日本燃焼学会誌　第 61 巻 196 号（2019 年）112-119

Journal of the Combustion Society of Japan
Vol.61 No.196 (2019) 112-119

■特集／FEATURE■

―大規模屋外火災現象解明における燃焼研究の役割／Applying Combustion Knowledge to Large Outdoor Fire Problem ―

On Flame Spread

FERNANDEZ-PELLO, Carlos[1]*, and MCALLISTER, Sara[2]

[1] *University of California, Berkeley, Berkeley, CA, USA*
[2] *RMRS Missoula Fire Sciences Laboratory, USDA Forest Service, Missoula, MT, USA*

Abstract: Flame spread is the process by which a flame propagates over the surface of a solid fuel. Its practical interest is that is a primary mechanism for a fire to develop and grow. However, it is also of fundamental interest because the spread of a flame is a complex process involving the interaction between solid thermo-physical processes (heat transfer, thermal decomposition, gasification) and gas thermo-chemical processes (transport, mixing, chemical kinetics). As these processes are complex, simplifications are often made to gain some traction. One approach that is discussed here is to non-dimensionalize the conservation equations, evaluate the dominant terms while neglecting those less important for the situation at hand. Using this approach, simplified models for both opposed and concurrent flame spread over the surface of solid combustible materials in laboratory scale environments are derived from the concept of flame spread as a series of ignitions where the flame is both the source of heating and ignition. Our treatise concludes by discussing the application of these concepts to spread in both microgravity and porous fuel beds (wildland fires). The insight gained from such a fundamental understanding of the flame spread process can inform many aspects of large outdoor fires, be they through structures or wildland fuels.

Key Words: Flame spread, Microgravity, Wildland fire

1. Introduction

Flame spread is referred to as the process by which a flame propagates over the surface of a condensed combustible material. Its practical interest is that is a primary mechanism for a fire to develop and grow. Flame spread also has a fundamental interest since it encompasses a wide range of complex thermo-chemical processes in the solid and gas phases. As the detailed examination of these processes and underlying physics is untenable in large outdoor fires, the fundamental understanding provided by studying the flame spread process on the material at “bench” scale can provide valuable insights.

Regardless of the scenario examined, a flame spreads over a solid fuel surface by first transferring heat to the virgin solid ahead of it and eventually producing gaseous fuel by pyrolysis. The fuel vapor (pyrolyzate) is convected and diffused outward, mixing with the adjacent oxidizing gas, forming a flammable mixture that is ignited by the flame. Thus, the flame spreads as a series of ignition steps where the flame acts both as the source of solid heating and pyrolysis, and also as a pilot for the ignition of the flammable gas [1-4]. Thus, the spread of a flame is a complex process involving the interaction between the solid phase (heat transfer, thermal decomposition, gasification) and the gas phase (transport, mixing, chemical kinetics). For this reason, several simplifications have been traditionally applied to study flame spread.

Since the spread of the flame occurs in the presence of an oxidizer gas flow, flame spread has been classified as opposed or concurrent flame spread (Fig. 1) to differentiate the direction of flame spread with respect to the direction of the flow [5,6]. In opposed flame spread (or backing fire spread in wildland fires), the directions of flame spread and the gas flow are opposite to each other (e.g. downward spread in buoyant flow and upstream spread in forced flow). In concurrent flame spread (or heading fire spread in wildland fires), the two directions are the same (upward spread in buoyant flow and downstream spread in forced flow). Although this classification appears simplistic, both forms of flame spread have important differences related to the combustion of the pyrolyzed fuel and incoming oxidizer. Another common simplification is to classify the solid combustible where the flame is spreading as either thermally thick or thermally thin. In the former, the thickness of the thermal layer heated by the flame is smaller than the thickness of the solid, and there is a gradient of temperature near the solid surface. In the later, the

* Corresponding author. E-mail: ferpello@me.berkeley.edu

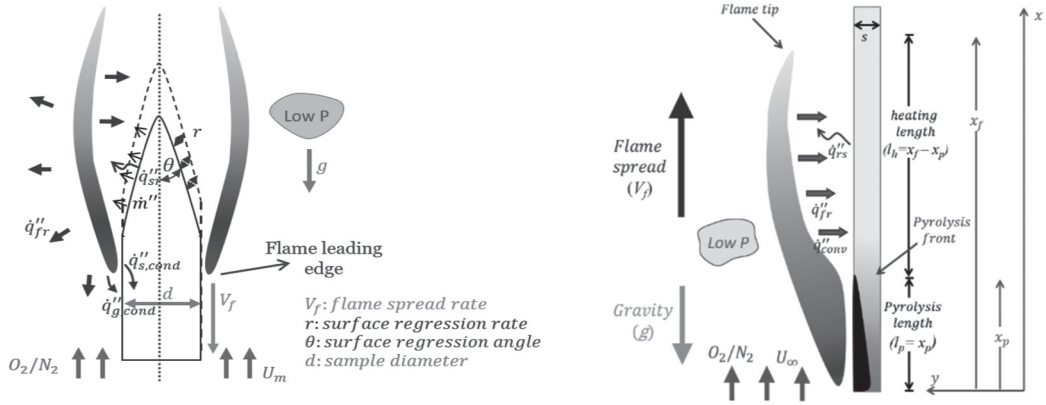

Fig. 1 Diagram of opposed and concurrent flame spread over a thin sample.

solid thickness is much smaller than the potential thermal layer thickness and, as a consequence, the temperature in the solid is approximately uniform. Both assumptions are valid in large outdoor fires as large structural materials are often thermally thick, yet the fine fuels on surrounding vegetation are likely thermally thin. There are other simplifications that have been applied to the study of the problem, such as assuming the gas-phase chemical kinetics are very fast so that the problem is totally controlled by the solid-phase heat transfer, that the gas flow is a forced flow only, and that radiation heat transfer is negligible, among others. Some of these simplifications will be discussed below.

2. Formulation of the Flame Spread Problem

The simplifications stated above are better understood by analyzing the equations governing the flame spread problem. In the gas phase, these equations include the mass, momentum, energy, and species equations for a reacting gas flow [7]. In the solid phase, the mass and energy equations for a pyrolyzing solid are required. For simplicity, only the one-dimensional version of the energy equation will be discussed here. The other equations follow a similar pattern.

For a gaseous reacting flow, this equation can be written as

$$\rho c_p \frac{\partial T}{\partial t} = -\rho u c_p \frac{\partial T}{\partial x} + k \frac{\partial^2 T}{\partial x^2} - \dot{Q}'''_{rad} + \dot{r}'''_{fuel} Q_c \qquad (1)$$

(the symbols are described in the nomenclature).

The mathematical determination of the reaction rate can be quite complex depending on the complexity of the fuel and the intermediate reactions that occur during its oxidation. However, in a global form it can be expressed by an equation of the form (Arrhenius reaction rate):

$$\dot{r}'''_{fuel} Q_c = \rho [O_2]^{n_{O_2}} [F]^{n_F} A \exp\left(-\frac{E}{RT}\right) Q_c \qquad (2)$$

Important things to observe are the exponential dependence of the reaction rate on temperature, its dependence on the mole fractions of fuel and oxidizer, and the dependence on pressure through the species concentrations.

The solid-phase energy equation provides the rate of fuel gasification at the solid surface which is required for the solution of Eq. (1). In 1-D it has the form

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\dot{m}'' h)}{\partial x} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \dot{\omega}''' L_v \qquad (3)$$

Most combustible materials have a polymeric structure and the gasification occurs through a pyrolysis process rather than a change of phase process. The material pyrolysis process can be complicated with several intermediate pyrolysis steps, sometimes melting, and complex transport processes of the gaseous pyrolyzate through the material as it travels toward the surface. Assuming that the pyrolysis process is described by a single, first-order (in fuel) Arrhenius-type reaction, and that the pyrolyzate travels unrestricted to the surface once formed, the rate of material gasification, or pyrolysis, is given by the equation

$$\dot{m}''_{pyr} = \int_0^\delta \dot{\omega}'''_{pyr} dx = \int_0^\delta \rho A Y_F \exp\left(-\frac{E}{RT}\right) dx \qquad (4)$$

An important result of Eq. (4) is that since most practical materials have a relatively large activation energy, the mass rate of pyrolyzate is strongly dependent on the material temperature. As a consequence, the mass rate of pyrolyzate is small until a certain temperature is reached. Since this temperature basically determines the initiation of material gasification, it can be viewed as a "pyrolysis temperature." As it will be explained below, this temperature plays an important role in modeling solid fuel ignition and flame spread.

When solving the flame spread problem, it may be necessary to use the differential formulation of the conservation equations if a detailed description of the combustion process is attempted.

However, its mathematical solution is generally difficult because of the nonlinear character of the equations and may require a numerical solution. One simplifying approach is to non-dimensionalize the governing equations, and to analyze the different non-dimensional terms that are formed in the process. Comparison of the different terms in the non-dimensional equations may lead to their simplification and their solution as described below.

Defining non-dimensional quantities based on the characteristic variables of the problem as [3,8]

$$\bar{t} = \frac{t}{\tau}, \bar{x} \equiv \frac{x}{\delta}, \quad \bar{T} \equiv \frac{T}{T_p - T_\infty}, \quad \bar{u} = \frac{u}{U},$$

The non-dimensional formulation of Eq. (1) becomes

$$\frac{\partial \bar{T}}{\partial \bar{t}} = -\frac{\tau}{\tau_{conv}} \bar{u} \frac{\partial \bar{T}}{\partial \bar{x}} + \frac{\tau}{\tau_{diff}} \frac{\partial^2 \bar{T}}{\partial \bar{x}^2} - \frac{\tau}{\tau_{rad}} + \frac{\tau}{\tau_{chem}} \frac{Q_c}{c_p (T_F - T_\infty)} \tag{5}$$

Where $\tau_{conv} = \frac{\delta}{U}$ is the convective time, $\tau_{diff} = \frac{\delta^2}{\alpha}$ is the diffusion time, $\tau_{rad} = \frac{c_p (T_F - T_\infty)}{\dot{Q}'''_{rad}}$ is the radiation time, and $\tau_{chem} = \frac{\delta}{\dot{r}'''_{fuel}}$ the chemical time. The characteristic time τ depends on the controlling mechanism of the combustion process. Depending on the comparative values of these parameters, some of the terms in Eq. (5) can be neglected, simplifying the solution of the problem. This is particularly useful in limiting conditions of heat and mass transport or chemical kinetics. For example, if diffusion is dominant, as often occurs in fire problems, the characteristic time of the problem will be the diffusion time, $\tau = \tau_{diff}$, and Eq. (5) would take the form

$$\frac{\partial \bar{T}}{\partial \bar{t}} = -\frac{\tau_{diff}}{\tau_{conv}} \bar{u} \frac{\partial \bar{T}}{\partial \bar{x}} + \frac{\partial^2 \bar{T}}{\partial \bar{x}^2} - \frac{\tau_{diff}}{\tau_{rad}} + \frac{\tau_{diff}}{\tau_{chem}} H_c \tag{6}$$

In Eq. (6) there are four distinct non-dimensional groups $\frac{\tau_{diff}}{\tau_{rad}} = \frac{\alpha}{U\delta}$ which is the inverse Peclet number that relates diffusion heat transfer to convection energy transport, $\frac{\tau_{diff}}{\tau_{rad}} = \frac{\alpha}{\delta^2} \frac{\dot{Q}'''_{rad}}{c_p (T_F - T_\infty)}$ that relates conduction to radiation heat transfer, $H_c = \frac{Q_c}{c_p (T_F - T_\infty)}$ which relates the heat of combustion to the heat necessary to raise the gas temperature to the flame temperature and is close to unity, and $\frac{\tau_{diff}}{\tau_{rad}} = \frac{\alpha}{\delta^2} \frac{\dot{r}'''_{fuel}}{\rho}$ which is the diffusion-based Damkohler number that relates the chemical time to the diffusion transport time. If the gas-phase chemical reaction is strong (high temperature and energy), and/or the ambient oxygen concentration is high, then the chemical time will be very short because the reaction rate will be fast. Consequently, the reaction term in Eq. (6) will be very large (large Damkohler number) in comparison with the other terms and can be removed from the equation by keeping the rate of heat released from the reaction. The latter is obtained from the rate of species transport to the reaction and the heat of combustion. Consequently, the ignition process becomes a heat and mass transport dominated process. Equation (6) becomes a transport equation only, with the flame spread process controlled by the balance between convection and diffusion transport of the reactants toward the flame location, and the transfer of heat from the flame to the reactants. As it is shown below, this is the approach followed in most of the analytical models of flame spread.

Another limiting case of interest is when the Damkohler number is small either because the oxidizer velocity is high (strong air currents or wind) or because the reaction rate is small (vitiated air, low temperature, low pressure), i.e., the characteristic chemical time is large. Selecting the characteristic time of the problem as the convection time, $\tau = \tau_{conv}$, Eq.(5) would take the form

$$\frac{\partial \bar{T}}{\partial \bar{t}} = -\bar{u} \frac{\partial \bar{T}}{\partial \bar{x}} + \frac{\tau_{conv}}{\tau_{diff}} \frac{\partial^2 \bar{T}}{\partial \bar{x}^2} - \frac{\tau_{conv}}{\tau_{rad}} + \frac{\tau_{conv}}{\tau_{chem}} H_c \tag{7}$$

In Eq. (7) there are three distinct groups, $\frac{\tau_{conv}}{\tau_{diff}} = \frac{U\delta}{\alpha}$ (Peclet number), $\frac{\tau_{conv}}{\tau_{rad}}$ that relates convection to radiation heat transfer, and $\frac{\tau_{conv}}{\tau_{chem}} = \frac{\delta}{U} \frac{\dot{r}'''_{fuel}}{\rho}$ which is the convective Damkohler number and relates the chemical time to the convective transport time. If the gas velocity is large, the convection time will be small and the conduction and radiation terms can be neglected in Eq. (7). Equation (7) becomes a convective reactive equation only, with the flame spread process controlled by the balance between the rate of convection transport of the reactants toward the flame location and the reaction rate. Flame spread will occur only if the reaction rate is strong enough to overcome the convective and radiative heat losses. If the ambient oxygen concentration or pressure are the parameters being changed, the reaction rate decreases as they are reduced (Eq. (3)) and the chemical time increases. Eventually the reaction rate would be too small to overcome the heat losses and flame spread cannot occur.

A similar approach can be used to analyze the solid phase energy equation (Eq. (3)). However, a major simplification that is often applied is that because the pyrolysis rate is small until the temperature is close to the pyrolysis temperature of the solid (Eq. (4)), the pyrolysis term in Eq. (3) can be assumed negligible until the solid reaches the pyrolysis temperature. Furthermore, assuming that the fuel pyrolyzes near the solid surface, the fuel

pyrolysis rate can then be determined from the ratio of the heat flux from the flame to the solid to its energy of pyrolysis.

Although the above approach of comparing terms in normalized equations to reduce their complexity is very useful, the availability of powerful computers is currently allowing the numerical solution of the flame spread problem using their full differential formulations [9]. However, analytical solutions of the flame spread rate are still useful, at least to understand experimental observations.

3. Opposed Flow Flame Spread

In opposed spread, the controlling region for flame spread is located close to the flame front. In this region the intricate coupling of processes in the solid and gas phase is strongly dependent on the various space and time scales described above. Consequently, the characteristics of the flame spread, and the rate of spread, are strongly dependent on the solid and environment. Despite the complexity of the opposed flame spread processes, simplified theoretical models have been developed to analytically determine the flame spread rate, such as those developed in Refs. [3, 10]. The analysis is based on the concept that flame spread can be viewed as a series of ignition steps where the flame acts both as the heating and the ignition source, and the spread rate calculated as the ratio of a heating length ahead of the flame to the ignition time in the solid [1-4]. Following these concepts and extending the seminal work of Niioka and co-workers [11, 12] on the stagnation point flow ignition of a solid fuel to a boundary layer flow, the following expression is obtained for the rate of flame spread over a thick solid [3, 10].

$$V_f = l_h \left[\frac{\pi k_s \rho_s c_s (T_p - T_o)^2}{4(\dot{q}''_{fc} + \dot{q}''_{fr} - \dot{q}''_{rs})^2} - \frac{Cx}{U_m} \varphi\,(t_{chem}) \right]^{-1} \qquad (8)$$

A similar equation is derived for a thermally thin solid [3, 10].

An important simplification is the assumption that the solid does not pyrolyze until the surface temperature reaches the pyrolysis temperature, and that the pyrolysis gases immediately mix with the oxidizer gas forming a flammable mixture ahead of the flame. There are also other simplifying assumptions related to the heat flux and gas-phase ignition [3].

Equation (8) incorporates most of the controlling mechanisms of opposed flame spread. The first term describes the heat transfer mechanisms of the solid fuel, and the second term includes the gas-phase chemical kinetics (Damkohler number) leading to the gas-phase ignition. These terms have different importance depending on the length and time scales of the problem (see formulation section). If the chemical time is small compared to the flow time (large Damkohler number) then second term in the Eq. (8) can be neglected, and the flame spread is controlled by the solid heating process, as is the case in most outdoor fire situations. This condition is referred to as the "thermal-dominated regime" of opposed flame spread and would occur if the oxygen concentration and pressure are high, and the flow velocity is low. The resulting expression for the opposed flame spread rate is the first term in Eq. (8), which has the same basic form as that developed by several investigators [1, 2, 4, 13, 14]. Since the convective heat flux in Eq. (8) can be expressed as $\dot{q}''_{fc} = h(T_f - T_p)$, with h representing the average convective heat transfer coefficient which depends directly on the Reynolds and/or Grashof, number, Eq. (8) predicts that in the thermal-dominated regime, the flame spread rate increases as the flow velocity or the oxygen concentration is increased, as observed experimentally [3, 10, 15]. This simplified version of Eq. (8) has been applied to predict flame spread under different conditions with surprisingly good results. It has also been used to interpret the results of some test methods [16].

The second term in Eq. (8) represents gas-phase chemical kinetic effects and predicts phenomenologically the gas-phase processes that affect the spread of the flame. These occur at conditions that reduce the Damkohler number and make the chemical kinetics term comparable with the heat transfer term, such as low oxygen concentration, low pressure, or at large flow velocity. Under these conditions the second term in Eq. (8) becomes large enough to counteract the first term. As a consequence, the flame spread rate decreases to the point of no flame spread (blow off and quenching) [3, 10, 15, 17]. The combination of both processes, as in Eq. (8), is capable of correlating experimental results quite well, such as those of Refs. [15] shown in Fig. 2, predicting both the effect of opposed flow velocity and oxygen concentration on the flame spread rate. There are other effects that Eq. (8) may not be capable of predicting. For example, as discussed later, at very low flow velocities, such as those encountered in microgravity, the flame temperature decreases making the surface radiative losses more important (diffusive transport and radiation losses) which causes a decrease of the spread rate [18-21].

More accurate description of the process requires the application of numerical models. One example is that shown in Fig. 2 from Lautenberger et al. [22] that can reproduce relatively well the data of Ref. [15], even although the gas-phase kinetics are very too simplified to simulate all the testing conditions.

Even though the opposed flow mode of flame spread is quite complex to analyze, it is the one that has been studied experimentally most through the years. This is probably because it propagates slowly and it is possible to follow the spread of the flame through its pyrolysis front. Early work was reviewed by Fernandez-Pello and Hirano [5]. Other more recent works have been reviewed in [2, 3], [14], and [23].

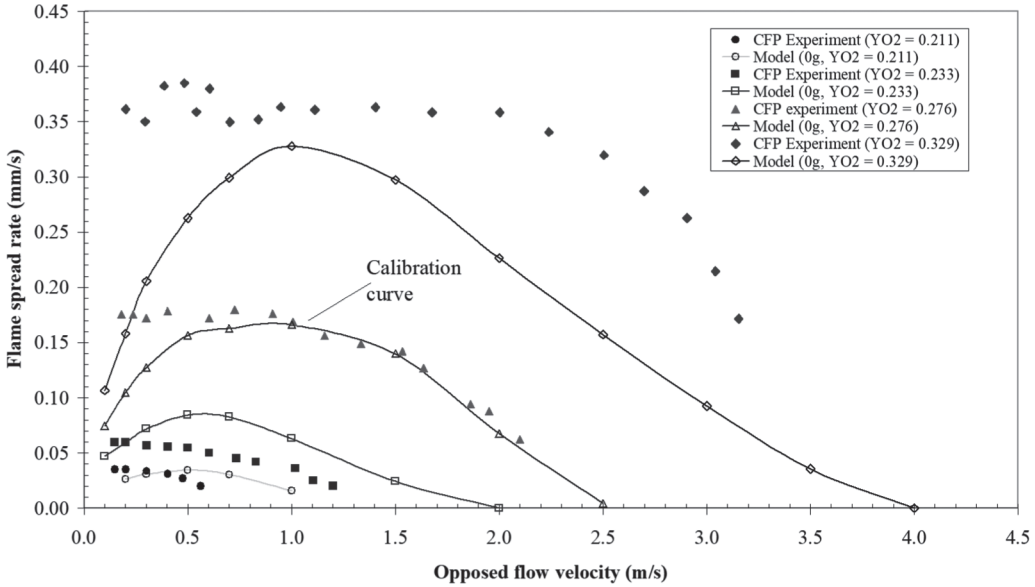

Fig. 2 Comparison of modeled and experimental flame spread rate as a function of forced flow velocity at four oxygen concentrations.

4. Concurrent Flow Flame Spread

In concurrent-flow flame spread, the spread of the flame depends on the length of the flame and its thermal plume, an important distinction compared to the opposed-flow case which normally depends only on the thermal length scale. In general, the spread rate is faster than in opposed flame spread and consequently more hazardous. In addition, because the flame covers the pyrolysis front, it is more difficult to determine the spread rate, which resulted in a smaller number of experimental studies compared with opposed flame spread. Interestingly enough, concurrent flame spread is easier to model theoretically because the gas-phase processes are less important than in opposed forced flow.

In this mode of flame spread, the oxidizing gas flows by convection (forced, free, or mixed) in the same direction as that of the flame propagation (Fig. 1). The hot, still reacting and post-combustion gases generated in the pyrolysis region move ahead of the pyrolysis front in the form of a flame transferring heat to the virgin fuel downstream. Since the pyrolyzed fuel and oxidizer are initially separated, the flame is primarily of the diffusion type. Because of its diffusion character, the flame is not strongly affected by finite-rate chemical kinetic effects. Thus, except in limiting conditions, the spread of the flame will be controlled primarily by the rate of heat transfer from the downstream flame to the virgin fuel ahead of the pyrolysis front. Furthermore, the flame spread rate can also be calculated as with the opposed flame spread through the ratio of the solid heated length to the ignition time. Consequently Eq. (8) would also apply neglecting the chemical kinetics term. The solid heating length would be basically the length of the flame downstream of the pyrolysis front that can be determined by the fuel pyrolysis rate and the burning rate of the pyrolyzate and oxidizer.

Experiments on concurrent flame spread have been reviewed in [3] and recently by Gollner et al. [24] and Honda and Ronney [25].

5. Flame Spread in Microgravity

Flame spread in microgravity has an important role in potential fires in spacecraft. In the absence of gravity, a flame would spread by diffusion of heat and mass in a quiescent oxidizer. However, in a spacecraft such as the International Space Station (ISS), the spacecraft ventilation system induces flows with velocities that are of the order 10 cm/s to 20 cm/s, so truly quiescent environments are rarely achieved. Although the basic mechanisms of flame spread are the same with or without gravity, the characteristics of the transport of heat and mass and the flame chemical kinetics may be different, which may cause different flame spread rates.

Still unknown is how the flammability of materials will change or how a flame behaves if only exposed to a low velocity forced convective flow in microgravity. A problem to study flame spread in normal gravity low velocity flows is that buoyant flows, typically on the order of 30 cm/s to 60 cm/s, overwhelm the forced low velocity flows, thus, fire testing of materials to be used in spacecraft requires the utilization of reduced gravity facilities, or alternative approaches to diminish the effects buoyancy.

The tests conducted using ground–based facilities, such as drop towers and airplanes flying parabolic trajectories, are limited by the short microgravity test duration, while most space-

based experiments have been limited to small samples due to safety considerations on the ISS. The reader is referred to the excellent review of the subject by Fujita [26] on this matter. One important observation from flame spread in microgravity is that gaseous and surface radiation are important in low-intensity flames typical of those near extinction [26, 27]. In microgravity, radiation becomes comparatively more important, not because the radiative flux decreases, but rather because of the absence of natural convection. When the convective velocity decreases, the ratio of radiative loss rate from the flame to the heat generation rate increases, so the flame temperature decreases [18].

Furthermore, since there are marked differences in the velocity distributions between a buoyant-induced flow on Earth and a purely forced flow in microgravity, it is expected that there will be notable differences in flame spread in buoyant and forced flows. For example, at low flow velocities the flame standoff distance will increase and so the convective heat flux from the flame to the solid will decrease. The relationship between these two effects determines whether the flame spread rate will increase or remain constant [18]. Furthermore, at very low flow velocities such as those encountered in microgravity, as the flame temperature decreases the surface radiative losses become more important (diffusive transport and radiation losses) which causes a decrease of the spread rate [18-21].

Recently several projects have been initiated in the USA and Japan to study different issues related to flame spread in microgravity. One of the projects, Saffire [28, 29], is a NASA-led multinational effort aimed to study the effect of scale and gravity on flame spread. The microgravity experiments are conducted in the unmanned spacecraft Cygnus that is used to resupply the ISS. One of the novelties of the experiments is the large scale of the samples tested. Other NASA supported projects are BASS [30] and SoFIE where several studies on flame spread over small samples of different materials and geometries in microgravity low velocity flows have been conducted or are planned in the ISS. The FLARE project [26, 31] is also a multinational effort led by JAXA to study the flammability of electrical wires in microgravity. The experiments will be conducted in the KIBO module of the ISS. It is expected that new and important information will be obtained from these projects about flame spread and flammability limits in spacecraft environments.

6. Flame Spread in Porous Fuels

As it is responsible for the major growth of an outdoor fire, concurrent (or heading) fire spread is the main focus of much research in porous fuels, such as vegetation. Despite the different context, many of the concepts outlined above for flame spread over a solid material apply. In particular, the idea that the spread process is simply a series of ignition events holds. In fact, one of the very first simplified models for wildland fire spread uses this notion and derives an expression similar to the first term in Eq. (8) [32]. Historically, however, analytical models for heading wildland fire spread more often apply a simple energy balance assuming a constant rate of spread (for example, [1, 33-36]). However, the nature of the fuels and the typical scales of the fires have resulted in several challenges to applying simplified, analytical models. Most often, it is the surface fuels, such as grass, needles, and leaves that are considered. The size of these fuel particles and their distribution on the ground can vary considerably, resulting in a very heterogeneous fuel bed. As simplified models are unable to accommodate this unique and often important aspect of wildland fuels, weighting schemes are often employed (for example, see [37]). It is also worth noting that even detailed numerical models of wildland fire spread are largely not run in fine enough resolution to capture this variability either (see for example [38, 39]).

The difficulties measuring the heat fluxes responsible for spread through these fuels and the inherent large range in the scale of the flames themselves has resulted in an ongoing debate as to the driving heat flux in wildland fires (see for example [40, 41]). Additionally, many of these models are not closed. As described above for concurrent flame spread, the heating length is often assumed to be the flame length, which is not known *a priori*. As a result, many simplified models make assumptions about the driving heat transfer mechanism and rely on empirical constants to fit experimental data [35]. The inability to simplify the problem by identifying and neglecting unnecessary terms in Eq. (8) or to describe the fuel in a simple manner means that wildland fire spread is largely predicted using empirical or semi-empirical relations during fire management activities (for example [42, 43]) or by detailed numerical models for research-related analyses (such as in [38, 39, and 44]). More recent research, however, has gone back to the concept of spread as a series of ignitions and is working to address these gaps, particularly in identifying and quantifying the mechanisms of heat transfer that drive ignition and spread in wildland fuels [45]. This approach will allow for prediction of unsteady fire spread, an important unanswered question in wildland fire.

For more information on fire spread in porous fuel beds, excellent reviews have been written in Refs. [46-48].

7. Conclusion

Despite the complexity of the fire spread problem, progress has been made to understand the controlling mechanism of flame spread over solid combustible materials, at least in laboratory scale earth environments. By non-dimensionalizing the conservation equations, one can gain insight into the important processes governing flame spread behavior. At its essence, flame

spread is simply a series of ignitions, where the flame acts as both a source of heating and as a pilot. This approach to understanding flame spread can be very helpful, regardless of whether the fire occurs in a spacecraft or on Earth in large outdoor environments.

Nomenclature

A	pre-exponential factor
c	specific heat
C	constant
E	activation energy
h	enthalpy, convective heat transfer coefficient
k	thermal conductivity
l_h	heated length of the solid ahead of the pyrolysis front
L_v	heat of vaporization
$\dot{m}''$	mass flux
n	number of moles
Q_c	heat of combustion
$\dot{q}''_{fc}$	convective heat flux from the flame to the solid surface
$\dot{q}''_{fr}$	flame radiant flux to the solid surface
$\dot{Q}'''_{rad}$	volumetric radiation
$\dot{q}''_{qrs}$	re-radiation from the solid
R	universal gas constant
$\dot{r}'''_{fuel}$	volumetric gas reaction rate
t	time
T	temperature
u,U	velocity, characteristic velocity
α	thermal diffusivity
δ	characteristic length of the problem
ϕ (t_{chem})	function of the chemical time
ρ	density
τ	characteristic time
$\dot{\omega}'''$	volumetric solid reaction rate

Subscripts

chem	chemical
con	convective
diff	diffusion
F	flame
M	mixed (forced and buoyant)
o	initial
pyr	pyrolysis
rad	radiative
s	solid
∞	ambient

Acknowledgments

We would like to thank the many colleagues that we have interacted with regarding the flame spread problem. The senior author (CFP) would like to acknowledge, in particular, the collaboration through the years with so many Japanese colleagues (friends) from whom he has learned so much about combustion/fire.

References

1. Williams, F. A., *Symp. (Int.) Combust.* 16: 1281–1294 (1977).
2. Quintiere, J. G. *Fundamentals of Fire Phenomena*, John Wiley & Sons (2006).
3. Fernandez-Pello, A.C. “The Solid Phase”, *Combustion Fundamentals of Fire*, Chapter 2. G. Cox, editor, Academic Press, pp. 31-100, (1994).
4. Delichatsios, M.A. *Symp. (Int) Combust* 26: 1495-1503 (1996).
5. Fernandez-Pello, A.C. and Hirano, T. Published jointly in *Fire Sci. Technol. (Japan)* 2(1): 17-54 (1982) and Combust. Sci. Tech. 32:1-31 (1983).
6. Olson, S. L, and Miller, F. J, *Proc. Combust. Inst.* 32: 2445–2452 (2009).
7. Williams, F.A. *Combustion Theory*, the Benjamin/Cummings Co. (1985).
8. McAllister, S., Chen, J.Y., and Fernandez-Pello, C. *Fundamentals of Combustion Processes*, Springer (2011)
9. Zhao, X. and T’ien, J.S., *Combust Flame* 162: 1829-1839 (2015).
10. Fernandez-Pello, A.C., *Proc. Int. Semin. Fire Explos. Hazards* 4: 13–26 (2004).
11. Niioka, T. *Symp. (Int.) Combust.* 18: 1807-1813 (1981).
12. Niioka, T., Takahashi, M. and Izumikawa M. *Symp. (Int.) Combust.* 18: 741-747 (1981).
13. de Ris, J. N. *Symp. (Int.) Combust.* 12: 241-252 (1969).
14. Wichman, I., *Prog. Energy Combust. Sci.* 18: 553–593 (1992).
15. Fernandez-Pello, A.C., Ray, S.R., and Glassman, *I. Symp. (Int.) Combust.* 18: 579-589 (1980).
16. Quintiere, J. *Fire Mater* 5(2): 52-60 (1981).
17. Olson, S.L. *Combust. Sci. Technol.* 76: 233–249 (1991).
18. T’ien, J.S. *Combust. Flame.* 4: 31–34 (1986).
19. Takahashi, S., Kondou, M., Wakai, K., A., Bhattacharjee, S., *Proc. Combust. Inst.* 29: 2579-2586 (2002).
20. Bhattacharjee, S., Wakai, K,. Takahashi, S. *Combust. Flame* 132: 523–532 (2003).
21. Bhattacharjee, S., Simsek, A., Miller, F., Olson, S., Ferkul, P. *Proc. Combust. Inst.* 36: 2963–2969 (2017).
22. Lautenberger, C., McAllister, S., Rich, D., Fernandez-Pello, C. *P Int Fire Safety Tall Buildings* GIDAI, Santander, Spain, pp. 255-271, (10/2006).
23. Zhang, X., Yu, Y. *Combust. Flame* 158(6): 1193-1200 (2011)

24. Gollner, M.J., Miller, C.H., Tang, W., Singh, A. V. *Fire Saf. J.* 91: 68–78 (2017).
25. Honda, L.K., Ronney, P.D. *Pro. Combust. Inst.* 28(2): 2793-2801 (2000).
26. Fujita, O. *Proc. Combust. Inst.* 35: 2487-2502 (2015).
27. Ronney, P. D. *Symp. (Int.) Combust.* 27: 2485-2506 (1998).
28. Jomaas, G., Torero, J. L,. Eigenbrod, C., Niehaus, J., Olson, S. L, Ferkul, P. V., Legros, G., Fernandez-Pello, A. C., Cowlard, A. J., Rouvreau, S., Smirnov, N., Fujita, O., T'ien, J. S., Ruff, G. A., Urban, D. L. *Acta Astronaut.* 109: 208-216 (2015).
29. Urban, D.L., Ferkul, P., Olson, S,. Ruff, G.A., James, S.T., Liao, Y.T., Fernandez-Pello, A.C., Torero, J.L., Legros, G., Eigenbrod, C., Smirnov, N., Fujita, O., Rouvreau, S., Toth, B., Jomaas, G. *Combust. Flame* 199: 168-182 (2019).
30. Olson, S.L., Ferkul, P. V., Bhattacharjee, S., Miller, F.J., Fernandez-Pello, A.C., T'ien, J.S. 29th Annu. Meet. Am. Soc. Gravitational Sp. Res. 5th Int. Symp. Phys. Sci. Sp., Orlando, FL (2013).
31. Fujita, O. *Int. J. Microgravity Sci. Appl.* 32 (4): 320402 (2015).
32. Fons, W.L. *J. Agr. Res.* 72(3): 93–121 (1946).
33. Emmons, H. *Fire Res. Abs. Rev.* 5(3): 163–178 (1963).
34. Thomas, P.H. *Forestry* 40: 139-164 (1967).
35. Rothermel, R.C. Research Paper INT-115 Odgen, UT: USDA Forest Service, Intermountain Forest and Range Experimental Station (1972).
36. Pagni, P.J., Peterson, T. G. *Symp. (Int.) Combust.* 14: 1099-1107 (1973).
37. Albini, F.A. Computer-based models of wildland fire behavior: a user's manual. Ogden, UT: USDA Forest Service, Intermountain Forest and Range Experiment Station. 71 p. (1976).
38. Mell, W., Jenkins, M.A., Gould, J., Cheney, C. *Int. J. Wildland Fire* 16: 1-22 (2007).
39. Pimont, F., Dupuy, J.L, Linn, R.R. *Int. J. Wildland Fire* 21(7) 828-842 (2012).
40. Morvan, D., Frangieh, N. *Int. J. Wildland Fire* 27: 636-641 (2018).
41. Finney, M.A., Cohen, J.D., McAllister, S.S., Jolly, W.M. *Int. J. Wildland Fire* 22: 25-36 (2013).
42. Heinsch, F. A. Andrews, P. L. RMRS-GTR-249. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station. 111 p. (2010).
43. Finney, M.A. RMRS-RP-4 Revised. Ogden, UT: USDA Forest Service, Rocky Mountain Research Station. 47 p. (2004).
44. Morvan, D., Dupuy, J.L. *Combust. Flame* 138(3): 199-210 (2004).
45. Finney, M.A., Cohen, J.D., Forthofer, J.M., McAllister, S.S., Gollner, M.J., Gorham, D.J., Saito, K., Akafua, N.K., Adam, B.A., English, J.D. *PNAS* 112(32): 9833-9838 (2015).
46. Weber, R.O. Prog. Energ. Combust. 17(1): 67–82 (1991).
47. Sullivan, A.L. *Int. J. Wildland Fire* 18: 349-368 (2009).
48. Pastor, E., Zarate, L., Planas, E., Arnaldos, J. *Prog. Energ. Combust.* 29(2): 139–153 (2003).