

A Study for Surface Fire Behavior and Flame Spread Model in Forest Fire

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I will do my best to study for forest fire disaster reduction.

ABSTRACT

The purpose of this thesis is to develop a 1-D Flame Spread Velocity Model for surface fire when fire breaks out in a forest. The research is carried out by relying on two major methods of execution: producing variable values by testing fuel combustion and flame characteristics and performing numerical analysis; developing an algorithm capable of performing computational analysis of flame spread via heat transfer analysis of the flame formed. Following are the conclusions reached on the model formula for 1-dimensional numerical analysis, which estimates the flame spread velocity based on heat transmission analysis, and algorithm development.

In the first part of the thesis, flame height equation is proposed based on semi-numerical analysis. The relation between dimensionless flame temperature and height of infinite line fire was used to derive the equation $H_f = 0.027\dot{Q}^{2/3}$ for calculating flame heights of surface fuel beds. Then, the flame heights calculated using this proposed equation was compared with those calculated using Heskestad's equation during combustion of fuel beds of *P. densiflora* and *Q. variabilis*. The comparison results showed that for both the *P. densiflora* fuel bed and the *Q. variabilis* fuel bed, the flame heights estimated using the proposed equation can be used in this surface fire spread model.

In the second of the thesis, equation for calculating flame tilt due to wind and slope was proposed based on semi-numerical analysis. In flame tilt due to wind, measurement of flame length and flame tilt angle was based on flame face. Flame length (L_f) showed consistent value regardless of wind speed, with error range $\pm 0.05\text{m}$. Therefore, flame height (H_f) can be calculated as $L_f \cos \phi_w$. The semi-numerical analysis on wind speed and flame tilt angle based on Froude number yielded coefficient A value of 1.36, which was proposed Equation. The value of flame tilt angle calculated from the equation and the experiment value showed average error of 1.09° , which is relatively smaller than the results in existing studies that used different coefficient. This suggests that the estimation method of the research for flame tilt angle is valuable. Coefficient A can be calculated in the method provided in this research for estimation of flame tilt angle of virgin fuel bed with varying thermal properties. In Flame tilt due to slope, slope effect not only causes variance in flame tilt angle but also impacts the speed of flame spread. Hence, flame tilt due to slope requires attention when predicting speed of flame spread in a slope. The average error angle of the tested flame tilt angle under the proposed equation was around 2.3° .

In third of the thesis, a 1-dimensional flame spread model and program is developed for surface fire spread in forest fires base on heat transfer mechanism with above research results. The comparison between experimental values and numerically analyzed values for *P. densiflora* surface fuel beds found that predicted flame spread velocity have an average error of approximately 12.15%. Thus, I conclude that the proposed equation and 1-diemnsional flame spread velocity model are expected to be effective in calculating the flame properties and in predicting surface flame spread velocity.

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NOMENCLATURE

Roman Letters

A_i	area of target surface
A_f	burning area of fuel bed (m^2)
A_d	section area of fuel bed (m)
c	specific heat ($\text{kJ/kg}\cdot\text{K}$)
c_p	specific heat of air at constant pressure ($\text{kJ/kg}\cdot\text{K}$)
D	flame depth (m)
E_f	emissive power of flame ratio of moisture
F_n	view factor
g	the gravity acceleration (m/s^2)
H_c	heat of combustion (kJ/kg)
H_0	initial flame height (m)
H_f	flame height (m)
h	flame height from flame to virgin fuel surface on each cell (m)
h_c	heat capacity (kJ/kg)
Δh_c	effective heat of combustion (kJ/kg).
I	flame intermittency
I_B	Byram's fire intensity (kW/m^2)
L_f	flame length (m)
L_v	Latent heat of water vaporization
M	fractional moisture content (%)
M_c	fuel moisture content (%)
$\dot{m}$	mass loss rate (MLR, kg/s)
m_{fd}	mass of fuel bed segment for unit width at dry condition
$\dot{Q}$	heat release rate (HRR, kW)
$\dot{Q}'$	heat release rate per unit length (HRR, kW/m)
Q_T	heat of ignition (kJ/kg)
Q_J	heat required to raise unit mass of dry fuel (kJ/kg)
Q_M	energy to heat unit mass of water to 100°C (kJ/kg)
$\dot{q}'$	heat release rate per unit length (HRR, kW/m)
q''	heat flux (kW/m^2)
q_r''	radiative heat flux (kW/m^2)
$\dot{q}_c$	conductive heat transfer
R, V	rate of spread (ROS, mm/s or km/hr)
r	mass to original dry fuel mass
r_f	lateral distance of flame tip and target position (m)
T_f	flame temperature (K)
T_∞, T_0	virgin fuel temperature (K)

T_{ig}	ignition temperature (K)
t_b	burning time (sec)
t_D	duration of flaming (time from ignition to burn out of fuel bed segment, sec)
t_{ig}	ignition time (sec)
U, u	wind speed (m/s)
W	weight of duff consumed (kg/m^2)
w	fuel consumption (kg/m)
X_f	radiation loss fraction
Δx	cell unit length of a fuel bed for calculation (m or cm)
Z_f	average flame height (m)
z/Z^*	the dimensionless flame height

Greek Letters

β	slope gradient (°)
δ	thickness of fuel bed (m)
ε	emissivity
ε_b	emissivity of fuel bed surface
θ	the angle between flame and surface (°)
ρ	fuel density(kg/ m^3)
ρ_0	fuel density(kg/ m^3)
σ	Stefan-Boltzmann constant
φ	the flame tilt angle (°)
η or η'	coefficient to be determined experimentally

Subscripts

∞	initial value
f	flame
ig	ignition
s	slope-induced
w	wind-driven
ws	combined wind and slope

Superscript

.	per unit time
'	per unit length
"	per unit area

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Chapter 1

Introduction

1.1 Motivation

Forest fire is a natural phenomenon that had already existed long before humankind started to use fire. In the past, naturally-induced forest fires were thought to be a circulation of the earth environment. As humankind started to use fire and evolved, however, not only naturally-induced forest fires but also artificially-induced forest fires have become frequent. These days, a forest fire is perceived as a natural disaster, set off by both nature and mankind that causes serious damage to human society. Extreme weather patterns and change in the earth environment largely triggered by global warming balloon the adverse consequences of forest fire and deforestation. Destruction of forests, which absorb carbon dioxide, and emission of carbon dioxide due to combustion of forest fuels are aggravating environmental damage.

Damages of forest fires are also getting bigger in Korea: Big forest fires in Goseong (3,762ha, 1996), East Sea (23,794ha, 2000), Cheongyang (3,095ha, 2002) and Yangyang (973ha, 2005) are wiping off not only forests but also precious cultural properties. Forest fires are also raging in many countries around the world e.g.: Heilongjiang, China in 1987, Yellowstone in 1988, Indonesia in 1997 and Australia's Christmas Fire in 2003 and Greece in 2007, which killed 63 people. As seen, forest fire is no longer an issue confined to a single region or a single country but one that impacts the entire earth.

A variety of efforts are made in forest fire prevention, mitigation and suppression to effectively control and mitigate damages of forest fires, which are growing both in size and frequency. In particular, research into early-stage forest fire characteristics from fire outbreak to fire spread is highly critical for effective fire extinguishment and protection of facilities adjacent to a forest fire. It's heartening to know that these research results are being applied to the real activities. For example, Rocky Mountain Research Station under US Forest Service studied factors impacting forest fire combustion characteristics and fire spread to develop forecast model on speed, intensity and type of forest fire spread. The model is currently used in forest fire extinguishment and mitigation activities (Finney, 1998). National Institute of Standard and Technology is studying forest fire spread forecast and fire intensity evaluation to protect houses adjacent to forests from potential fires, which was stimulated by the big California forest fires in 2003 and 2007. In Europe, as many as 13 countries have embarked on the joint cross-border research project titled PARADOX Project since 2006 to study forest fire characteristics, fire spread, protection of facilities adjacent to forest and forest fire protection, etc.

Both fixed factors (topography factors i.e. slope, sides, height, and fuel factors i.e. forest type and fuel density) and variable factors that vary by time such as velocity and wind direction that impact forest fires should be accounted when studying forest fire characteristics and fire spread. Existing researches have been engaged in both experiments and numerical analysis but no suggestions, thus far, have been made on spread prediction model approach employing semi-numerical analyses or studies into forest fuel's flame characteristics. In light of such precedents, this research aims at clarifying flame characteristics and developing flame spread analysis model, for developing three-dimensional forest fire spread prediction as the final goal.

1.2 Background

Forest fire spread can be classified into surface fire, crown fire, spotting fire and ground fire depending on fire type. Surface fire refers to combustion of surface fuel beds such as fallen leaves, twigs, dead fuel and grass. Crown fire refers to entire combustion all the way to treetop. Spotting fire refers to virgin fuel catching fire due to brands transported by the wind. Ground fire refers to combustion of underground organic matters or peat layer. Among these types, surface fire is the most common type of early-stage forest fire, which starts off with horizontal flame spread followed by vertical flame spread to trees' crown layer. Speed of forest fire spread, in general, refers to the flame spread velocity of ground fire and crown fire, of which the speed varies by flame characteristics, combustion characteristics and by the transfer process of heat energy created from flames. Most solid-type fuels emit heat energy through flames, during which the emitted heat flux causes a virgin fuel to go through heat decomposition, temperature rise and eventually ignition when the fuel reaches ignition temperature. Flame spread takes such a series of process and the same goes for forest fire spread where flames created by such combustibles as fallen leaves,

branches and trees spread under heat transfer mechanism. Hence, development of flame spread model requires numerical analysis of each fuel's combustion and flame characteristics to figure out changes in flame behavior and heat energy transfer process.

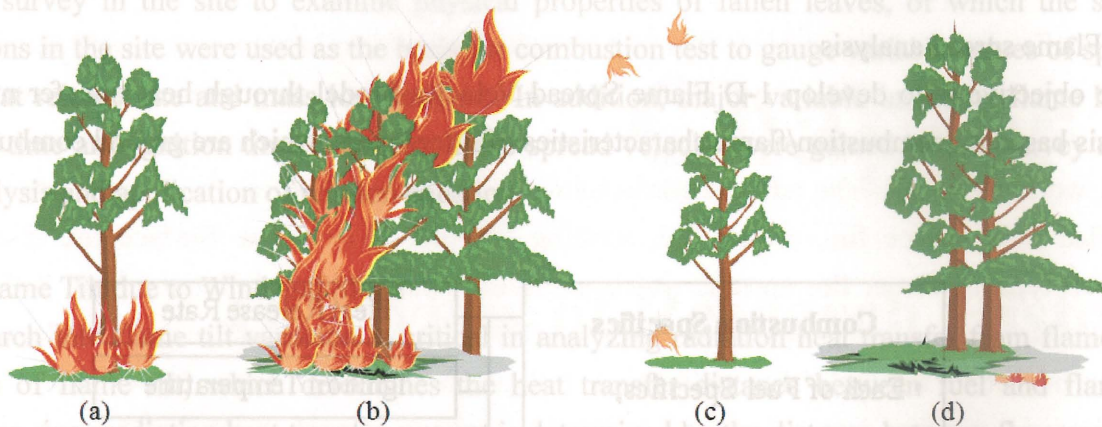


Figure 1-1 Type of Forest Fire Spread; (a)Surface Fire, (b)Crown Fire, (c)Spotting Fire, (d)Ground Fire

1.3 Approaches and Objectives

The objective of this research is to identify combustion and flame characteristics to analyze flame spread of forest fire, which will then be used to develop a flame spread model through numerical analysis.

(1) Combustion characteristics

Substances in forest consisting of solid fuels are different each other in ignition temperature to burning time and heat release rate. Identifying combustion characteristics of forest fuels is the key area that should come first for flame characteristics analyses and flame spread velocity prediction. With this in mind, the research set out the objective to identify combustion characteristics by testing major tree species in Korea with cone-calorimeter and ignition tester.

(2) Flame Specifics

Flame characteristics can be described by its height, length, width, ignition temperature and time of burning. Flame characteristics show different value depending on forest fuels and flame tilt, which varies by velocity and slope. Hence, the objective of this research is to propose a flame height estimation equation for forest fire fuel, which other preceding researches have failed to propose and a slope estimation equation, of which the latter will be suggested by testing and making numerical analysis of a phenomenon where slope and wind cause flame to tilt to a certain direction.

(3) Heat transfer model

Most surface fuel beds of forest are composed of porous fuel layer created on the upper part alongside soil level surface. Flame spread of forest fire is governed by radiant and conductive heat transmissions, which are affected by wind and topographical slope.

(4) Flame spread analysis

The objective is to develop 1-D Flame Spread Velocity Model through heat transfer numerical analysis based on combustion/flame characteristics of litter layers, which are ground combustibles.

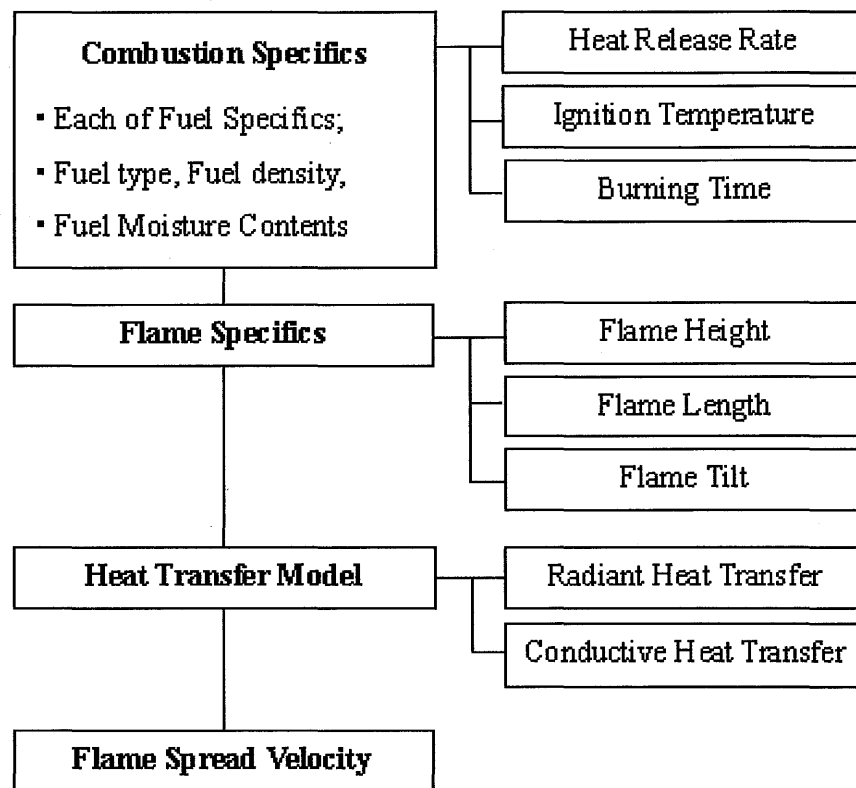


Figure 1-2 Research Flow Chart Covering Test and Analysis Process

1.4 Outline of the Thesis

The purpose of this thesis is to develop a 1-D Flame Spread Velocity Model for surface fire when fire breaks out in a forest. The research is carried out by relying on two major methods of execution: producing variable values by testing fuel combustion and flame characteristics and performing numerical analysis; developing an algorithm capable of performing computational analysis of flame spread via heat transfer analysis of the flame formed.

(1) Fuel Combustion and Flame Properties

Research on fuel's physical property and combustion property are critical in predicting flame spread in a forest fire. In this research, physical characteristics and combustion characteristics were tested for litter layer, which is a surface fuel bed composed of Korea's main *Pinus densiflora* and *Quercus variabilis*. Density, thickness and moisture content of litter layer were measured via a sample survey in the site to examine physical properties of fallen leaves, of which the sample conditions in the site were used as the basis for combustion test to gauge variable values of specific heat, heat release rate and mass loss rate, etc. In addition, major variable including flame height, burning time and ignition time to predict flame spread velocity were gained by site survey above, test analysis and application of relation equation.

(2) Flame Tilt due to Wind and Slope

Research into flame tilt variation is critical in analyzing radiation heat transfer from flame. The analysis of flame tilt, which determines the heat transfer distance between fuel and flame, is necessary since radiation heat transfer amount is determined by the distance between flame and fuel. The thesis, in particular, tried a re-examination on the definition of flame angle. As such, flame tilt, which varies due to wind and slope, was predicted by relying on the following methods. In flame tilt due to wind, actual variation in the flame tilt was measured by using the wind tunnel in a level condition and equation was produced by using Froude number. In flame tilt due to slope, actual variation in the flame angle was measured by the slope test in no-wind condition and equation was produced by estimating change in the slope-triggered air inflow velocity and by using Froude number. Meanwhile, test value on the flame tilt variation and value in the equation proposed were compared to assess equation's applicability

(3) Flame Spread Test

Flame spread velocity changed due to slope and wind velocity was tested and measured under three conditions below. First, flame spread velocity under different wind velocities was measured by using a wind tunnel in no slope condition. Second, flame spread velocity in different slopes was measured by using slope combustion burner in no wind condition. Third, flame spread velocity in conditions combining both slope and wind was measured by setting slope angle in a wind tunnel.

(4) Flame Spread Velocity Model

Flame spread of surface fire in a forest can be predicted by radiation and conduction heat transfer analysis. Accordingly, this research applied a basic variable value for the test above, fuel combustion and flame characteristics in order to apply an analysis algorithm. For this, conduction heat transfer and analysis of radiation heat that reaches virgin fuel from flame by applying view factor were put in place for heat transfer analysis algorithm. Furthermore, an algorithm model for the flame formed when temperature of a virgin fuel reaches ignition temperature via heat transfer was developed with numerical analysis.

The test value of flame spread velocity caused by wind velocity, slope and combined wind-slope, and prediction value of surface flame spread model were compared to evaluate applicability.

1.5 Summary

Forest fire is a serious problem that had already damaged to human society and forest, which absorb carbon dioxide. These days, forest fire is growing both in damaged area and frequency in the world. Also, extreme weather patterns and change in the earth environment largely triggered by global warming balloon the adverse consequences of forest fire. Forest fire spread pattern can be classified into surface fire, crown fire, spotting fire and ground fire. Surface fire is the most common type of forest fire spread, which starts off with horizontal flame spread followed by vertical flame spread to the top of tree. Study on forest fire behavior and fire spread velocity, which is very important for forest fire prevention, mitigation and suppression. Development of flame spread model requires experiment and numerical analysis of each fuel's combustion and flame characteristics with heat energy transfer model. This objective of this research is to identify combustion and flame characteristics to analyze flame spread of forest fire, which will then be used to develop a flame spread model through numerical analysis. To develop a 1-D Flame Spread Velocity Model for surface fire when fire breaks out in a forest, this research is carried out by relying on two major methods of execution: producing variable values by testing fuel combustion and flame characteristics and performing numerical analysis; developing an algorithm capable of performing computational analysis of flame spread via heat transfer analysis of the flame formed.

Chapter 2

Overview of Research History

2.1 Forest Fire Combustion Characteristics

“Combustion is exothermic (heat releasing) chemical reactions in flow with heat and mass transfer (Williams, 1985; Linan and Williams, 1993)”. Pyrolysis is the thermal degradation of molecules or polymers prior to combustion; it is chemical decomposition through the application of heat. The word pyrolysis, in fact, means “heat divided.” The pyrolysis of plant material produces the volatiles, tars, carbonaceous char, and mineral ash. Two general reaction pathways of cellulose degradation are recognized (Figure 2-1)

Governing equation or conservation equations can provide mathematically strict relationships among various quantities. In combustion science, conservation equations are partial differential equations expressing conservation of mass, momentum, energy, and chemical species. Derivation of conservation equations are detailed by Williams (1985) and Linan and Williams (1993), of which the details are beyond the scope of this chapter; only the concepts of these equations together with mathematical formulae for only mass and momentum conservation (because of their simple formulae) are explained.

Taking a volume element of flame fluid, assuming the disturbances fluid velocity due to probes to be negligible for forest fires, but they may become important for small-scale laboratory flames.

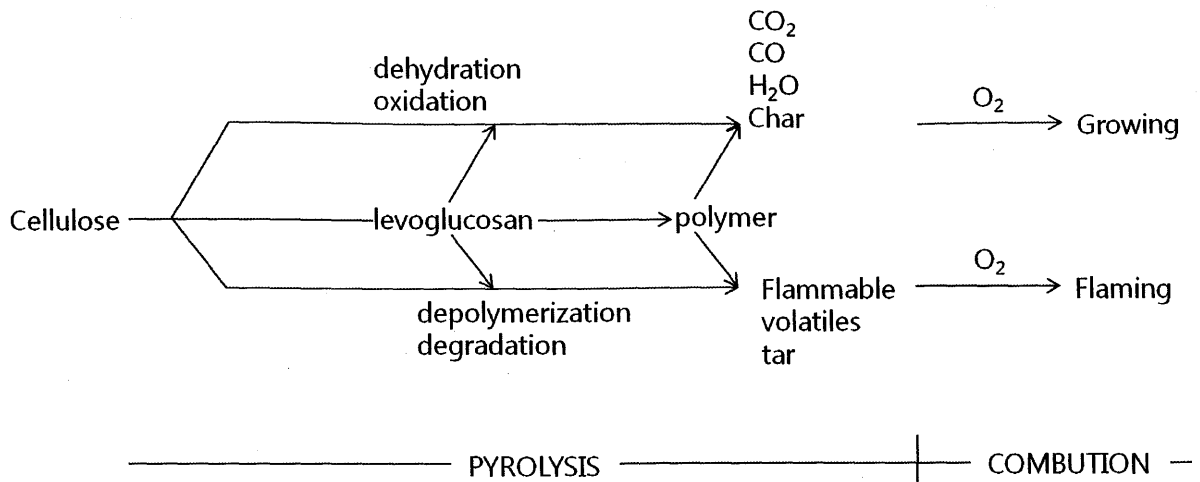


Figure 2-1 Pathways for the Pyrolysis of Cellulose. From Philpot (1971)

2.1.1 Ignition

Ignition can be achieved either by heating the system containing a combustible mixture with thermal energy or by creating chain reactions with autocatalytic reactions. Chemical reactions whose reaction rate is controlled by the concentration of initially present reactants are called thermal, whereas reactions whose rate is affected by the concentrations of the intermediate and final products are called autocatalytic.

Thermal ignition can be achieved by supplying heat from an external source to the system. An electric arch, a spark plug, or pilot flame can be the external heat source. The external heat source provides excess heat to the system and raises its temperature continuously if the heat input exceeds the heat loss. At some point, the temperature rise will become highly accelerative and a high heat evolution will occur. This is called ignition.

Autocatalytic ignition can be achieved by increasing the rate of chain carrier generation over the termination reaction of chain carries. The initiation of chain carrier generation may be achieved by thermal energy. After the initiation reaction has started, the reaction may become self-accelerative even after the external heat is removed. Then the system will ignite by satisfying the self-sustaining condition. Lightning may be a good example of autocatalytic ignition.

An important topic in forest fires is determining the condition under which given combustible forest materials can ignite. There are two types of ignition spontaneous (unpiloted) ignition and piloted ignition. Self-ignition can be achieved by raising the temperature of the system with hot boundaries and adiabatic compression. Piloted ignition can be achieved by adding heat to the system with an external heat source. Ignition temperature (explained later) for self-ignition is higher than for piloted ignition. For example, ignition temperature for piloted ignition of cellulose is approximately 350°C, whereas that for self-ignition is approximately 500°C (William, 1982). Other important aspects of ignition related to forest fires include ignition temperature, flammability limits,

and minimum ignition energy.

Ignition temperature can be defined as the critical temperature that the condensed phase needs to achieve for burning to begin (William, 1985). The ignition temperature is useful criterion to assess the flammability of materials and estimate flame spread velocity. However, there are some variations among different ignition conditions. For example, some researchers use a black body as the heating source, and others use a halogen or infrared lamp (Babrauskas, 1998).

Ignition tests conducted in an inert atmosphere under various external heat flux conditions showed that the ignition temperature indeed varies as a function of external radiant heat flux. The higher the external heat flux, the higher is the ignition temperature (Delichatsios and Saito, 1991). Thus, some caution should be taken when laboratory ignition temperature data are applied to forest fire problems.

2.1.2 Fuel Burning Rates and Moisture Content

The effect of fuel moisture on fire behavior is to slow the rate of burning, or rate of fuel consumption. For a spreading line of fire, the average burning rate can be computed from the mass of fuel consumed per unit area of ground divided by the time required to consume fuel on the area. Thus high fuel moisture content retards the rate of fuel consumption per unit of burning area ($\text{kg/m}^2 \text{ s}$) by decreasing the mass of fuel consumed and increasing the particle burning time, or particle residence time (the time during which flame resides on individual particles in the fuel layer combustion zone). In addition, it increases the fuel preheating time. With respect to the thermal history of unit mass of fuel, the various phases of combustion include the processes of preheating, volatilization, charring, smoldering, and glowing.

Consider first the fuel preheating time (or ignition time). The heat required for the onset and completion of volatilization of the fuel (volatilization begins at about 200°C and is assumed complete when the fuel temperature reaches 400°C) is called the heat of ignition Q_T (kJ/kg) by Wilson (1990) and is computed from the defining equation.

$$Q_T = Q_J + MQ_M \quad 2-1$$

where Q_J (kJ/kg) is the heat required to raise unit mass of dry fuel from ambient temperature to 400°C Q_M (kJ/kg) is the energy to heat unit mass of water to 100°C and then vaporize it, and M is the fractional moisture content (a fuel particle of layer average expressed on an oven-dry weight basis).

Thus an increase in M increases the amount of heat required to raise the temperature of unit mass of fuel from ambient temperature to 200°C and increases the preheating time. Various investigators have observed increases in ignition time with increasing M in dead and live fuels (Föns, 1950; Xanthopoulos and Wakimoto, 1993). The analytical studies of Albini and Reinhardt (1995) suggest that the increase in ignition time is due to increases in particle thermal conductivity and volumetric

heat capacity with increasing M . A different aspect of ignition deals with what happens when firebrands, either short or long range, are blown or dropped into unburned fuels. Again, preheating and ignition are slowed by fuel moisture content, and the heat demand may be estimated by Equation 2-1. Blackmarr (1972) has shown that the probability of ignition in slash pine litter is a strong function of moisture content and firebrand characteristics.

A second effect of fuel moisture on the burning rate involves a decrease in fuel consumption owing to the interaction among various fire behaviors characteristic. The available fuel loading, defined here as the mass of fuel consumed per unit area of ground during flaming combustion, depends in a complicated way on moisture content, flame temperature, and the mass fractions of volatiles and char produced during combustion of unit mass of original fuel. The fuel chemical composition and rate of thermal decomposition are two factors affecting the relative amounts of volatiles and char produced which, in turn, determine the heat of combustion and the fraction of fuel available for flaming combustion. These relationships are discussed in detail by Albini (1980) and Susott (1982). The presence of moisture also causes a reduction in flame temperature because some of the heat generated in combustion is used to heat the inert water vapor in the products of combustion and because oxygen in the air is diluted by water vapor leaving the heated fuel (Byram, 1959). The reduced temperature retards the rate of decomposition and tends to drive the combustion process toward production of char rather than toward production of high-temperature volatiles. Results from burns of Eucalyptus leaves in a flow calorimeter (Pompe and Vines, 1966) suggest that water in fuel promotes smoke formation, reduces the heat of combustion, lowers the rate of temperature rise of air flowing in the calorimeter, and leads to much less intense burns. The effect of moisture on fuel consumption was estimated by Van Wagner (1972a) who used data from experimental fires spreading in jack pine, red pine, and white pine stands to develop a semi-empirical relationship showing that duff consumption decreases as M increases. His equation for the weight of duff consumed, W (kg/m^2), is given by

$$W = 0.941 (1.418 - M) / (0.1774 + M) \quad 2-2$$

suggesting that consumption of these fuels approaches zero when M approaches 1.418. In this model, downward transfer of heat by radiation in the fuel layer combustion zone drives off moisture and then raises the temperature of the dry duff to the ignition point. Closure of the model requires a decrease in the emissivity of the flaming front with increasing M , suggesting that reduced radiative transfer to unburned fuel constitutes yet another means of slowing the rate of fuel consumption. King (1973) discusses the reduction of flame emissivity due to presence of moisture in terms of a reduction in soot concentration and an increase in carbon monoxide and hydrogen.

The third effect of fuel moisture on the rate of burning is an increase in the fuel particle residence time. Albini and Reinhardt (1995) have shown with experimental and theoretical studies that, to the extent that flaming combustion is fueled by a simple sublimation process, the characteristic particle burning time is proportional to Q_f from Equation 2-1. Because this demand for heat is satisfied by

radiative and convective heat transfer within the combustion zone, moisture also will increase the burning time by reducing radiation to the particles (King, 1973). It is noted that the effects of M on particle ignition time and particle burning time are sometimes difficult to separate because a fraction of M is lost in preheating and the remainder is lost during particle consumption by flaming combustion. Research has not yet clarified how moisture change takes place while a fuel layer burns, but the relative amounts of water lost during preheating and flaming combustion seemingly would depend on particle size, shape, and arrangement and on the initial value of M (i.e., on the amounts of liquid and/or adsorbed water present)

2.2 Surface Fire Behavior

Modern combustion research is composed of four theoretical supporting structures; thermodynamics, chemical kinetics, fluid mechanics, and transport processes (Williams, 1992). Additionally, three basic tools (experiment, theory, and computation) are available to help researchers approach combustion problems. Each tool has strengths and weakness.

Experiments have two roles; “insightful observation” and verification of assumptions that theory and computational methods employ (Hirano and Saito, 1994). The term “insightful observation” means to see things with unbiased minds using imagination and intuition. The second role of an experiment is well explained elsewhere in the scientific literature, while the first role is rarely emphasized, although it is important. In scientific research, the first and second roles often play together. For example, a simple experiment designed to verify assumptions also offers additional information to researchers. When a researcher conducts an experiment, two different points of view need to be kept on her or his mind; confirmation of assumptions and insightful observation. When the researcher’s mind is entirely occupied by the confirmation role only, she or he may miss the opportunity for discoveries and inventions through insightful observation. Our history proves that insightful observation is the source of discoveries and inventions (Ferguson, 1993).

Computation, also referred to as computer experiments, can provide detailed results and even a virtual reality by simulation. The combination of two or more of these tools will increase not only the accuracy of the results but also the chance of getting correct answers, especially during the early stages of a research and development project (Wilson, 1954). Computational methods not only save time and energy of human calculation but also provide details of virtual reality under ideal initial and boundary conditions, which may be difficult to achieve by experiments.

I will survey spread models and try to illuminate the main ideas behind the modeling as well as provide an overview of the different approaches and the relative merits of various fire spread models. The emphasis will be on the explanation of relevant physical principles and the way in which they are encapsulated into the mathematical models. In some cases, it will be possible to completely define the model; in others, only a sketch will be possible, and the reader will need to consult the references for a complete understanding. Among the earliest published papers on

ROS(Rate of Spread) are Föns (1946), Bruce et al. (1961), Emmons (1964), Emmons and Shen (1971), Anderson (1968, 1969) Hottel et al. (1964, 1971), McCarter and Broido (1965), McArthur (1996), Rothermel and Anderson (1966), Albini (1967), Berlad et al. (1971), Thomas (1967, 1971), van Wagner (1967), and Rothermel (1972). Later studies include Albini (1976a, 1976b, 1981, 1985, 1986), Beer (1991a, 1991b, 1993, 1995), Catchpole (1987), Cekirge (1978), De Mestre et al. (1989), Dorrer (1984), Duarte (1997a), Frandsen and Andrews (1979), Fujii et al. (1980), Gill et al. (1995), Green et al. (1985, 1990), Grishin (1984), Konev and Sukhinin (1977), Larini et al. (1998), Pagni and Peterson (1973), Steward (1974), Telisin (1974), Weber (1989, 1990), Weber et al. (1995), and Williams (1982), Literature surveys of the history and the mathematical models themselves are available in papers by Catchpole and De Mestre (1986) and Weber (1991, also translated for the Chinese Journal of Mechanics and Practice).

2.2.1 Flame Properties

2.2.1.1 Flame Height

A purpose of flame height measurement is to estimate radiation intensities from the flame, an important parameter for assessing hazards to personnel and the rate of flame spread. A most widely accepted interpretation of flame height is the height where a flame achieves the maximum temperature. Another definition that has more practical application to forest fires is the vertical distance from a flame base to the yellow visible flame tip. These two definitions may not always give the same flame height. For a small candle flame the maximum temperature is near the visible yellow flame tip while for a 1-m diameter crude oil fire the maximum temperature is achieved at about two thirds of the time-averaged visible flame height, probably because a fire-induced strong turbulent air flow cools the upper portion of the 1-m diameters fire.

Here, two different methods of determining flame height will be introduced. The first is to measure the visible flame up, and the second is to identify the location of the maximum flame temperature. The values obtained by these techniques are valid to within $\pm 10\%$ uncertainty.

To measure the time-average visible yellow flame height, a motor-driven 35mm still camera or a motion color video camera can be used. Both are capable of measuring temporal flame behavior from which time-averaged flame height can be measured. The latter equipment has an advantage in accuracy because it offers the measurement of flame height over the slow motion video screen. For a smoke-covered flame, however, neither technique is applicable because the flame up is invisible. For these types of fires and infrared camera can be used to penetrate the smoke layer and measure the maximum flame temperature location. Caution is required when the infrared camera is used to identify the maximum flame temperature and/or visible flame tip because emissivity of the flame is unknown, and it varies with fuel and location in the flame.

2.2.1.2 Flame Tilt

(1) Flame tilt due to wind

Flame tilt of wind-blown flame can be deduced from the relation between the Froude number (Fr) and the wind speed under a uniform wind. Albini (1981) and Putnam (1965) proposed the value of coefficient in the correlation equation between Froude number and flame tilt angle, obtained using algebraic solution. Here, Albini offered coefficient from the experimental data on the flame of forest fuel beds and Putnam offered coefficient from the experimental data on the flame of natural gas. Taylor (1961) also deduced this relationship from consideration of the strongly buoyant limit of the thermal plume from a line source in cross flow. Nelson and Adkins (1986) proposed flame tilt angle equation with the constants acquired through the convection number (N_c) relation and statistical analysis of experiment data. Here N_c is the ratio of 'power of the fire' (P_f) to 'power of the wind' (P_w), which describe the rate of conversion of thermal energy to kinetic energy and the rate of flow of kinetic energy in the atmosphere due to the wind field (Nelson 1993).

(2) Flame tilt due to slope

Angle between flame and inclined plane accelerates the spread of flame as heat flux from flame heavily stretches out to virgin fuel on inclined plane. Rothermel (1972) suggested $V=V_0(1+\phi_s)$ as the result of analysis for the velocity of flame spread affected by flame tilt angle variance. Existing researches report that speed of flame spread arising from flame tilt angle variance on inclined plane has less impact than wind velocity, which is also verified in experiment results (Dupuy, 1995). Less researches were done about flame tilt angle change on inclined plane than about wind velocity and only a limited number of researches were carried out to study the impact of slope on flame tilt angle (Dupuy 1995, Morandini 2000). Morandini (2001) applied flame tilt as the angle between flame and inclined plane ($\theta_s=90-\beta$) for the flame tilt angle in his research to compare experiment value and theory value under slope-wind velocity conditions with the assumption that 'slope angle has little impact on flame tilt angle'. Therefore, Morandini did not adopt ϕ_s for flame tilt angle.

2.3 Flame Spread Velocity

The characteristics of the spread of a forest fire are affected by geographical features (slope, surface direction, etc.), meteorological features (wind velocity, wind direction, relative humidity, etc.) fuel (fuel type, fuel humidity, heat emission energy, etc.) and other conditions concerning surrounding forest fire environment. Following four considerations should be given to develop forest fire spread model applicable to real forest fires. First, fixed factors as topographical factors (slope, surface direction, height) and fuel factors (species of trees and fuel distribution) that affect forest fires and variable factors such as meteorological conditions that vary with time. Second, physicochemical changes witnessed in general fire spread and experimental/theoretical

considerations on the correlations between geographical (surface direction, slope) – meteorological conditions (wind velocity, wind direction) and meteorological (relative humidity) – fuel (fuel humidity). Third, development of forest fire spread prediction algorithm by analyzing governing equation and experimental values of variables having relevance with forest fire spread. Finally, development of a program that can display on GIS predicted value obtained through numerical arithmetic processing. These series of processes are being constantly studied all over the world. Forest Fire Research Center at US Forest Service under Department of Agriculture has done a lot of practical research over the past few decades to predict flame spread of forest fire. Most commonly used models assume the correlation of the spread velocity and others related factors obtained from experiments and observations to predict the spread of forest fire. US' BehavePlus and FARSITE, Canada's Forest Service Fire Behavior Prediction System, Australia's Mk 4 MacArthur Fire Danger Meters and CSIRO Grassland Fire Spread Meter, among others, suggested that a spread prediction model assuming wind velocity, slope, humidity and fuel characteristics can serve as predictors for forest fire spread. However, by excluding how fuel and meteorological conditions work together to determine the course of fire, Hirich and Nobel et al. presented an estimated equation of forest fire spread based on the outdoor experiment values while Albini and Rothermel used flame spread obtained in an indoor experiment.

Among these, the widely known forest fire spread prediction programs by BehavePlus and FARSITE use semi-empirical techniques as the basis. Non-physical models, which are based on empirical indoor experiments with external environmental conditions, are designed to easily predict forest fire spread and make a quick application. These models, however, are not without weaknesses. The absence of analysis on internal/external heat flow and gas flow field change raises questions on the accuracy of predictions analyses, which is one of the areas where overseas forest fire researchers from US, France, Portugal and Greece, to name a few, are working on.

2.3.1 Surface Fire Spread Models

Fire spread is determined by the rate of heat transferred from the burning fuel to virgin fuel. The way to describe this mathematically begins with a precise statement of the rate at which the heat energy is accumulated in virgin fuel as a balance between energy inputs and energy outputs. To do this, it is necessary to consider the energy conservation expressed in a "word equation" as

$$\{\text{Rate of accumulation of heat energy}\} = \{\text{Rate at which energy flows in}\} - \{\text{Rate at which energy flows out}\}$$

This is to be applied to each small element of a virgin fuel, with the fuel being considered to be a collection of many such small elements. When coupled with some ignition criteria, it then allows one to determine how quickly successive elements of fuel ignite and consequently the rate of fire

spread. An algebraic relation can be obtained from this approach (Williams, 1977, 1982, 1985); namely,

$$\rho V Q_{ig} = q \quad \text{with} \quad Q_{ig} = \int_{T_a}^{T_i} c_p dT \quad 2-3$$

This can be rearranged to give (what some people refer to as the fundamental equation for) the rate of spread

$$V = \frac{q}{\rho Q_{ig}} \quad 2-4$$

or in words

$$\{\text{Rate of spread}\} = \frac{\{\text{Heat flux from the active combustion}\}}{\{\text{Heat required for fuel ignition}\}}$$

Early purely thermal models (as described in Weber, 1991) embodied the idea of many small elements in a differential equation for the temperature. An example of this style of modeling can be found in the equations in De Mestre et al. (1989), which then needs to be solved by integration. In fact, the solution of these models usually proceeds by assuming a constant rate of spread for the fire and changing frame of reference to a coordinate “moving with the fire.” It is in this new coordinate system that the differential equation can be integrated and boundary conditions applied to complete the determination of the arbitrary constants of integration and the rate of spread. The essential requirement for accurate prediction of the rate of spread is a good description of the heat transfer processes from the fire to the fuel.

2.4 Summary

In forest fire combustion characteristic, ignition temperature and fuel burning rate were proposed by William (1982) and Wilson (1990), respectively. Modern combustion research is composed of four theoretical supporting structures; thermodynamics, chemical kinetics, fluid mechanics, and transport processes (Williams, 1992). Additionally, three basic tools (experiment, theory, and computation) are available to help researchers approach combustion problems. Studies for estimating the flame height in a forest fire have not considered the conditions of forest fuel. A typical example of general formulas for calculating the flame height of pool fires of liquid fuels under no wind, proposed by Heskestad. Albin (1981) derived the equation for estimating flame height in one-dimensional fires: $H \propto I_B/U$. Albin’s equation does not yield accurate result when the

velocity is zero. Flame tilt of wind-blown flame can be deduced from the relation between the Froude number (Fr) and the wind speed under a uniform wind. Albini (1981) and Putnam (1965) proposed the value of coefficient in the correlation equation between Froude number and flame tilt angle, obtained using algebraic solution. Morandini (2001) applied flame tilt as the angle between flame and inclined plane ($\theta_s=90-\beta$) for the flame tilt angle. Fire spread is determined by the rate of heat transferred from the burning fuel to virgin fuel. The way to describe this mathematically begins with a precise statement of the rate at which the heat energy is accumulated in virgin fuel as a balance between energy inputs and energy outputs. In the development of fire spread model in the world, the widely known forest fire spread prediction programs by BehavePlus and FARSITE use semi-empirical techniques as the basis. Non-physical models, which are based on empirical indoor experiments with external environmental conditions, are designed to easily predict forest fire spread and make a quick application. These models, however, are not without weaknesses. The absence of analysis on internal/external heat flow and gas flow field change raises questions on the accuracy of predictions analyses, which is one of the areas where overseas forest fire researchers from US, France, Portugal and Greece, to name a few, are working on. Fire spread is determined by the rate of heat transferred from the burning fuel to virgin fuel. The way to describe this mathematically begins with a precise statement of the rate at which the heat energy is accumulated in virgin fuel as a balance between energy inputs and energy outputs.

Chapter 3

Fuel Combustion and Flame Properties

3.1 Properties of Fuel Combustion

Fuel characteristics are key in predicting flame spread. In this thesis tests were carried out to obtain fuel's HRR, ignition temperature, burning time and flame height, among others. In this research, experiments were conducted for the properties of surface fuel bed of *Pinus densiflora* and *Quercus variabilis* fallen leaves, which are the main coniferous type and the main broadleaved type in Korea, respectively.

3.1.1 Fuel and Fuel Combustion Properties

Fuel density, fuel depth and fuel moisture content of litter layer were measured by sample surveys in the site to acquire physical properties of fallen leaves, then the conditions of the sample from the site were used as the basis for combustion test. Table 3-1 shows that the average fuel density of litter layer is 22.5 kg/m^3 , fuel depth of litter layer is 0.1m and fuel moisture content (FMC) of litter layer is 15% during period with high risk forest fire season. Fuel Moisture content is highly sensitive to relative humidity in the air. To set the moisture content at 15%, which is what litters contain during high forest fire risk periods, litters were dried in the dryer for 8 hours and stored in thermo-hydrostat for 24 hours under 30% in relative humidity and 21°C in temperature for test. Fuel moisture content is calculated as a percentage to $(\text{Fuel weight} - \text{Dried fuel weight}) / (\text{Dried}$

fuel weight). Litter layers in 20 spots in both coniferous forest and *Q. variabilis* forest were surveyed to observe fuel density and fuel depth. Fallen leaves usually consist of three different layers: litter layer, fermentation layer and humus layer. A surface flame on a litter layer usually spreads to litter layer and fermentation layer but it combusts in the form of smoldering fire in humus layer due to high moisture content and insufficient air supply. Hence, fuel density and fuel depth were measured only in the litter layer and fermentation layer in this study. Fuels other than fallen leaves such as twigs, barks of tree and cone were not accounted for in measuring fuel density because of their slow thermal reaction velocity, which means they have little impact on flame formation, and substances other than fallen leaves in a forest have huge deviation in the volume piled up. The test found that the fuel density was $22.5 \pm 2.5 \text{ kg/m}^3$ and fuel thickness was $10 \pm 5 \text{ cm}$. Combustion tests of the fuels in a square basket made of steel wire net was carried out based on the sample conditions at the site as shown in Figure 3-1, which measured mass loss rate, burning time and temperature uniformity of flame surroundings. K-type thermocouples are installed with 25cm interval above the fuel basket to measure temperature of the flame and plume. Conditions of *P. densiflora* and *Q. variabilis* were used as the basis for fuel test shown in Table 3-1.

The square basket lengths were set 0.2~0.5m, each changed by 0.1m length. In the preceding research, flame's average width during litter layer combustion under no wind, no slope condition was measured to find that flame length was 0.15m.

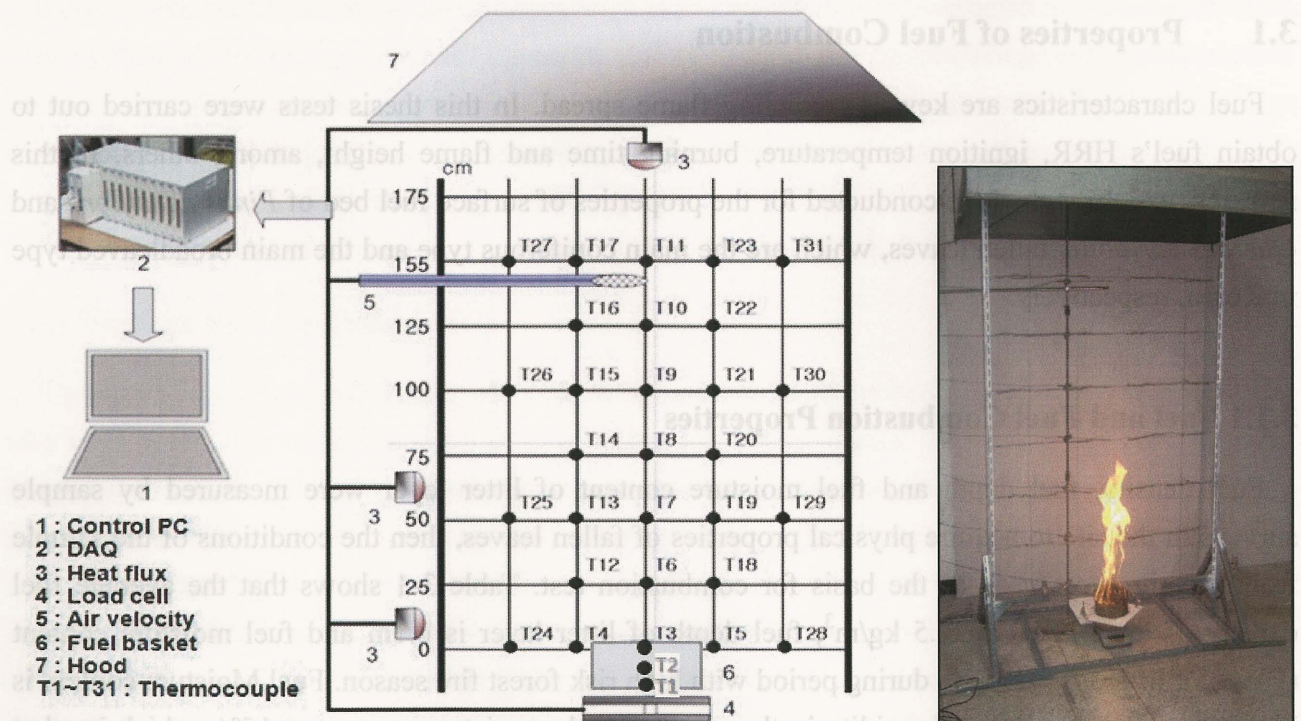


Figure 3.1 Schematic of Fuel Combustion Tester for Measuring Flame Height, Mass Loss Rate and Distribution of temperature; Square Fuel Basket Type

Table 3-1 Fuel Properties during Period with High Risk Forest Fire in Palgong Mt. Daegu, Korea

Parameters	Fuel density (kg/m^3)	FMC* (%)	Fuel depth (cm)
<i>P. densiflora</i>	22.5 ± 2.5	15	10 ± 5
<i>Q. variabilis</i>	22.5 ± 2.5	15	10 ± 5

*FMC of litter layer measured on high risk forest fire season

3.1.1.1 Flame Temperature

Figure 3-2 shows the temperature around litter layer combustion of fuel basket using test apparatus shown in Figure 3-1. Figure 3-3 shows vertical thermal distributions by different litter fuels and fuel basket sizes. Highest temperature exceeding 700°C was measured at around 25cm altitude from the basket during litter combustion of fuel basket in Figure 3-2 and Figure 3-3. The temperature was measured at $80\text{--}160^\circ\text{C}$ to be around 1.2m altitude from the basket. Temperature at 30cm to the left and to the right of flame center was measured to be $80\text{--}160^\circ\text{C}$. Figure 3-3 shows vertical thermal distribution during combustion in 20cm, 40cm basket diameter of *P. densiflora* and *Q. variabilis* litter. The highest temperatures, at 25cm above the basket surface did not show a big difference but higher flame temperatures were measured 50cm or more in altitude from the basket when basket diameter was bigger.

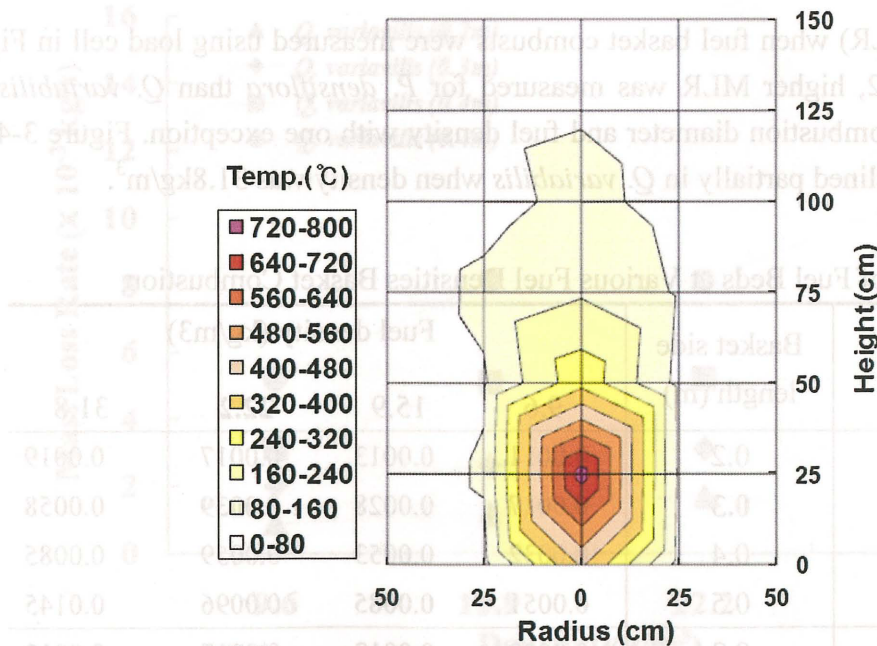


Figure 3-2 A distribution Temperature of *P. densiflora*'s Fallen Leaves Combustion in Fuel Density 22.2 kg/m^3 and Fuel Basket Size 0.3m

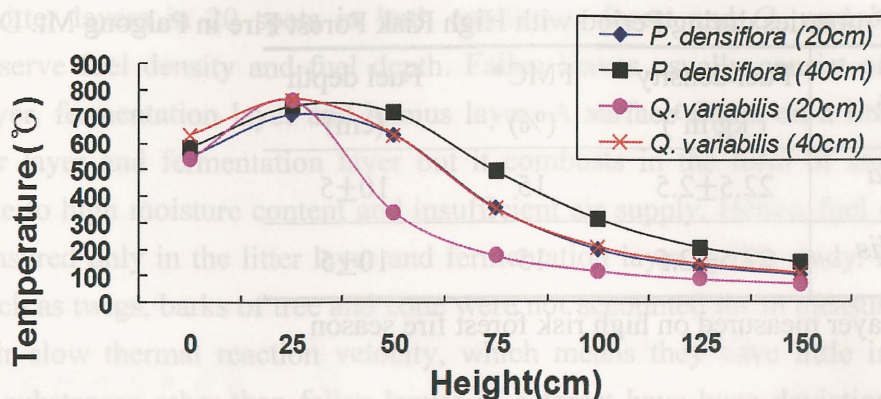


Figure 3-3 Vertical Distribution Temperature of *P. densiflora* and *Q. variabilis* Fallen Leaves
Combustion in Fuel Density 22.2 kg/m³

3.1.1.2 Heat Release Rate

The flame height varies depending on the type of ignition source, the heat release rate (HRR) and with physical properties of fuels, such as combustion duration and fuel density. The HRR $\dot{Q}$ (kW) of combustibles is calculated using Equations 3-1.

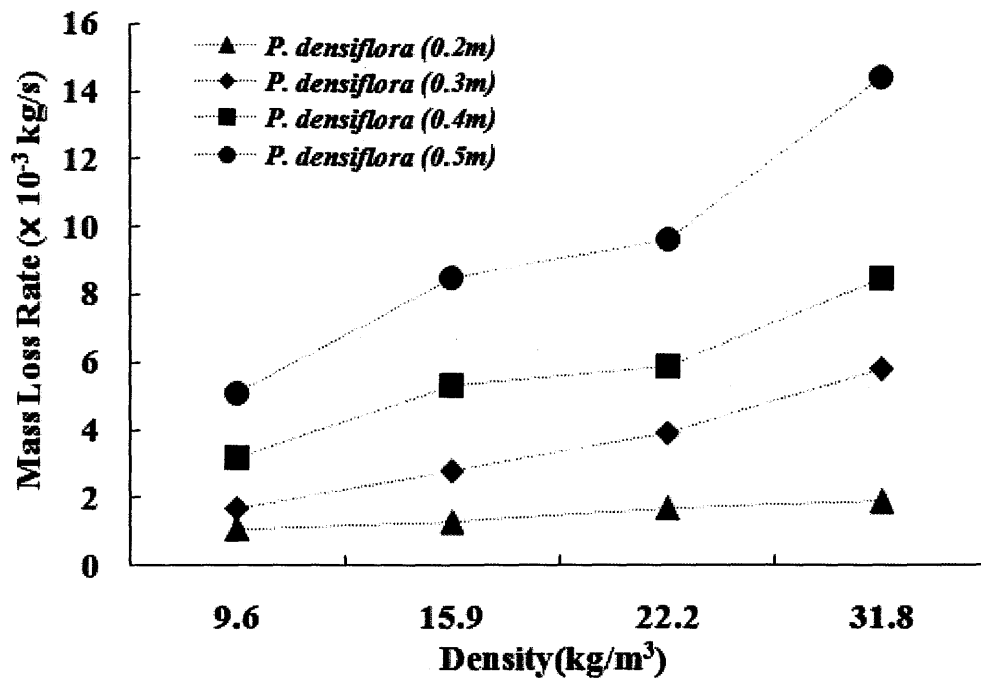
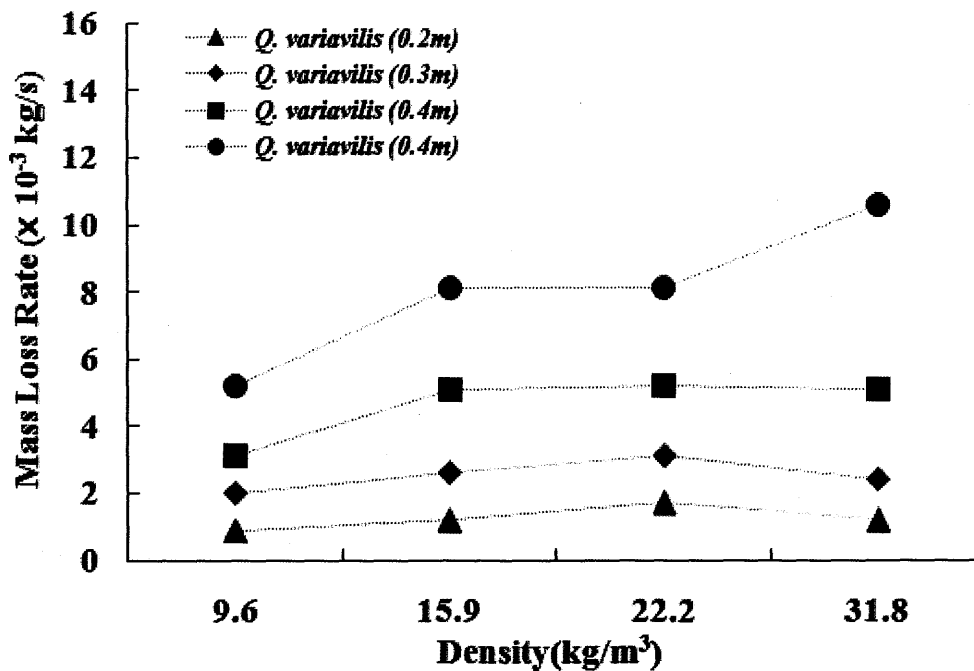
$$HRR(kW) = \Delta h_c \times \dot{m} \quad 3-1$$

where Δh_c is the effective heat of combustion (kJ/kg).

Mass Loss Rate (MLR) when fuel basket combusts were measured using load cell in Figure 3.1. As shown in Table 3-2, higher MLR was measured for *P. densiflora* than *Q. variabilis* and the MLR corresponds to combustion diameter and fuel density with one exception. Figure 3-4 and 3-5 show that the MLR declined partially in *Q. variabilis* when density was 31.8kg/m³.

Table 3-2 MLR (kg/s) of Fuel Beds at Various Fuel Densities Basket Combustion

Fuel type	Basket side length (m)	Fuel density (kg/m ³)			
		9.6	15.9	22.2	31.8
<i>Pinus densiflora</i>	0.2	0.0011	0.0013	0.0017	0.0019
	0.3	0.0017	0.0028	0.0039	0.0058
	0.4	0.0032	0.0053	0.0059	0.0085
	0.5	0.0051	0.0085	0.0096	0.0145
<i>Quercus variabilis</i>	0.2	0.0009	0.0012	0.0017	0.0012
	0.3	0.0020	0.0026	0.0031	0.0024
	0.4	0.0031	0.0051	0.0052	0.0051
	0.5	0.0052	0.0081	0.0081	0.0106

Figure 3-4 MLR of *P. densiflora* in Each Fuel Densities and Fuel Basket SizesFigure 3.5 MLR of *Q. variabilis* in Each Fuel Densities and Fuel Basket Sizes

According to site survey, fuel density at 22.2kg/m^3 is the average value in Korean forests and litter flame at no wind, no slope conditions usually combusts with around 30cm flame width. These figures were taken into account to make comparison with MLR in the test value for fuel density of 22.2 kg/m^3 and fuel basket size of 0.3m using Figure 3-3. The test result of MLR found 0.0036kg/sec for *P. densiflora* and *Q. variabilis*.

$$\dot{m} = \frac{\rho \times A_f \times \delta}{t_b} \quad 3-2$$

where ρ is the fuel density (kg/m^3), A_f is the burning area of the fuel bed (m^2), δ is the fuel bed depth (m) and t_b is burning duration of fuel bed (sec). Where δ is 0.1m, A_f is 0.09 m^2 and t_b values are about 55sec in shown Figure 3-6. In the test, the burning time t_b was measured where the flame height was taken as the point at which the I value was over 0.1 (Figure 3-10). The error of 8% for the MLR between measured value and calculated value therefore means it can be possible to apply the MLR value gained via test and calculation.

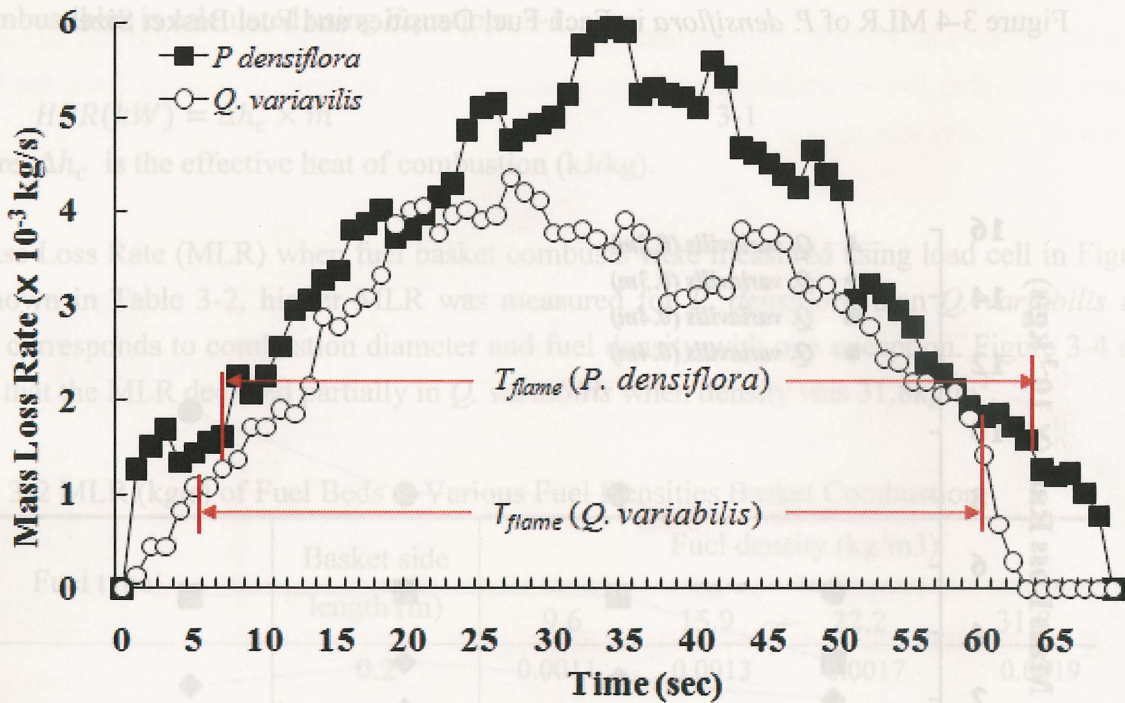


Figure 3-6 MLR of *P. densiflora* and *Q. variabilis* in Fuel Density 22.2 kg/m^3 , Basket Size 0.3m.

HRR(kW) can be derived as shown in Table 3-3 if MLR value in Table 3-2 is applied to Equation 3-1. *P. densiflora* fuel bed's HRR is 40.49 kW and *Q. variabilis* fuel bed's HRR is 22.12 kW as shown in Table 3-3, respectively, assuming 22.2 kg/m^3 in fuel density, 0.1 cm in litter layer depth.

Table 3-3 HRR (kW) of Fuel Beds at Various Fuel Densities Square Basket Combustion

Fuel type	Basket side length (m)	Fuel density (kg/m ³)			
		9.6	15.9	22.2	31.8
<i>Pinus densiflora</i>	0.2	11.63	13.91	17.65	19.72
	0.3	17.65	29.07	40.49	60.21
	0.4	33.22	55.02	61.25	88.24
	0.5	52.94	88.24	99.66	150.52
<i>Quercus variabilis</i>	0.2	6.21	8.56	12.13	8.56
	0.3	13.99	18.55	22.12	17.13
	0.4	22.01	36.39	37.11	36.39
	0.5	37.11	57.80	57.80	75.64

3.1.1.3 Ignition Temperature and Burning Time

The ignition temperature of fallen leaves of *Pinus densiflora* and *Quercus variabilis*, which are Korea's major acicular tree and broadleaf tree, are indicated Table 3-4 and Figure 3-7. The test was performed for *Pinus densiflora* and *Quercus variabilis* fallen leaves with FMC (Fuel Moisture Contents) of 15%, which are the typical FMC of fallen leaves in Korea forest at fire-prone season.

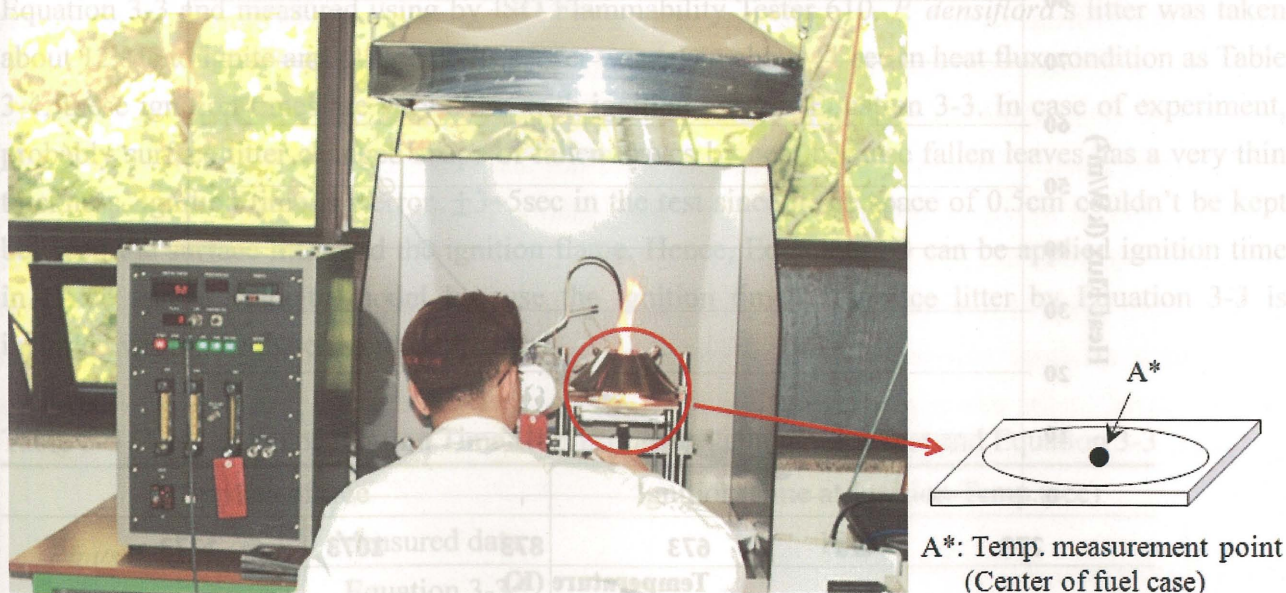


Figure 3-7 Measurement of Ignition Temperature and Burning out Time by ISO Flammability Tester

610 Examination

Temperature at A* point in Figure 3-7, which is the center of fuel basket, was measured using t-type thermocouple to measure litter's self-ignition temperature and pilot (with ignition source) ignition temperature under conditions by radiation heat flux. Temperature when fuel is heated by radiation heat without pilot flame was measured for self-ignition temperature. Pilot ignition temperature was measured by supplying 0.5~1cm flame to fuel surface at every second, which was performed with a flame that has 0.5cm space from fuel surface, according to the basic test method of flammability test under ISO-610.

Figure 3-8 is the relation graph between radiation heat flux (kW/m^2) and temperature under ISO Flammability Tester 610. Radiation heat release of *P. densiflora* and *Q. variabilis* in self-ignition temperature and piloted ignition temperature is shown in Table 3-4. For pilot ignition, radiation heat fluxes of at least 4.96kW/m^2 and 4.6kW/m^2 are needed to ignite *P. densiflora* and *Q. variabilis* litter, respectively. For self-ignition which doesn't accompany pilot flame ignition, radiation heat fluxes of at least 7.9kW/m^2 and 4.7kW/m^2 are needed. Table 3-4 shows that self-ignition and piloted ignition temperature of *P. densiflora* were higher than those of *Q. variabilis*. While difference between self-ignition and piloted ignition temperature was 73K in *P. densiflora*, the difference was only 2K in *Q. variabilis*. This indicates that pilot ignition temperature is more appropriate as piloted ignition temperature than self-ignition since both radiation heat and flame exist in flame propagation of surface fuel in a forest fire. Accordingly, the study assumes piloted ignition takes temperature when surface fuel bed's temperature reaches 584K and 578K, respectively in predicting flame spread velocity of *P. densiflora*, *Q. variabilis* surface fuel.

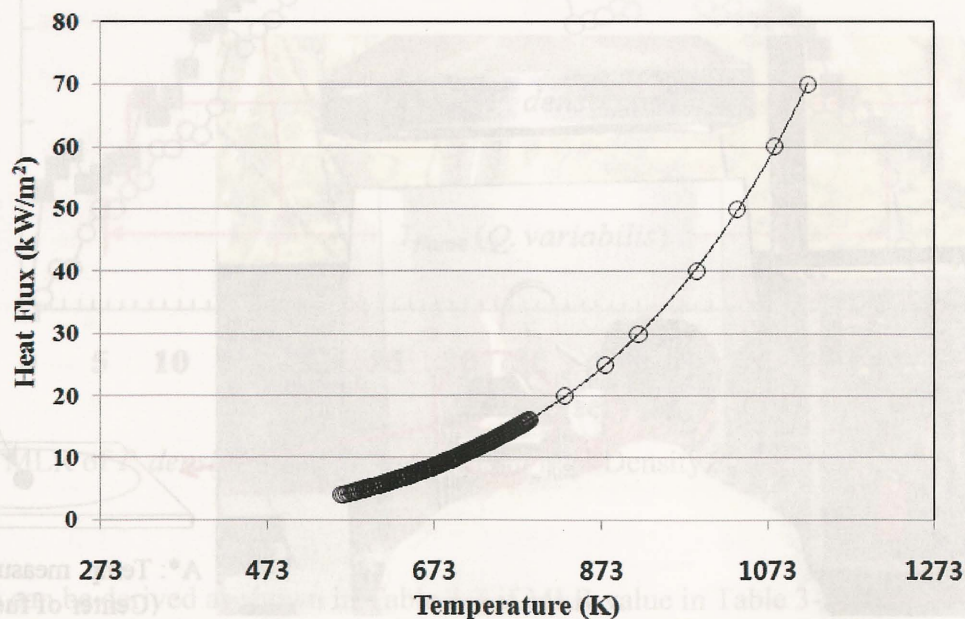


Figure 3-8 Relation to Temperature and Heat Release Rate of ISO Flammability Tester 610

Table 3-4 Ignition Temperature of the Main Surface Litter by Radiation Heat (ISO Flammability Tester 610)

Species of tree	Self-ignition		Pilot ignition		Fuel Moisture Content (FMC, %)
	Temp. (K)	Heat Flux (kW/m ²)	Temp. (K)	Heat Flux (kW/m ²)	
<i>Pinus densiflora</i>	657	7.9	584	4.9	15
<i>Quercus variabilis</i>	580	4.7	578	4.6	15

The piloted ignition temperature of surface litter fuels shown here can be used to calculate the ignition time (t_{ig}) of litter layers exposed to radiation heat transmission from the flame. Although different thickness requires different equations to be applied in determining combustibles ignition time, Equation 3-3 can be applied to a single fallen leaf since the thickness is less than 2mm in surface fire.

$$t_{ig} = \rho c \delta \times \frac{T_{ig} - T_{\infty}}{\dot{q}''} \quad 3-3$$

Table 3-5 shows the results of piloted ignition time for surface litter that were calculated by Equation 3-3 and measured using by ISO Flammability Tester 610. *P. densiflora*'s litter was taken about 12 sec to ignite and *Q. variabilis*'s litter was taken about 11 sec in heat flux condition as Table 3-4, these ignition times are very close with ignition time of Equation 3-3. In case of experiment, probably surface litter changed shape of fallen leaves by heat because fallen leaves has a very thin thickness. Ignition time has error $\pm 3 \sim 5$ sec in the test since it the space of 0.5cm couldn't be kept between the surface litter and the ignition flame. Hence, Equation 3-3 can be applied ignition time in flame spread velocity model because the ignition time of surface litter by Equation 3-3 is included within the experiment error range.

Table 3-5 Comparison of Ignition Time with ISO-610 Flammability Test and Equation 3-3

Species of tree		Ignition Time at Ignition Temp.(sec)
<i>Pinus densiflora</i>	Measured data	12 $\pm$ 5
	Equation 3-3	11.8
<i>Quercus variabilis</i>	Measured data	11 $\pm$ 3
	Equation 3-3	12.3

* Fuel Moisture Content (FMC): 15%

3.1.1.4 Summary of Fuel Properties to be used for Predicting Flame Spread

Pinus densiflora and *Quercus variabilis* have heat release rate and burn out time as analyzed in Chapter 3.1.1 and Table 3-4 whose data were obtained from experiments and calculations from equations 3-1, 3-2 and 3-3. The flame temperature in Table 3-4 was measured by k-type thermocouple in the flame height test in Chapter 3.1.1. The emissivity of 0.9 out of the 0.9~0.95 in cellulose's emissivity range was taken. For other major factors, the existing experimental values were employed as shown in Table 3-6.

Table 3-6 Parameters for Predicting 1-Dimensional Flame Spread Velocity

Parameters	HRR (kW)	Emissivity (ε)	Specific heat (kJ/kg·K)	Burn out time (sec)	Initial Temp. (K)	Flame Temp. (K)
<i>P. densiflora</i>	40.49	0.9	2.3	55	294	1143
<i>Q. variabilis</i>	22.12	0.9	2.3	55	294	973

3.2 Flame Height

For predicting flame spread of a forest fire, horizontal or vertical, driven by radiation heat transfer, it is important to estimate the flame height of the fire. Flame height can be considered as the average height of luminous part of flame. In this study, flame heights of the *Pinus densiflora* fuel bed and the *Quercus variabilis* fuel bed were measured by visual observation, and these values were compared with those estimated in a numerical analysis using an equation derived on the basis of the heat release rate. While deriving this equation, conditions such as external wind velocity and slope, which could cause a variation in flame height, were not taken into consideration. Then, the flame heights obtained by visual observation and by the equation proposed in this study were compared with those obtained using the existing Heskestad's equation (1998). The comparison results showed that for both types of fuel beds, the flame heights calculated using the proposed equation were just as accurate as those calculated using Heskestad's equation. Because the proposed equation is derived based on the existing study for line fire, it is expected to be more consistent for estimating the flame height of surface fuel beds and for predicting the spread of forest fires.

3.2.1 Background

When a forest fire spreads, flame height could change with the change in fuel characteristics, wind and slope conditions. In general, flame height and flame length are identical under no wind, no slope conditions. However, in the case of wind and slope are involved, flame height becomes

smaller than flame length (Figure 3-9). Either wind or slope causes the flame to bend over the surface of combustibles, which causes increase in the radiation heat transfer rate and hence accelerates the spread of fire. Therefore, it is crucial to estimate the flame height under the conditions involving wind and slope for predicting the spread of a forest fire and also for evaluating the risk of a forest fire.

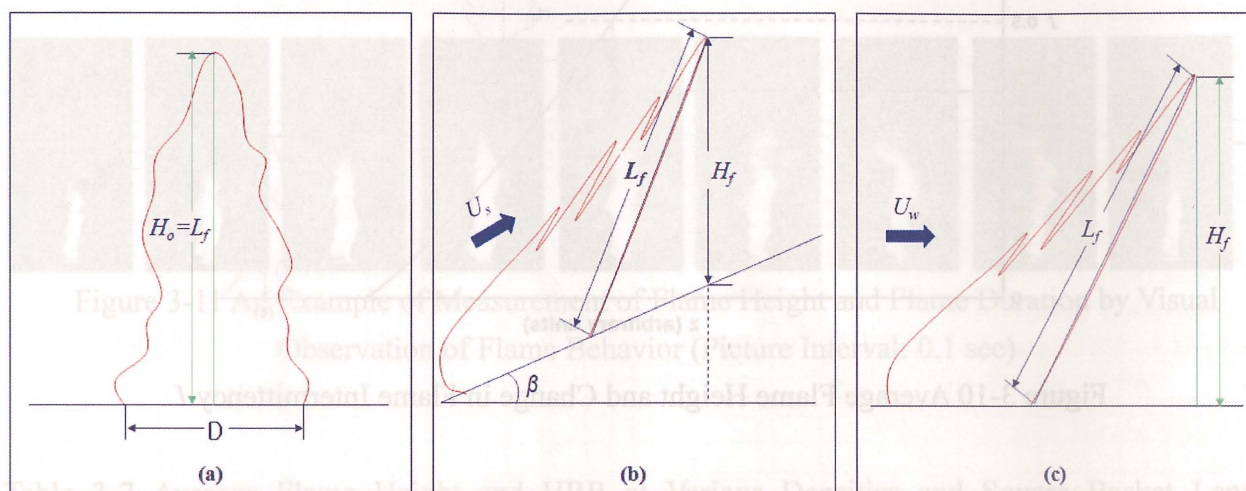
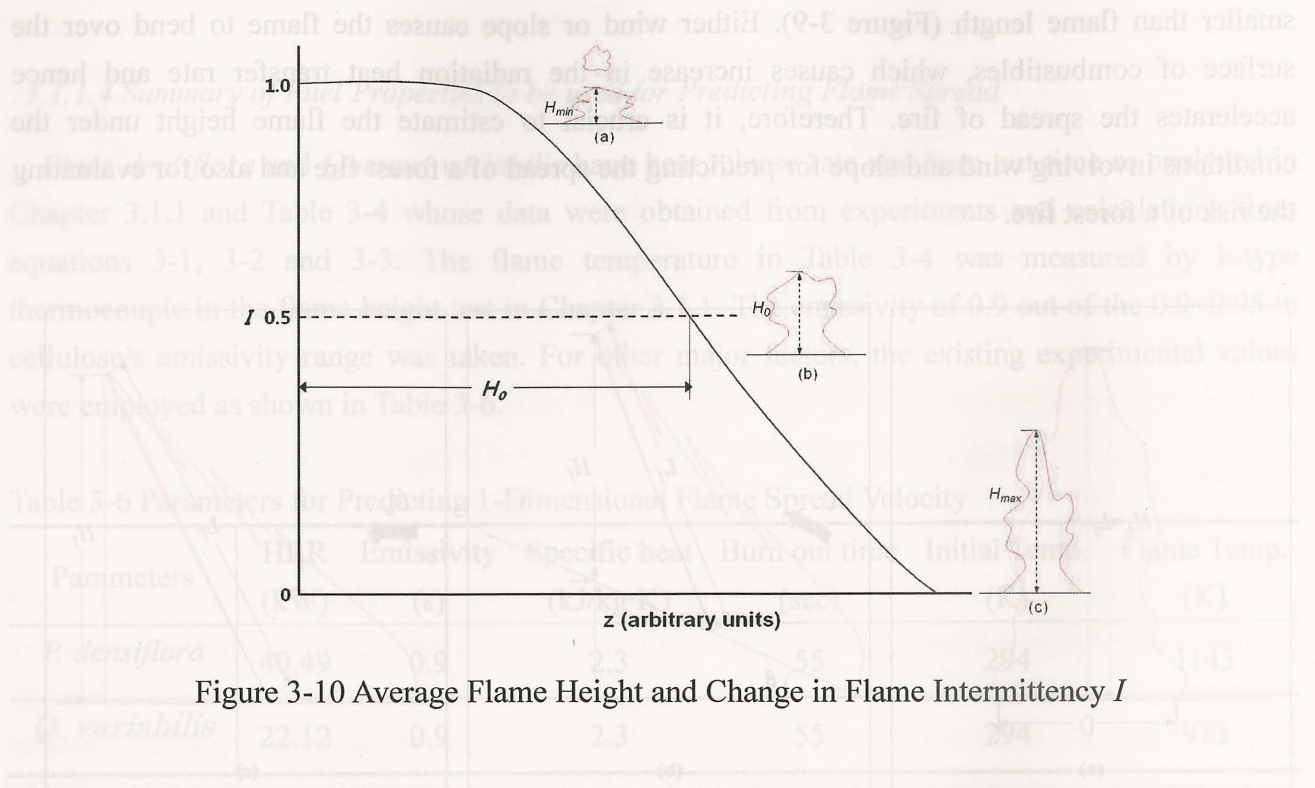


Figure 3-9 Change in Flame Height with Change of Slope and Wind Conditions: (a) No Wind, No Slope; (b) No Wind and with Slope; and (c) with Wind and Slope

Figure 3-10, in which the average flame height H_0 is defined, roughly shows the change in the flame intermittency I with height, z . The flame intermittency I is the fraction of time when flame exists at arbitrary height, is defined as the average flame height H_0 , is the height from the fire source at which the intermittency decreases to 0.5. The average flame heights measured using the flame intermittency by visual observation. In this chapter, visual observation is employed to measure the flame height of thermally thin surface fuels under no wind, no slope conditions, i.e., to determine the distance from the ignition source to where flame intermittency drops to 0.5.

Figure 3-10 Average Flame Height and Change in Flame Intermittency I

(1) Flame Height Model

In the past, studies for estimating the flame height in a forest fire have not considered the conditions involving wind and slope. Equation 3-4 is a typical example of general formulas for calculating the flame height of pool fires of liquid fuels under no wind, proposed by Heskestad.

$$H = 0.23\dot{Q}^{2/5} - 1.02D \quad 3-4$$

where, D is the fire source diameter.

Further, some researchers conducted tests to estimate the flame height of a fire under conditions involving wind (Fernandes 2002; Catchpole 1998; Dupuy 1996) and derived equations on the basis of the mass and energy conservation. Albin (1981) derived the equation for estimating flame height in one-dimensional fires: $H \propto I_B/U$. Here, I_B is Byram's fire intensity (kW/m), and U is the wind velocity (m/s). Byram's fire intensity is the rate of energy release, or rate of heat release, per unit time per unit length of fire front as like $I_B = HW$, where H is heat of combustion (kJ/kg), W is fuel consumed (kg/m²) and R is rate of fire spread (m/sec). Further, Nelson and Adkins (1986) used this equation as the basis for deriving equation $H \propto aI_B/U$ for flame height estimation where a is 1/360; however, this equation does not yield accurate result when the velocity is zero.

3.2.2 Definition of Flame Height by Visual Observation

In this study, the flame height from the fire source basket of square shape was measured by visual observation in a test environment, where the average flame height was taken as the point at which

the I value was 0.5 (Figure 3-10). This visually measured flame height was compared with theoretical flame height derived by numerical analysis. In the test, a video camera was used to measure the visual flame height at various fuel densities of the surface fuel bed. Figure 3-11 shows an example of flame behavior taken by the video camera at every 0.1 sec. The average flame heights measured by visual observation in the test environment are listed in Table 3-7.

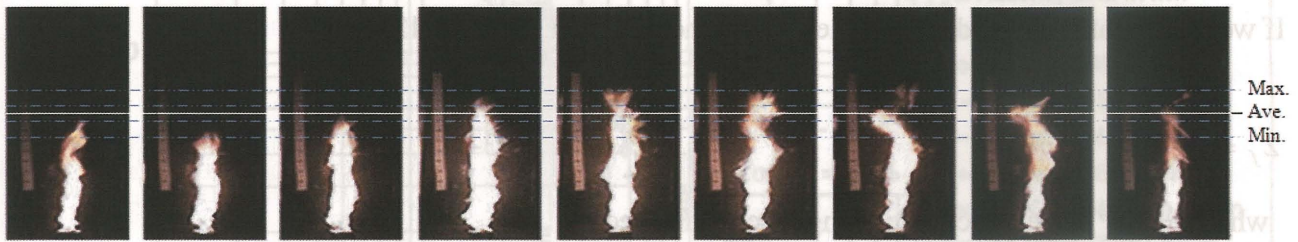


Figure 3-11 An Example of Measurement of Flame Height and Flame Duration by Visual Observation of Flame Behavior (Picture Interval: 0.1 sec)

Table 3-7 Average Flame Height and HRR at Various Densities and Square Basket Length, Measured by Visual Observation of Tangible Flame

Fuel type	Square basket length (m)	Flame height (m) & HRR (kW)			
		Fuel density (kg/m ³)			
		9.6	15.9	22.2	31.8
<i>Pinus densiflora</i>	0.2	0.45	0.50	0.51	0.53
		(11.63)	(13.91)	(17.65)	(19.72)
	0.3	0.46	0.53	0.61	0.61
		(17.65)	(29.07)	(40.49)	(60.21)
	0.4	0.55	0.64	0.68	0.70
		(33.22)	(55.02)	(61.25)	(88.24)
	0.5	0.50	0.70	0.94	0.88
		(52.94)	(88.24)	(99.66)	(150.52)
<i>Quercus variabilis</i>	0.2	0.28	0.30	0.35	0.28
		(6.21)	(8.56)	(12.13)	(8.56)
	0.3	0.39	0.42	0.40	0.34
		(12.99)	(18.55)	(22.12)	(17.13)
	0.4	0.46	0.56	0.51	0.40
		(22.01)	(36.39)	(37.11)	(36.39)
	0.5	0.50	0.62	0.65	0.72
		(37.11)	(57.80)	(57.80)	(75.64)

Note: () HRR data from Table 3-3

3.2.3 Proposed Equation for Estimation of Flame Height

In this chapter, a numerical analysis is carried out using an equation as shown by Equation 3-5, derived by Quintiere, et. al. (1998), to estimate the flame height of line fire that erupts from combustibles of a surface fire. Quintiere and Grove (1998) plotted experimental data from many existing tests for the height of line fire flame vs. the dimensionless flame ratio z/Z^{**} (used in Equation 3-5) as shown in Figure 3-12.

If we take 3 for average dimensionless flame height from Figure 3-12, i.e.

$$Z_f = \frac{z}{Z^{**}} = 3 \quad 3-5$$

where, Z^{**} is the characteristic length scale defined by

$$Z^{**} = \left(\frac{\dot{Q}'}{\rho_0 c_p T_0 \sqrt{g}} \right)^{2/3} \quad 3-6$$

where, ρ_0 is the air density (kg/m^3), c_p is the specific heat of air at constant pressure ($\text{kJ/kg}\cdot\text{K}$), T_0 is the initial temperature (K) and g is the gravity acceleration (m/s^2).

or more concretely,

$$Z_f = 3Z^{**} = 3 \left(\frac{\dot{Q}'}{\rho_0 c_p T_0 \sqrt{g}} \right)^{2/3} \quad 3-7$$

Substituting ρ_0 and T_0 values of 1.2045 kg/m^3 and 293 K in Equation 3-7, the former value of which is the standard air density and a typical room temperature (Table 3-8), the flame height of line fire is estimated as shown in Equation 3-8.

$$H_f = Z_f = 0.027(\dot{Q}')^{2/3} \quad 3-8$$

Table 3-8 Physical Properties of Fuel Bed and their Corresponding Values Used for Estimating Flame Height

Variable	Air density ρ_0 (kg/m^3)	Specific heat c_p ($\text{J/kg}\cdot\text{K}$)	Initial temperature T_0 (K)	Gravity acceleration g (m/s^2)
Value	1.2045 ¹⁾	1.01	293	9.81

Note: 1) Standard air density

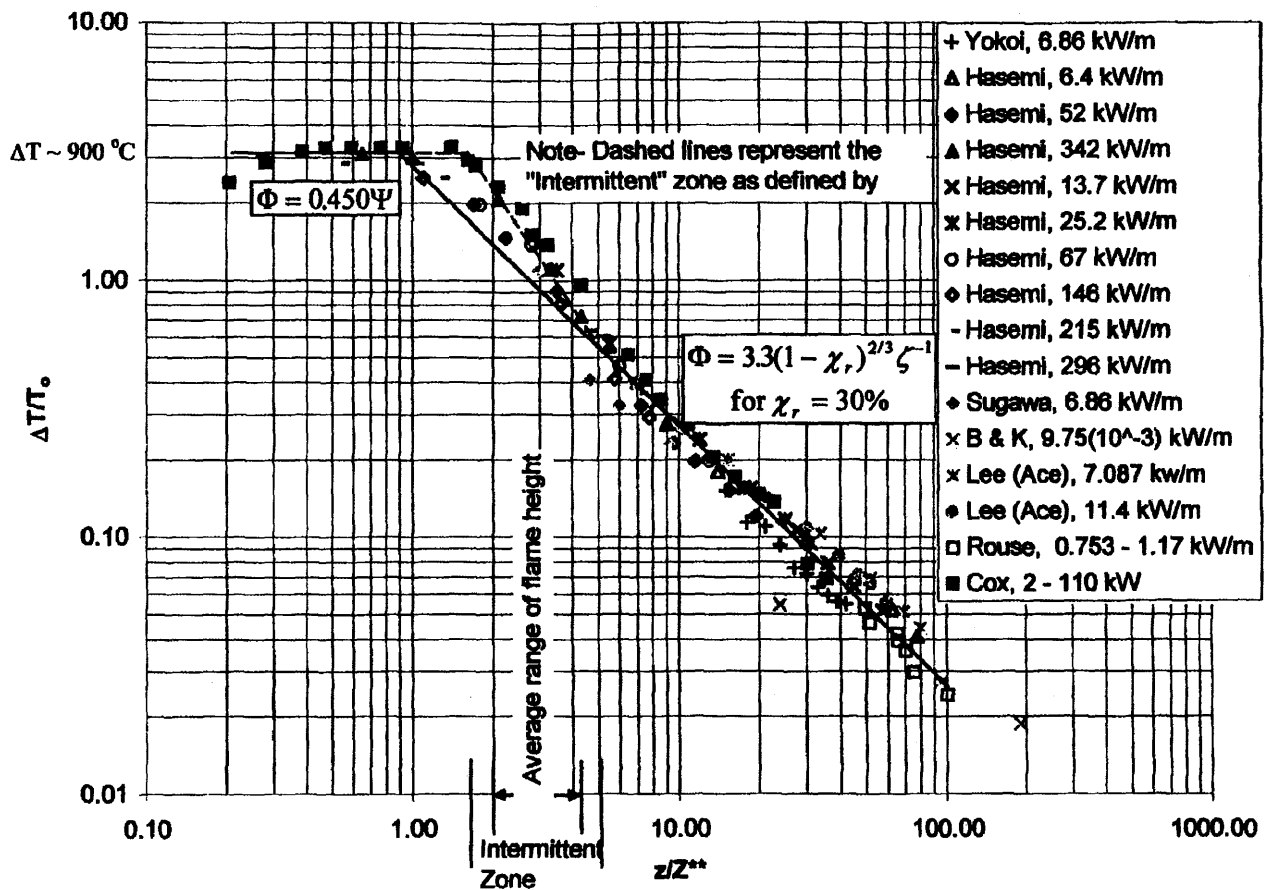


Figure 3-12 Dimensionless Temperature vs. Height for the Infinite Line Flame, for Flame Radiation Portion $X_f=30\%$

3.3 Analysis and Discussion about Flame Height

The measured flame heights of the *Pinus densiflora* and *Quercus variabilis* fuel beds at various fuel densities are compared with Equation 3-4 and 3-8 in order to evaluate the accuracy of these equations for estimating flame height of surface fuel beds. The flame heights of the *Pinus densiflora* and *Quercus variabilis* fuel beds by using Equation 3-8 (equation derived from Quintiere's equation for estimating flame height) and Equation 3-4 (Heskestad's equation for estimating flame height) are shown in Tables 3-9 and 3-10, respectively. The comparison results are shown in Figures 3-13, 3-14 from Tables 3-9, 3-10.

Table 3-9 Flame Height Values Measurement Using Equation 3-4 at Various Fuel Densities and Square Basket Length during Fuel Bed Combustion

Fuel type	Square basket length (m)	Flame height (m)			
		Fuel density (kg/m ³)			
		9.6	15.9	22.2	31.8
<i>Pinus densiflora</i>	0.2	0.41	0.46	0.52	0.55
	0.3	0.42	0.58	0.70	0.88
	0.4	0.53	0.73	0.78	0.97
	0.5	0.62	0.87	0.94	1.20
<i>Quercus variabilis</i>	0.2	0.27	0.34	0.42	0.34
	0.3	0.35	0.43	0.49	0.41
	0.4	0.38	0.56	0.57	0.56
	0.5	0.47	0.66	0.66	0.79

Table 3-10 Flame Height Values Measurement using Equation 3-8 at Various Fuel Densities and Square Basket Length during Fuel Bed Combustion.

Fuel type	Square basket length (m)	Flame height (m)			
		Fuel density (kg/m ³)			
		9.6	15.9	22.2	31.8
<i>Pinus densiflora</i>	0.2	0.41	0.46	0.54	0.58
	0.3	0.41	0.57	0.71	0.93
	0.4	0.51	0.72	0.77	0.99
	0.5	0.60	0.85	0.92	1.21
<i>Quercus variabilis</i>	0.2	0.27	0.33	0.42	0.33
	0.3	0.35	0.42	0.47	0.40
	0.4	0.39	0.55	0.55	0.55
	0.5	0.48	0.64	0.64	0.77

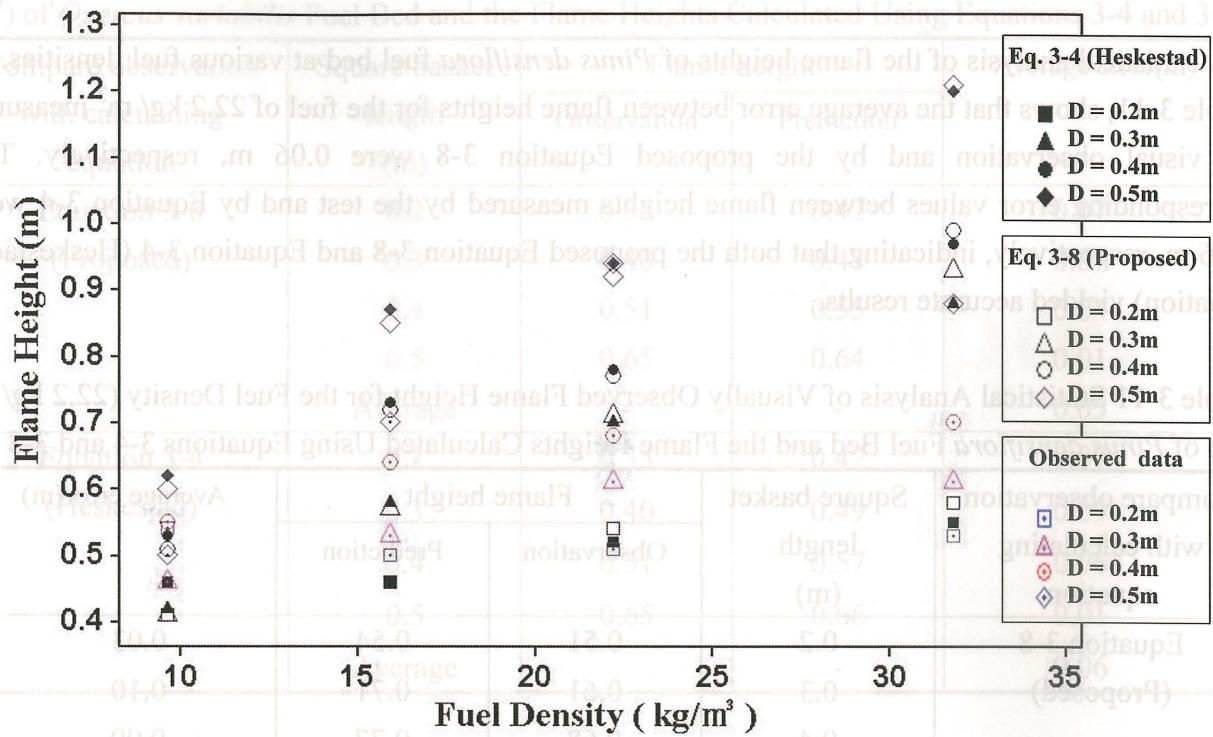


Figure 3-13 Comparison among Flame Heights of *Pinus densiflora* Fuel Bed Obtained by Visual Observation, Equation 3-4 and Equation 3-8

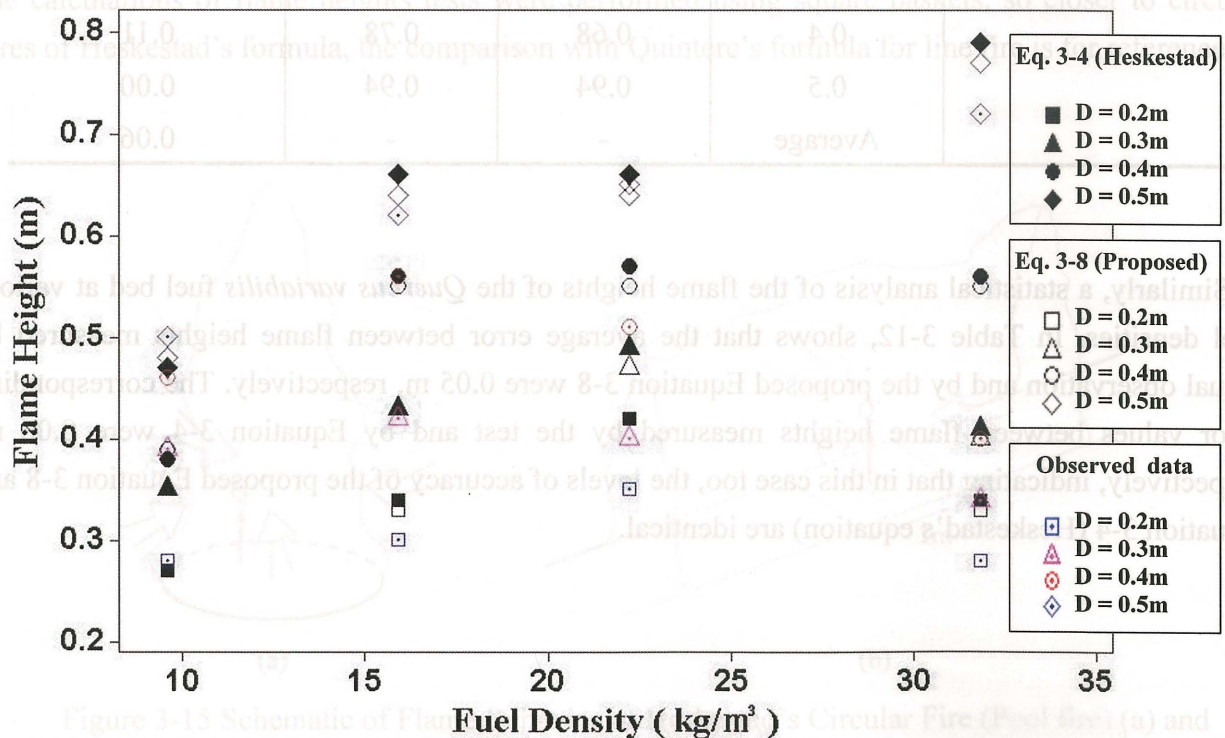


Figure 3-14 Comparison among Flame Heights of *Quercus variabilis* Fuel Bed Obtained by Visual Observation, Equation 3-4 and Equation 3-8

A statistical analysis of the flame heights of *Pinus densiflora* fuel bed at various fuel densities. In Table 3-11, shows that the average error between flame heights for the fuel of 22.2 kg/m^3 measured by visual observation and by the proposed Equation 3-8 were 0.06 m, respectively. The corresponding error values between flame heights measured by the test and by Equation 3-4 were 0.06 m, respectively, indicating that both the proposed Equation 3-8 and Equation 3-4 (Heskestad's equation) yielded accurate results.

Table 3-11 Statistical Analysis of Visually Observed Flame Height for the Fuel Density (22.2 kg/m^3) of *Pinus densiflora* Fuel Bed and the Flame Heights Calculated Using Equations 3-4 and 3-8

Compare observation with calculating equation	Square basket length (m)	Flame height		Average error(m)
		Observation	Prediction	
Equation 3-8 (Proposed)	0.2	0.51	0.54	0.03
	0.3	0.61	0.71	0.10
	0.4	0.68	0.77	0.09
	0.5	0.94	0.92	0.02
	Average	-	-	0.06
Equation 3-4 (Heskestad)	0.2	0.51	0.52	0.02
	0.3	0.61	0.70	0.09
	0.4	0.68	0.78	0.11
	0.5	0.94	0.94	0.00
	Average	-	-	0.06

Similarly, a statistical analysis of the flame heights of the *Quercus variabilis* fuel bed at various fuel densities. In Table 3-12, shows that the average error between flame heights measured by visual observation and by the proposed Equation 3-8 were 0.05 m, respectively. The corresponding error values between flame heights measured by the test and by Equation 3-4 were 0.06 m, respectively, indicating that in this case too, the levels of accuracy of the proposed Equation 3-8 and Equation 3-4 (Heskestad's equation) are identical.

Table 3-12 Statistical Analysis of Visually Observed Flame Height for the Fuel Density (22.2 kg/m^3) of *Quercus variabilis* Fuel Bed and the Flame Heights Calculated Using Equations 3-4 and 3-8

Compare observation with calculating equation	Square basket length (m)	Flame height		Average error(m)
		Observation	Prediction	
Equation 3-8 (Proposed)	0.2	0.35	0.42	0.07
	0.3	0.40	0.47	0.07
	0.4	0.51	0.55	0.04
	0.5	0.65	0.64	0.01
	Average	-	-	0.05
Equation 3-4 (Heskestad)	0.2	0.35	0.42	0.07
	0.3	0.40	0.49	0.09
	0.4	0.51	0.57	0.06
	0.5	0.65	0.66	0.01
	Average	-	-	0.06

Figure 3-15 shows different flame behaviors depending on combustion type. Heskestad's equation 3-4 is for flame heights of circular fires (Pool fire) as shown in Figure 3-15 (a) while the proposed Equation 3-8 is for flame heights of line fires as shown in Figure 3-15 (b). In this research, the calculations of flame heights tests were performed using square baskets, so closer to circular fires of Heskestad's formula, the comparison with Quintere's formula for line fire is for reference.

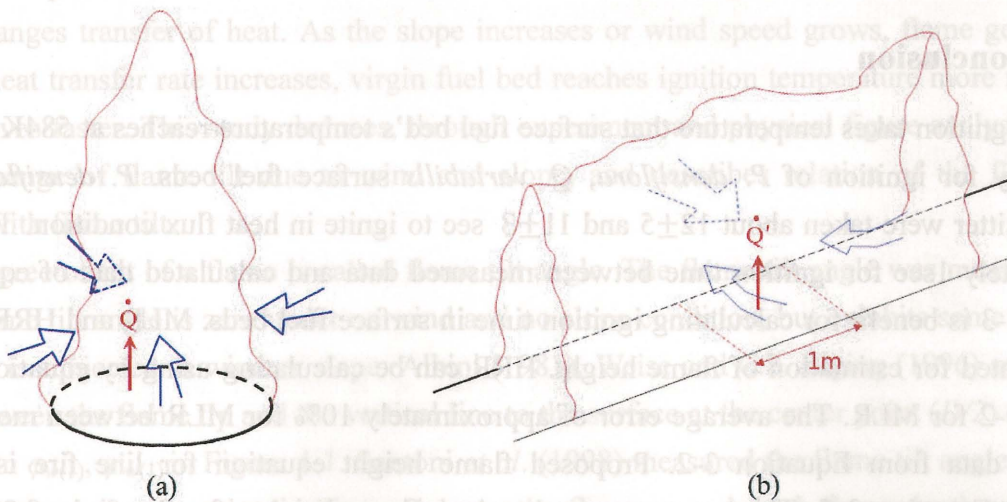


Figure 3-15 Schematic of Flame Behavior of Heskestad's Circular Fire (Pool fire) (a) and Quintere's Line Fire (b)

The reason why Quintiere's formula for line fire flame heights also agreed well with the flame heights of square fire is respected that the line fire illustrated in Figure 3-16 is just imaginary and the actual line fire is a series of many circular like fires as illustrated below.

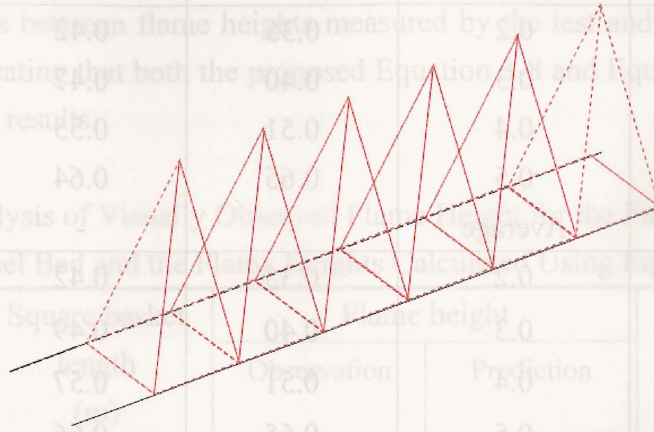


Figure 3-16 The Line Fire Illustration of an Imaginary and the Actual Line Fire

Flame height equation based on Quintiere's line fire leads us to propose that flame shape and diffusion show a nearly identical pattern with that in a forest fire as shown in (b), Figure 3-15. Flame shape of the pool fire during liquid fuel combustion in a limited circular space as proposed in Heskestad's equation is substantially different from the flame shape and diffusion in a forest fire. Hence, it is valid to apply flame height equation based on Quintiere's line fire, which will also prove to be useful in interpreting two-dimensional, three-dimensional flame diffusion later.

3.4 Conclusion

Piloted ignition takes temperature that surface fuel bed's temperature reaches at 584K and 578K, respectively for ignition of *P. densiflora*, *Q. variabilis* surface fuel beds. *P. densiflora* and *Q. variabilis* litter were taken about 12 ± 5 and 11 ± 3 sec to ignite in heat flux condition. The error of approximately 1sec for ignition time between measured data and calculated data of equation 3-3. Equation 3-3 is benefit for calculating ignition time in surface fuel beds. MLR and HRR are tested and calculated for estimation of flame height. HRR can be calculating using by equation 3-1 with Equation 3-2 for MLR. The average error of approximately 10% for MLR between measured and calculated data from Equation 3-2. Proposed flame height equation for line fire is based on Quintiere's Equation 3-7. The average error between flame heights for the fuel of 22.2 kg/m^3 measured by visual observation and by the proposed Equation 3-8 was 0.06 m. Proposed Equation 3-8 is the first equation for calculating the flame height and it will be more beneficial for calculating the flame height in forest fire as line fire with solid fuel combustion.

Chapter 4

Flame Tilt due to Wind

4.1 Definition of Flame Tilt

Forest fires show various flame spread velocities depending on conditions of the wind speed and slope. In order to analyze forest fire flame spread velocity, change of flame tilt as a function of wind speed and slope should be considered first. This is because flame spread velocity varies by flame tilt, which changes transfer of heat. As the slope increases or wind speed grows, flame gets closer to surface, heat transfer rate increases, virgin fuel bed reaches ignition temperature more rapidly, and flame moves faster. This study deduces, through experiment and physical figure analysis, relations on the change of flame tilt due to wind and slope, and describes relation of the flame spread velocity with flame tilt.

The degree of tilt of a flame is called flame tilt angle. The flame tilt angle was measured in two ways. Flame tilt angle is zero under no wind and no slope condition, but exhibits some value when the flame is subjected to wind or slope: Albini (1981), Weise and G.S. Biging (1996) measured the angle between the flame tip and the vertical line to the surface at the center point ($D/2$) of the flame depth as in $\varphi_{w(1)}$, $\varphi'_{w(1)}$ in Figure 4-1. Santoni *et al.* (1998) measured the flame tilt angle of the front face of flame as in $\varphi_{w(2)}$, $\varphi'_{w(2)}$ in Figure 4-1. As the flame spread, both flame depth and flame tilt angle change separately. Therefore, the flame tilt angle with consideration of the flame depth becomes $\varphi_{w(1)} \leq \varphi'_{w(1)}$ and flame length in consideration of the flame depth is $L_{fl(1)} \leq L'_{fl(1)}$ when flame depth increases the flame spreads, and the flame length changes greatly from the initial flame height

($H_0 \neq L_f$). When placing the flame front face as the reference, both the flame length and the flame tilt angle tend to be nearly the same, i.e. $L_{f(2)} \approx L'_{f(2)}$ and $\phi_{w(2)} \approx \phi'_{w(2)}$, during the spreading. Since the heat energy from a flame is transferred in the form of radiated heat energy from the flame face, this study was conducted under the conditions where the flame tilt angle and flame length are consistent under the same conditions. First, the tilt angle is defined as the angle of the flame front face to the vertical line. Second, the flame length is defined as the length of the flame face.

Thus, under the same condition, change of flame tilt angle is consistent, and flame length tend to be nearly the same as the initial flame height.

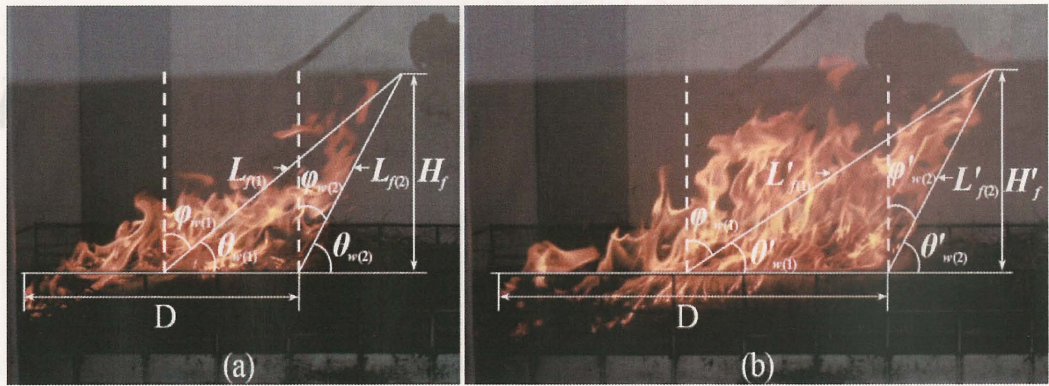


Figure 4-1 Change of Flame Tilt Angle Depending on Flame Width

4.2 Flame Tilt Model due to Wind

In this section, I deduce, through experiment and physical analysis, the relations on the change of flame tilt angle due to wind, and derives correlations between flame spread velocity. According to Albini, Putnam etc., flame tilt angle (ϕ_w) of wind-blown flame can be deduced as in Equation 4-1 from the relation between the Froude number (Fr) and the wind speed under a uniform wind.

① Froude number

$$\phi_w \propto \tan^{-1} \left(A \frac{U_\infty}{\sqrt{gH_f}} \right) = \tan^{-1} (A \times Fr) \quad 4-1$$

where, $Fr = \frac{U_\infty}{w} = \frac{U_\infty}{\sqrt{gH_f}}$, U_∞ is wind velocity (m/s), w is vertical air velocity, g is gravity acceleration (m/s^2), H_f is flame height (m), and A is coefficient.

Albini (1981) proposed coefficient $A=1.22$ as Equation 4-2 through correlation analysis between Froude number and flame tilt angle (ϕ_w), using the algebraic solution for $\tan(\phi_w)$, and Putnam (1965) proposed coefficient $A=1.4$ as Equation 4-3 from the experimental data on the flame of natural gas. Refer to their flame tilt angle (ϕ_w) is $\phi_{w(1)}$ or $\phi'_{w(1)}$ in Figure 4-1.

$$\varphi_w = \tan^{-1} \left(1.22 \frac{U_\infty}{\sqrt{gH_f}} \right) \quad 4-2$$

$$\varphi_w = \tan^{-1} \left(1.4 \frac{U_\infty}{\sqrt{gH_f}} \right) \quad 4-3$$

where, coefficient A varies by the fuel type and the correlation analysis method.

② Byram number

Taylor (1961) also deduced this relationship from consideration of the strongly buoyant limit of the thermal plume from a line source in cross flow as shown by Equation 4-4. Thus an exponent of 0.5 is to be expected from fully developed buoyant convection.

$$\varphi_w = \tan^{-1} \left\{ A \left(\frac{U_\infty}{\sqrt{I_B}} \right)^{1/2} \right\} \quad 4-4$$

$$\varphi_w = \tan^{-1} (2.58 N_c^{-0.29}) \quad 4-5$$

$$I_B = h_c w R \quad 4-6$$

where, I_B : fire intensity (kW/m), h_c : heat capacity (kJ/kg), w : fuel consumption (kg/m), R : Speed of flame spread (m/s).

The term $(U^3 / I_B)^{0.5}$ is closely related to the dimensionless ratio P_w / P_f (the ‘power of the wind’ (P_w)’ divided by the ‘power of the fire’ (P_f)) introduced by Byram (Brown and Davis 1973). This term was also considered as a potential predictor for flame tilt angle. Nelson and Adkins (1986) proposed Equation 4-5 with the constants acquired through the convection number (N_c) relation and statistical analysis of experiment data. Here N_c is ‘power of the fire’ (P_f) and ‘power of the wind’ (P_w), describe the rate of conversion of thermal energy to kinetic energy and the rate of flow of kinetic energy in the atmosphere due to the wind field (Nelson 1993). When this energy criterion is expressed as the ratio P_f / P_w , a dimensionless group $2gh_c w R / (\rho c_p T (U - R)^3)$, sometimes called the convection number (N_c), is formed. Assuming that $(2g/\rho c_p T)$ is constant. U is much larger than R , and using Equation 4-6 (Byram 1959), the relationship $N_c \propto I_B / U^3$ results.

This study suggested the method of calculating coefficient A through the flame tilt angle change experiment using *Pinus densiflora* surface fuel bed and the statistical correlation analysis with Froude number, and compared the experimental data with Equations 4-2 and 4-3.

4.3 Experiment on Wind-driven Change of Flame Tilt Angle

Although some existing results are available for flame tilt due to wind, it is not known which one is the most accurate. Also, the flame height H_f in flame tilt formulas by Albin, Putnam etc. is a result of flame tilt so it is difficult to use them in flame spread model. Therefore it is necessary to conduct flame tilt tests a new in this study.

4.3.1 Methods

① Test apparatus

As shown in Figure 4-2, a wind tunnel was constructed to produce a consistent wind speed to understand the relation between the change of flame tilt angle due to wind and the flame spread velocity. The section for measurement is 1m in width, 1m in height and 2.5m in length. A side wall of this section is made of glass for observation purpose. Wind speed can be controlled by 0.1m/s using the wind controller. The surface combustion test device, which is placed on the wind tunnel floor at measurement section as shown in Figure 4-2, is 0.5m wide and 2.2m long. Although the width of the fuel bed is not so large, the flame is consider to behave as that of a line fire since there is virtually no wind velocity vector across the tunnel axis due to the constraint by the tunnel wall.

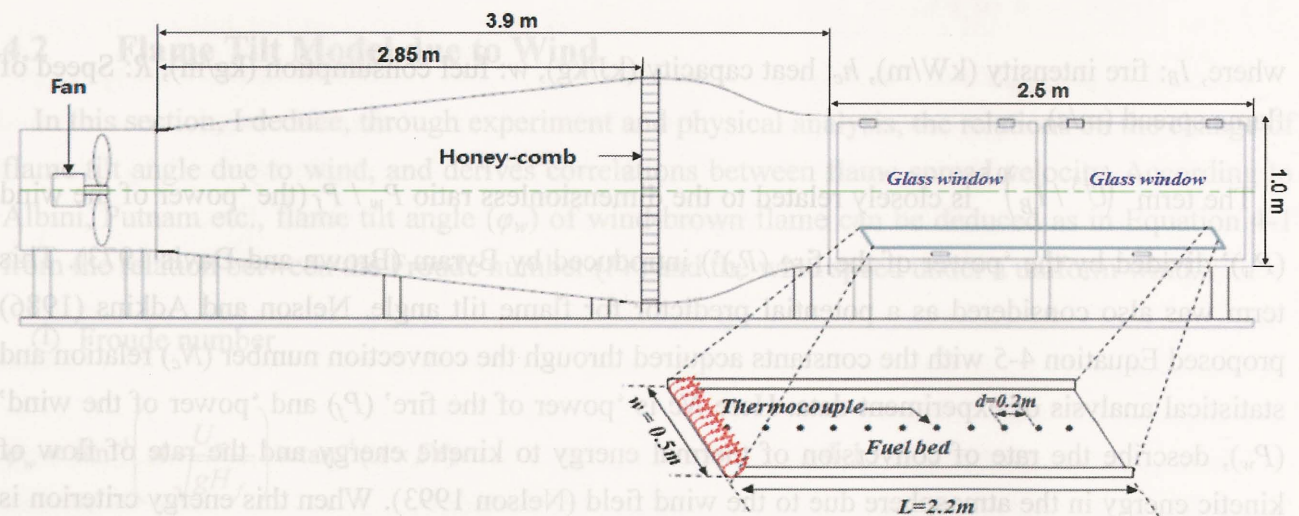


Figure 4-2 Wind Tunnel Device to Measure Flame Tilt Angle and Flame Spread Velocity

② Test conditions

The experiments were made under the 10 wind conditions from 0 to 5m/s at an interval of 0.5m/s. The tests were performed for *Pinus densiflora* fallen leaves with FMC (Fuel Moisture Contents) of

13±2%, which are the typical characteristics of *Pinus densiflora* fallen leaves in Korea. The fuel properties are shown in Table 4-1.

Table 4-1 Fuel Characteristics for the Flame Tilt and Spread Test

Species of Fuel	Fuel density (kg/m ³)	FMC (%)	Fuel depth (m)
<i>P. densiflora</i> fallen lives	20	13±2	0.1

③ Measurement

In order to measure the flame spread velocity, k-type thermocouples were installed inside the fuel bed specimen at an interval of 0.2m, and the time that flame reaches each thermocouple was recorded at every 1 second. Flame was recorded at every 1 sec by Digital Camera.

4.3.2 Result of Experimental Flame Properties due to Wind

4.3.2.1 Flame Length due to Wind

Measuring change of flame length due to wind speed was based on flame face $L_{f(2)}$, $L'_{f(2)}$) as shown in Figure 4-1. There can be questions about the influence of external wind on the flame lengths but Figure 4-3 demonstrated that increasing wind speed did not significantly affect flame length.

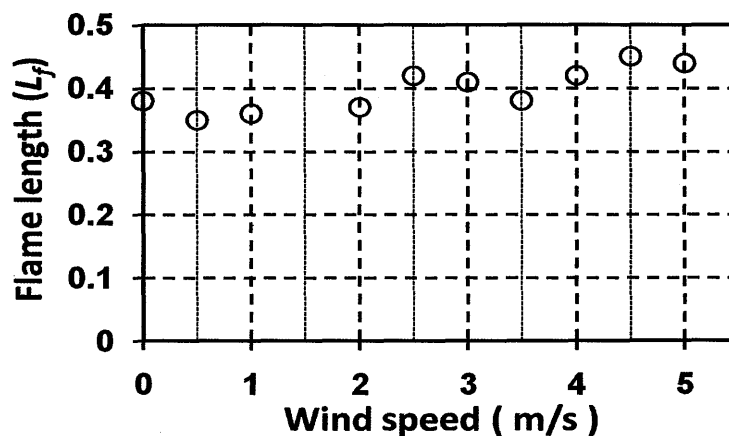


Figure 4-3 Experimental Flame Length Due to Wind Speed

The average flame length was 0.4 m with maximum error range ± 0.05 m. Therefore, it is reasonable to measure flame length based on flame face in determining flame tilt angle.

4.3.2.2 Flame Tilt due to Wind

As a result of the experiment on wind-driven change of flame tilt angle, it is found that flame tilt angle changes according to wind speed as shown in Figure 4-4. Figure 4-4 shows an example of the change of flame tilt angle according to wind.

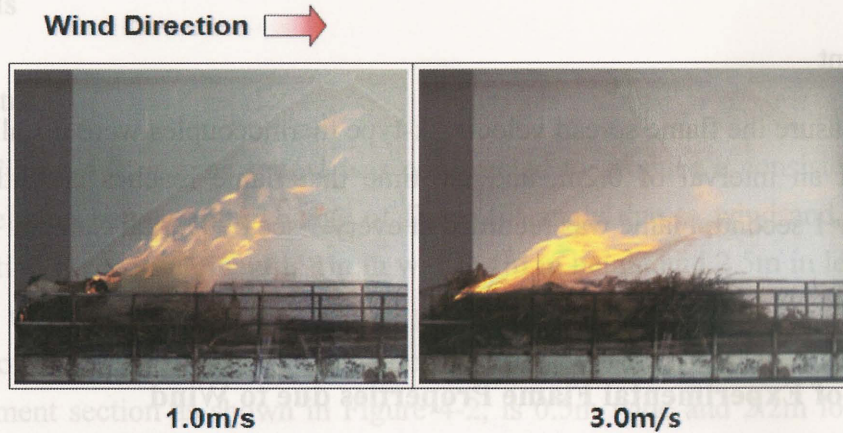


Figure 4-4 Experiment on Wind-Driven Change of Flame Tilt Angle at No-Slope Condition

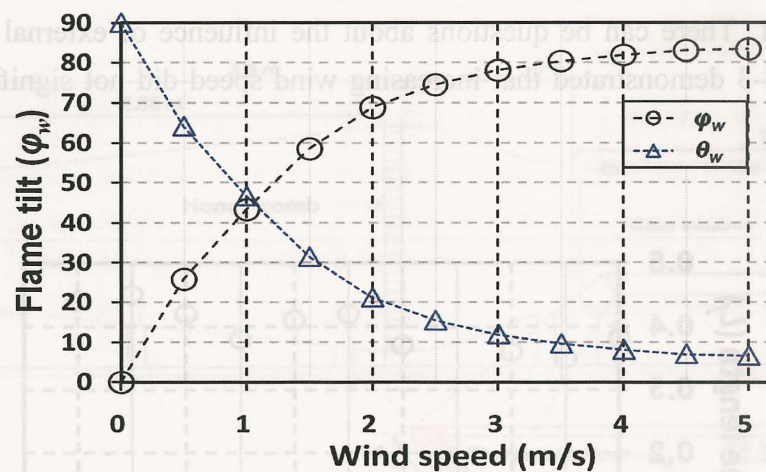


Figure 4-5 Experimental the Flame Tilt Angle (ϕ_w) and the Angle between Flame and Surface (θ_w)

The flame tilt angle ϕ_w and the angle between flame and the fuel surface θ_w are plotted in Figure 4-5. As seen by the result as wind speed increases, the flame tilt angle increase, i.e. the angle between the flame and the surface decreases. The experiment also showed that the flame tilt angle and the angle between flame and surface become equivalent (45°) when the wind speed is approx. 1.05m/s , and that if the wind speed is 3m/s or higher, the flame tilt angle becomes 80° and the flame almost contacts with the surface.

4.4 Semi-numerical estimation of flame tilt

The result shown in Figure 4-5 are only from a specific conditions of fire and external wind, so it is necessary to generalize the flame tilt relationship in order to use it in a fire spread model. The experiment on flame behavior due to different wind speed demonstrated that flame length was nearly constant (Figure 4-3) while flame height (H_f) varied depending on flame tilt angle (Figure 4-6). This is a very beneficial fact in constructing the generalized relationship concerning flame tilt. Also, using flame length as the index of fire size is convenient since flame length is determined reflecting combustion magnitude of fire.

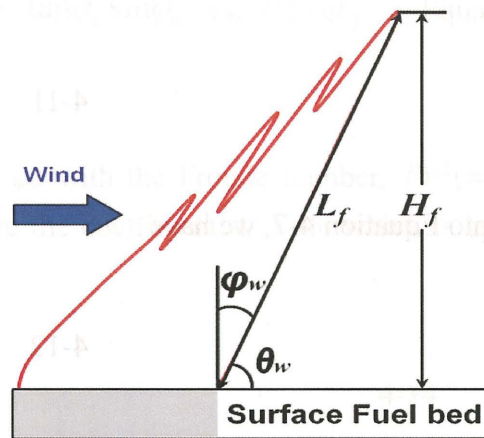


Figure 4-6 Diagram on Change of Flame Tilt Angle due to Wind Speed

It is considered that flame tilt angle is determined in combination of the upward velocity induced by strong buoyancy due to high temperature of flame and wind velocity, that applies to flame.

Letting w be the upward velocity due to the flame buoyancy,

$$\tan \phi_w \propto \frac{U_\infty}{w} \quad 4-7$$

Considering that the flame gas is accelerated by buoyancy up to the height of the order of flame height and letting $\Delta\rho_f$ be the representative flame temperature, we have

$$\rho_f w^2 \propto \Delta\rho_f g H_f \quad 4-8$$

or

$$w \propto \sqrt{\frac{\Delta\rho_f}{\rho_f} g H_f} = \sqrt{\frac{\Delta T_f}{T_\infty} g H_f} \quad 4-9$$

Since flame temperature is considered to be nearly the same regardless the size of flame, ΔT_f can be assumed constant, therefore

$$w \propto \sqrt{g H_f} \quad 4-10$$

where the flame height H_f which is different flame length L_f , is expressed as a function of the flame tilt angle φ_w as

$$H_f = L_f \cos \varphi_w \quad 4-11$$

Using Equations 4-10, 4-11 into Equation 4-7, we have

$$\tan \varphi_w = A' \frac{U_\infty}{\sqrt{g L_f \cos \varphi_w}} \quad 4-12$$

where, A' is a constant to be determined experimentally.

Rearranging Equation 4-12 yields Equations 4-13 below :

$$\tan \varphi_w \sin \varphi_w = A \frac{U_\infty^2}{g L_f} = A Fr^2 \quad 4-13$$

where, $A = A'^2$.

Estimation of coefficient A may be algebraically solved from experiments as in Albini (1981) and Putnam (1965), or could be calculated via a correlation analysis if flame tilt definition were the same as that in this study. But their proposed equations used to flame tilt definition as $\varphi_{w(1)}$ or $\varphi'_{w(1)}$ in Figure 4-1. Hence, in this study, correlation between the wind-driven flame tilt angle data acquired from experiment based on $\varphi_{w(2)}$ or $\varphi'_{w(2)}$ in Figure 4-1. Figure 4-7, plots the result of $\tan \varphi_w \sin \varphi_w$ vs. $U_\infty^2 / g L_f (= Fr^2)$.

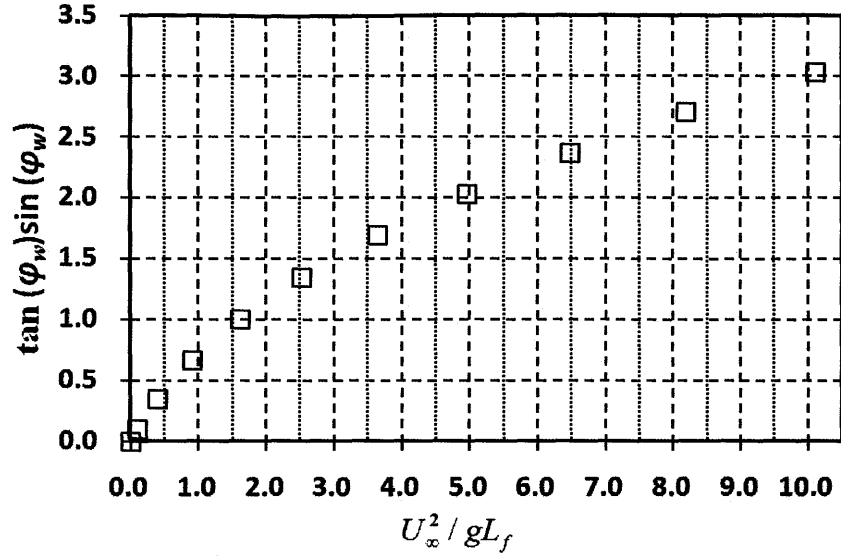


Figure 4-7 $\tan\phi_w \sin\phi_w$ vs. U_{∞}^2 / gL_f in Equation 4-13

The relationship of $\tan\phi_w \sin\phi_w$ with the Froude number, $Fr^2 (= U_{\infty}^2 / gL_f)$, were analyzed and statistically processed to acquire the coefficient $A=1.36$, which is applied to Equation 4-13 to get Equation 4-14.

$$\tan\phi_w \sin\phi_w = 1.36 \frac{U_{\infty}^2}{gL_f} \quad 4-14$$

where, the following statistical analysis was conducted to calculate Fr^2 number coefficient A .

•Step 1: Estimate the average flame tilt angle error ($\bar{y}$) between experiment data and Fr^2 number for each

level of wind speed

•Step 2: Estimate the deviation ($d_i = y_i - \bar{y}$)

where, $\sum_{i=1}^n (y_i - \bar{y}) = 0$

•Step 3: Estimate the standard deviation (σ)

•Step 4: Apply coefficient A of the standard error of mean

where, $A = \sigma / \sqrt{N}$, N is the total number of data

4.5 Analysis and Discussion about Flame Tilt due to Wind

Equation 4-14 can be proposed for calculating flame tilt angle (ϕ_w) based on Froude number (Fr^2). Although Albini and Putnam purposed $\tan\phi_w = A \cdot Fr$ type of correlation as Equation 4-2 and 4-3, they used $\phi_{w(l)}$ in Figure 4-1 as the definition of flame tilt angle and flame height H_f for Fr . So it is too difficult to compare their equations with ours that proposed in this study because the definitions of flame tilt are different as described at Chapter 4.1 and 4.2 above.

The coefficient A in Equation 4-13 were statistically obtained to yield

$$\tan\phi_w \sin\phi_w = 1.36Fr^2 \quad 4-15 \text{ (4-14)}$$

where $Fr^2 = U_\infty^2 / gL_f$.

The other hand, the coefficient may be obtained graphically, considering in mind the important range of Fr^2 for flame spread prediction. One of such is as follow :

$$\tan\phi_w \sin\phi_w = 1.2Fr^2 \quad 4-16$$

Here, we examine the merit of the two. Nothing that $\tan\phi_w \sin\phi_w = \frac{\tan^2\phi_w}{\sqrt{1+\tan^2\phi_w}}$ from

$$\sin\phi_w = \frac{\sin\phi_w}{\sqrt{\sin^2\phi_w + \cos^2\phi_w}} = \frac{\tan\phi_w}{\sqrt{1+\tan^2\phi_w}}, \text{ we may be able to compare } \tan\phi_w \text{ with } \tan\phi_w \sin\phi_w.$$

Table 4-2 The Results of Some Calculation about Wind Speed vs. $\tan\phi_w \sin\phi_w$, $\tan\phi_w$, Proposed Fr^2 as Equation 4-16 ($A=1.2$) and Equation 4-15 ($A=1.36$)

Wind speed(m/s)	Experiment data		Fr^2	$1.2Fr^2$ (Eq. 4-16)	$1.36Fr^2$ (Eq. 4-15)
	$\tan\phi_w$	$\tan\phi_w \sin\phi_w$			
0	0.00	0.00	0.00	0.00	0.00
0.5	0.48	0.17	0.10	0.12	0.14
1.0	0.94	0.58	0.40	0.49	0.55
1.5	1.64	1.24	0.91	1.09	1.24
2.0	2.58	2.16	1.62	1.94	2.20
2.5	3.61	3.21	2.53	3.04	3.44
3.0	4.70	4.32	3.64	4.37	4.96
3.5	5.90	5.54	4.96	5.95	6.75
4.0	7.04	6.70	6.48	7.77	8.81
4.5	8.10	7.78	8.20	9.84	11.15
5.0	8.62	8.34	10.12	12.15	13.77

Figure 4-8 shows the relation between $\tan\phi_w \sin\phi_w$, $\tan\phi_w$ and Fr^2 with proposed $A=1.36(Fr^2)$ and method A $A=1.2(Fr^2)$ for the wind-driven change of flame tilt angle at no slope condition. Figure 4-8 plots $\tan\phi_w$ as well as $\tan\phi_w \sin\phi_w$ vs. Fr^2 , which show no significant difference. This is considered to be because $\sin\phi_w$ is almost 1 for most of the range of the wind velocity in the tests. Hence, theoretical view is $\tan\phi_w \sin\phi_w = 1.2Fr^2$ but $\tan\phi_w = 1.2Fr^2$ may be also used from practical view point. And the coefficient $A=1.2$ is better than proposed $A=1.36$ for calculating of flame tilt angle. For Fr^2 bigger than 6 (Approximately wind speed is over 4m/s), the correlation deviates from the test data. This is probably because the flame tilt is so large that the flame almost touches the fuel surface in the region.

However, the value of $\tan\phi_w \sin\phi_w$ tends to be almost linear with Fr^2 for $Fr^2 \leq 4 \sim 5$, so if we seek for a convenient formula that is proportional to Fr^2 , the form $\tan\phi_w \sin\phi_w$ will be more beneficial.

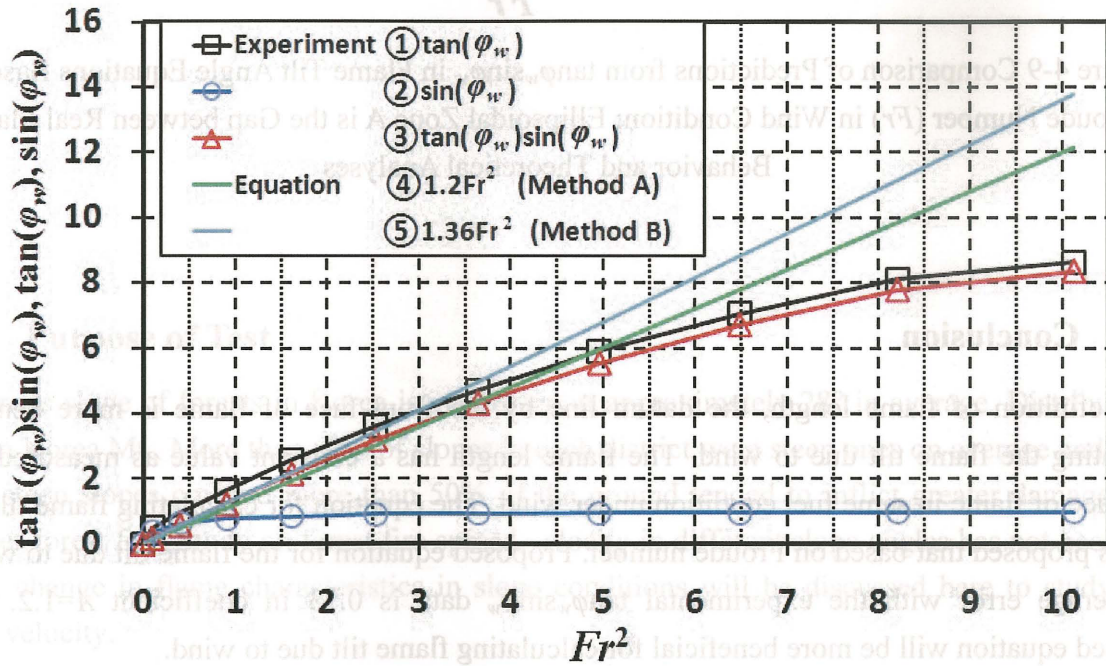


Figure 4-8 The Relation between $\tan\phi_w \sin\phi_w$, $\tan\phi_w$ and Fr^2 with Proposed $A=1.36$ and $A=1.2$

Figure 4-9 shows the comparison for the experimental $\tan\phi_w \sin\phi_w$ data vs. results of equations (4-15, 4-16) which based on the Froude number at the wind conditions. Ellipsoidal zone A in Figure 4-9 is the gap that is thought to be because flame is very close to the fuel surface, so ϕ_w cannot increase according to wind velocity any more. The average error with the experimental $\tan\phi_w \sin\phi_w$ data is 1.09 for proposed Equation 4-15 ($A=1.36$), 0.73 for method A Equation 4-16 ($A=1.2$). As can be seen method A Equation 4-16 is very close to test data for $Fr < 2.5$.

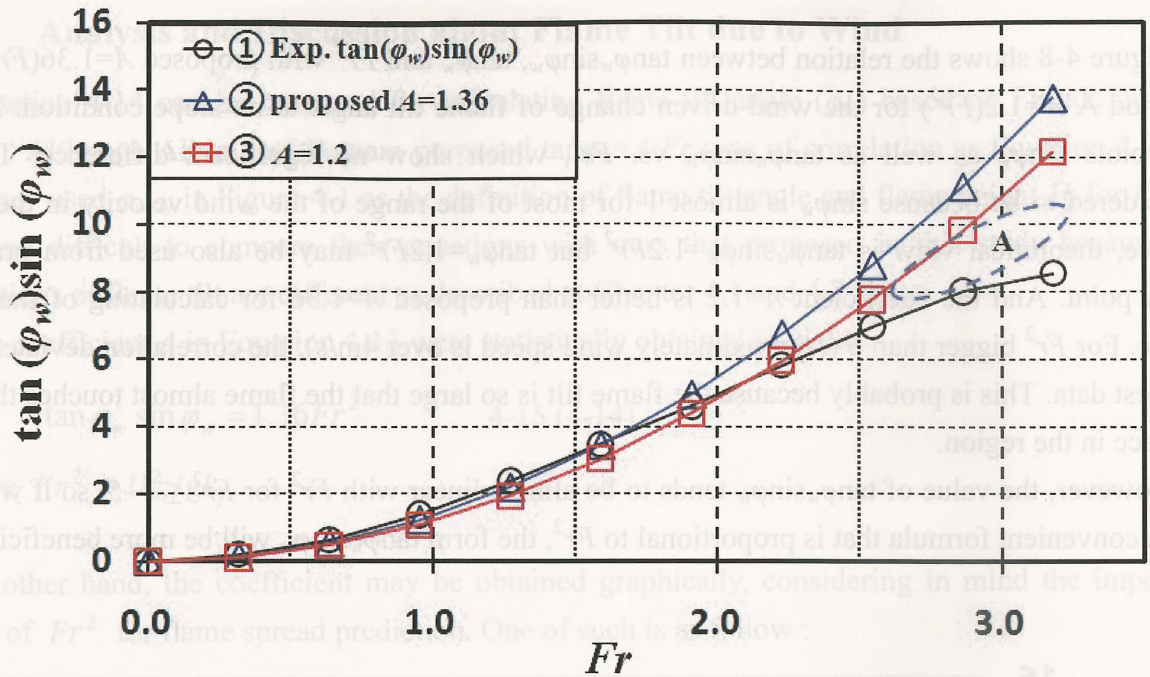


Figure 4-9 Comparison of Predictions from $\tan\phi_w\sin\phi_w$ in Flame Tilt Angle Equations Based on Froude Number (Fr) in Wind Condition; Ellipsoidal Zone A is the Gap between Real Flame Behavior and Theoretical Analyses

4.6 Conclusion

In definition of flame length, the datum line by the front face of flame is more benefit for calculating the flame tilt due to wind. The flame length has a constant value as measured by the front face of flame in same fuel condition under wind. The equation for calculating flame tilt due to wind is proposed that based on Froude number. Proposed equation for the flame tilt due to wind has the average error with the experimental $\tan\phi_w\sin\phi_w$ data is 0.73 in coefficient $A=1.2$. Hence, proposed equation will be more beneficial for calculating flame tilt due to wind.

Chapter 5

Flame Tilt due to Slope

5.1 Purpose of Test

Average slope of forests in Korea is very steep at approximately 28° in average. Distribution of slope in Korea Mt., More than 60% of slopes in each district were steep ones on average and forests where steep slopes covered more than 50% of the ground tended to inflict greater damage to the floor per forest fire. Study on forest fire spread velocity in different slope angles has not been done. Hence, change in flame characteristics in slope conditions will be discussed here to study flame spread velocity.

5.2 Existing Flame Tilt Model due to Slope

Flame spread velocity over virgin surface fuel bed on a slope ground increases as the flame gets closer to the slope. The existing studies have generally assumes that the angle between flame and slope surface decreases by the same angle as the slope angle increases, without considering the change of flame tilt due to the effect of slope. Morandini et. al. (2001) adopted $\theta_s=90-\beta$ as the angle between flame and surface disregarding flame tilt (ϕ_s), under the assumption that ‘influence of slope to the change of flame tilt is insignificant’ (Morandini 2001). It has been reported in some existing studies and experiments that slope has less influence than wind speed to the flame spread

velocity (Dupuy 1995, F. Morandini 2000, 2001). There have been fewer studies on slope-driven change of flame tilt than those on wind-driven change. Studies on the slope-driven flame spread have been made in limited number of experiments (Viegas DX 1994, Dupuy 1995, Santony 1998). The effect of slope is taken into consideration of the law of Stefan-Boltzmann, which allows the amount of energy radiated by the flame in the direction of the unburned area to be calculated in Computational Fluid Dynamic (Santoni, 1988). This study deduces, through experiment and physical analysis, the relations on the change of flame tilt angle due to slope, and derives correlation between flame tilt and flame spread velocity. Figure 5-1 is the diagram on the relation between gradient and flame tilt angle. The experiment shows that flame tip F bends toward slope surface as the slope angle increases as shown in Figure 5-1.

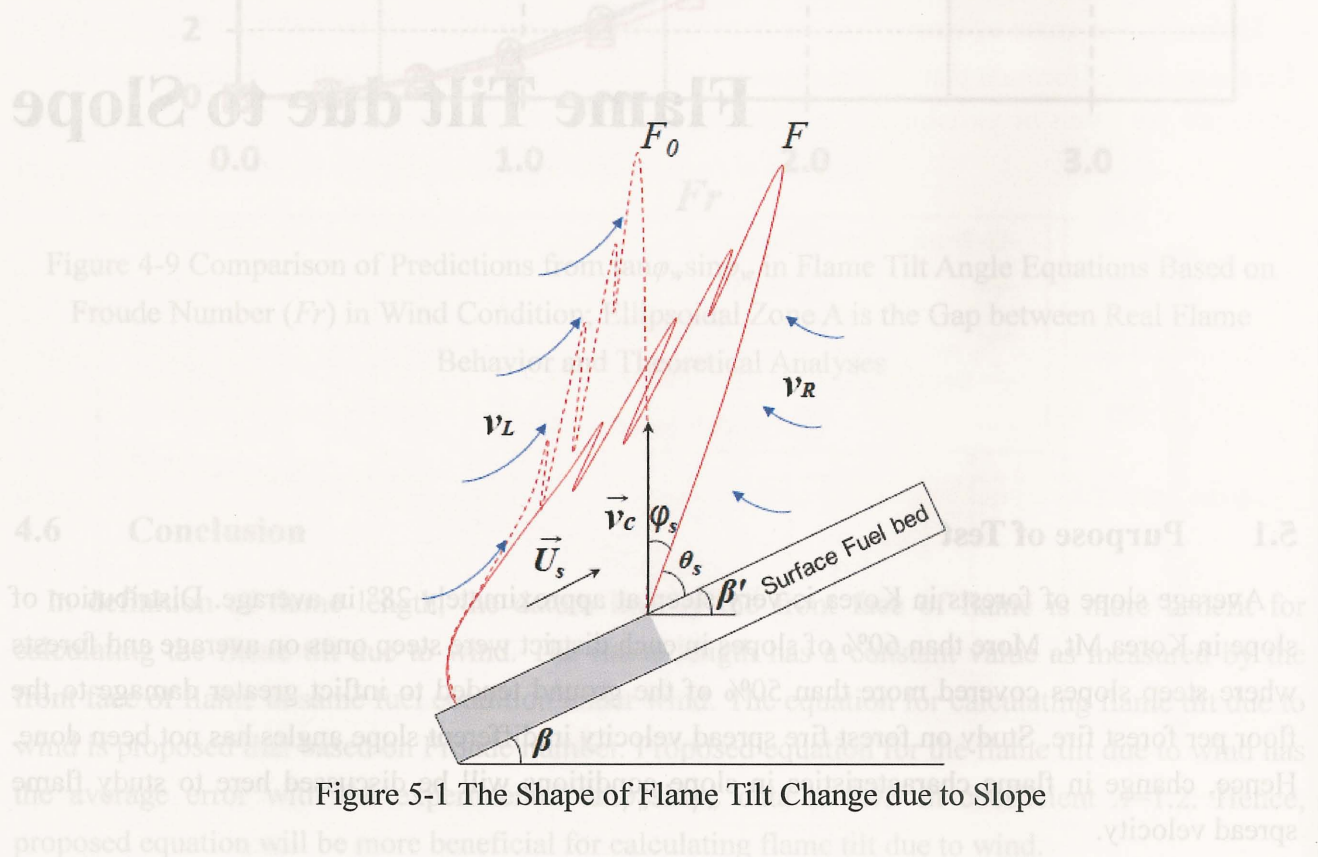


Figure 5-1 The Shape of Flame Tilt Change due to Slope

Existing researches, however, assumed F_0 as the position of flame tip and $\phi_s + \theta_s$ ($=90^\circ - \beta$) as the angle between flame and inclined plane to see how flame tilt angle varies by slope (Albini 1981, Morandini 2001). In this study, hence, the effect of actual slope on flame tilt angle and velocity of flame spread is investigated. This chapter considers change in flame tilt that is caused by air inflow velocity in different slope angles. Existing studies have assumed F_0 in Figure 5-1 as the flame tip position while this study considers F as the position, which accounts for slope impact. Hence, this study will aim to find F in flame characteristics change in slope and reflect the value to propose equation for flame tilt and flame spread velocity.

5.3 Experiments on Change of Flame Tilt due to Slope

5.3.1 Methods

① Test apparatus

As shown in Figure 5-2, a test device was made to investigate the relation between the flame tilt induced due to slope and the flame spread velocity under no wind condition. Size of the slope, fuel conditions, measurement methods of the time at which flame reaches and flame tilt are the same as those of the test for flame tilt by wind. In the fuel bed of 0.5m wide and 2.2m long, k-type thermocouples were arrayed with 0.2m interval to measure the speed of flame spread based on the time at which flame reaches the thermocouples.

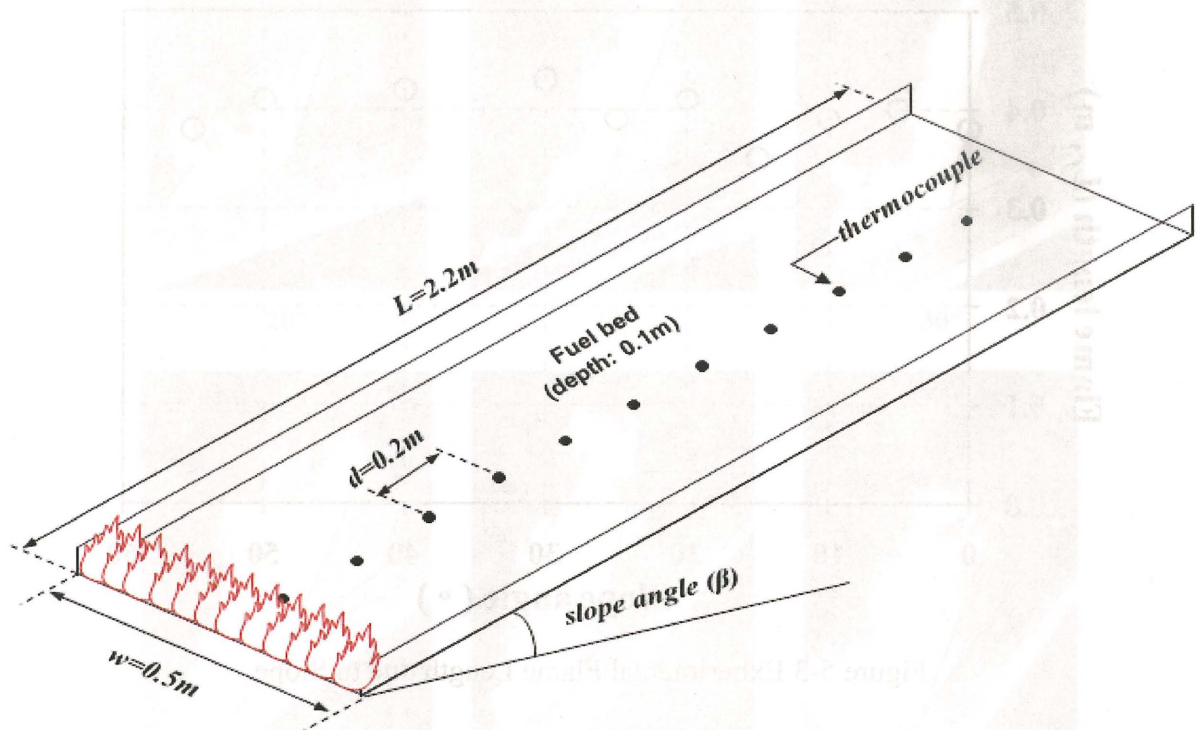


Figure 5-2 Setup to Measure Flame Tilt and Flame Spread Velocity due to Slope

② Test conditions

Experiments were made under the 10 slope angles in the range 0° to 55° . The tests were performed for *P. densiflora* fallen leaves with FMC (Fuel Moisture Contents) of 15%, which are the typical characteristics of *P. densiflora* fallen leaves in Korea, where properties are shown Table 4-1.

③ Test procedure

Two portable butane gas lighters were used to ignite the litter in the bottom of Figure 5-2. Because the fuel bed was only 0.5m wide, less than 0.5 seconds was all it took to ignite at the same time, after which the gas lighters were turned off. Flame shape and spread velocity were recorded using video camera.

5.3.2 Result of Experimental Flame Properties due to Slope

5.3.2.1 Flame length due to slope

Measurement of flame length due to slope was based on flame face $L_{f(2)}$, $L'_{f(2)}$ as shown in Figure 4-1 like as Figure 4-3 in wind condition. The flame lengths were not significantly affected by slope as shown in Figure 5-3, like the flame lengths under different wind velocities. The flame lengths were fairly constant at about 0.4m, which is not different either from the case of flames in wind.

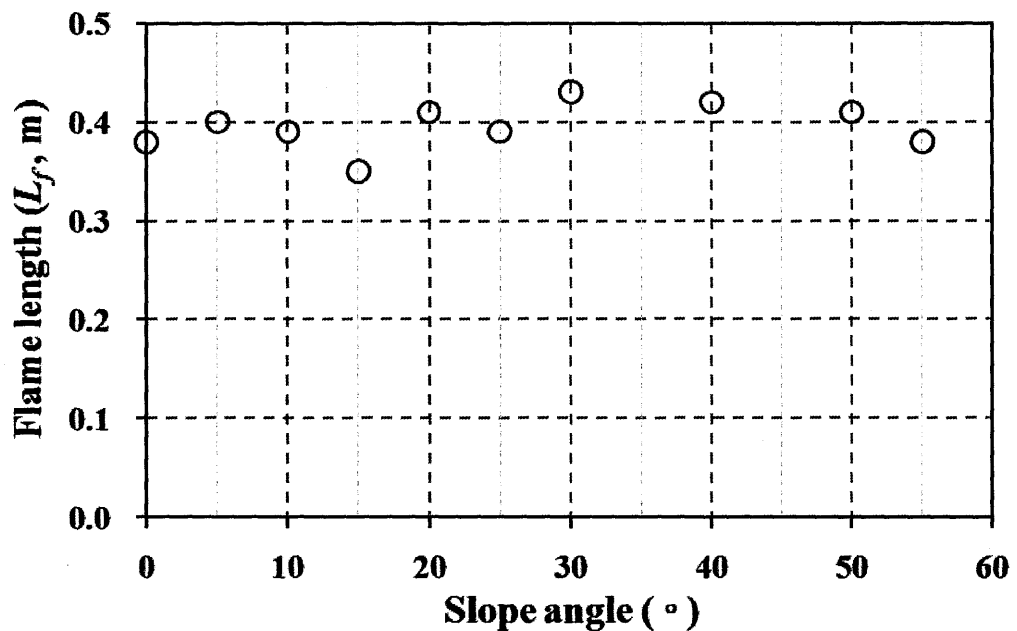


Figure 5-3 Experimental Flame Length due to Slope

5.3.2.2 Flame tilt due to slope

An experiment on the slope-driven change of flame tilt shows that flame tilt changes according to change of slope as shown in Figure 5-4 using by experiment device in Figure 5-2. Concerning flame tilt due to slope, test in Figure 5-4 confirms that flame tip position does not stay at F_0 shifts to F in Figure 5-1. Therefore, flame tilt due to slope is ' $\varphi_s = 90 - (\beta + \theta_s)$ '. The angle between surface and flame in flame characteristic in Figure 5-3 was measured using trigonometric function.

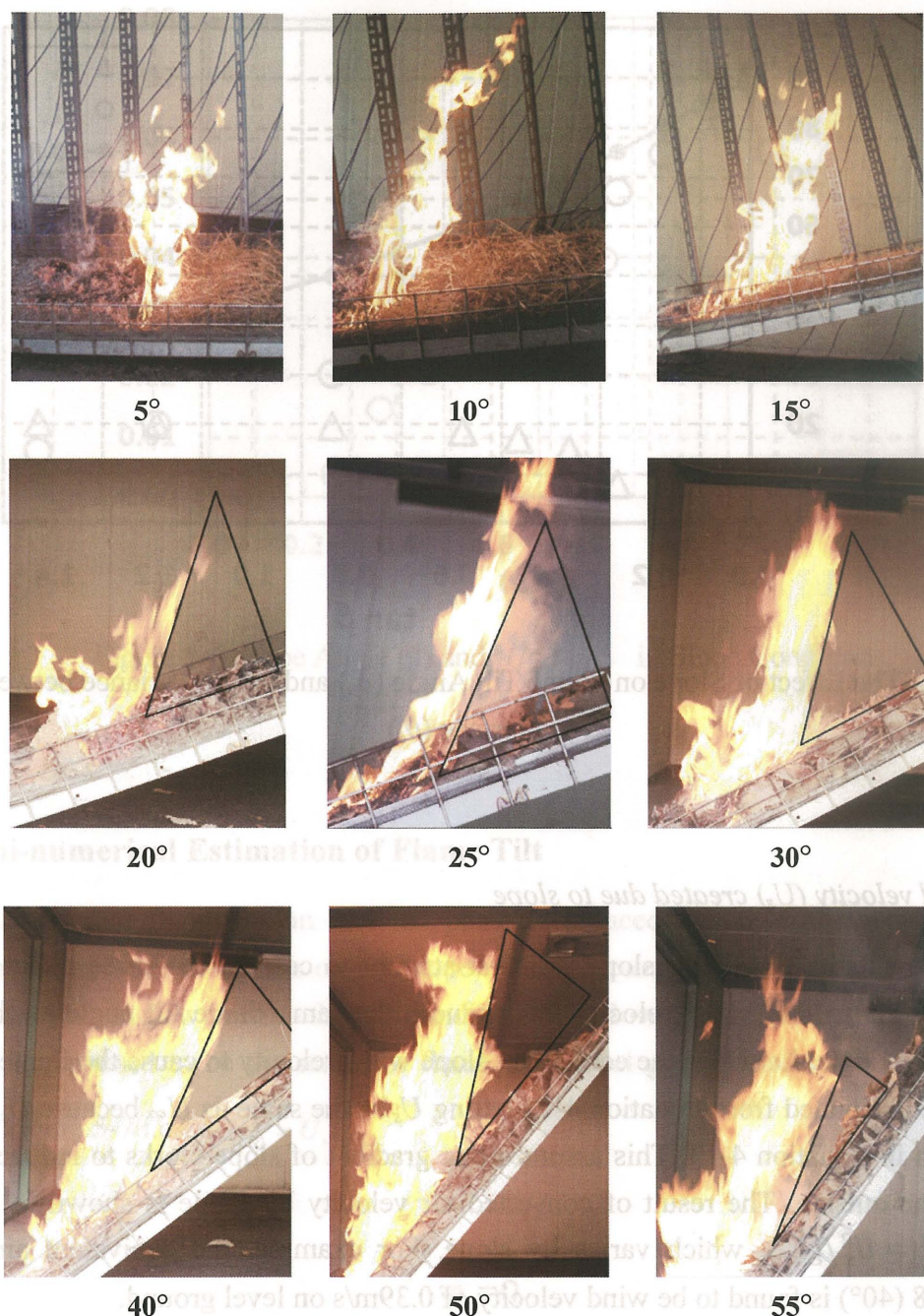


Figure 5-4 Slope Induced Flame Tilt for Different Angle under No Wind Condition

Experiment on the effect of slope on flame tilt angle resulted the correlation between slope and flame tilt angle as shown in Figure 5-5. In particular, flame tilt angle, ϕ_s , demonstrates a kind of proportional increase up to approximately 30° ($\tan \beta = 0.58$) in slope but beyond that ϕ_s tends to be constant at 20° range. The angle between flame and inclined plane, θ_s , tended to become smaller continuously with the increase of slope, unlike flame tilt angle. In summary, the angle between flame and slope surface is considerably smaller than the angle assumed by Albini, etc, i.e. $90^\circ - \beta$, by about 20° for slope angle greater than 0.5 .

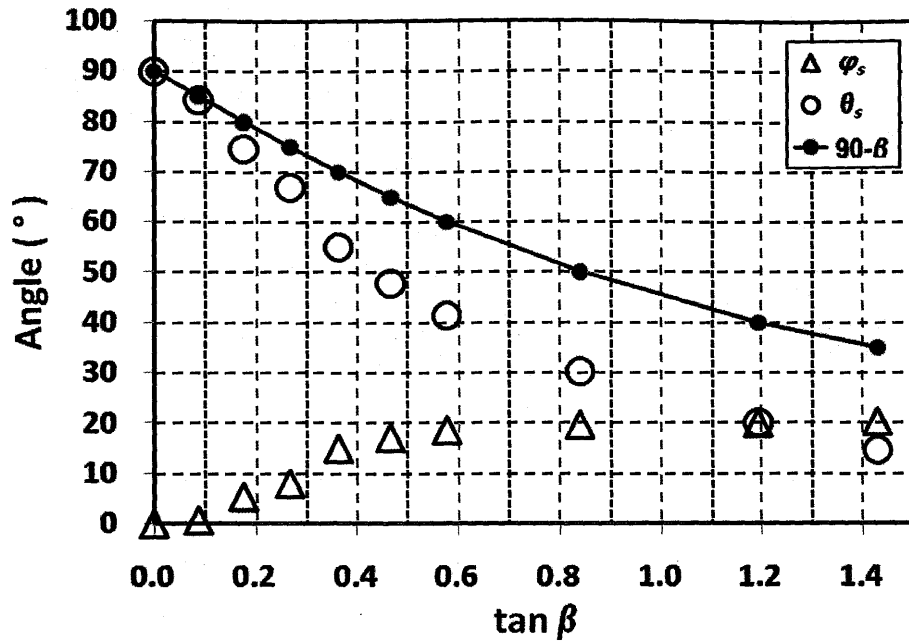


Figure 5-5 The Effect of Slope on Flame Tilt Angle (ϕ_s) and Angle Variance between Flame & Surface (θ_s)

5.3.2.3 Wind velocity (U_s) created due to slope

For modeling flame tilt due to slope, we first attempt to convert the slope effect to equivalent wind velocity, i.e. to find wind velocity that induces the same flame tilt angle as that caused by effect of a slope angle. Let U_s be the equivalent slope wind velocity to cause the flame tilt angle, ϕ_s . The U_s can be calculated from Equation 4-13 letting U_s be the same as U_∞ because U_s is slope wind velocity given in Equation 4-13. This assumes that gradient of slope works to induce air inflow to flame from the outside. The result of converted air velocity by flame is shown in Figure 5-6 in terms of $Fr^2 (= U_s^2 / gL_f)$, which varies by slope. For example, the equivalent air velocity for gradient of 0.8 (40°) is found to be wind velocity of 0.39m/s on level ground.

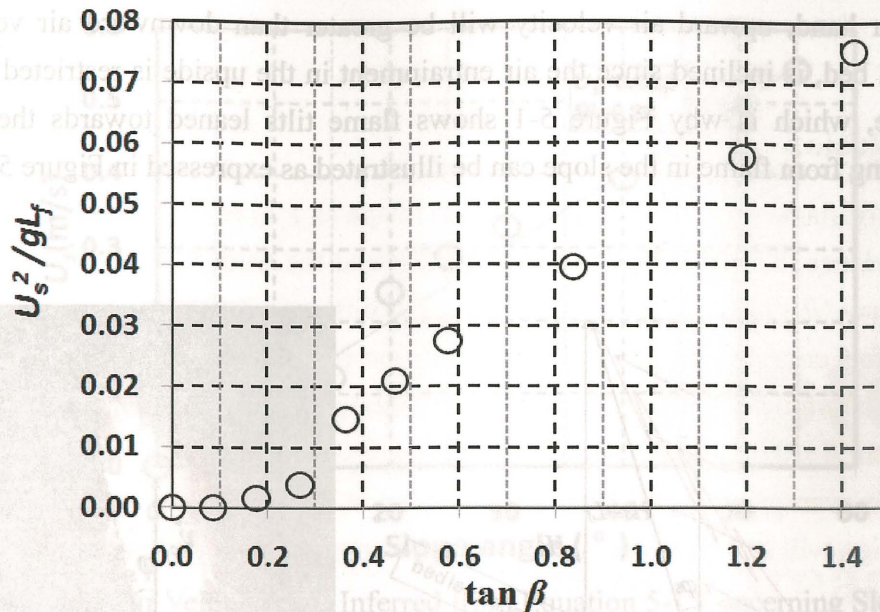


Figure 5-6 Slope Angle (β) and U_s^2 / gL_f in Slope Condition

5.3.3 Semi-numerical Estimation of Flame Tilt

It is considered that flame tilt on inclined plane is induced by the difference in air velocity between below and above the flame on the slope, which occurs when buoyant flame as shown in Figure 5-1 causes air to flow in from the surrounding. Air inflow speed from both left and right side of the flame is supposed to be the same for flame on a level ground under no-wind condition as illustrated in Figure 5-7 i.e. $U_{\infty(L)} = U_{\infty(R)}$.

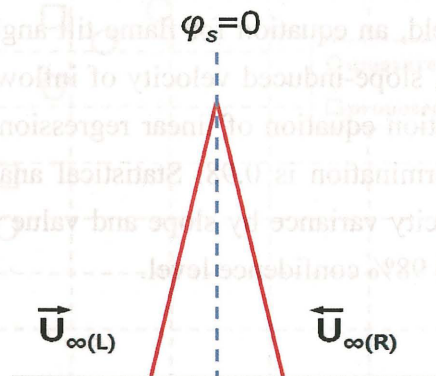


Figure 5-7 Schematic Diagram on Flame and Air Inflow on Level Ground with No-Wind Condition

On the other hand, upward air velocity will be greater than downward air velocity when the ground, or fuel bed, is inclined since the air entrainment in the upside is restricted as the flame get closer to slope, which is why Figure 5-1 shows flame tilts leaned towards the upside. Hence, velocity resulting from flame in the slope can be illustrated as expressed in Figure 5-8.

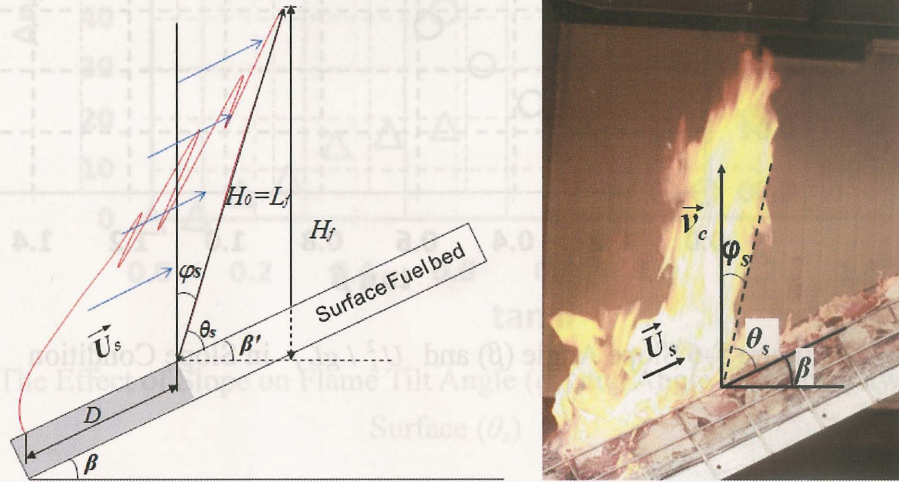


Figure 5-8 Air Inflow Speed and Flame Tilt Variance in Upward Slope

The flow field around a flame on a slope is expected to be very complicated. Entrained air will approach from both side of the flame, and stream lines may be more horizontal at upper part of a flame while more along slope surface at lower part of the flame. In any case, it is the horizontal component of the air velocity that causes flame tilt component.

This research will invokes Equation 4-14, derived from the experiment under same fuel conditions, to establish an equation for the impact of slope on flame tilt. In Equation 4-16, U_{∞} is the horizontal wind velocity on level ground condition. Here U_{∞} is replaced the equivalent flow velocity, U_s , due to slope to yield, an equation for flame tilt angle for slope as shown in Equation 5-1. As analyzed in Figure 5-9, slope-induced velocity of inflowing air (U_s) makes a proportional increase with the slope. Estimation equation of linear regression analysis is the same as Equation 5-1 and the coefficient of determination is 0.98. Statistical analysis of the value gained 0.01 β , which estimates inflowing velocity variance by slope and value gauged in the experiment showed 0.025 (m/s) in average error and 98% confidence level.

$$\tan \phi_s \sin \phi_s = 1.2 \frac{U_s^2}{gL_f}$$

5-1

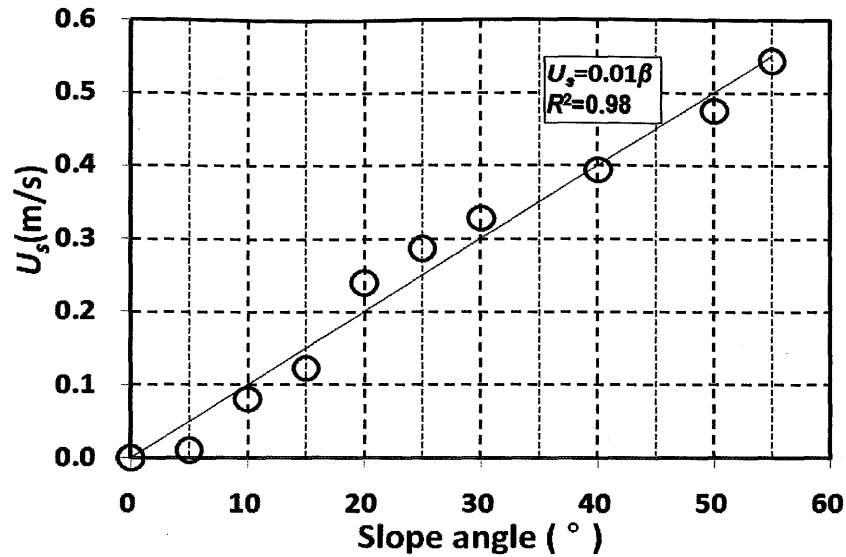


Figure 5-9 Inflowing Air Velocity (U_s) Inferred from Equation 5-1 Concerning Slope's Effect on Flame Tilt Angle Variance

5.4 Analysis and Discussion for Flame Tilt due to Slope

Figure 5-10 shows the comparison between the experimental data vs. result of proposed Equation 5-1 for the slope-induced change of flame tilt angle at no wind condition.

The average error and the Standard deviation with the experimental data and proposed Equation 5-1 is 2.3° . The standard error is 95% confidence level by the result of t-test.

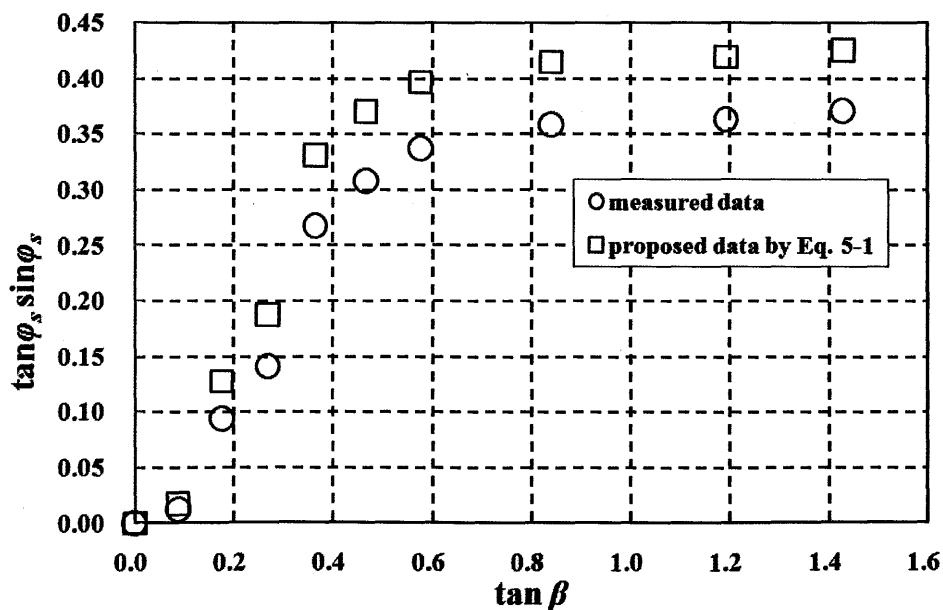


Figure 5-10 Comparison of Experimental Data vs. Proposed Equation 5-1 for Slope Induced Change of Flame Tilt Angle

5.5 Conclusion

In definition of flame shape due to slope, flame shape as F is more accuracy than flame shape F_0 in Figure 5-1. Hence, the angle between surface fuel and the front face of flame can be propose as ' $\theta_s=90-(\beta+\varphi_s)$ ' not ' $\theta_s=90-\beta$ '. The flame length has a constant value as measured by the front face of flame in same fuel condition under slope. The equation for calculating flame tilt due to slope is also proposed like as wind condition that based on Froude number. Flame tilt φ_s increases as $\tan\beta$ increase up to $\tan\beta < 0.6$, φ_s has constant 20° for $\tan\beta \geq 0.6$. Proposed equation for the flame tilt due to wind has the average error with the experimental φ_s data is 2.3° in coefficient $A=1.2$. Hence, proposed equation will be more beneficial for calculating flame tilt due to slope.

Chapter 6

Flame Spread Tests

6.1 Purpose of the Test

Surface flame spread velocity on fuel bed with the same fuel conditions varies depending on slope and wind conditions. In a real forest fire, however, it is literally impossible to accurately measure flame spread velocity in each different condition of wind speed, wind direction, slope and fuel type, etc. Hence flame spread velocities in three different situations were measured. The measured value will be compared with the value obtained in a flame spread velocity prediction model, which is the ultimate goal in this research, to verify or improve the model.

6.2 Test Method and Conditions

Three types of flame spread tests were conducted in this study. The method and conditions of each of the three types of tests are as follows:

(1) Flame spread on level surface with wind (10 tests)

Flame spread velocity augmented by wind was measured for *Pinus densiflora* fallen leaves as the fuel bed using the same test method as stated in Chapter 4.3.1 and specimen conditions using wind tunnel device in Figure 4-2. The time taken for flame to reach the end of the 2.2 m long fuel bed

was measured to determine flame spread velocity in each of the 10 tests with different wind velocities ranging of 0.5m/s from 0 to 5m/s interval.

(2) Flame spread on slope with no wind (9 tests)

Flame spread velocity on slope with no wind was measured for *P. densiflora* fallen leaves with the same test method shown in Chapter 5.2.1 and fuel bed conditions using slope test device in Figure 5-2. The time taken for the flame to reach the end of the 2.2m long fuel bed was measured to determine flame spread velocity, by the same manner as in flame spread velocity in wind velocity conditions. The slope tests were conducted for 9 slope angles, i.e.: 0°, 5°, 10°, 15°, 20°, 30°, 40°, 50°, 55°.

(3) Flame spread on slope with wind (16 tests)

Flame spread velocity on slope with wind velocity was measured for *P. densiflora* fallen leaves with the same sample conditions using wind tunnel device in Figure 4-2. The time taken for the flame to reach the 2.2m length fuel bed was measured to determine flame spread velocity. The tests were conducted for the total of 16 conditions by applying four different angle conditions at 0°, 10°, 20°, 30° with wind velocities ranging 0~3m/s at 1 m/s interval.

6.3 Flame Spread on Level Surface with Wind

Figure 6-1 shows the correlation between wind speed and flame spread velocity. As can be seen in this figure, the higher the wind speed the larger the flame spread velocity. In particular, the spread velocity was 254 times faster when the wind speed was 5m/s compared to condition of no wind. Regarding the relationship between the flame tilt angle and flame spread rate, Figure 6-1 shows that the flame spread velocity increased rapidly once $\sin(\phi_w)$ value exceeded approximately 0.9 and that the flame spread velocity increase a gradually while $\sin(\phi_w) \approx 1$ in region A in Figure 6-1.

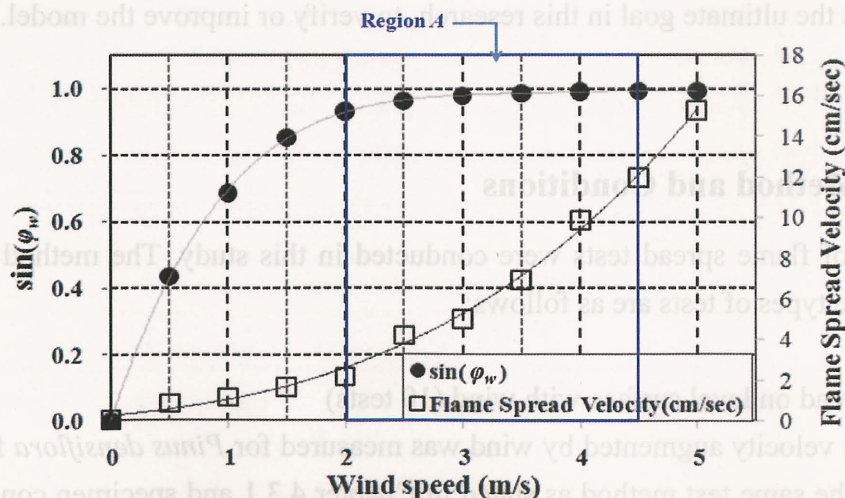
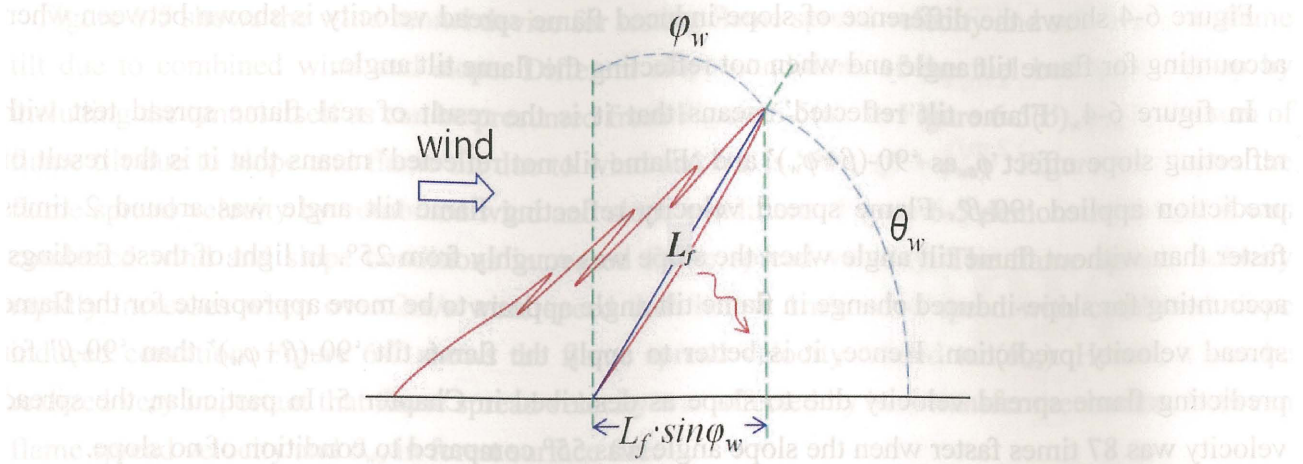
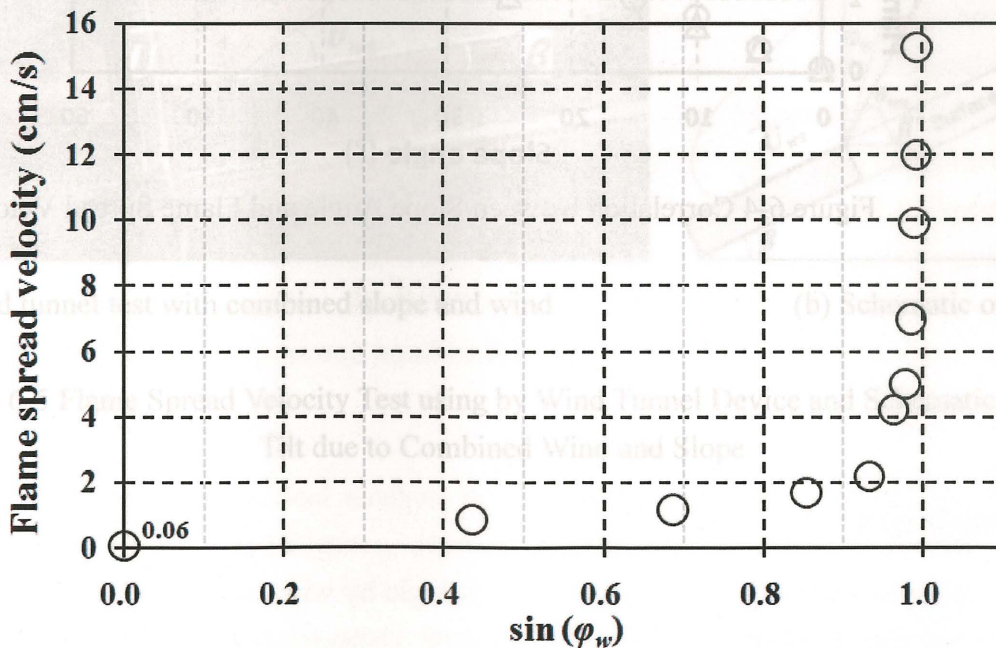


Figure 6-1 Experimental Result of the Flame Spread Velocity and $\sin(\phi_w)$ by Wind Speed

6.4 Flame Spread Velocity and Slope

Figure 6-2 Schematic of the Flame Tilt Angle (ϕ_w) and the Angle between Flame and Surface (θ_w)

In regard to flame spread rate due to changes in flame tilt angle, Figure 6-3 demonstrated that increase in flame tilt angle (ϕ_w) led to faster flame spread velocity as the angle (θ_w) between fuel surface narrows. The flame spreads faster at the wind speed of 5m/s than at 0m/s by approximate 254 times. It is suspected that the thermal energy radiated from flame, which depends on the distance between the flame and the surface, plays a major role in the flame spread.

Figure 6-3 Experimental Result the Flame Spread Velocity by Flame Tilt Angle (ϕ_w)

6.4 Flame Spread Velocity on Slope with No Wind

Figure 6-4 shows the difference of slope-induced flame spread velocity is shown between when accounting for flame tilt angle and when not reflecting the flame tilt angle.

In figure 6-4, 'Flame tilt reflected' means that it is the result of real flame spread test with reflecting slope effect ϕ_s as ' $90-(\beta+\phi_w)$ ' and 'Flame tilt not reflected' means that it is the result of prediction applied ' $90-\beta$ '. Flame spread velocity reflecting flame tilt angle was around 2 times faster than without flame tilt angle when the slope was roughly from 25° . In light of these findings, accounting for slope-induced change in flame tilt angle appears to be more appropriate for the flame spread velocity prediction. Hence, it is better to apply the flame tilt ' $90-(\beta+\phi_w)$ ' than ' $90-\beta$ ' for predicting flame spread velocity due to slope as described in Chapter 5. In particular, the spread velocity was 87 times faster when the slope angle was 55° compared to condition of no slope.

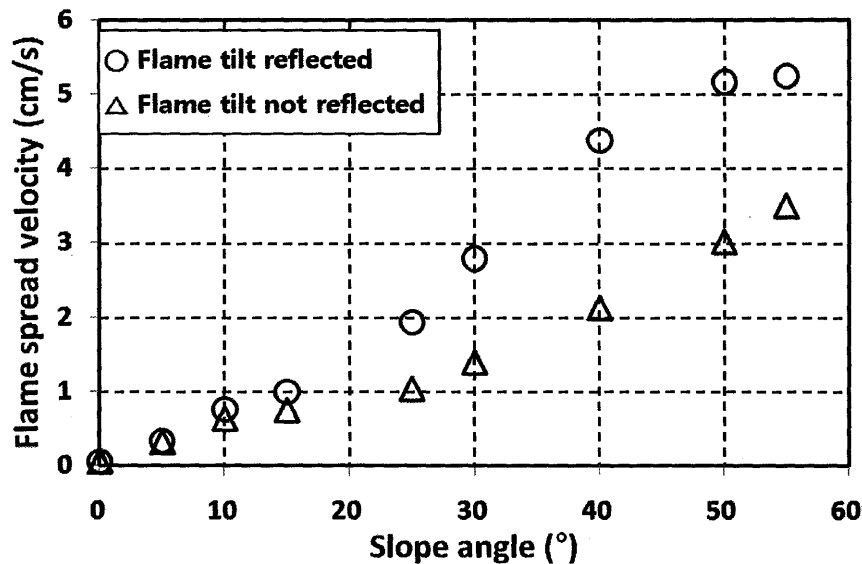
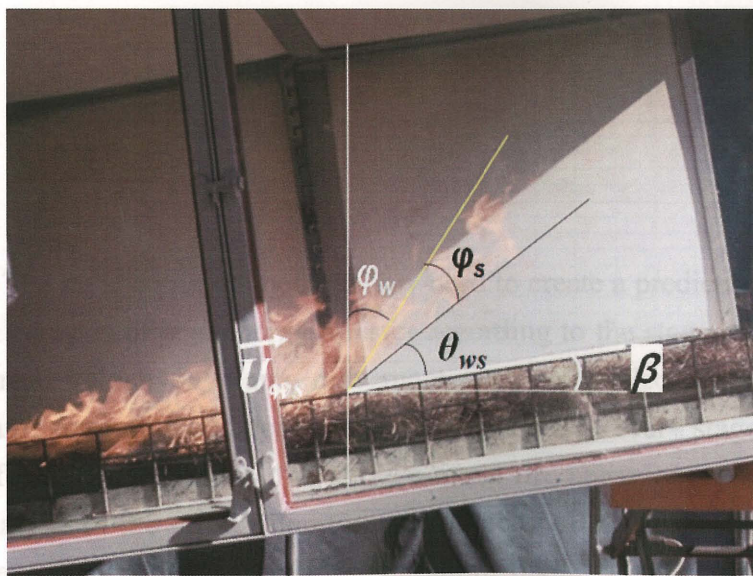


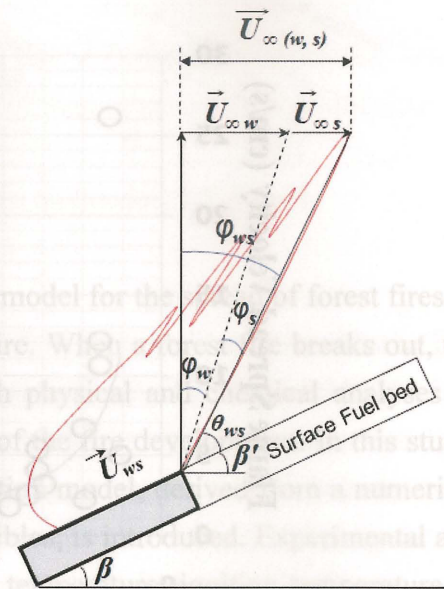
Figure 6-4 Correlation between Slope Angle and Flame Spread Velocity

6.5 Flame Spread Velocity on Slope with Wind

Figure 6-5 shows the wind tunnel device for testing flame spread velocity and schematic of flame tilt due to combined wind and slope. Different slope conditions of the fuel bed were set up by including the tunnel itself as can be presumed from Figure 6-5(a). In Figure 6-5(b), ϕ_{ws} is the sum of flame tilt due to slope and flame tilt due to wind and θ_{ws} is '90 - ($\beta + \phi_{ws}$)'. Figure 6-6 shows the flame spread velocity by combined wind and slope conditions. Figure 6-5 demonstrates that it was combined wind and slope conditions increased flame spread velocity. The flame spread velocity rapidly increases when over 2m/s wind speed than below 1m/s wind speed with combined slope induced condition. Figure 6-7 shows the flame spread velocity related $\tan(\theta_{ws})$. Hence, it can be realized very important that flame spread velocity was affected by heat transfer mechanism between flame spread velocity and θ_{ws} in forest surface fire.



(a) Wind tunnel test with combined slope and wind



(b) Schematic of Flame tilt

Figure 6-5 Flame Spread Velocity Test using by Wind Tunnel Device and Schematic of Flame Tilt due to Combined Wind and Slope

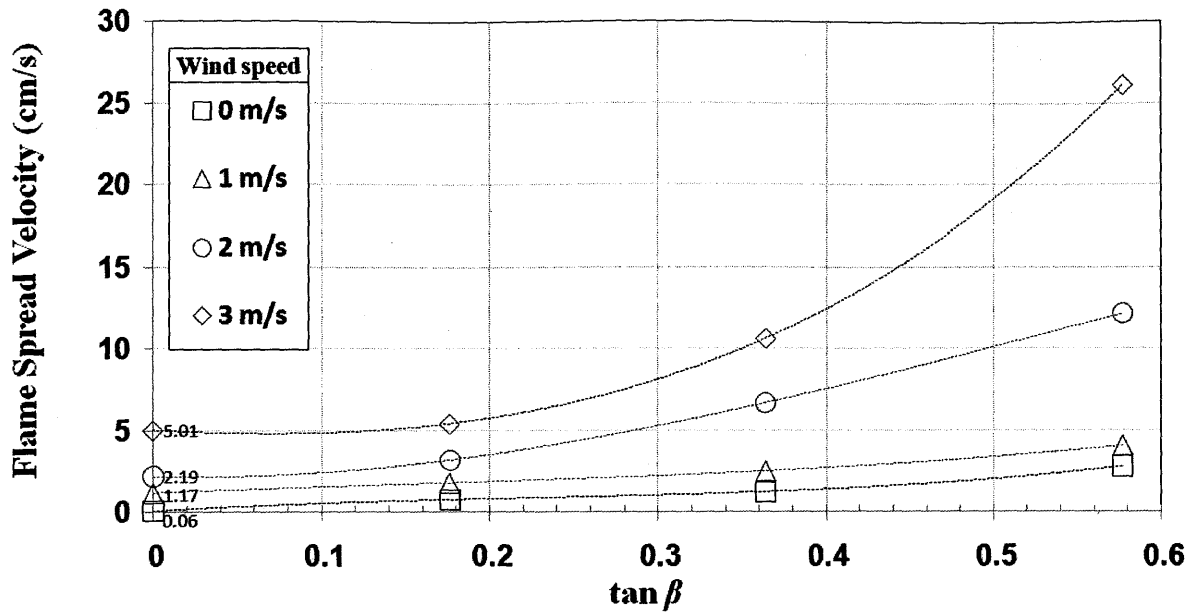
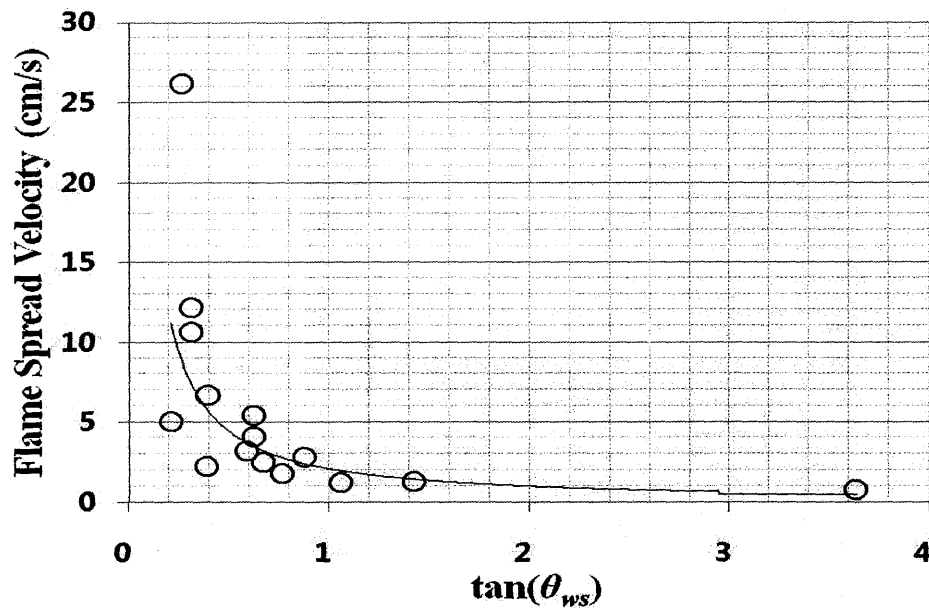


Figure 6-6 Experimental Result of the Flame Spread Velocity by Combined Wind and Slope

Figure 6-7 Experimental Result of the Flame Spread Velocity vs. $\tan(\theta_{ws})$

6.6 Conclusion

Flame spread velocity due to changes in flame tilt angle by wind, that increase in flame tilt angle (ϕ_w) led to faster flame spread velocity as the angle (θ_w) between fuel surface narrows. The flame spread velocity increase slowly for $\sin \phi_w < 0.9$ and increase very rapidly for $\sin \phi_w \geq 0.9$. The flame spread velocity under combined wind and slope, that increase slowly for $\tan \theta_{ws} > 0.9$ and increase very rapidly for $\tan \theta_{ws} \leq 0.9$.

Chapter 7

Surface Flame Spread Model

The most common methodology used to create a prediction model for the spread of forest fires, is an analysis of heat energy transfer according to the stage of fire. When a forest fire breaks out, the spread velocity of flame movement can be modeled through physical and chemical analyses of flame formation and heat transfer to its targets at every stage of the fire development. In this study, a formula used for the 1-D surface forest fire behavior prediction model, derived from a numerical analysis of the surface flame spread velocity of solid combustibles, is introduced. Experimental and theoretical equations on flame duration, flame height, flame temperature, ignition temperature of surface fuels, etc., has been applied to derive of this formula.

7.1 Configuration

The research executed numerical analysis on heat transfer from flame based on the result of combustion experiment on fallen leaves, which are surface combustibles, to develop 1-D surface flame spread prediction algorithm.

In general, flame spread velocity of forest fire is mostly controlled by radiant heat transfer and convection heat, which are affected by wind and topographical slope. Majority of forest fuels are composed of porous fuel layer deposited on the upper part alongside soil level surface. Accordingly, the flame spread of forest fires is analyzed with surface flame spread analysis of solid combustibles

as shown in Figure 7-1. In other words, flame spread can be analyzed with an equation to produce heat energy that heats non-combustibles, whose initial temperature is T_∞ , into T_{ig} , the ignition temperature, via heat transmission ahead of front flame.

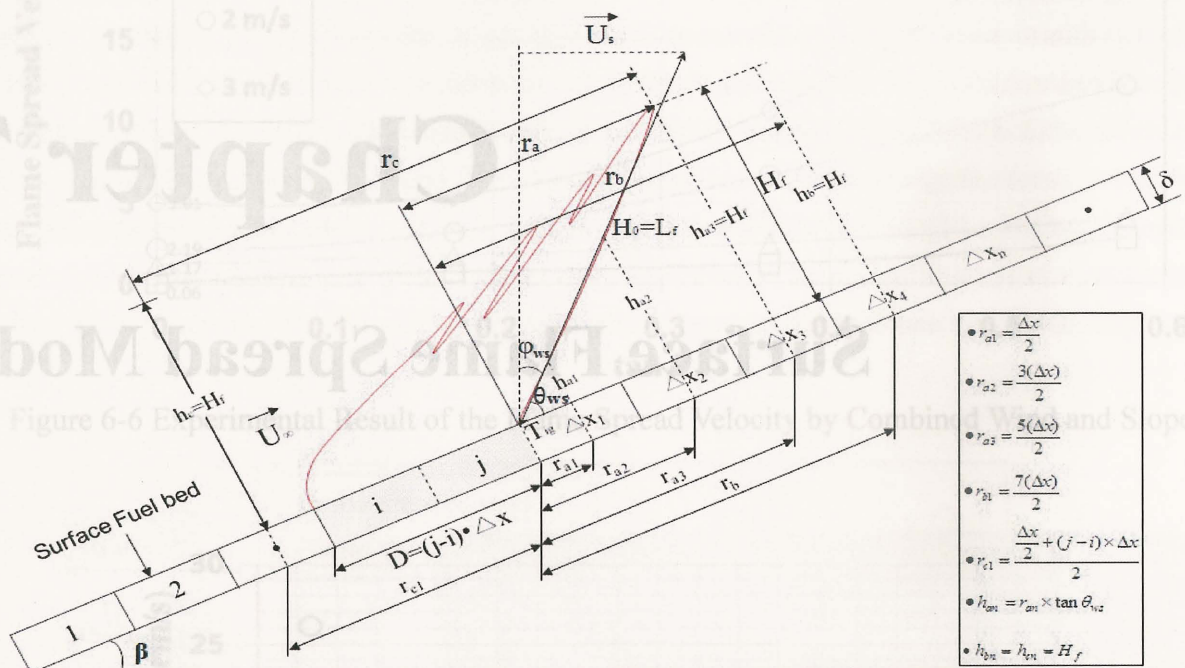


Figure 7-1 Schematic of Heat Flux of the One-Dimensional Flame Spread

The schematic in Figure 7-1 is the section view of an infinite line flame that spreads over a fuel bed with thickness δ . The fuel bed is divided into finite segment with uniform physical properties. A segment receives radiative heat from the flame and conductive heat from adjacent segment. The heat transferred to a segment raises the temperature of the segment and vaporizes the moisture contained in the segment. A segment where temperature reached the ignition temperature starts to burn. The flame is formed on the burning segment and the length of the flame is determined by the total heat release rate of the burning segments. The flame on a segment vanishes when the fuel of the segment is consumed.

7.2 Stage of Burning of Fuel Segment

For analyzing of fuel segment burning, we consider the following 5 stages for each segment, i.e.;

Stage (1): Temperature rise with moisture

The fuel bed segment contains moisture and the temperature of the segment rises together with the moisture

Stage (2): Vaporization of moisture

Moisture vaporizes in proportion to net heat gain. The temperature of the fuel bed segment remains to be constant at 100 °C until the moisture vaporization has completed.

Stage (3): Temperature rise without moisture

The fuel bed segment no longer contains moisture. The temperature of the dried segment rises.

Stage (4): Flaming

The fuel bed segment burns with forming flames until the fuel has been consumed. The temperature of the segment remains to be constant at flame temperature, T_{flame} .

Stage (5): Burnout

The fuel of the bed has been consumed so the fuel bed no more exists.

7.3 Mathematical Formulation of Model

This section deals with the mathematical formulation of the 1-D fire spread model, which consists of the formulations of burning and temperature rise of fuel segment, heat transfer to the target fuel segment and flame properties.

7.3.1 Burning of Fuel Segment

Here we formulate the burning of arbitrary fuel segment base on the conservation of fuel mass, moisture mass and heat. Figure 7-2 illustrates the section of an arbitrary segment with unit width and the involved heat transfer.

A segment receives radiative heat on the surface from flame, $\dot{q}_{rad}$, and conductive heat from the adjacent segment at higher temperature. It also lose conductive heat to the adjacent segment at lower temperature

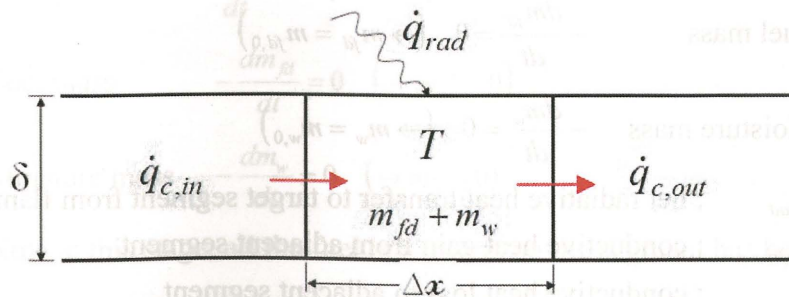


Figure 7-2 Schematic of Heat Transfer to the Segment with Unit Width

(1) Fuel mass

$$m_{fd} = \rho_{dry} A_s \delta = \rho_{dry} \cdot 1 \cdot \Delta x \cdot \delta = \rho_{dry} \Delta x \delta$$

where m_{fd} : mass of fuel bed segment for unit width at dry condition
 ρ_{dry} : density of fuel bed
 δ : thickness of fuel bed

(2) Moisture mass

$$m_f = r \cdot m_{fd,0}$$

where $m_{fd,0}$: initial mass of fuel bed at dry condition
 r : ratio of moisture mass to original dry fuel mass defined below

$$r = \frac{m_w}{m_{fd,0}}$$

(3) Initial condition: Temperature $T = T_0$

$$\text{Dry fuel mass} \quad m_{fd} = m_{fd,0}$$

$$\text{Moisture mass} \quad m_w = m_{w,0}$$

(4) Transient conditions

Assuming that moisture evaporate at 100°C and fuel mass loss occurs only after fuel segment reaches the ignition temperature of fuel according to the definitions of the burning stages in the above, the equations for transient temperature, fuel mass and moisture mass can be formulated as follows;

$$\text{Stage (1):} \quad \text{Temperature} \quad \frac{d}{dt} \{ (C_f m_{fd} + C_w m_w) T \} = \dot{q}_{rad} + (\dot{q}_{c,in} - \dot{q}_{c,out})$$

$$\text{Fuel mass} \quad -\frac{dm_{fd}}{dt} = 0 \quad (\rightarrow m_{fd} = m_{fd,0})$$

$$\text{Moisture mass} \quad -\frac{dm_w}{dt} = 0 \quad (\rightarrow m_w = m_{w,0})$$

where $\dot{q}_{rad}$: net radiative heat transfer to target segment from flame
 $\dot{q}_{c,in}$: conductive heat gain from adjacent segment
 $\dot{q}_{c,out}$: conductive heat loss to adjacent segment
 C_f : specific heat of fuel at dry condition
 C_w : specific heat of water

Stage (2): Temperature $\frac{dT}{dt} = 0 \quad (\rightarrow T = 373)$

Fuel mass $-\frac{dm_{fd}}{dt} = 0 \quad (\rightarrow m_{fd} = m_{fd,0})$

Moisture mass $-L_v \frac{dm_w}{dt} = \dot{q}_{rad} + (\dot{q}_{c,in} - \dot{q}_{c,out})$

where L_v : Latent heat of water vaporization

Note that fuel temperature stagnates at 100°C (373K) until all the moisture has vaporized.

Stage (3): Temperature $\frac{d}{dt} \{C_f m_{fd} T\} = \dot{q}_{rad} + (\dot{q}_{c,in} - \dot{q}_{c,out})$

Fuel mass $-\frac{dm_{fd}}{dt} = 0 \quad (\rightarrow m_{fd} = m_{fd,0})$

Moisture mass $-\frac{dm_w}{dt} = 0 \quad (\rightarrow m_w = 0)$

Note that no moisture remains at this stage but temperature of fuel bed is still below the ignition temperature.

Stage (4): Temperature $\frac{dT}{dt} = 0 \quad (\rightarrow T = T_{ig})$

Fuel mass $-\frac{dm_{fd}}{dt} = \dot{m}_b$

Moisture mass $-\frac{dm_w}{dt} = 0 \quad (\rightarrow m_w = 0)$

Here we assume that once fuel bed segment is ignited its temperature suddenly goes up to ignition temperature.

Stage (5): Temperature $\frac{dT}{dt} = 0 \quad (\rightarrow T = T_0)$

Fuel mass $-\frac{dm_{fd}}{dt} = 0 \quad (\rightarrow m_{fd} = 0)$

Moisture mass $-\frac{dm_w}{dt} = 0 \quad (\rightarrow m_w = 0)$

Note at this stage, all the fuel is burnout, so the segment has become vacant.

7.3.2 Heat Transfer Model

7.3.2.1 Radiant Heat Transfer from Infinite Flame to a Target Surface

(1) Rate of the radiant heat transfer

$$\dot{q}_{rad} = \{E_f F + \sigma T_\infty^4 (1 - F) - \varepsilon_b \sigma T_i^4\} A_i$$

where E_f : emissive power of flame follow as;

$$E_f = \varepsilon_f \sigma T_{flame}^4$$

where ε_b : emissivity of fuel bed surface

F : view factor of flame from target point

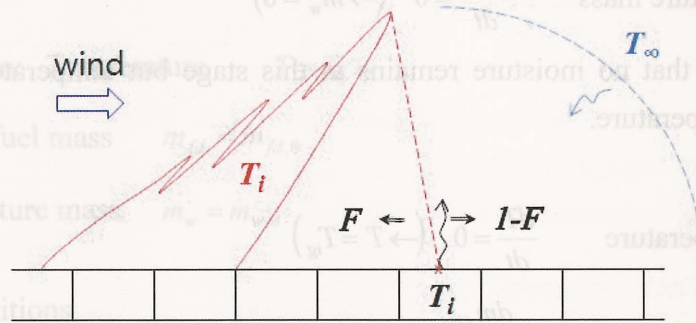


Figure 7-3 Schematic of the Radiative Heat Transfer to the Segment

(2) View factor of infinite strip

For the configuration that an infinite strip shape radiation source exist right above a target area element, the projection of the strip or to the circular base of semi-sphere becomes an ellipse as shown Figure 7-4. Noting that the area of an ellipse with long radius a and short radius b is calculate as πab , the view factor of the infinite strip, F_{strip} is calculated.

$$F_{strip} = \frac{\pi ab}{\pi} = ab$$

Consider the semi-circle with the radius of the shortest distance from a target point and the flame tip in front of the infinite line flame and a infinite strip at the height of the flame tip that cut off by the semi-circle.

Then applying the solid angle projection method, we find $a=1$, and $b = \frac{r_f}{\sqrt{h_f^2 + r_f^2}}$ hence,

$$F_{strip} = 1 + \frac{r_f}{\sqrt{h_f^2 + r_f^2}}.$$

where h_f : flame height

r_f : horizontal distance between target point and flame tip

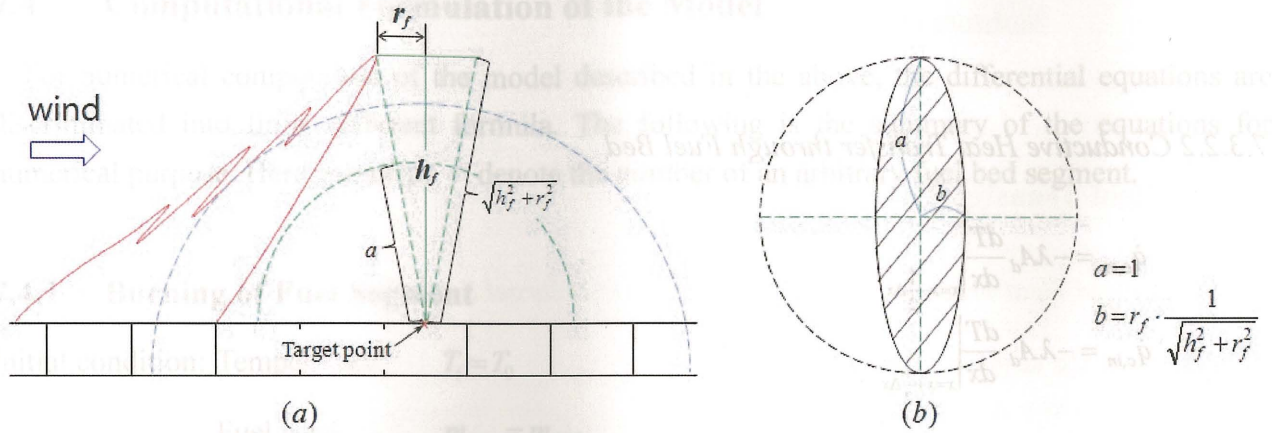


Figure 7-4 Schematic of View Factor: (a) Infinite Strip to the Segment, (b) the Projection of the Strip or to the Circular Base of Semi-sphere Becomes an Ellipse

(3) View factor of infinite flame

The view factor of the infinite flame is

$$F = \frac{1}{2} \pm \frac{1}{2} F_{strip}$$

depending on whether or not the flame hangs over the target (heat receiving) point.

However, if the lateral distance of the flame tip and the target position is defined as

$$r_f \equiv x_f - x_i$$

the view factor F is given by the single equation as follows:

$$F = \frac{1}{2} \left(1 + \frac{r_f}{\sqrt{h_f^2 + r_f^2}} \right)$$

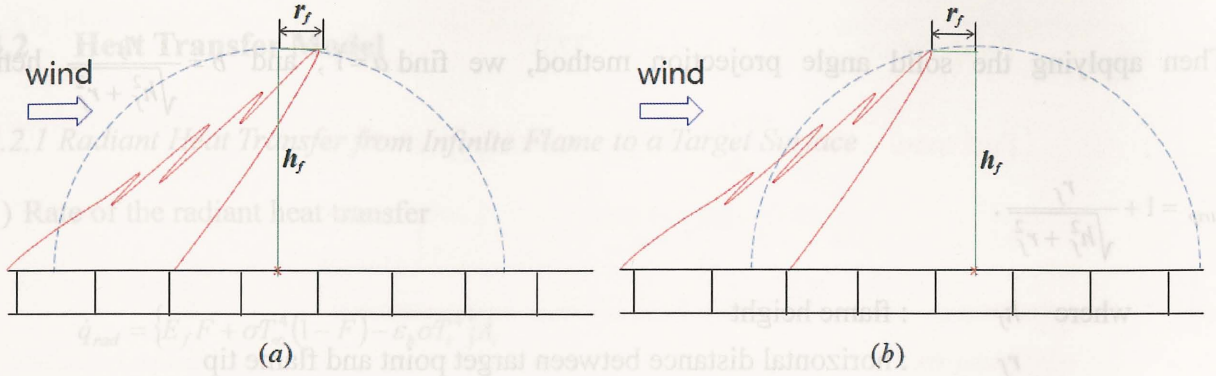


Figure 7-5 Schematic of View Factor of Infinite Flame: (a) the Inside Segment of Flame Tip, (b) an Outside Segment from Flame Tip

7.3.2.2 Conductive Heat Transfer through Fuel Bed

$$\dot{q}_{c,in} = -\lambda A_d \left. \frac{dT}{dx} \right|_{x=x-\frac{1}{2}\Delta x}$$

$$\dot{q}_{c,in} = -\lambda A_d \left. \frac{dT}{dx} \right|_{x=x+\frac{1}{2}\Delta x}$$

where A_d : Section area of fuel bed for unit width ($=1 \times \delta = \delta$)
 λ : Effective conductive heat transfer coefficient (to be determined from tests)

7.3.3 Infinite Flame

7.3.3.1 Flame Length

Since flame length is not significantly affected by wind velocity as was shown by Figure 4-3, flame length is assumed using Equation 3-8 proposed by Quintiere et al for infinite line fire given as

$$L_f = 3.0 \left(\frac{\dot{Q}'}{\rho_\infty c_p T_\infty g^{1/2}} \right)^{2/3} = 0.027 \dot{Q}'^{2/3}$$

7.3.3.2 Flame Tilt due to Wind

$$\tan \phi_w \sin \phi_w = 1.2 \frac{U_\infty^2}{gL_f}$$

7.3.3.3 Flame Tilt due to Slope

$$\tan \phi_w \sin \phi_w = 1.2 \frac{U_s^2}{gL_f}$$

7.4 Computational Formulation of the Model

For numerical computation of the model described in the above, the differential equations are discriminated into finite different formula. The following is the summary of the equations for numerical purpose. Here subscript i denote the number of an arbitrary fuel bed segment.

7.4.1 Burning of Fuel Segment

Initial condition: Temperature $T_i = T_0$

Fuel mass $m_{fd,i} = m_{fd,0}$

Moisture ratio $m_{w,i} = m_{w,0}$

Stage (1): Temperature $T_i = T_i + \frac{\dot{q}_{rad} + (\dot{q}_{c,in} - \dot{q}_{c,out})}{(C_f m_{fd,0} + C_w m_{w,0})} \Delta t$

Fuel mass $m_{fd,i} = m_{fd,0}$

Moisture mass $m_{w,i} = m_{w,0}$

Stage (2): Temperature $T_i = 373$

Fuel mass $m_{fd,i} = m_{fd,0}$

Moisture mass $m_{w,i} = m_{w,i} - \frac{\dot{q}_{rad} + (\dot{q}_{c,in} - \dot{q}_{c,out})}{L_v} \Delta t$

Stage (3): Temperature $T_i = T_i + \frac{\dot{q}_{rad} + (\dot{q}_{c,in} - \dot{q}_{c,out})}{C_f m_{fd,0}} \Delta t$

Fuel mass $m_{fd,i} = m_{fd,0}$

Moisture mass $m_{w,i} = 0$

Stage (4): Temperature $T_i = T_{ig}$

Fuel mass $m_{fd,i} = m_{fd,i} - \dot{m}_b \Delta t$

Moisture mass $m_{w,i} = 0$

Stage (5): Temperature $T_i = T_0$

Fuel mass $m_{fd,i} = 0$

Moisture mass $m_{w,i} = 0$

7.4.2 Heat Transfer Model

7.4.2.1 Radiant Heat Transfer from Infinite Flame to a Target Surface

(1) Area of the target surface

$$A_i = 1 \cdot \Delta x = \Delta x$$

(2) Lateral distance of the flame tip and the target position

$$x_i = \left(i - \frac{1}{2}\right) \Delta x, \quad x_f = k_{front} \Delta x + L_f \cos \theta$$

$$r_f \equiv x_f - x_i = \left(k_{front} - i + \frac{1}{2}\right) \Delta x + L_f \cos \theta$$

(3) Flame height

$$h_f = L_f \sin \theta$$

(4) Flame view factor, F

$$F = \frac{1}{2} \left(1 + \frac{r_f}{\sqrt{h_f^2 + r_f^2}} \right)$$

(5) Rate of radiant heat transfer

$$\dot{q}_{rad} = E_f F A_i$$

7.4.2.2 Conductive Heat Transfer through Fuel Bed

(1) Section area of fuel bed

$$A_d = 1 \cdot \delta = \delta$$

(2) Conductive heat transfer

$$\dot{q}_{c,in} = -\lambda \delta \frac{T_{i+1} - T_i}{\Delta x}$$

$$\dot{q}_{c,out} = -\lambda \delta \frac{T_i - T_{i-1}}{\Delta x}$$

or

$$\dot{q}_{c,in} - \dot{q}_{c,out} = -\lambda \delta \frac{T_{i+1} - 2T_i + T_{i-1}}{\Delta x}$$

7.4.3 Infinite Flame

7.4.3.1 Flame Length

(1) Mass burning rate

$$\dot{m}_b = \frac{\varepsilon \sigma (T_{flame}^4 - T_{ig}^4) \Delta x}{L_p}$$

where L_p : latent heat of thermal decomposition

or

$$\dot{m}_b = \rho_{dry} \Delta x \frac{\delta}{t_D} \left(= \frac{m_{fd,0}}{t_D} \right)$$

where t_D : duration of flaming (time from ignition to burnout of fuel bed segment)

(2) Heat release rate

$$\dot{Q}' = \Delta H_{fuel} \dot{m}_b D_f = \Delta H_{fuel} \dot{m}_b (k_{front} - k_{back}) \Delta x$$

where k_{front} : number of the segment at the fire front of flaming segments

where k_{back} : number of the burnout segment immediately behind flaming segment

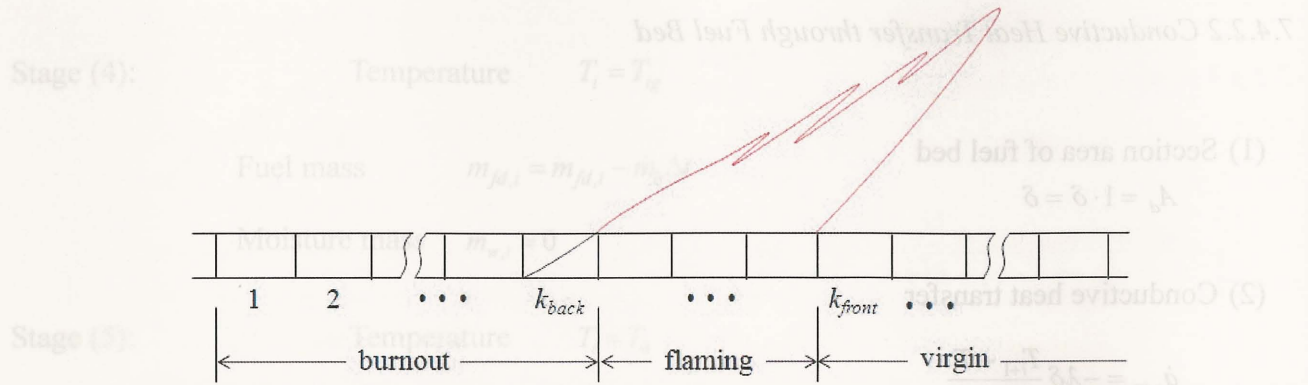


Figure 7-6 Schematic of Location and Number of Segment Based Flaming Segment

(3) Flame length

$$L_f = 3.0 \left(\frac{\dot{Q}'}{\rho_\infty c_p T_\infty g^{1/2}} \right)^{2/3} \approx 0.027 \dot{Q}'^{2/3}$$

7.4.3.2 Flame Tilt Angle

Solve

$$\tan \phi \sin \phi = \eta \left(\frac{U_\infty^2}{gL_f} \right) \quad \text{for } \phi$$

and calculate θ by

$$\theta = \frac{\pi}{2} - \phi$$

or directly solve

$$\frac{\tan \theta}{\cos \theta} = \eta \left(\frac{gL_f}{U_\infty^2} \right) \quad \text{for } \theta$$

where η or η' : coefficient to be determined experimentally

or, instead of obtaining the angles, obtain the values of $\sin \theta$ and $\cos \theta$ as follows;

Letting

$$Fr^2 \equiv \eta \left(\frac{U_\infty^2}{gL_f} \right)$$

and noting $\tan \phi \sin \phi = \sin^2 \phi / \cos \phi$, and $(\tan \phi \sin \phi)^2 = Fr^2$ gives $\sin^4 \phi = Fr^2 \cos^2 \phi = Fr^2 (1 - \sin^2 \phi)$

so that

$$\left(\sin^2 \varphi + \frac{1}{2} F_{r2}^2 \right)^2 = \frac{1}{4} F_{r2}^4 + F_{r2}^2$$

$$\sin^2 \varphi = -\frac{1}{2} F_{r2}^2 \pm \frac{\sqrt{F_{r2}^4 + 4F_{r2}^2}}{2}$$

$$\sin \varphi = \sqrt{-\frac{F_{r2}^2}{2} + \frac{\sqrt{F_{r2}^4 + 4F_{r2}^2}}{2}}, \quad \cos \varphi = \sqrt{1 - \sin^2 \varphi} = \sqrt{1 + \frac{F_{r2}^2}{2} - \frac{\sqrt{F_{r2}^4 + 4F_{r2}^2}}{2}}$$

and convert φ to θ as $\cos \theta = \sin \varphi$, $\sin \theta = \cos \varphi$.

7.5 Computational Procedure

Major variable values and relation equation for flame behaviors required to predict flame spread velocity by testing and making numerical analysis of heat transfer process conducted and radiated by the flame formed are suggested in this research. The equations suggested accordingly are put into a flowchart for computational numerical analysis as shown in Figure 7-7.

Initial data entered set fuel's density, wind velocity, slope, initial temperature measured in the test and site survey, and such conditions as the size of grid to be analyzed, the number of grid and computation time. For analysis of a flame formation in fuel segment, it is heated until it reaches 100 °C, at which fuel's moisture evaporates, and once it is there, temperature variation via heat transfer is repeatedly computed until fuel segment reaches ignition temperature. Once computation according to the distance (number of grid) or time defined in the initial setting is over, the time taken for the flame in the epicenter to reach the final grid is computed to obtain flame spread velocity value. Analysis for flame height, flame angle and heat transfer is sub-routinely computed with a flowchart in Figure 7-8 and 7-9, respectively.

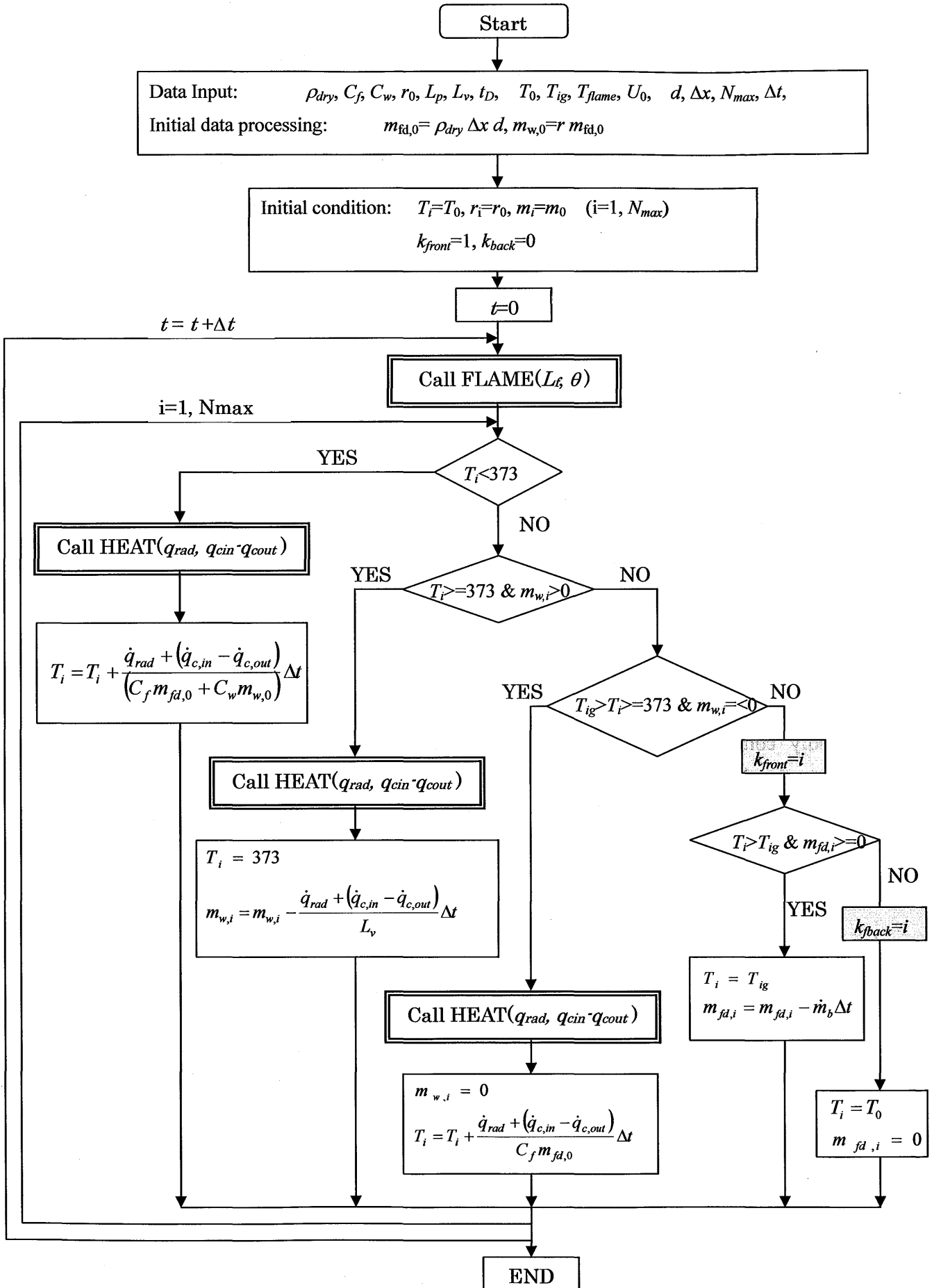


Figure 7-7 The Flowchart for Calculating Flame Spread Velocity

Subroutine FLAME

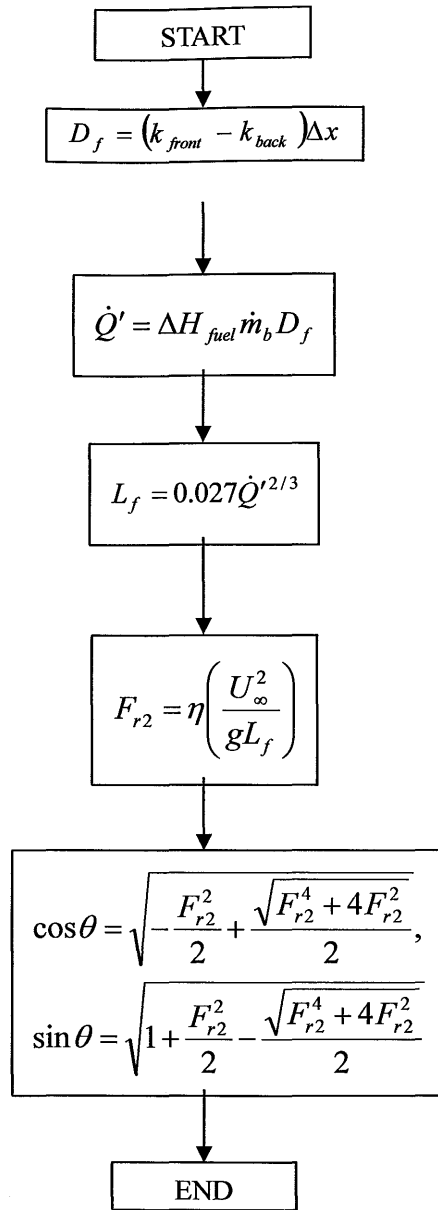


Figure 7-8 The Flowchart of Subroutine for Calculating Flame Height and Flame Tilt

Subroutine HEAT

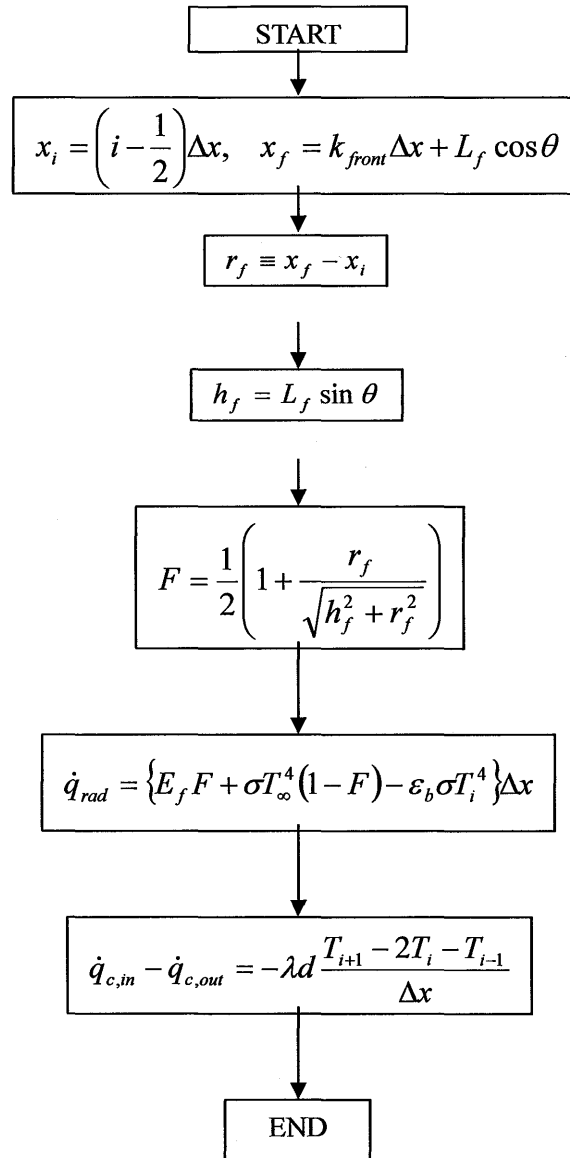


Figure 7-9 The Flowchart of Subroutine for Calculating Heat Transfer

7.6 Calculation for Flame Spread Velocity

The line fire to reach any point of time that a unit needs 1 sec to yield calculation that describes the program. The main flowchart for calculating flame spread rate shows as Figure 7-10. Figure 7-10 has 5 steps; 1st step as read data from a definition value of factors, 2nd step as the initial setting, 3rd step as flame height calculation, 4th step as calculation of flame tilt due to slop and wind, 5th step is calculation of flame spread and finally calculation time to arrive at the end of cell.

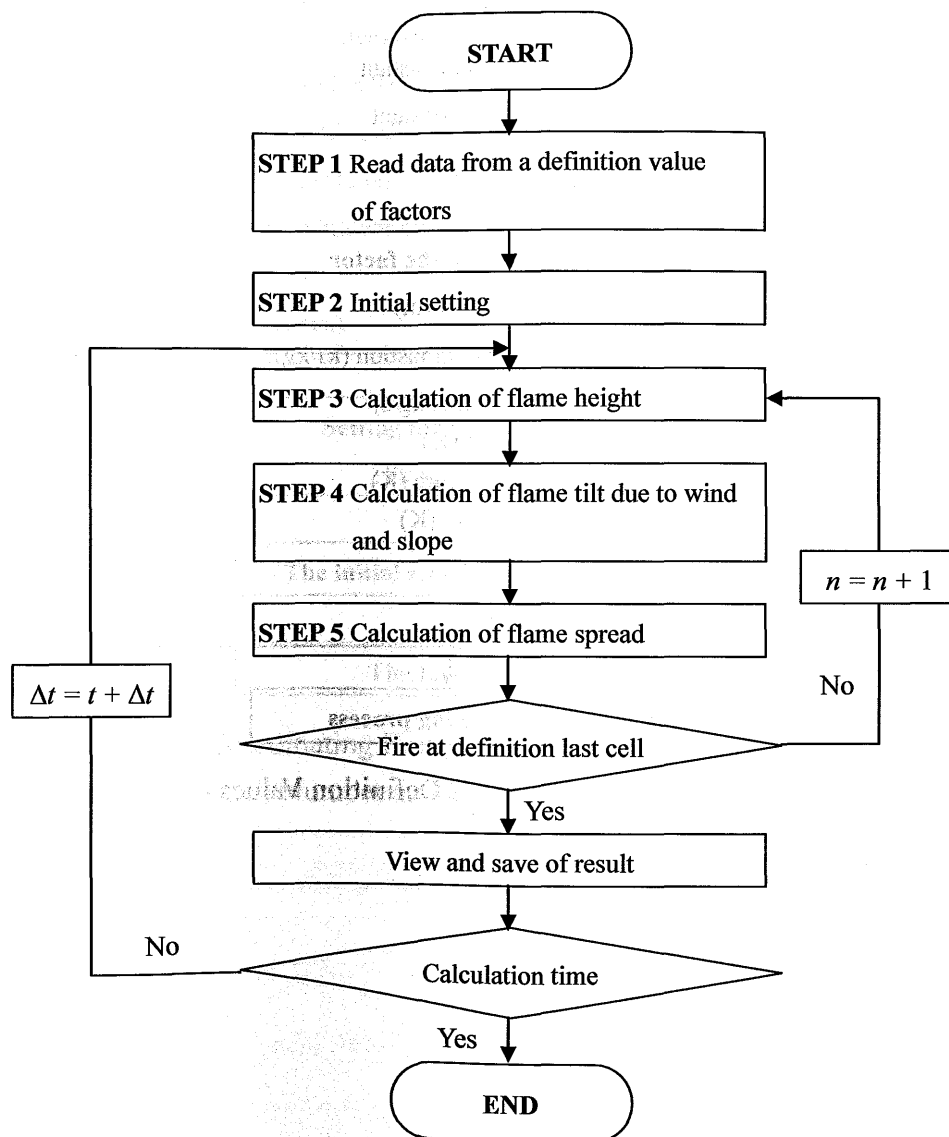


Figure 7-10 The Main Flowchart of Calculation for Line Flame Spread Velocity Prediction

7.6.1 Read Data from a Definition Value of Factors

Figure 7-11 shows flowchart for reading a necessary data from a measured data and a constant to calculate.

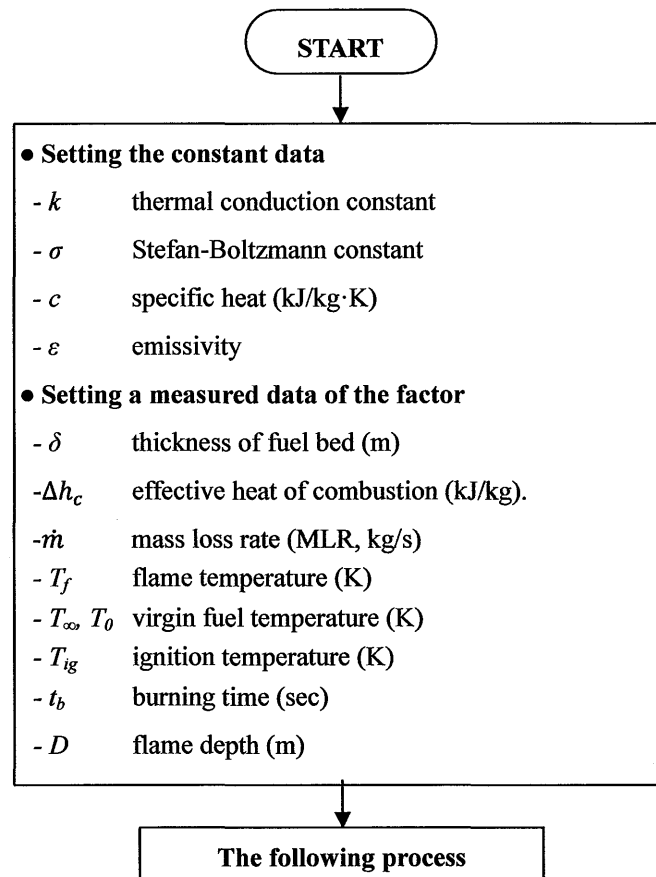


Figure 7-11 Setting a Data as Definition Values of Factors

7.6.2 The Initial Setting

Figure 7-12 shows flowchart for coordinating firing range of advanced computation as a size of cell, cell number and calculation time, etc.

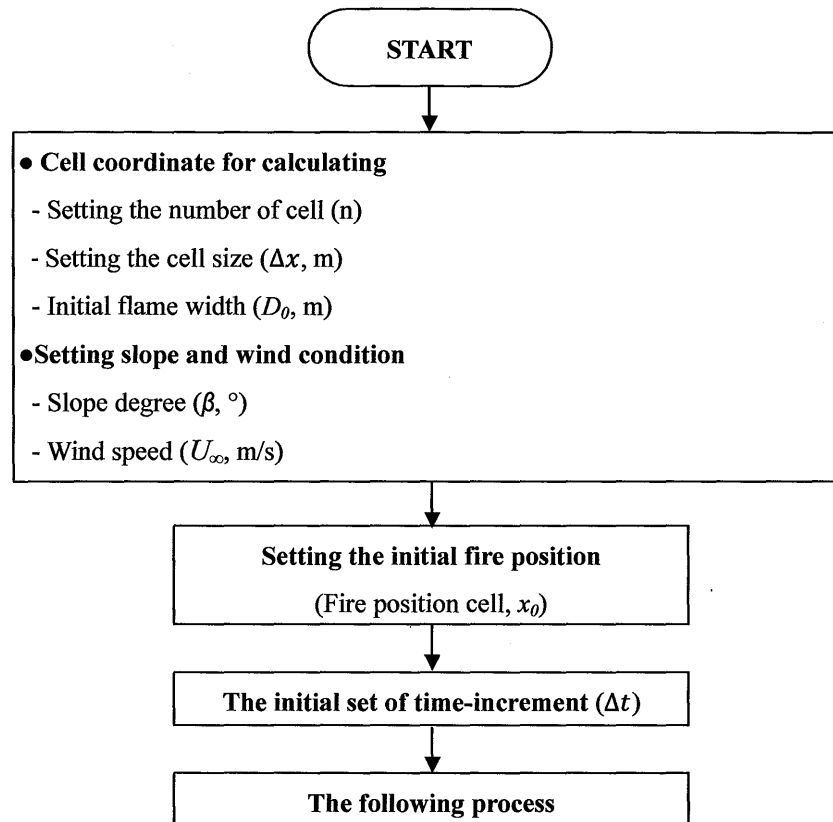


Figure 7-12 Flowchart for Coordinating Firing Range of Advanced Computation as a Size of Cell, Cell Number and Calculation Time, etc.

7.6.3 Calculation of Flame Height

Figure 7-13 shows flowchart for calculating flame height it will calculate continually until calculation time or the end of definition cell point.

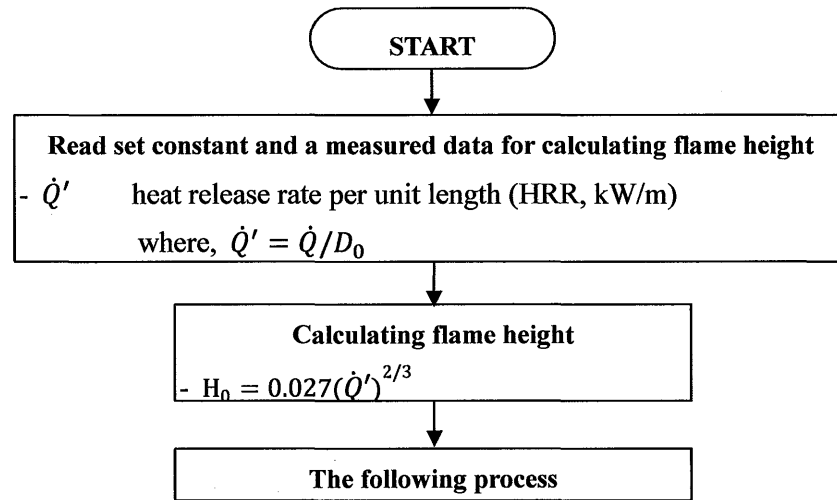


Figure 7-13 Flowchart for Calculating Flame Height.

7.6.4 Calculation of Flame Tilt

Figure 7-14 shows flowchart for calculating flame tilt due to slope and wind.

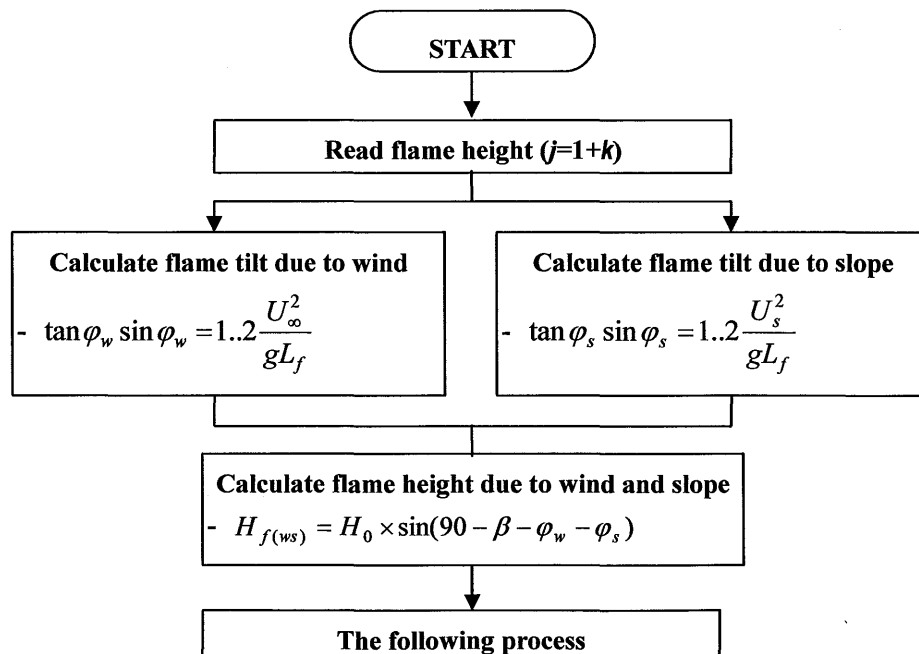


Figure 7-14 Flowchart for Calculating Flame Height due to Wind and Slope.

7.6.5 Calculation of Flame Spread

Figure 7-15 shows flowchart for calculating flame spread model using by a radiative and a conductive heat transfer mechanism.

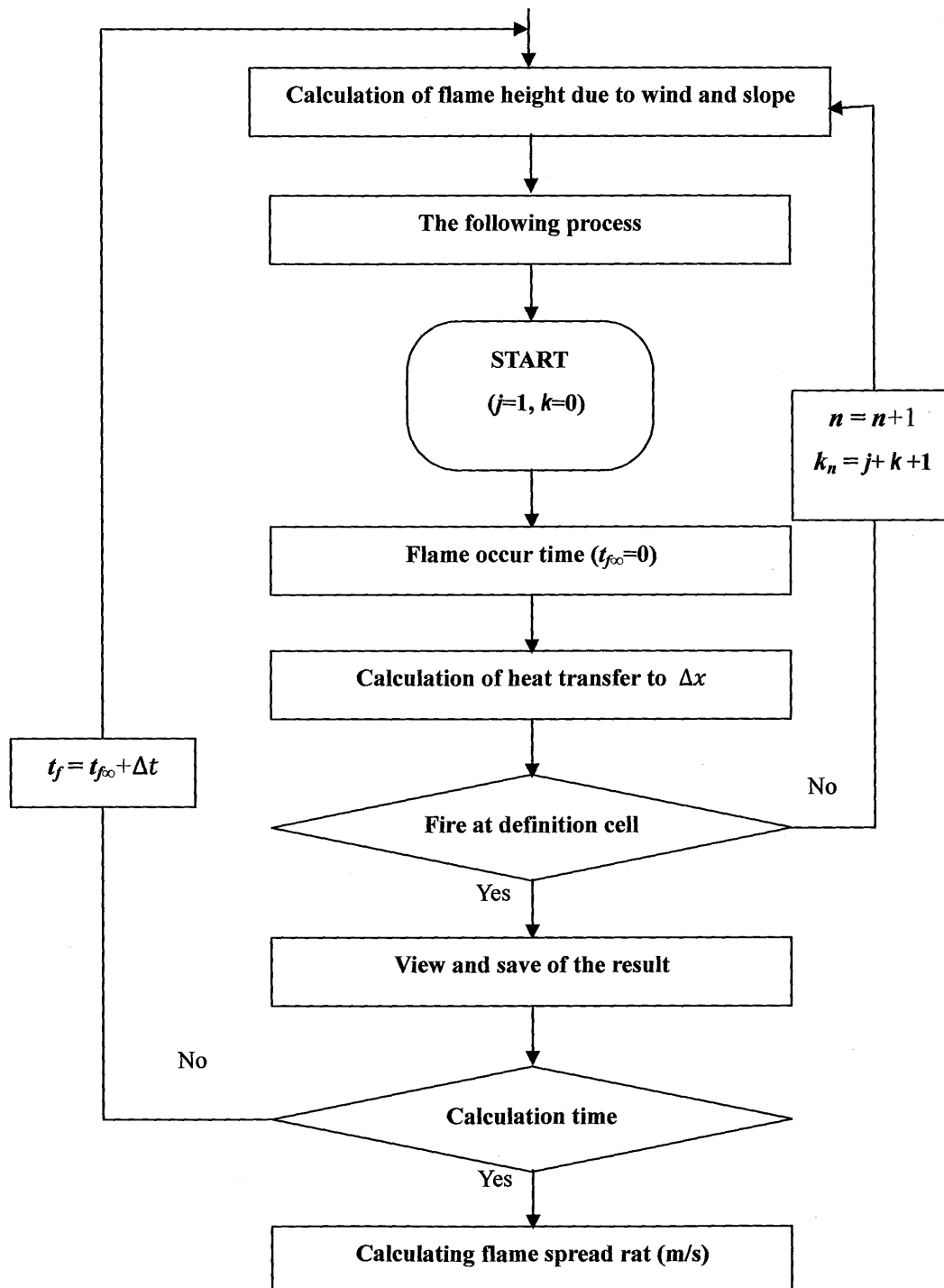


Figure 7-15 Flowchart for Calculating Flame Spread with Heat Transfer

7.6.6 Results

I used Visual Studio to set up a program for computational numerical analysis. Structure of program's source is divided into MODULES.for, MAIN.for and NUMERICAL.for, of which the details are as follows;

- (1) MODULES.for : This is a source that classifies various variables to realize them into modules. As the variables defined can be retrieved by using a USE grammar in multiple subroutines, variables do not need to be separately designated in the subroutine and variable management becomes easier
- (2) MAIN.for : This is a file that includes main program and subroutine.
- (3) NUMERICAL.for : This is a source for computation. This is added with mathematic routine to reduce errors in floating point arithmetic and have fault-tolerancing, ensuring stable computation.

Figure 7-16 shows the graph of temperature and time when ignition temperature arrived at Δx_n , accordingly Flame Spread Velocity can be calculating for using this program. Figure 7-16 was simulated in wind speed 3m/s and slope angle 30°.

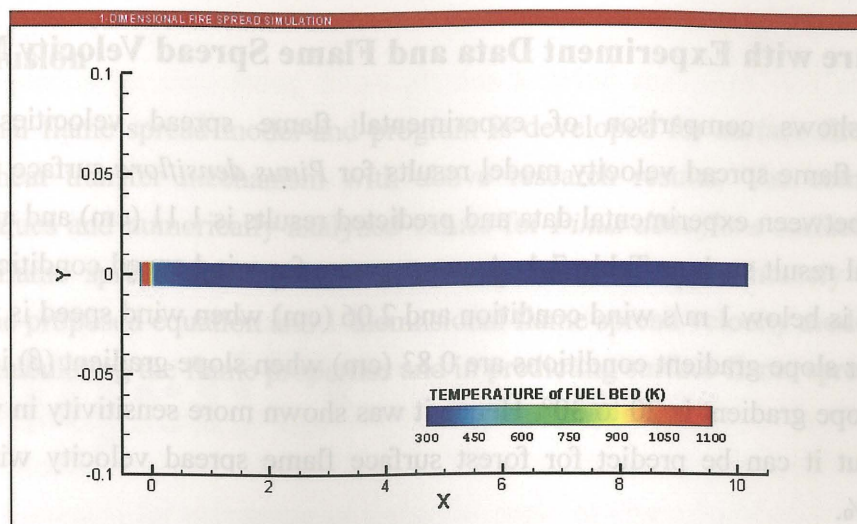
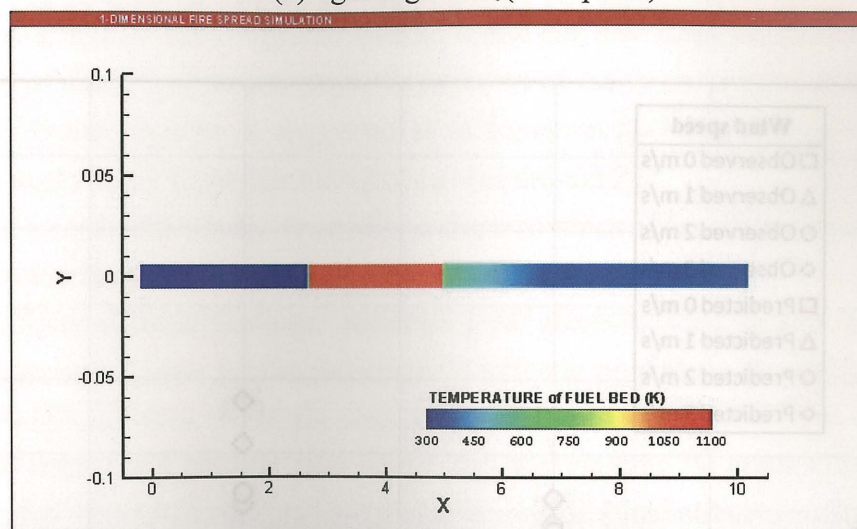
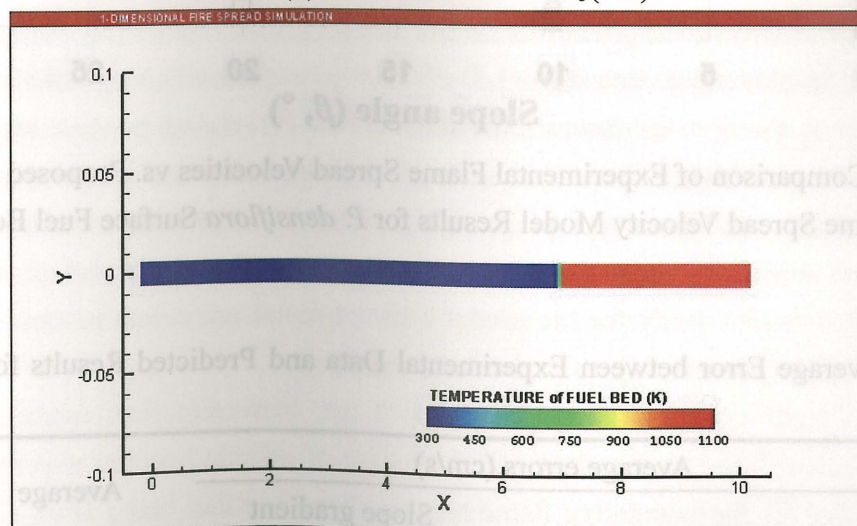
(a) Igniting at Δx_0 (Start point)(b) Flame arrived at Δx_5 (5m)(c) Flame arrived at Δx_{10} (10m) after 32.4sec

Figure 7-16 Scenes of 1-Dimensional Flame Spread Velocity when Ignition Temperature Arrived at Δx_n in Wind Speed 3m/s and Slope Angle 30°

7.7 Compare with Experiment Data and Flame Spread Velocity Model

Figure 7-17 shows comparison of experimental flame spread velocities vs. proposed One-dimensional flame spread velocity model results for *Pinus densiflora* surface fuel beds. Here, an average error between experimental data and predicted results is 1.11 (cm) and an average errors have a differential result such as Table 7-1. Average errors for wind speed condition are 0.17 (cm) when wind speed is below 1 m/s wind condition and 2.06 (cm) when wind speed is from 2 to 3 m/s. Average errors for slope gradient conditions are 0.83 (cm) when slope gradient (β) is below 10° and 1.4 (cm) when slope gradient is 20 to 30° . Hence it was shown more sensitivity in wind speed than slope gradient but it can be predict for forest surface flame spread velocity with error rate of maximum 12.15%.

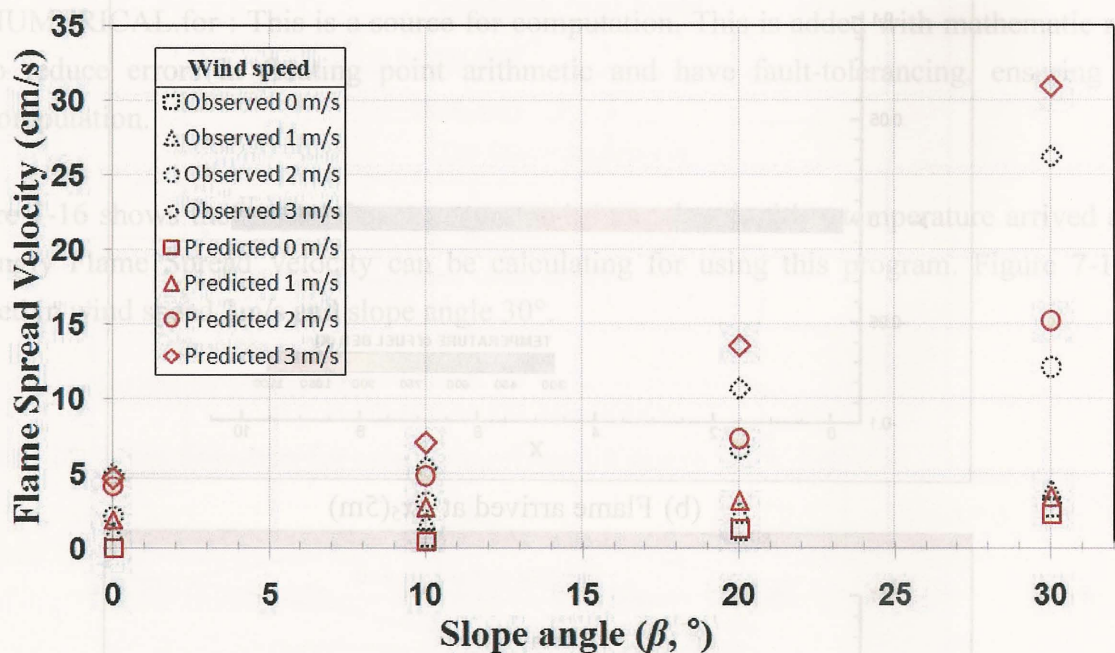


Figure 7-17 Comparison of Experimental Flame Spread Velocities vs. Proposed 1-Dimensional Flame Spread Velocity Model Results for *P. densiflora* Surface Fuel Beds

Table 7-1 An Average Error between Experimental Data and Predicted Results for Flame Spread Velocity

Statistics analysis	Average errors (cm/s)					Average error rate (%)	SE of error rate
	Total	Wind speed		Slope gradient (β , °)			
		≤ 1 m/s	≥ 2 m/s	$\leq 10^\circ$	$\geq 20^\circ$		
Value	1.11	0.17	2.06	0.83	1.40	12.15	23.98

7.7 Conclusion

A 1-dimensional flame spread model and program is developed for surface fire spread in forest fires base on heat transfer mechanism with above research results. The comparison between experimental values and numerically analyzed values for *Pinus densiflora* surface fuel beds found that predicted flame spread velocity have an average error of approximately 12.15%. Thus, I conclude that the proposed equation and 1-diemnsional flame spread velocity model are expected to be effective in calculating the flame properties and in predicting surface flame spread velocity

Chapter 8

Conclusion and Future Work

Forest fire usually starts off with surface fire, which later spreads into crown fire and spot fire. Predicting forest fire spread velocity in the initial stages could be extremely helpful in forest fire extinguishment at the outset. The experiment-based model was used to calculate flame properties (Flame Height, Flame Tilt) and to predict forest fire spread velocity including surface fire.

The purpose of this thesis is to develop a 1-D Flame Spread Velocity Model for surface fire when fire breaks out in a forest. The research is carried out by relying on two major methods of execution: producing variable values by testing fuel combustion and flame characteristics and performing numerical analysis; developing an algorithm capable of performing computational analysis of flame spread by heat transfer analysis of the flame formed. Following are the conclusions reached in this study for the model 1-dimensional numerical model, which estimates the flame spread velocity based on heat transmission analysis.

Firstly, flame height equation is proposed based on semi-numerical analysis. The relation between dimensionless flame temperature and the height of infinite line fire was used to derive the equation $H_f = 0.027\dot{Q}^{2/3}$ for calculating flame heights of surface fuel beds. Then, the flame heights calculated using this proposed equation was compared with those calculated using Heskestad's equation during combustion of fuel beds of *Pinus densiflora* and *Quercus variabilis*. The comparison results showed that for both the *Pinus densiflora* fuel bed and the *Quercus variabilis* fuel bed, the flame heights estimated using the proposed equation can be used in the surface fire

spread model.

Secondary, equation for calculating flame tilt due to wind and slope was proposed based on semi-numerical analysis. In flame tilt due to wind, measurement of flame length and flame tilt angle was based on flame face. Flame length (L_f) showed consistent value regardless of wind speed, with error range $\pm 0.05\text{m}$. Therefore, flame height (H_f) can be calculated as $L_f \cos \phi_w$. The semi-numerical analysis on wind speed and flame tilt angle based on Froude number yielded coefficient A value of 1.36, which was proposed to Equation 4-14. The value of flame tilt angle calculated from the equation and the experiment value showed average error of 1.09° , which is relatively smaller than the results in existing studies that used different coefficient. This suggests that the estimation method of the research for flame tilt angle is valuable. Coefficient A can be calculated in the method provided in this research for estimation of flame tilt angle of virgin fuel bed with varying thermal properties. In Flame tilt due to slope, slope effect not only causes variance in flame tilt angle but also impacts the speed of flame spread. Hence, flame tilt due to slope requires attention when predicting speed of flame spread in a slope. Correlation of the slope-induced flame tilt angle from experiment with Froude number is suggested as in Equation 5-4. The average error angle of the tested flame tilt angle under the proposed equation was around 2.3° .

Thirdly, flame spread velocity due to wind and slope combined condition was measured by which it was found that the flame velocity, rapidly increases when over 2m/s wind speed than below 1m/s wind speed. In light of these findings, accounting for slope-induced change in flame tilt angle appears to be more appropriate for the flame spread velocity prediction. Hence, it is better to apply the flame tilt ' $90-(\beta+\phi_w)$ ' than ' $90-\beta$ ' for predicting flame spread velocity due to slope as described in Chapter 5.

Fourthly, a 1-dimensional flame spread model and program is developed for surface fire spread in forest fires base on heat transfer mechanism with above research results. The comparison between experimental values and numerically analyzed values for *Pinus densiflora* surface fuel beds found that predicted flame spread velocity have an average error of approximately 12.15%. Thus, I conclude that the proposed equation and 1-diemnsional flame spread velocity model are expected to be effective in calculating the flame properties and in predicting surface flame spread velocity. The results attained in this study will be beneficial in the successive studies for developing 2-D and 3-D numerical forest fire spread prediction model.

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Appendix

- Program Language Edit

MODULES.for

```

!   MODULE DEFINITION FOR FIRE SPREAD MODEL
!
!   ALL VARIABLES ARE SAVED FOR PORTABILITY BETWEEN SUBPROGRAMS
!   ALL SOURCES ARE COMPILED IN INTEL FORTRAN COMPILER
!   SEE FORTRAN 90 LANGUAGE IMPLEMENTATION FOR MORE INFORMATION
!
!   (C) 2009 DONG-HYUN, KIM
!
!   VERSION HISTORY
!
!   09-11-21(SAT) - FIRST DEVELOPMENT VERSION CREATED
!                   - PORTED FROM VISUAL BASIC CODE MADE BY PROF. TANAKA
!
!
!   UNIVERSAL CONSTANTS (CONSTANT VARIABLES)
!   THESE VARIABLES ARE CANNOT BE MODIFIED IN SCOPE OF OTHER PROCEDURES
MODULE CONSTANTS
  IMPLICIT NONE
  SAVE

  REAL*8, PARAMETER :: SGM = 5.67D-11  ! STEFAN-BOLTZMANN CONST [KW/M^2/K^4]
  REAL*8, PARAMETER :: CWATER = 4.19D0  ! SPECIFIC HEAT OF WATER [KJ/KG/K]
  REAL*8, PARAMETER :: LV = 2.25841D3   ! HEAT OF VAPORIZATION OF WATER [KJ/KG]
  REAL*8, PARAMETER :: T100 = 3.73D2    ! VAPORIZATION TEMPERATURE OF WATER [K]
  REAL*8, PARAMETER :: G = 9.8D0         ! ACCELERATION DUE TO GRAVITY [M/S^2]
  REAL*8, PARAMETER :: TFLM = 1.073D3   ! FLAME TEMPERATURE [K]
  REAL*8, PARAMETER :: XR = 3.0D-1      ! RADIATIVE FRACTION [-]

END MODULE CONSTANTS

!   INPUT DATA FOR FUEL BED PROPERTIES AND DIMENSIONS
!   DEFAULT VALUES ARE DEFINED, BUT CAN BE MODIFIED IN SCOPE OF OTHER PROCEDURES

```

```
MODULE VAR_FUEL_BED
```

```
  IMPLICIT NONE
```

```
  SAVE
```

```
  ! VARIABLES FOR FUEL BED PROPERTIES
```

```
  REAL*8 :: RDRY = 1.0D2 ! DRY-BASE MASS DENSITY OF THE FUEL BED [KG/M^3]
```

```
  REAL*8 :: CFUEL = 1.0D0 ! DRY-BASE SPECIFIC HEAT OF THE FUEL BED [KJ/KG/K]
```

```
  REAL*8 :: DHF = 1.2D4 ! EFFECTIVE HEAT OF COMBUSTION OF THE DRY-BASE FUEL BED  
[KJ/KG] (16MJX0.75)
```

```
  REAL*8 :: R0 = 1.0D-1 ! MASS RATIO OF WATER CONTENT TO THE DRY-BASE FUEL BED [KG/KG]
```

```
  REAL*8 :: LP = 1.6D3 ! HEAT OF THERMAL DECOMPOSITION OF THE DRY-BASE FUEL BED [KJ/KG]
```

```
  REAL*8 :: TIG = 6.0D2 ! IGNITION TEMPERATURE OF THE FUEL BED [K]
```

```
  REAL*8 :: EFB = 8.0D-1 ! EMISSIVITY OF THE FUEL BED [-]
```

```
  REAL*8 :: KFB = 1.0D-4 ! EFFECTIVE HEAT CONDUCTIVITY OF THE FUEL BED [KW/M/K]
```

```
  ! PREPROCESSED VARIABLES FOR INITIAL CALCULATION
```

```
  REAL*8 :: DX ! LENGTH OF THE UNIT FUEL BED SEGMENT [M]
```

```
  REAL*8 :: T0 ! INITIAL TEMPERATURE OF THE FUEL BED [K]
```

```
  REAL*8 :: MFD0 ! INITIAL MASS OF THE DRY-BASE FUEL BED SEGMENT [KG]
```

```
  REAL*8 :: MW0 ! INITIAL MASS OF WATER CONTENT IN THE FUEL BED [KG]
```

```
  REAL*8 :: MB ! MASS BURNING RATE OF THE FUEL BED [KG/S]
```

```
  REAL*8 :: EFLM ! EMISSIVE POWER OF FLAME [KW/M^2]
```

```
  REAL*8 :: E00 ! EMISSIVE POWER OF AMBIENT ENVIRONMENT [KW/M^2]
```

```
  ! VARIABLES FOR FUEL BED DIMENSIONS
```

```
  REAL*8 :: LFB = 1.0D1 ! LENGTH OF THE FUEL BED [M]
```

```
  REAL*8 :: DFB = 1.0D-1 ! THICKNESS OF THE DRY-BASE FUEL BED [-]
```

```
  REAL*8 :: TBOUT = 1.0D2 ! BURNOUT TIME OF THE DRY-BASE FUEL BED [S]
```

```
  INTEGER :: NBSEG = 1.0D2 ! NUMBER OF THE FUEL BED SEGMENTS [-]
```

```
END MODULE VAR_FUEL_BED
```

```
! VARIABLES WHICH ARE CHANGED WITH TIME
```

```
MODULE VAR_CHANGED_WITH_TIME
```

```
  IMPLICIT NONE
```

```
  SAVE
```

```
  TYPE PROP ! GRID PROPERTIES
```

```
    REAL*8 :: TFB ! TEMPERATURE OF A FUEL BED SEGMENT [K]
```

```
    REAL*8 :: MFD ! MASS OF DRY-BASE IN A FUEL BED SEGMENT [KG]
```



```

REAL*8 :: MW      ! MASS OF WATER CONTENT IN A FUEL BED SEGMENT [KG]
REAL*8 :: FFLM    ! VIEW FACTOR OF FLAME FROM A FUEL BED SEGMENT [-]
REAL*8 :: QRAD    ! NET RADIANT HEAT TRANSFER TO A FUEL BED SEGMENT [KW]
REAL*8 :: QCND    ! NET CONDUCTIVE HEAT TRANSFER TO A FUEL BED SEGMENT [KW]
END TYPE PROP

```

```

REAL*8 :: DFLM      ! DEPTH OF FLAME FOOT [M]
REAL*8 :: LFLM      ! LENGTH OF FLAME [M]
REAL*8 :: HFLM      ! HEIGHT OF FLAME [M]
REAL*8 :: COSQ      ! FLAME TILT = Z/LFLM
REAL*8 :: SINQ      ! FLAME TILT = X/LFLM
REAL*8 :: QDD       ! HEAT RELEASE RATE OF FIRE PER UNIT WIDTH [KW/M]
REAL*8 :: TM_CALC = 0.0D0 ! TIME FROM START OF FIRE [S]
REAL*8 :: DTM = 1.0D0  ! TIME INCREMENT FOR COMPUTATION [S]
INTEGER :: KFRONT, KBOUT ! ORDER NUMBER OF A FUEL BED SEGMENT
END MODULE VAR_CHANGED_WITH_TIME

```

```

! VARIABLES FOR AMBIENT CONDITION
! DEFAULT VALUES WILL BE ASSIGNED, BUT CAN BE MODIFIED

```

```

MODULE VAR_AMBIENT

```

```

    IMPLICIT NONE

```

```

    SAVE

```

```

REAL*8 :: T00 = 3.0D2 ! AMBIENT TEMPERATURE [K]
REAL*8 :: U00 = 2.0D0 ! EXTERNAL WIND VELOCITY [M/S]
REAL*8 :: CFR2 = 1.0D0 ! EXPEIMENTAL COEFFICIENT OF FLAME TILT DUE TO WIND (TENTATIVE) [-]

```

```

END MODULE VAR_AMBIENT

```

MAIN.for

```

!   MAIN PROGRAM FOR 1-D FIRE SPREAD SIMULATION
!
!   ALL VARIABLES ARE SAVED FOR PORTABILITY BETWEEN SUBPROCEDURES
!   ALL SOURCES ARE COMPILED IN INTEL FORTRAN COMPILER
!   SEE FORTRAN 90 LANGUAGE IMPLEMENTATION FOR MORE INFORMATION
!
!   (C) 2009 DONG-HYUN, KIM
!
!   VERSION HISTORY
!
!   09-11-21(SAT) - FIRST DEVELOPMENT VERSION CREATED
!                   - PORTED FROM VISUAL BASIC CODE MADE BY PROF. TANAKA
!
PROGRAM FIRESREAD
! IMPORTS MODULES
USE CONSTANTS
USE VAR_FUEL_BED
USE VAR_CHANGED_WITH_TIME
USE VAR_AMBIENT
!
IMPLICIT NONE
INTEGER :: I, J, K ! INDICES
!
! GENERATE GRID
TYPE (PROP), ALLOCATABLE :: GRID( : )
ALLOCATE (GRID(0:NBSEG+1))
!
! CALCULATE VARIABLES FROM INPUT DATA
DX  = LFB / NBSEG
T0  = T00
MFD0 = RDRY * DX      * DFB
MW0  = R0   * MFD0
MB   = MFD0 / TBOUT
EFLM = SGM  * TFLM**4
E00  = SGM  * T00**4
!
! INITIALIZE GRID PROPERTIES

```

```

GRID%TFB = T0
GRID%MFD = MFD0
GRID%MW = MW0
GRID%FFLM = 0.0D0
GRID%QRAD = 0.0D0
GRID%QCND = 0.0D0

! INITIALIZATION ORDER NUMBER
KFRONT = 1; KBOUT = 0

! CALCULATE GRID TEMPERATURE
DO WHILE (KBOUT .LT. NBSEG)
    CALL FLAME_SHAPE

    DO I = 1, NBSEG
        IF (GRID(I)%MFD .EQ. 0.0D0) THEN
            GRID(I)%TFB = T00
        ELSEIF (GRID(I)%TFB .LT. T100) THEN
            CALL HEAT_TRANS(I)
            GRID(I)%TFB = GRID(I)%TFB + ((GRID(I)%QRAD + GRID(I)%QCND) / &
                (CFUEL * GRID(I)%MFD + CWATER * GRID(I)%MW)) * DTM

            IF (GRID(I)%TFB .GT. T100) THEN
                GRID(I)%TFB = T100
            END IF
        ELSEIF (GRID(I)%MW .GT. 0.0D0) THEN
            CALL HEAT_TRANS(I)
            GRID(I)%TFB = T100
            GRID(I)%MW = GRID(I)%MW - ((GRID(I)%QRAD + GRID(I)%QCND) / LV) * DTM

            IF (GRID(I)%MW .LT. 0.0D0) THEN
                GRID(I)%MW = 0.0D0
            END IF
        ELSEIF (GRID(I)%TFB .LT. TIG) THEN
            CALL HEAT_TRANS(I)
            GRID(I)%TFB = GRID(I)%TFB + ((GRID(I)%QRAD + GRID(I)%QCND) / (CFUEL *
GRID(I)%MFD)) * DTM

            IF (GRID(I)%TFB .GT. TIG) THEN

```

```

        GRID(I)%TFB = TFLM

    END IF

    GRID(I)%MW = 0.0D0

    ELSEIF (GRID(I)%MFD .GT. 0.0D0) THEN

        GRID(I)%TFB = TFLM

    IF (I .GT. KFRONT) THEN

        KFRONT = I

    END IF

    GRID(I)%MFD = GRID(I)%MFD - MB * DTM

    IF (GRID(I)%MFD .LT. 0.0D0) THEN

        GRID(I)%MFD = 0.0D0

    IF (I .GT. KBOUT) THEN

        KBOUT = I

    END IF

    END IF

    END IF

    END DO

    TM_CALC = TM_CALC + DTM

    END DO

    PRINT *, GRID%TFB

    PRINT *, TM_CALC

    ! DEALLOCATE GRID ARRAY

    DEALLOCATE (GRID)

CONTAINS

    ! SUBROUTINE FOR CALCULATION OF HEAT TRANSFEER FLUX

    SUBROUTINE HEAT_TRANS (INDEX)

        USE CONSTANTS

        USE VAR_FUEL_BED

        USE VAR_CHANGED_WITH_TIME

        IMPLICIT NONE

        REAL*8 :: XF, XI, RF

        INTEGER :: INDEX

```

```

      XI = (INDEX - 5.0D-1) * DX
      XF = KFRONT * DX + LFLM * COSQ
      RF = XF - XI

      ! CALCULATION OF Q (HEAT FLUX)
      GRID(INDEX)%FFLM = 5.0D-1 * (1.0D0 + RF / DSQRT(HFLM**2 + RF**2))
      GRID(INDEX)%QRAD = (EFLM * GRID(INDEX)%FFLM + E00 * (1.0D0 - GRID(INDEX)%FFLM) -&
          EFB * SGM * GRID(INDEX)%TFB**4) * DX
      GRID(INDEX)%QCND = -KFB * DFB * (GRID(INDEX+1)%TFB - 2.0D0 * GRID(INDEX)%TFB +
      GRID(INDEX-1)%TFB) / DX

      RETURN
END SUBROUTINE

! SUBROUTINE FOR FLAME SHAPING
SUBROUTINE FLAME_SHAPE
  USE CONSTANTS
  USE VAR_FUEL_BED
  USE VAR_AMBIENT
  USE VAR_CHANGED_WITH_TIME

  IMPLICIT NONE
  REAL*8 :: FR2, FR22, SQFR22

  DFLM = (KFRONT - KBOUT) * DX
  QDD = (KFRONT - KBOUT) * MB * DHF * (1.0D0 - XR)
  LFLM = 3.0D-2 * QDD**(0.67)
  FR2 = CFR2 * U00**2 / (G * LFLM)
  FR22 = FR2**2

  ! SQUARE-ROOT CALCULATION
  SQFR22 = DSQRT(      FR22**2      + FR22*4.0D0)
  COSQ = DSQRT(      - FR22/2.0D0 + SQFR22/2.0D0)
  SINQ = DSQRT(1.0D0 + FR22/2.0D0 - SQFR22/2.0D0)
  HFLM = LFLM * SINQ

  RETURN
END SUBROUTINE FLAME_SHAPE
END PROGRAM

```


NUMERICS.for

```

!   NUMERIC MANIPULATION ROUTINES
!
!   ALL SOURCES ARE COMPILED IN INTEL FORTRAN COMPILER
!   SEE FORTRAN 90 LANGUAGE IMPLEMENTATION FOR MORE INFORMATION
!
!   (C) 2009 DONG-HYUN, KIM
!
!   VERSION HISTORY
!
!   09-11-21(SAT) - FIRST DEVELOPMENT VERSION CREATED

! COMPARE FLOATING POINT VALUES USING RELATIVE TOLERANCE
LOGICAL FUNCTION ISEQUAL(A, B)

    IMPLICIT NONE

    REAL*8, INTENT(IN) :: A, B      ! VALUES TO BE COMPARED
    REAL*8 :: MAX_REL_TOL          ! RELATIVE TOLERANCE (OPTIONAL)
    REAL*8 :: REL_ERR

    MAX_REL_TOL = 1.0D-8

    ! RETURN TRUE IF IT IS EQUAL TRIBVIALY
    IF (A .EQ. B) THEN
        ISEQUAL = .TRUE.
    END IF

    ! COMPARE WHETHER TO VARIABLES ARE IN RANGE OF MAX_REL_TOL
    ! B HASN'T TO BE ZERO
    IF (B .EQ. 0.0D0) THEN
        REL_ERR = ABS((B-A) / A)
    ELSE
        REL_ERR = ABS((A-B) / B)
    END IF

    IF (REL_ERR .LE. MAX_REL_TOL) THEN
        ISEQUAL = .TRUE.
    END IF

```

```
ISEQUAL = .FALSE.  
END FUNCTION ISEQUAL
```

- List of Paper Publications

1. Chapter 3. Fuel Combustion and Flame Properties

- 1) 2007. 6, Journal of Korean Institute of Fire Science and Engineering, 21(3): 41-43
A Combustion Characteristic Analysis of *Quercus variabilis* and *Pinus densiflora* Fallen Leaves Using Radiation Heat Flux.
- 2) 2008.9, Journal of Korean Institute of Fire Science and Engineering, 22(3): 258-264
A Study of Calorie Analysis Methods about Surface Fire Fuel
- 3) 2008. 9, Journal of Korean Institute of Fire Science and Engineering, 22(3): 252-257
A Numerical Study on the Effect of the Wind Velocity and Height of Grassland on Flame Spread Rate of Forest Fire
- 4) 2009.12, Journal of Korean Institute of Fire Science and Engineering, 23(6): 10-15
Study on Flame Height Equation for the *Pinus densiflora* Surface Fuel Bed
- 5) 2009.9 submitted, Canadian Journal of Forest Research
Flame height Definition of Surface Fuel bed

2. Chapter 4. Flame Tilt due to Wind

- 6) 2009.10, Journal of Korean Institute of Fire Science and Engineering, 23(5): 90-95
Semi-numerical Study on the Flame Tilt Equation due to Wind on the Surface Fire in Forest Fire
- 7) 2009.9 submitted, International Journal of Wildland Fire
Flame Tilt and flame Spread due to Wind in Surface Fuel Beds Under No-slope Conditions

3. Chapter 5. Flame Tilt due to Slope

- 8) 2009.10, Journal of Korean Society of Hazard Mitigation, 9(5)57-62
A Study on the Flame Tilt and Flame Spread rate due to Up-slope on the Surface Fuel Bed –No wind condition

4. Chapter 7. Surface Flame Spread Model

- 9) 2008. 4, Journal of Korean Institute of Fire Science and Engineering, 22(2): 63-69
A Numerical Study of 1-D Surface Flame Spread Model –Based on a Flatland Conditions-