International Journal of Latest Research in Science and Technology **ISSN (Online):2278-5299**
Volume 2, Issue 5: Page No.12 -17 ,September-October 2013
https://www.mnkpublication.com/journal/ijlrst/index.php

MATHEMATICAL MODELING OF FOREST FIRE INTERACTION WITH WATER BARRIER

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Abstract – This paper presents results of mathematical modeling and analysis of the water-fire interaction problem. It will be shown how terrain influence amount of water in the barrier required for fire extinction. Proofed that despite sufficient loss of spread rate fire extinction in ravines is not effective due to ravine's flow-around which causing fire front to stretch.

Keywords: water barrier, wildfire, fire control, numerical simulation

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INTRODUCTION

Water is used the most in fire-fighting operations nowadays and it is important to use it effectively. However most of modern approaches to fire-fighting lack this effectiveness. There are a lot of things to consider while using this ultimate tool. Terrain can influence fire behavior in very dramatic way causing flow-around and other effects. Most of current semiempirical models produce fire front line and its spread rate. Those models do not take into account fire hydrodynamics while velocity profile determines heat energy flow during combustion. As opposed to existing semiempirical models this paper presents physical model of fire interaction with water.

MATHEMATICAL MODEL

Mathematical model described by Kataeva [1] and Maslennikov [2] uses Arrhenius law for calculation physicochemical processes, including water evaporation. Free water (in contrast with moisture) has steam point which can be considered constant taking into account pressure difference within combustion area.

Boiling rate is determined by heat flow intensity and it is assumed that liquid's temperature cannot be higher than steaming point.

This paper defines fire extinguishing as a process of interaction of free water with a fire front. During this process water consumes fire energy and evaporates. It leads to oxygen deficiency and fire spread rate decrease. If fire propagation stops due to this process, fire extinguishing said to be successful.

In order to model free water correctly an addition to mathematical description [3, 4] is required. New phase and ratios are introduced [5] (1-4):

$$\rho_4 \frac{\partial \varphi_4}{\partial t} = -R_4, \tag{1}$$

$$R_4 = \begin{cases} \theta\varphi_4\varepsilon^{-1}, \ npu\ \ T > 373K + \varepsilon, \\ 0, \qquad npu\ T < 373K - \varepsilon, \\ 0.5\theta\left[T - (373K - \varepsilon)\right]\varphi_4\varepsilon^{-2}, \\ \qquad npu\, 373K - \varepsilon \le T \le 373K + \varepsilon, \end{cases} \tag{2}$$

$$\begin{aligned} &\frac{\partial\left(\left(\sum_{i=1}^{4}\rho_i\varphi_i c_{pi} + \rho_5 c_{p5}\right)T\right)}{\partial t} + \frac{\partial\left(\rho_5 c_{p5} UT\right)}{\partial x} + \frac{\partial\left(\rho_5 c_{p5} WT\right)}{\partial z} = \\ &= \frac{\partial}{\partial x}\left(\lambda_t \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(\lambda_t \frac{\partial T}{\partial z}\right) - \\ &- q_2 R_2 + q_3 R_3 - q_4 R_4 + q_5 R_5 + k_s\left(cU_R - 4\sigma(T^4 - T_e^4)\right), \end{aligned} \tag{3}$$

$$Q = (1 - \alpha_c)R_1 + R_2 + R_4 + \frac{M_c}{M_1} R_3 . \tag{4}$$

Equation (2) models rapid emergence of boiling reaction when certain temperature achieved. On the other hand rate of a reaction dependency on temperature is continuous. Equations (3) and (4) introduce boiling reaction heating effect and transfer of evaporated water mass into vapor mass.

This paper analyzes fire extinction modeling with a water barrier on the fire's way. Barrier is placed 20 meters off the left end of calculation area; it is 0.4 meters wide and equals forest height. At starting point water in the barrier is uniformly distributed. Initial conditions of water volume ratio in a barrier are:

$$\varphi_{4b} = \varphi_1 \frac{\rho_1}{\rho_4} w_b \tag{5}$$

Publication History
Manuscript Received : *21 October 2013*
Manuscript Accepted : *27 October 2013*
Revision Received : *28 October 2013*
Manuscript Published : *31 October 2013*

Such water barrier can be represented by drenched forest fuels. There is the following ration to calculate amount of water required for water barrier:

$$m_w = V_b \rho_4 \varphi_{4b} \eta^{-1} \tag{6}$$

In equations above (1-6): ε - sufficiently small positive constant value, K; $\theta = \frac{кг \cdot К}{c}$; φ_4 - free water volume fraction; w_b - ratio of water mass to mass of forest fuels in barrier; ρ_4- water density, kg/m^3; T – local temperature, K; $\rho_i, \varphi_i, c_{pi}$- density, volume fraction and specific heat of i-th phase, kg/m^3, dimensionless quantity, J/(kg·К); U, W - horizontal and vertical velocity components of gas phase, m/s; λ_t- thermal conduction of gas phase, W/(m·K); q_i, R_i- specific heat effect and physicochemical processes mass velocity respectively (i=2 – forest fuels moisture evaporation, i=3 – condensed pyrolysis products combustion, i=4 – free water boiling, i=5 – volatile pyrolysis products combustion) , J/kg, kg/s; k_s- spectral absorption coefficient; c – light velocity, m/s; U_R - radiation-flux density, kg·(m/s2); σ - Stefan-Boltzmann constant, kg·s^{-3}·К$^{-4}$; T_e - temperature of environment, K; m_w- water mass required to build barrier, kg; V_b - water barrier volume, m^3; η- a fraction of wasted water which remains in barrier.

It is assumed while performing computations that boiling process takes place in every cell with temperature above 373K and non-zero fraction of free water. Boiling process rate is defined as a minimum between quantity of free water in a cell and a quantity of free water which have enough energy already to evaporate.

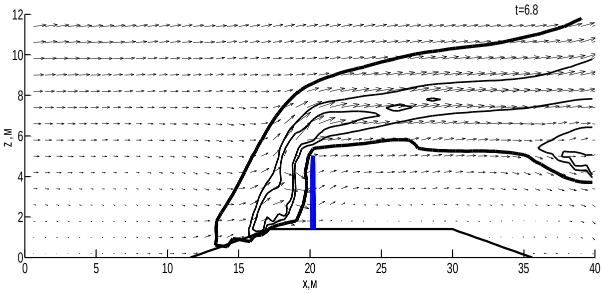
According to specifics of initial fire modeling it takes time for forest fire to reach equilibrium state. Taking this into account initial fire was set 12 meters away from water barrier. Right after fire front meets water barrier boiling processes start. Even when fire core is still away heated gaseous mixture starts to vaporize the barrier.

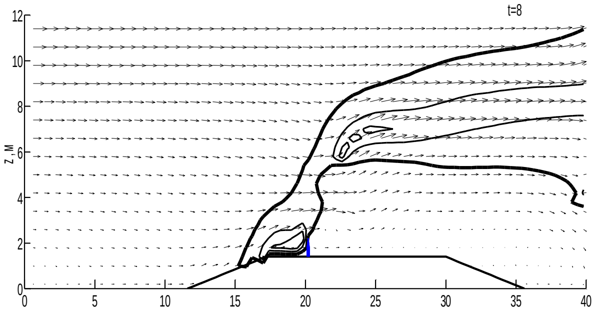
Dichotomy method was selected to determine amount of water in the barrier required to stop a fire. During computations it is assumed that there is a critical value $w_{b,кр}$. Fire breaches the barrier if $w_b < w_{b,кр}$ and stops if $w_b > w_{b,кр}$. $w_{b,кр} = 0$ means fire stops itself without any barrier encountered. To verify that fire was extinguished by barrier the following criteria are used: temperature within forest canopy and mass fraction of organic dry substance 4 meters away from right end of calculation area. If peak temperature in canopy decreased below 700K fire was stopped by barrier. If mass fraction of organic dry substance 4 meters away from the end of calculation area is less than $0.5\varphi_{1e}$ fire has breached the barrier.

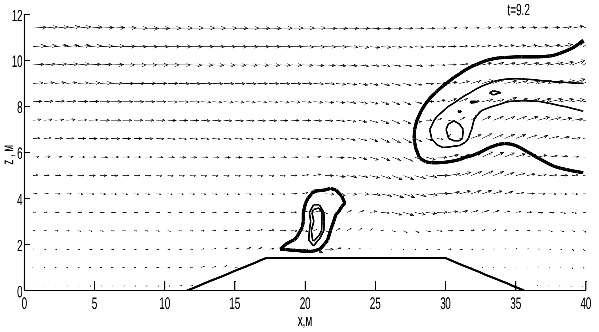
It is important to use any opportunity to decrease computing time as hydrodynamics modeling restricts time steps width significantly. One of the options to decrease computing time is to use first-order accuracy methods like algorithm for correcting the rates of chemical reactions [2]. High accuracy methods like Gear's method [6] are not efficient for physicochemical processes modeling as it requires far more computing time. At the same time Harlow first-order accuracy scheme is used for solving PDE. Another approach to decrease computing time is optimization of data allocation in memory [7]. Key concept of this optimization is to compute cached data whenever possible. As opposite to [8] where fire was spreading on homogeneous flat terrain, paper [9] concentrates on trapezoidal hill and ravine terrain.

RESULTS AND ANALYSIS

Three different terrain configurations have been selected for computing: hill, flat and ravine.Figures 1-6 demonstrates forest fire dynamics. Thin continuous line represent 1500K temperature while thin dash-line and solid continuous line stands for 1000K and 500K. Velocity field is represented by arrows. Water barrier is presented as a blue area. Its width corresponds to amount of water remained in barrier's horizontal component.It was discovered during computer modelling that fire could pass through barrier or fade out depending on the amount of water in the barrier. Figures 1-2 shows fire spread dynamics at different time steps on trapezoidal hill. Ratio of mass of water in the barrier to mass of dry organic substance w_b =1.23 and 1.24 respectively.







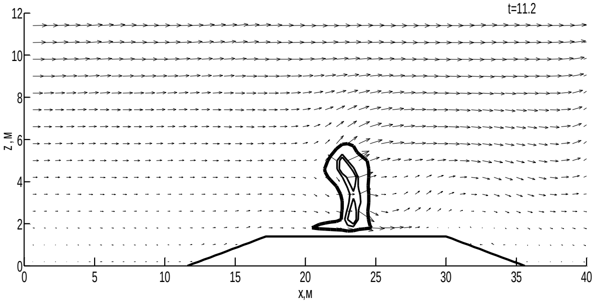


Fig. 1 Fire spread uphill with a barrier located on a top; ratio of water mass in the barrier to mass of organic dry substance is $w_b = 1.23$

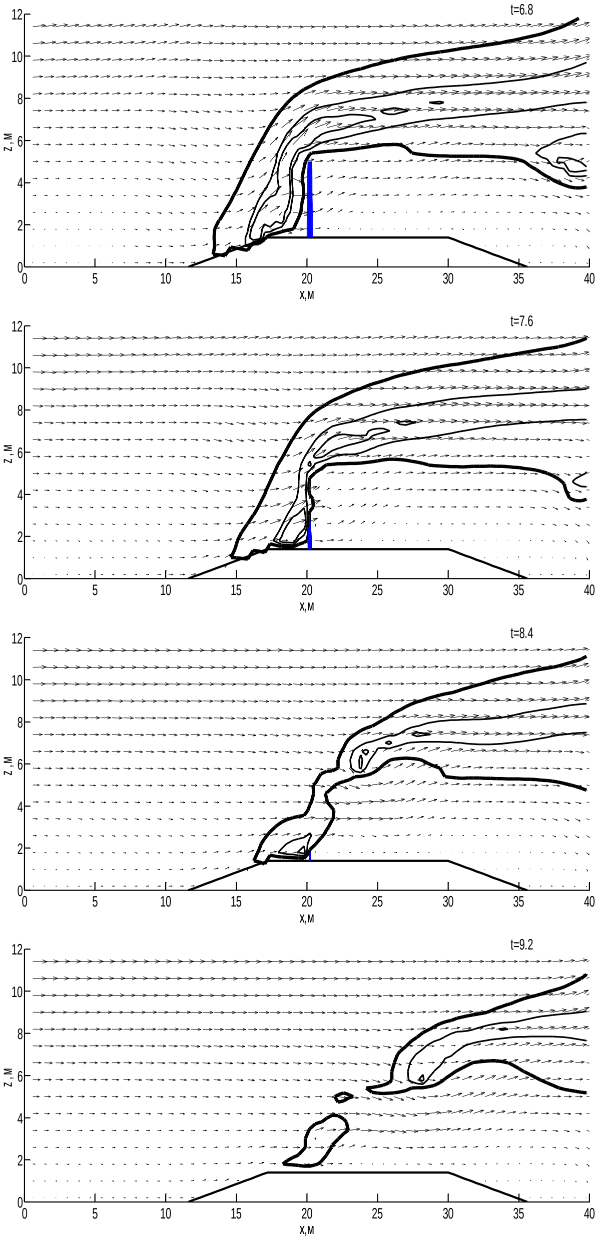
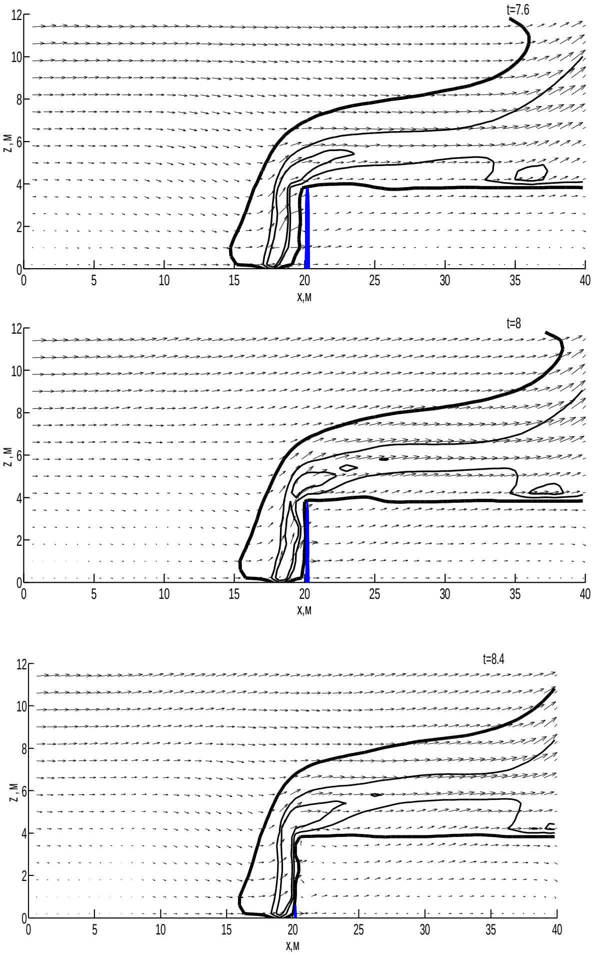


Fig.2. Fire spread uphill with a barrier located on a top; ratio of water mass in the barrier to mass of organic dry substance is $w_b = 1.24$

According to Figures 1-2 difference in fire spread dynamics are small at time t=6.8 sec. Since flame bends forward water evaporation from the barrier takes place mostly at the top of the barrier. Increasing of speed can also be noted. Further fire spread is characterized by temperature decrease in upper part of forest canopy due to use of energy for barrier evaporation. Figure 2 depicts isoline 1500K remained at the bottom level of forest and above canopy at the time t=7.6 sec. Figure 1 at the time t=8 sec demonstrates that high temperature (above 1000K) can only take place in ground level and above canopy, at the same time velocity fields starts to straighten. Small changes in amount of water in a barrier have a great influence on a fire behavior after barrier evaporation. It is demonstrated on Figure 1 how new fire front is building at time t=9.2 sec and t=10.4 sec. On the other hand Figure 2 shows release of heated gas and gradual fade of fire. It is worth noticing that water barrier in both cases is completely evaporated.

Figures 3 and 4 present fire spread dynamics on a flat terrain at different times. Ratio of water mass in the barrier to mass of organic dry substance are w_b=0.78 and 0.79 respectively.

Figures 5 and 6 present fire spread dynamics on a ravine terrain at different times. Ratio of water mass in the barrier to mass of organic dry substance are w_b=3.48 and 3.49 respectively.



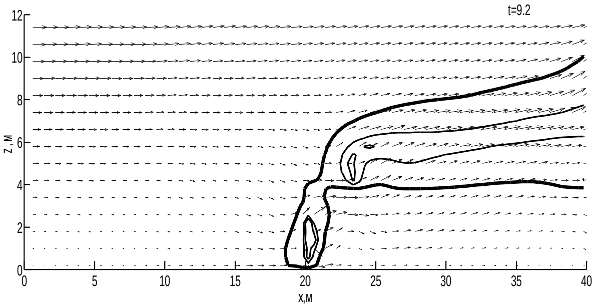


Fig.3. Fire spread on flat terrain with a barrier in front; ratio of water mass in the barrier to mass of organic dry substance is $w_b = 0.78$

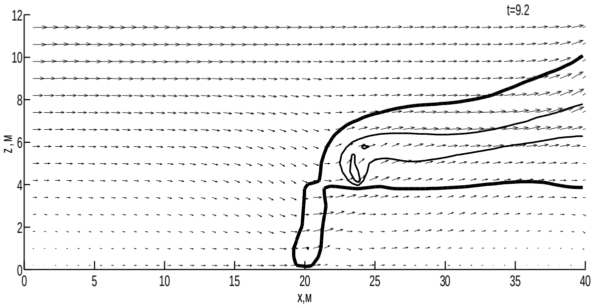
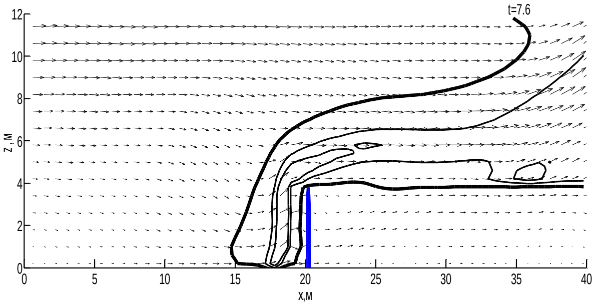


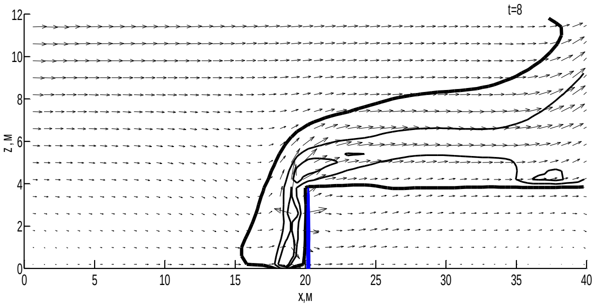
Fig.4. Fire spread on flat terrain with a barrier in front; ratio of water mass in the barrier to mass of organic dry substance is $w_b = 0.79$

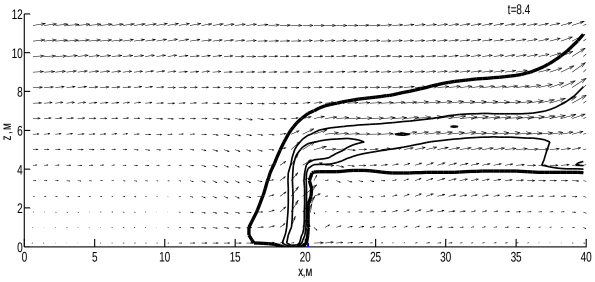
Water in a barrier starts to evaporate even before fire core approaches the barrier. Even when difference in amount of water in a barrier is small velocity fields before barrier start to vary. It can be seen on Figures 3 and 4. It is also worth noticing that at moments t=7.6 sec and t=8 sec velocity vectors increasinglydirected upward in case of smaller amount of water in a barrier.

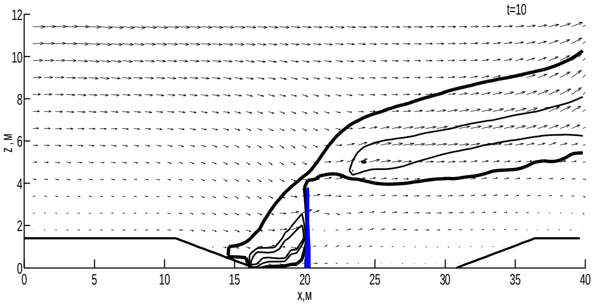
As a result at time t=8.4 sec barrier vaporize greater when there is less water in it.

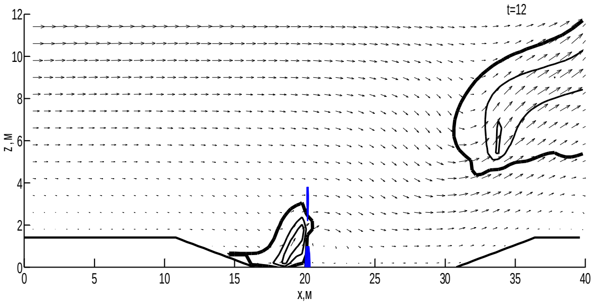
There is an active cool down of fire front taking place in a time frame between 8.4 – 9.2 seconds even when barrier is almost evaporated. It can be explained by the fact that barrier prevents heat spread and as a result slows pyrolysis and fuels drying processes. It leads to most of energy be wasted on fuel drying. This effect is increased due to greater volumetric heat capacity of forest untouched by fire compared to heat capacity of decomposed and partially burned-out fuels right before a barrier.

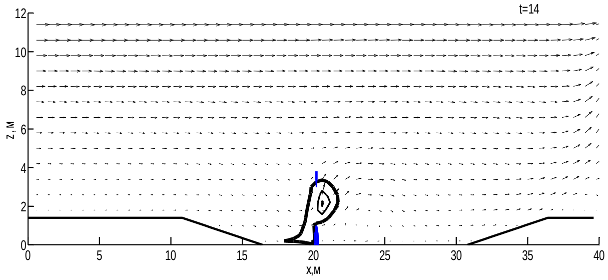












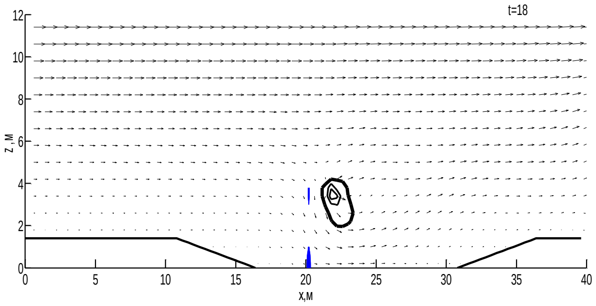


Fig.5. Fire spread dynamics through a water barrier over ravine terrain. Ratio of water mass in the barrier to mass of organic dry substance is $w_b = 3.48$

First 10 seconds of fire spread are not depicted on Figure 6 because influence of water amount in a barrier on temperature and velocity field is small enough to make a difference. Strong fire flame bend is common for fire spreading uphill and in ravines. As a result if fire flame cut (10 seconds from fire ignition) fire energy is concentrated on a barrier instead of flowing it around and diffusing in environment. Fire breaches barrier in the middle first as gas speed increasing with a height. At the same time in the bottom and top parts of the barrier there is still enough amount of water left for holding fire spread and continue to evaporate. At time t=14 sec fire core breaches barrier completely. It depends on amount of water in a barrier if fire proceeds or stops. Low wind speed near fire core prevents energy outflow giving fire an opportunity to gain more power and flame up.

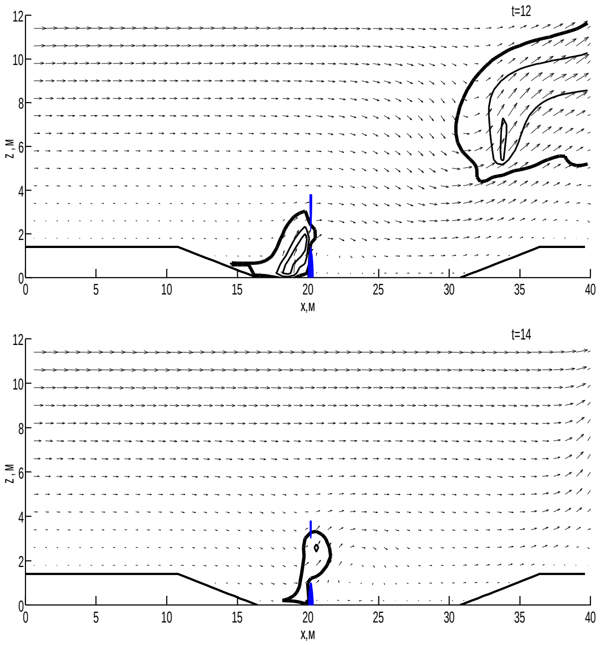


Fig.6. Fire spread dynamics through a water barrier over ravine terrain. Ratio of water mass in the barrier to mass of organic dry substance is $w_b = 3.49$

CONCLUSION

Limitation of the developed algorithm is that it answers a question about ratio of water amount in barrier required to stop fire but not answering question how to store such amount of water in forest fuels.This paper has demonstrated an approach to fire extinction modeling with a help of free water using physical model and hydrodynamics computations. Velocity field determines flame bend angle which in its turn influence of water barrier efficiency (with an increase of flame bend angle water amount required to stop fire increase as well). This paper doesn't answer a question about possibility of forest fuels to hold specified amounts of water.

ACKNOWLEDGMENT

Work has been done with a financial help from 13-03-91164- NSFC _a "Experimental study of the kinetics and mechanism of thermal decomposition of forest fuels and the propagation of a flame on their layer"

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