the fuel's surface (see Fig.1) the energy balance in the fuel bed is rewritten as

$$\int_x q_s dx = R_o \rho h[C(T_s - T_0) + QM] \tag{3}$$

The integration of the heat flux over the fuel's surface yields:

$$\int_x q_s dx = q_r \Phi L \tag{4}$$

The equation for the flame angle factor Φ can be expressed as follows [8]:

$$\Phi = \frac{1 + Cos\gamma}{2}, \tag{5}$$

For the horizontal fuel bed this angle depends upon the mutual interaction between vectors of wind velocity and flame buoyancy flow velocity and can be estimated by the following expression [8]:

$$Cos\gamma = \frac{U}{\sqrt{U^2 + V^2}} \tag{6}$$

The buoyant flow velocity has been measured at the upper level of flames of laboratory fires and the following formula has been achieved:

$$V=2.5H^{0.5} \tag{7}$$

The flame height of cellulosic fuels depends rather on percentage of volatiles than on the caloric value of fuels. Hence, the well-known Byram's formula [11] for flame height based on fuel's caloric value has been modified [12] into another one based on volatile percentage:

$$H = A(WR)^{0.5} \tag{8}$$

where coefficient $A = 7$ for volatiles percentage of 65-75 %; and $A = 8$ for higher percentage.

The outward radiative flux preheats and ignites the surface fuel particles only and can not penetrate into the subsurface layers of fuel bed. Therefore, heat transfer effect due to outward heat flux is limited by the layer of fuel's isothermal thickness within which the fuel material is heated by conduction. Actually, since the conductive heat transfer between fuel particles is negligible, the isothermal thickness corresponds to the thickness of one-particle layer. Thus, deriving the fire spread rate due to outward heat flux we mean under the characteristics of fuel material their isothermal values. The isothermal fuel loading of the fuel bed, for which the Eq.(3) is valid, is expressed as follows:

$$W_{is}=\rho_{is}h_{is} \tag{9}$$

Based on measurements the flame outward emissivity is estimated as

$$E_o=1-\exp(-0.16D) \tag{10}$$

Further investigations have shown that observed fire spread rate values are generally much higher than calculated using the model of outward heat flux while the good agreement has been achieved only for very thin fuel beds of loading values within
0.1 - 0.2 kg/m^2. Thus, the additional considerations have been employed.

Inward Radiative Heat Flux

In the case of fire spread along the thick fuel beds which fuel loading exceeds an isothermal value, subsurface particles are not exposed to the outward radiative heat flux, and they become exposed to the internal radiative heat flux only inside the flaming zone, where the surface particles are already burnt. Thus, flame spread is ensured by inward heat flux emitted by internal space of the flame onto the surface of particles which it covers.

Based on the laboratory and field observations the inward emissivity is estimated as

$$E_i=1-\exp[-0.16(L+0.4)] \tag{11}$$

where coefficient **0.4**, most probably, describes the effect of the ember radiative heat flux.

Fire Spread Rate Formula

The joint influence of outward and inward heat transfer on the fire spread process results the following expression for the fire spread rate:

$$R=R_o+R_i \tag{12}$$

where R_o and R_i stand for the contribution of outward and inward heat fluxes correspondingly.

Finally, the following formula for the rate of forest fire spread is derived:

$$R = \frac{\sigma(T_f^4-T_0^4)}{C(T_s-T_0)+QM}\left(\frac{E_i}{\rho}+\frac{E_o\Phi L}{\rho_{is}h_{is}}\right) \tag{13}$$

The isothermal fuel loading can be estimated also in the following form

$$W_{is} = l\rho \tag{14}$$

The thickness of leaves of grasses and foliage of hardwoods is 0.1 mm, so their surface-volume ratio (or the specific surface) is 20,000 m^{-1}, and the mean free path of radiation in the fuel bed of leaves and grass is defined as

$$l = 0.0002\ \frac{\rho_{is}}{\rho} \tag{15}$$

Thus, the formula for fire spread rate is rewritten as

$$R = R_i\left(1+\frac{R_o}{R_i}\right)= R_i\left(1+\frac{E_o\Phi L}{E_i\ l}\right) \tag{16}$$

For very thin flames of low-intensity fires with negligible flame width, the outward emissivity is also negligible. The inward heat flux always exists in forest fires even of minimal intensity.

The ratio $E_o\Phi L\ /\ E_i l$ is a certain function of wind speed vector, so we have:

$$R = R_i\ (1+f\ (U)\ Cos\alpha) \tag{17}$$

The inward heat exchange between the internal flame space and lower particles of the fuel bed is not influenced by slope and wind velocity vector, except of some increase of flame temperature for 10-20 °K by winds of up to 10 m/s.

The effect of terrain slope on the upward fire spread rate can be described as [13]

$$R_{sl}=R_i\ (1-Sin\Theta)^{-2} \tag{18}$$

Following the published data [3,7,8,12-13], some parameters of Eq.(13) are assumed to be constant as indicated in Table 2.

Table 2. Burning Characteristics of Eq.(13).

Parameter	Value	Units
T_f	1200	K
T_s	573	K
T_0	293	K
C	1400	J/(kg·K)
Q	26000	J/kg

COMPUTER CODE

The forest fire behavior model described in previous section has been used for the development of computer code for the prediction of forest fire propagation process. For some specified conditions (fuel type, terrain slope, weather, wind velocity) the model provides the value of fire spread rate vector in each direction from the fire source or from the point where fire is already occuring to unburnt area. Depending upon the discontinuity of above mentioned conditions (of two first factors esspecially), the fire perimeter can result very complicated form and special algorithm should be applied for the approximation of fire perimeter at the next time step. We used the procedure developed by Knight and Coleman [14] which is based on the Huygens' wavelet propagation principle.

For the final arrangement of developed computer code the database of geographic information system is necessary. Creation of such database is currently under way at the Forest Fire Lab of Khabarovsk State University of Technology in collaboration with the Forest Service of Khabarovsk Territory in Russian Far East region.

CONCLUDING REMARKS

The study on the development of presented forest fire behavior model has been conducted for many years and not only theoretical considerations but many field and laboratory observations also have been analysed. The considerable amount of experimental information has been collected from different sources over the world through which the model has been verified [7]. However, the theoretical model of such level, itself, is unable to predict the fire propagation process from initial parameters of fuel and other factors of fire environment only and some half-empirical correlations must be included. On the other hand, it is hardly believed that very comprehensive forest fire behavior model, such of Grishin [15], can be used on present stage in the forest fire management since the computer resources (and, probably most important, the information on the fuel's burning characteristics) available to fire fighters in their practical activity are far from required by comprehensive model. Therefore, the way for further investigations in the field discussed in this paper tends to use deep theoretical study as well as real and laboratory fire observations for the improvement of model which should be kept as simple as possible.

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