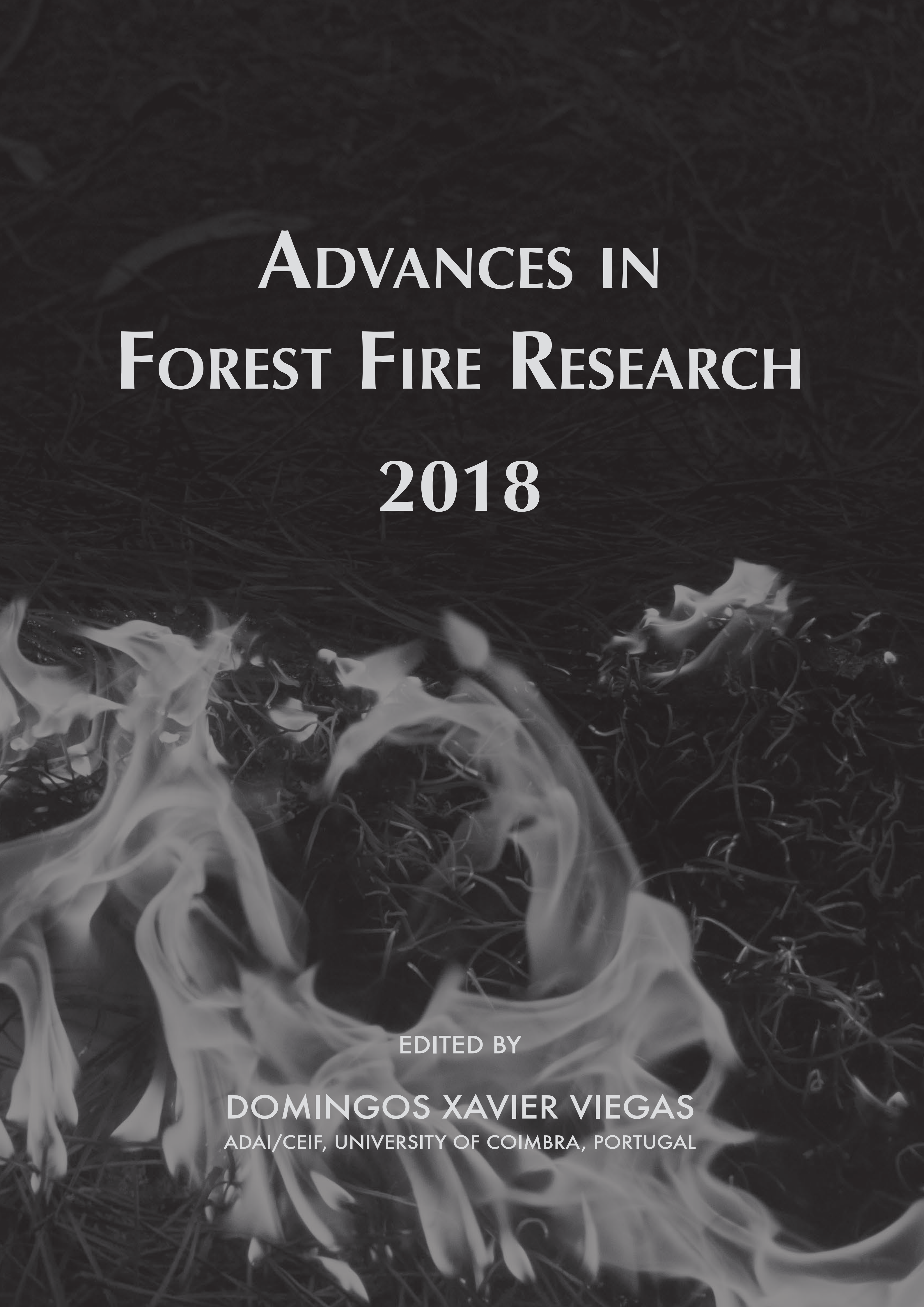
Advances in Forest Fire Research 2018



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https://doi.org/10.14195/978-989-26-16-506_92

Proper Width Calculation to a firebreak line to protect flame spread from forest fire

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Abstract

Building a firebreak line against forest fire spread is a typical indirect suppression method that stops spread of flame by removing fuel, such as trees and bushes. In the view of fire dynamic, building a firebreak line is to set a section which will block thermal energy from igniting on virgin fuel. This study suggests and evaluates a calculation method for width of firebreak against forest fires for variant wind and slope conditions by applying the Point Source Model (PSM) to Korean fuel types. Width of firebreak was measured based on the distance the threshold radiant heat igniting forest surface fuels wat the heat flux of 4.9kW/㎡ from surface and crown fires in forest. This study applied the condition of wind and slope as the wind velocity of 0~5m/s and the slope of 0~50°. As a result, Proper width of a firebreak line was calculated 1.1m in surface fires and 14.6m in crown fires. Additional comparative analyses through experiments and field surveys are deemed necessary to determine appropriate widths of firebreak for different types of surface fuel.

Keywords: Forest Fires, Firebreak Line, Heat Transfer, Flame Spread, Point Source Model (PSM)

1. Introduction

Fire forests spread to surface fire and even crown fire due to radiant heat flux generated from flames. In a case where materials are burned in open space as forest fires, most of heat transfer is conducted by radiant heat transfer (McCaffery, 1995). Fire line has a function to prevent flame expansion from forest fire and protect main facilities adjacent to the forest while securing safety zones for fire fighters and ordinary people. In establishing a fire line, there are several methods including eliminating combustible materials and spaying fire extinguishing agents such as Foam Chemical and Retardant toward incombustible materials with a specific amount to prevent flame expansion. Therefore, to prevent spread of forest fire, appropriate width and promptness of the establishment of fire line. Figure 1 is a conceptual diagram on the establishment of fire line to prevent spread of surface fire and fire line establishment can be explained as securing Section (A) as shown in Figure 1. It can be said that appropriate width of fire line is key to success of indirect extinguishment of forest fires. For example, if fire line width is less than the distance to prevent ignition of unburned materials by heat transfer, flames will continue to spread, while if fire line width is too large, it will be waste of resources and it will take a long time to establish fire line, and accordingly a problem may occur in extinguishing forest fires effectively. In this regard, this research aims to provide methods and results to calculate appropriate width of fire line in order to prevent spread of surface fire flames.

2. Background

In Korea, width of fire line shall be about 1.5m according to guidelines prepared by Korea Forest Service in 2005), while in the USA and Canada, ground surface fuels including standing trees shall be eliminated in width of 6~ 9m in accordance with the applicable guidelines (NWCF, 2004), and in particular, it is specified to set width of fire line to four times the flame height to prevent spread of crown fire (NWCG, 2004) and it is reported that fire line width should be set considering fire intensity depending on fuel load per unit area. In the case of studies conducted by overseas countries, there was a study using a mathematical model on fire line width and flame height, but in Korea, there is lack of research on the calculation of fire line width to prevent spread of forest fires. Although fire line should be established by calculating fire intensity (kW/m or kW/m^2) or flame length, it has limitations to consider all of the conditions changed by fuel load per unit area, slope, and wind velocity.

2.1. Fire Break Building Work

Building of forest fire break line on the ground is conducted by forest fire extinguishers in groups of more than one person or two persons by using fire rakes or air pumps. The progress of fire line building work varies by skills of fire extinguishers, the number of workers, and fire line establishment method. Figure 1 shows fire line building methods for the group of one, group of two and group of three.

Figure 1 - Fire break line establishement methods (a: group of one. b: group of two, c: group of three)

As the result of measuring working hours for each fire extinguisher to build a fire line (1m (width) x 100m (length)) in the forest with 23-degree slope, working hours in deciduous were shorter than that in forest coniferous forest by 22%, which indicated that working in coniferous forest is more difficult. It was reported that the difference was caused by forest density and securing of moving passages. In terms of working speed, smoke jumpers were two times faster than normal fire fighters, and in relation to the number of workers, the group of three was 1.85 and 1.2 times faster than the group of one and group of two, respectively. Likewise, previous studies suggested that work efficiency varied by operation and methods of limited fire extinguishing resources. Therefore, as the calculation of effective fire line width reduces risk of fire expansion as well as suggesting the most effective fire line establishment work, it can suggest standards to extinguish forest fires efficiently with limited manpower.

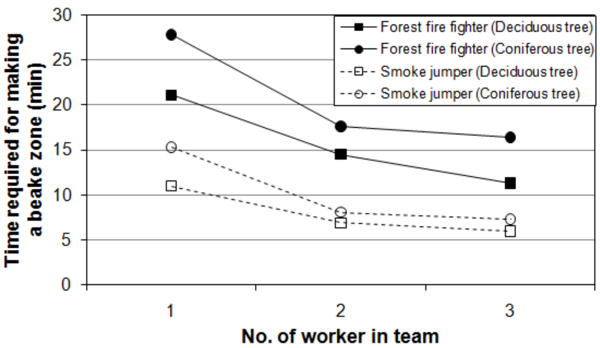

Figure 2 - Work amount for fire line establishment

2.2. Specifications of Surface Fire

2.2.1. Flame Height

Spread of forest fire undergoes the pyrolysis process of unburned fuel by heat flux emitted through flames. Then, when the surface temperature of the burning substance reaches the igniting temperature, the process of creating flames causes the expansion of the forest fire. To assess heat flux emitted from flames, height of flames should be considered. First, to calculate the height of flames, heat release rate (HRR, kW) should be estimated using Effective Heat of Combustion (kJ/kg) and Mass Loss Rate (MLR, kg/s). Heat release rate can be calculated from Equation (1) and is proportional to MLR and Effective Heat of Combustion changed by energy equivalent, water content, combustion diameter, and density.

$$HRR(\mathrm{kW}) = \Delta h_c \times MLR \qquad (1)$$

Flame height calculation models were proposed by McCaffrey (1995) and Heskestad (1998) for horizontal-plane fire of liquid flammable materials under the condition of no wind. The calculation Equation of fire flame height was presented by Albini (1981) as $H \propto IB/U$, which is an estimation Equation for one dimensional flame height, and Nelson (1986) suggested Equation (2). However, when wind velocity is 0, it is not possible to calculate flame height with the Equation.

$$H = \frac{aI_B}{U} \qquad (2)$$

where, I_B is Byram' fire intensity (kW/m^2) and a is 1/360 and U is wind velocity (m/s).

Kim (2009 a) suggested a calculation Equation of flame height of solid fuel such as surface fire fuel materials as the following Equation (3):

$$H = 0.027(\dot{Q}')^{2/3} \qquad (3)$$

where, $\dot{Q}'$ (kW/m) is heat release rate in length, and unit length, which is an experiment setting of Q calculated by Equation (1) was applied. Equations (2) and (3) are to calculate flame height under the condition of no wind and flat area, and flame height changed by wind and slope can be calculated with Equation (4).

$$H_{ws} = H \times \sin(\theta) \qquad (4)$$

where, θ (°) is angle between ground surface and the flame changed by wind and slope and it is obtained by subtracting flame angle ($\emptyset$) from 90°. Calculation of flame angle can be conducted using Equation (5), which represents correlation between Froude Number (Fr) and wind velocity under the condition of uniform wind (Kim, 2009b, 2009c).

$$Fr = \frac{U_\infty}{\sqrt{gH}} \qquad (5)$$

$$tan\emptyset_{ws} sin\emptyset_{ws} = 1.2\frac{U_{ws}^2}{gH} \qquad (6)$$

where, g is acceleration of gravity (m/s^2), H is initial flame height (m), and U_{ws} is air entrainment rate (m/s).

3. Methods

3.1. Application Conditions

As shown in Table 1, to calculate appropriate fire line width, there were a total of 12 conditions set: 6 conditions at 1 m/s intervals within 0~5 m/s of wind velocity for the dried pine tree litter layer in the spring season of Korea and the other 6 conditions at intervals of 10° within gradient 0~50°. Properties of the pine tree litter layer are factors to calculate flame height and heat release rate and conditional variables applied to Formulas 1 and 4. From Formula 4, flame height of the pine tree liter layer was 0.71m on average and 1.46m at maximum (Kim, 2009b).

Table 1 - Conditions for wind speeds, slopes and surface fuels

Surface fuels			Wind speed (m/s, 6 conditions)	Slope (°, 6 conditions)
Fuel density (kg/m^3)	FMC (%)	Fuel depth (m)		
20	13±2	0.1	0~5 (each 1m/s)	0~50 (each 10°)

3.2. Heat Flux Calculation

3.2.1. Point Source Model Flame Height

Spread of forest fire undergoes the pyrolysis process of unburned fuel by heat flux emitted through flames. Then, when the surface temperature of the burning substance reaches the igniting temperature, the process of creating flames causes the expansion of the forest fire. To assess heat flux emitted from flames, height of flames should be considered.

As shown in Table 1, to calculate appropriate fire line width, there were a total of 12 conditions set: 6 conditions at 1 m/s intervals within 0 – 5 m/s of wind velocity for the dried pine tree litter layer in the spring season of Korea and the other 6 conditions at intervals of 10° within gradient 0 – 50°. Properties of the pine tree litter layer are factors to calculate flame height and heat release rate and conditional variables applied to Formulas 1 and 4. From Formula 4, flame height of the pine tree liter layer was 0.71m on average and 1.46m at maximum (Kim, 2009b).

First, to calculate the height of flames, heat release rate (HRR, kW) should be estimated using Effective Heat of Combustion (kJ/kg) and Mass Loss Rate (MLR, kg/s). Heat release rate can be calculated from Equation (1) and is proportional to MLR and Effective Heat of Combustion changed by energy equivalent, water content, combustion diameter, and density.

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where, g is acceleration of gravity (m/s^2), H is initial flame height (m), and U_{ws} is air entrainment rate (m/s).

3.3. Heat Flux of Forest Fires

Radiation heat transfer by surface fire flame is conducted through calculation of total radiant heat flux received by unburned section from individual flame for the grid defined as follows (Figure 3), where three-dimensional position values against the center point of flame obtained by Equation (3) are x_f, y_f, and z_f. To calculate heat energy per unit area emitted from flames, Point Source Model in Equation (7) was used. With the Point Source Model can be used when calculating radiant heat flux per unit area and unit time delivered target distant by r from emitting flame. Therefore, when the total heat flux reaches ignition energy, flame combustion is conducted and expanded.

$$\dot{q}'' = \frac{\dot{Q}_r}{4\pi r^2} cos\theta' \quad (7)$$

Where, $\dot{Q}_r$ is radiant flux, r is radius of flame depth (m), and θ' is angle between the center of flame and z_f vector and expressed as Equation 7. Location coordinates of the center of flame (x_f, y_f, z_f) needed to calculate heat flux transfer from flame can be moved by slopes and wind, which can be represented as the following Equation (9).

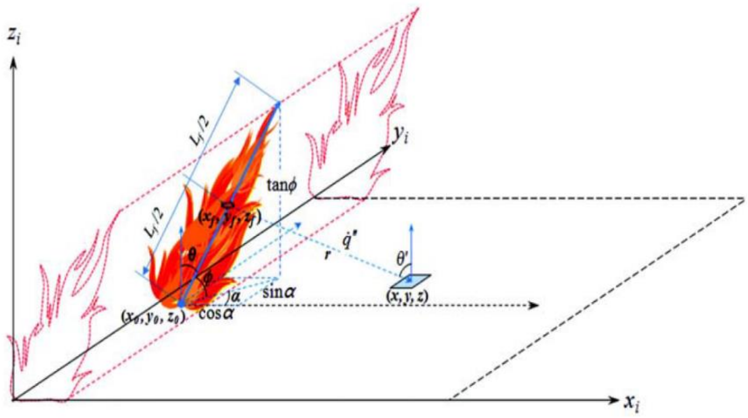


Figure 3 - The concept of heat flux transfer

$$cos\theta' = \frac{Z_f - Z}{r} \quad (8)$$

where, $r = \sqrt{(x_f - x)^2 + (y_f - y)^2 + (z_f - z)^2}$

$$\overrightarrow{P_f} = \begin{pmatrix} x_f \\ y_f \\ z_f \end{pmatrix} = \begin{pmatrix} x_0 + \frac{1}{2}L_f cos\emptyset cos\alpha \\ y_0 + \frac{1}{2}L_f cos\emptyset sin\alpha \\ z_0 + \frac{1}{2}L_f sin\emptyset \end{pmatrix} \quad (9)$$

In this case, the cell condition was set to 0.3m × 0.3m for numerical analysis of radiative heat transfer in Figure 4, which is the experimental size of the existing P. densiflora litter layer basket (Kim, 2009b). In this study, a y-axis flame grating is to 9 grids, total 2.7 meters in order to analyze the heat transfer of individual flames for each surface fuels. Therefore, the radiant heat flux of the surface fuels for each unit flame can be calculated from Equation 7 to Equation 10. Where F is the individual flame and S is the target cell.

$$\dot{q}'' = \int_F \int_S \frac{\dot{Q}_r}{4\pi r} dFdS \qquad (10)$$

4. Results

4.1. Characteristics of Heat Flux Distribution

Analysis of flame heat flux distribution using PSM revealed that under the condition of no wind and flat area as shown Figure 4, 5, heat flux decreased as distance from flames were longer and horizontal heat influx for fire line is distributed the highest at the center of fire line. Based on the characteristics of heat flux, maximum heat flux should be calculated focusing on the main axis of fire line (y_5).

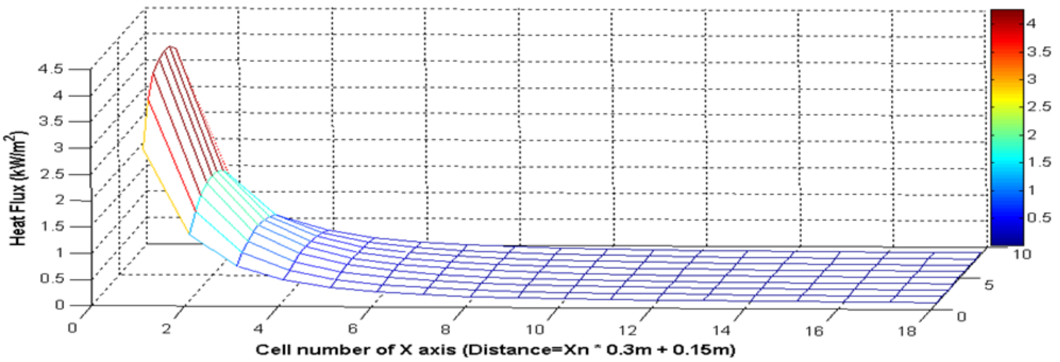


Figure 4 - Heat flux under the condition of no wind – flat area

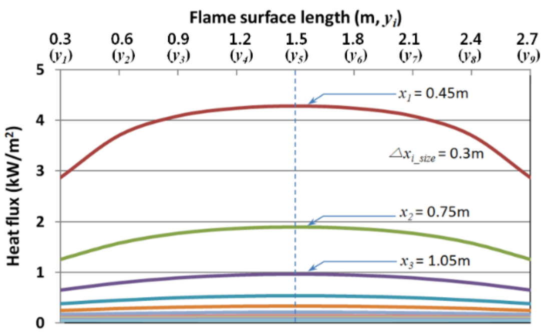


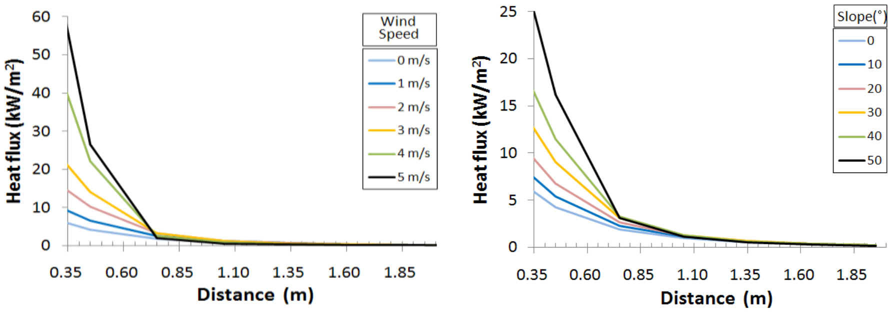
Figure 5 - Distribution of heat flux per distance according to average flame height

4.2. Distribution of Heat Flux According to Distance

4.2.1. Average Flame Height

As shown in Figure 6, heat flux distribution under the condition of wind velocity and slop for about 0.71m of average flame height of the pine tree litter layer was in inverse proportion by distance and as wind velocity and slope increased, heat flux raised. Distribution of heat flux per distance from flames was calculated based on about 0.35m, which is center height of the flames. At that time, heat flux at

0.35m was measured to 4.28~106.98 kW/m^2 for 0–5m/s of velocity and 4.28~21.81 kw/m^2 for 0~50° of slope. In addition, heat flux at 1.2m was 1 kW/m^2 or less in both conditions.

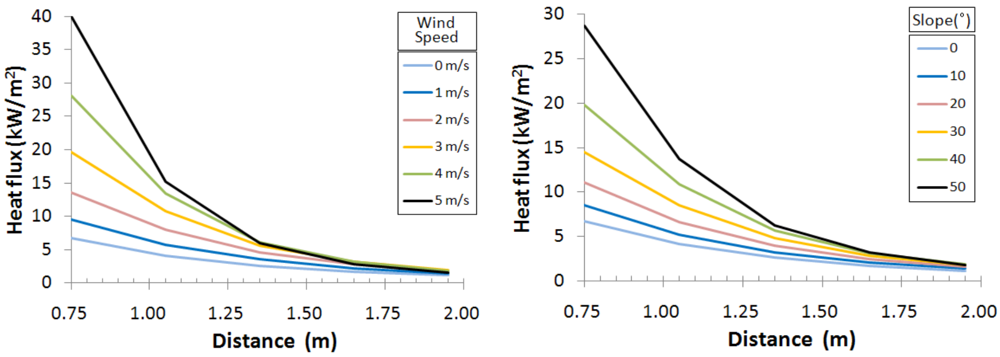


(a) *(b)*

Figure 6 - Distribution of heat flux per distance according to average flame height; (a) Wind velocity condition, (b) Slope condition

4.2.2. Maximum Flame Height

As shown in Figure 7, heat flux distribution under the condition of wind velocity and slop for about 1.46m of maximum flame height of the pine tree litter layer was in inverse proportion by distance and as wind velocity and slope increased, heat flux raised. Distribution of heat flux per distance from flames was calculated based on about 0.75m, which is center height of the flames. At that time, heat flux at 0.75m was measured to 4.28~106.98 kW/m^{2}for0–5m/s of velocity and 4.28 – 21.81 kw/m^2 for 0~50° of slope. In addition, heat flux at 1.2m was 1 kW/m^2 or less in both conditions.



(a) *(b)*

Figure 7 - Distribution of heat flux per distance according to maximum flame height; (a) Wind velocity condition, (b) Slope condition

4.2.3. Width of Fire Break Line

Radiant heat flux required for ignition of fallen leaves of pine trees is 7.9 kW/m^2 and 4.9 kW/m^2 in case of self-ignition and pilot ignition, respectively (Kim, 2010). Considering characteristics of surface fire flame spread and safety rate, it is desirable to apply 4.9 kW/m^2 of heat flux for pilot ignition as critical radiant heat flux for ignition of pine tree fallen leaves. Influential distances at 4.9 kW/m^2 of critical radiant heat flux for flame angle ( ) at 0~5 m/s of velocity and 0~50° of slope were calculated to be 0.35~0.65m for the average flame height and 0.75~1.05m for maximum flame height as shown in Figure 8. Therefore, optimal fire line width to prevent flame spread was appeared to be about 1.05m based on maximum flame height applied

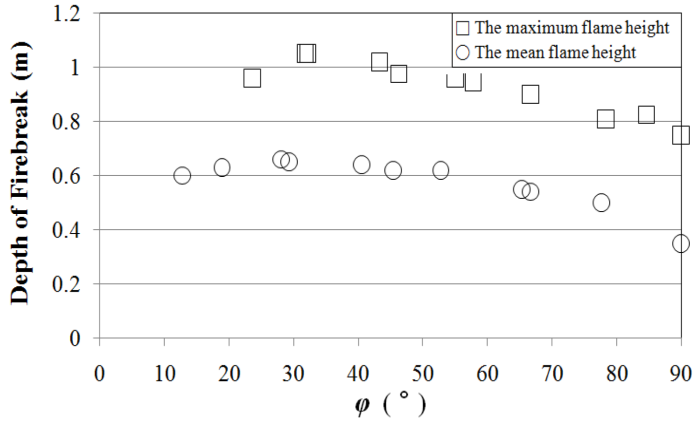


Figure 8 - Results of calculating fire line establishment width for P. densiflora tree litter layer

5. Conclusion

To prevent spread of surface fire flame in the pine tree litter layer, optimal fire line establishment widths were calculated. For the calculation, numerical analysis of two-dimensional radiant heat transfer was conducted using a heating point model. As a result, the following conclusion was derived.

First, calculating optimal width of fire line for surface fire can be an approach to increase work efficiency of forest fire fighters as well as minimizing spread of flames according to errors in working on appropriate fire line width.

Second, as of 4.9 kW/m^2 of critical radiant heat flux for ignition of pine tree fallen leaves, fire line establishment width at 0~5 m/s of velocity and 0~50° of slope were calculated to be 0.35~0.65m for the average flame height and 0.75~1.05m for maximum flame height.

Third, optimal fire line considering safety rate is deemed to be about 1.05m based on maximum flame height applied.

Fourth, assessment for rolling fire and spotting fire by strong wind has yet to be conducted, and therefore, when establishing fire line on the site, it should be considered.

In the near future, it is deemed to need to conduct follow-up studies including research on the comparative analysis of appropriate fire line establishment width per ground surface-layer fuel and research on the methods to calculate fire line establishment width to prevent spread of crown fire, through experiments and field case studies.

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