ARTICLE IN PRESS

Fire Safety Journal xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

The effect of flow and geometry on concurrent flame spread

Michael J. Gollner[a,*], Colin H. Miller[a], Wei Tang[a], Ajay V. Singh[b]

[a] Department of Fire Protecting Engineering, University of Maryland, College Park, MD, USA
[b] Department of Mechanical Engineering, Stanford University, Stanford, CA, USA

ARTICLE INFO

Keywords:
Flame spread
Concurrent
Burning rate
Inclined
Wind-driven
Wildland fires

ABSTRACT

Flame spread is an important parameter used in the evaluation of hazards for fire safety applications. The problem of understanding and modeling flame spread has been approached before, however new developments continue to challenge our current view of the subject, necessitating future research efforts in the field. In this review, the problem of flame spread will be revisited, with a particular emphasis on the effect of flow and geometry on concurrent flame spread over solid fuels. The majority of this research is based on that of the senior author, who has worked on wind-driven flame spread, inclined fire spread, flame spread through discrete fuels and the particular problem of wildland fires, where all of the above scenarios play an important role. Recent developments in these areas have improved our understanding of flame-spread processes and will be reviewed, and areas for future research will be highlighted.

1. Introduction

Complete description of the initiation and development of unwanted fires still eludes researchers because of its complexity. These complications arise not only from the multitude of processes controlling fire development (e.g., chemical kinetics, fluid dynamics, heat transfer, etc.), but also the varying influence of these processes depending on the scale and precise flow and configuration in which the fire is occurring. This review will address recent developments on this problem with regard to concurrent flame spread, where flames spread in the same direction as ambient flow and are most rapid and hazardous.

Previous reviews on the concurrent flame-spread problem are prevalent in literature; however significant developments have been made since the publication of the last review on the subject. The first review on flame spread by Friedman [1] summarized some of the primary mechanisms influencing the process before models reached a mature development. Effects of ambient air velocities (wind-aided flame spread), sample orientations (inclined flame spread), material composition, width effects, ambient pressure and oxygen concentrations have all proven to be relevant to the proper description of the problem. Elucidating these mechanisms and their precise influence on the process has been important and development to that end has been clearly demonstrated between the reviews of Williams [2] and Fernandez-Pello and Hirano [3]. The development of models for flame spread has also been addressed [4], and reviews and description of the subject have been featured in recent books [5–8]. Many other relevant configurations for flame spread exist, such as opposed-flow flame spread or spread over liquid fuel surfaces, but these will not be addressed because recent reviews by Wichman [9] and Ross [10] covered these subjects well. Since the publication of these books and reviews, the field has seen advancements in the understanding of concurrent flame spread in diverse configurations which often arise in practice, including spread over inclined fuels, wind-driven spread, and spread through discrete fuel arrays. We will first review the basics of flame spread and the classical upward flame spread problem before addressing flame spread in newly-studied configurations, i.e., inclined, wind-driven and discrete flame spread. Finally, the relationship between these topics and their impact on the particular problem of wildland fires and related future research opportunities will be discussed.

2. The flame spread problem

When a solid or liquid fuel surface is sufficiently heated, flammable vapors are either pyrolyzed (solid fuels) or evaporated (liquid fuels), liberating them from the fuel surface and into the gas phase [11]. When the proportion of fuel vapors to the surrounding oxidizer exists at a flammable ratio, a spark or enough thermal input will cause the fuel and oxygen mixture to ignite in the gas phase. Sometimes the heat generated by the ensuing flame will not be capable of maintaining the supply of fuel vapor to the gas phase and the mixture will simply "flash", quickly extinguishing. If, however, the heat from the flame to the fuel surface or another applied source of thermal energy is capable

* Corresponding author.

http://dx.doi.org/10.1016/j.firesaf.2017.05.007
Received 2 May 2017; Accepted 4 May 2017
0379-7112/

of sustaining the necessary flow of flammable vapors from the fuel to the gas phase, sustained combustion of the fuel will proceed.

Gaseous vapors diffusing from either the solid or liquid-phase fuel surface react with diffused atmospheric oxygen at a thin flame sheet, appropriately called a diffusion flame. The rate at which the combustion process proceeds is then governed by the rate at which fuel vapor is liberated and diffused from the solid or liquid phase and by the fraction of the heat directed back to the burning surface. Describing the gas-phase combustion of fuel vapors and generated heat fluxes primarily requires description of fluid-dynamic effects which control the structure of the diffusion flame, chemical-kinetic effects which govern the rate of reaction, and radiative effects from soot produced within the flame. Description of any liquid fuel vaporization is complicated, and that of a solid fuel is even more complex because the process is governed by many effects (radiative absorption, chemical kinetics, charring, etc.). While recent attempts have begun to numerically model the pyrolysis process within some solid fuels [12,13], often it is necessary to apply simple approximations to these complex problems in order to describe relevant macro-scale physics. These assumptions often include infinite reaction rates in the gas phase and a constant temperature for ignition of the fuel surface, T_{ig}. The first assumption is typically accurate for well-ventilated fire spread problems because reaction times are orders of magnitude smaller than flow and diffusion times, however it is not appropriate if the production of specific products is to be considered. A constant ignition temperature also ignores many relevant effects within the solid phase. Despite introducing these errors, the assumption that T_{ig} is constant is usually accurate enough when describing processes such as flame spread.

2.1. Theory

Fundamentally, fire spread occurs because of some type of heat transfer between a burning region and nearby, unburnt fuel [2]. This communication can take the form of one of many different heat-transfer mechanisms; regardless, all modes require a requisite heat flux per unit area, $\dot{q}''$, to be received by the nonburning fuel in order for spread to occur. The flame-spread rate, V_p, is then the rate at which this expanding combustion zone, called the pyrolysis zone, x_p, moves through a fuel bed; in other words, $V_p = dx_p/dt$.

Fuels can be solid combustibles, pools of flammable liquids, porous fuel beds or discrete, or separated items. The rate of fire spread through any of the above fuel beds can be fundamentally described by taking an energy balance across the flame front,

$$V_p \rho \Delta h = \dot{q}'', \tag{1}$$

where V_p is the flame-spread rate, ρ the density of the fuel bed and Δh the difference in thermal enthalpy (per unit mass) between the unburnt and burning fuel. This equation has been called the *fundamental equation of fire spread* [2,14]. Neglecting phase changes, assuming a constant ignition temperature, T_{ig}, and assuming steady state, the flame-spread rate can be re-written in a more familiar form,

$$V_p = \int_{x_p}^{x_f} \frac{\dot{q}''_f(x)}{\rho c_p (T_{ig} - T_0)} dx = \frac{\dot{q}''_f \delta_f}{\rho c_p (T_{ig} - T_0)}, \tag{2}$$

where c_p and T_0 are the specific heat capacity and initial temperature of the fuel, respectively. Because $\rho c_p (T_{ig} - T_0)$ tends to be a pre-defined property of the fuel, the heat flux to unburnt fuel, $\dot{q}''_f$ arises as the primary quantity controlling flame spread. The region over which most of this heat flux is applied, $\delta_f = x_f - x_p$ is often termed the pre-heat region and is also shown to be an important quantity. Flame spread is commonly divided between thermally-thin and thick regimes, the first where a constant temperature is obtained throughout the thickness of a fuel and the latter a limit where a temperature gradient is observed through some thickness of a material. For thermally-thin fuels, steady rates of spread are often reached as material burns out and a constant x_p is reached. For thermally-thick fuels this is rarely the case, as the fuel does not burn out, meaning flame spread will accelerate for an upward configuration, at least theoretically. For a thermally-thin fuel of thickness d, a steady rate of flame spread can be found when an energy balance is applied and $\dot{q}''_f$ averaged between δ_f,

$$V_p = \dot{q}'' \delta_f / \rho c_p d (T_{ig} - T_0). \tag{3}$$

For a thermally-thick fuel, incorporating a heat-transfer solution for ignition of a thermally-thick solid, the spread rate becomes

$$V_p = 4(\dot{q}'')^2 \delta_f / \pi (k \rho c_p)(T_{ig} - T_0)^2, \tag{4}$$

however this solution will only provide an instantaneous value of spread rate at some point, as spread is often acceleratory. While these solutions incorporate gross simplifications to the flame spread process, they provide a general picture of the behavior of flame spread. Other solutions for more specific configurations will be mentioned in the following review, but the focus will be on knowledge of the flame length and heat flux to the unburned surface, as universal solutions to the configurations of interest here (inclined, wind-driven, discrete) are not yet available in the literature.

3. Upward flame spread

Before proceeding to more complicated configurations, the canonical configuration of upward flame spread over a homogeneous surface will first be reviewed. The general model for upward flame spread, represented graphically in Fig. 1, consists of three primary regions, the pyrolysis zone, extending to height x_p, where ignited material contributes fuel to the flame, the combusting plume, $\delta_f = x_f - x_p$, where unburnt fuel from the pyrolysis zone continues to burn and heat

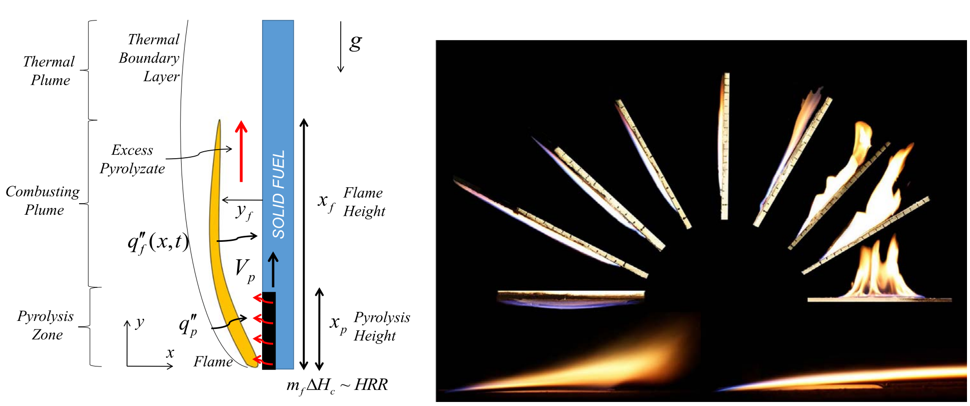

Fig. 1. (left) Diagram showing the various processes occurring during concurrent flame spread over a solid fuel in an upward configuration, (right) a compiled photograph of flame spread over a thermally-thick sheet of PMMA at multiple orientations from [18] and horizontal with wind applied from left to right at 0.79 m/s (bottom left) and 2.06 m/s (bottom right) from [19].