An Examination of Fuel Particle Heating During Fire Spread

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Abstract
Recent high intensity wildfires and our demonstrated inability to control extreme fire behavior suggest a need for alternative approaches for preventing wildfire disasters. Current fire spread models are not sufficiently based on a basic understanding of fire spread processes to provide more effective management alternatives. An experimental and theoretical approach for improved understanding is necessary particularly for shrub and tree canopy fuels. Preliminary experiments of radiation heating resulted in coarse fuels (12-mm cross-section) heating to ignition while fine fuels (1-mm cross-section) did not. These results generally agree with other prior research results and indicate that radiation heating may not be sufficent for ignition. This study and our associated research will continue with the goal of developing a physical fuel particle ignition model as a basis for appropriate fire spread modeling assumptions.

Keywords: fuel preheating, fuel particle heat exchange, fire spread modeling, physical fire modeling

1. Introduction

Although U.S. federal policy has recognized the important ecological role of fire (USDA and USDI 2000), most fires continue to be actively suppressed (NIFC 2009). Ecological considerations in fire management have become well accepted; however, alternatives to reactive suppression are not simple. More than one-third of western U.S. undeveloped forest and rangelands have fire regimes where the appropriate ecological fire occurrence is stand-replacement, that is, the fire involves all above-ground vegetation (Hardy et al. 1998; Schmidt et al. 2002). However, another one-third of western U.S. wildlands (Hardy et al. 1998; Schmidt et al. 2002) has forest cover types, notably ponderosa pine (*Pinus ponderosa*), where spatially extensive crown fires threaten sustainability (Wright and Bailey 1982, Allen et al. 2002). To be effective, fire managers will require the ability to identify and implement ecologically appropriate management that facilitates limited active crown fire in some areas while inhibiting crown fire in others and at the same time operationally providing for life-safety and property protection. Such complex proactive fire management will require fire spread prediction capabilities over a wide range of conditions – most notably high intensity, crown fire conditions. This capability does not currently exist and will require a more explicit understanding of fire spread processes in general and specifically involving active crown fires. Increasing our understanding of fire spread processes will potentially reveal opportunities that can then be developed into applications for improving wildland fire management effectiveness.

The State of Wildland Fire Spread Modeling

Current operational fire spread models are empirically based and, thus, do not describe fuel-heating processes that produce the spread. Using laboratory and field experiments and actual wildfires, researchers have related observed fire behavior (principally spread rate and intensity) to measured fuel, weather and topography without describing the specific physical processes (Weber 1991; Sullivan 2009a; Sullivan 2009b). For example, the empirical Rothermel (1972) surface fire spread and Byram (1959) fireline intensity-flame length models are the basis for calculations in many operational systems. These include the National Fire Danger Rating System (Deeming et al. 1978; Cohen and Deeming 1985), BehavePlus (Andrews *et al*. 2005), FARSITE (Finney 1998) and FlamMap (Finney et al. 2006). The Canadian Fire Behavior Prediction Model is also empirically based on wildfires and experimental burns (Hirsch 1996). Australia and others use the empirically-based McArthur grassland and forest fire meters (Noble et al. 1980). Project Vesta (Gould et al. 2007), a recent Australian empirical fire behavior study potentially refines the existing wildland fire meters. Although fire managers use these models to predict fire spread and intensity, the models cannot be reliably extended beyond their basis conditions and do not provide explicit physical insights into wildland fire processes.

Current physically-based models include representations of physical processes such as radiation and convection heat transfer (Weber 1991, Sullivan 2009a, Sullivan 2009b). These models, however, do not account for specific fuel particle heat exchange. The spread models are built around bulk fuel bed assumptions; the fuel beds are a continuum of uniformly distributed average fuel characteristics and heat transfer properties. Heat transfer and ignition processes have been assumed for fuel particle scales without an experimental determination. For example, radiation has been generally assumed to be the principal heating mechanism responsible for wildland fire spread. Sen and Puri (2008) in their survey of radiation in wildland fire modeling state the following:

> "*Radiation has been unsurprisingly identified as the controlling heat transfer mechanism that fixes the rate of spread of wildland fires.*"

However, no definitive experimental evidence of heat transfer processes during wildland fire spread supports this statement.

Notably, Albini assumed that radiation dominated fuel heating during fire spread. He reasoned that under most cases a developed flame zone blocks the ambient wind and therefore flame does not extend into adjacent fuel (Albini 1985). Without experiment he then assumed the flame front to be a steady plane interface with radiation as the principal heating mechanism for fire spread. Albini continued to assume radiation to be the principal mechanism for fire spread in his crown fire spread model (Butler et al. 2004). Although he recognized convective cooling of preheated fuels from fire induced inflow, he never questioned the sufficiency of radiation heating for ignition and thus fire spread. Radiation parameters were 'tweaked' to make model spread rates match actual spread rates (Butler et al. 2004).

The Need to Understand Fuel Particle Heating

Researchers have previously questioned the sufficiency of radiation in heating fuels to ignition and thus, in fire spread (Byram et al. 1964, McCarter and Broido 1965, Anderson 1969, Van Wagner 1977, de Mestre et al. 1985, Baines 1990, Beer 1990, Pitts 1991). In particular, Weber (1991) found that radiation models could not account for how fuel particles preheated ahead of a flame zone. In modeling, the radiation calculations can be post-case adjusted to make spread rates match actual fires. This changes the magnitude

of heating but does not reproduce an appropriate fuel time-temperature sequence. Weber (1991) showed measured fuel preheating temperatures having a different profile than those predicted by models. The actual fuel temperature rise leading to ignition occurred nearer to the fire and over a much shorter duration than model predictions based on radiation as the principal heating mechanism (Figure 1). This suggests more complicated fuel heat exchange for at least some conditions where flame radiation is not sufficient for fire spread.

Several years ago a series of "deep-fuel" laboratory experiments suggested that flame contact to adjacent fuel was necessary for fire spread (Finney et al. 2010). Furthermore, fire spread was facilitated in deeper fuel beds because the longer length scale increased flame volume and lateral flame extension (Yedinak et al. 2010). This was consistent with previous research that suggested deeper live shrub twig and foliage fuel beds (high moisture contents) had a higher potential for maintaining fire spread (Cohen and Bradshaw 1986). In all laboratory deep-fuel experiments, visual inspections did not reveal significant "smoky" pyrolyzate emissions from preheated fuels prior to flame contact and ignition (Figure 2). This suggested that flame contact was not solely a pilot igniter but rather contributed convection heating necessary for ignition and thus fire spread. The apparent lack of significant pyrolysis in fuel adjacent to the flaming region indicates insufficient radiation heating and thus fuel temperatures too low for significant thermal decomposition. These observations are consistent with findings by Rothermel and Anderson (1966) that showed the temperature of an instrumented fuel particle about 177 C (350 F) upon flame arrival (Figure 3). This fuel surface temperature was 100 C too low for significant pyrolysis rates and flammable pyrolyzates (Fairbridge et al. 1978; Tillman et al. 1981; Simmons 1995; Drysdale 1998).

The temperature response of fuel particles to externally applied thermal radiation

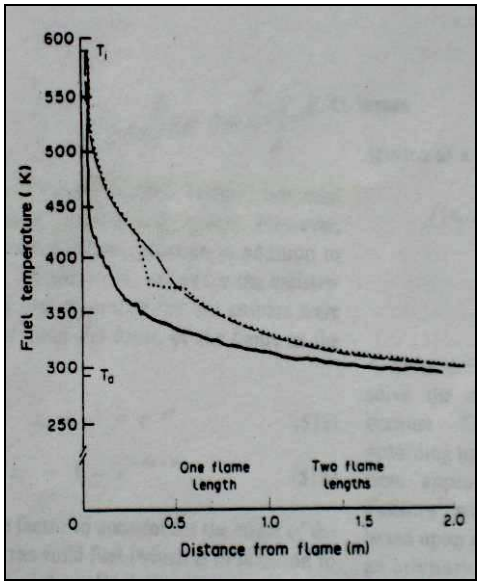


Figure 1 Preheating fuel particle surface temperature. Experimental data (solid line) with radiation model (broken lines). [from de Mestre et al. (1989) as cited by Weber (1991).]

Figure 2 Experimental fire spreading right to left through fine excelsior (shredded Populus spp.). Observations revealed the ignition of adjoining fuels without significant pre-ignition pyroyzate emissions (clear gaps) and only after flame contact.

was explored by Don Latham at the Missoula Fire Sciences Laboratory. His work revealed that radiation heat fluxes capable of igniting wood slabs in 60 seconds (Tran et al. 1992; Cohen 2004) did not ignite nor significantly char fine fuels (< 1 mm thick). This prompted our own exploratory experiments at incident radiation heat fluxes (~37 kW/m^2) greater than those of Latham's (~25 kW/m^2). For our exploratory experiments we used wood excelsior (*Populus* spp.) and a small wood block (*Psuedotsuga menziesii*) (Figure 4a). The exposed wood block pilot ignited in 35 seconds (Figures 4b and 4c). The time to ignition was consistent with the ignition model of Tran et al. (1992). Paradoxically, the radiation exposure that quickly ignited the wooden block did not ignite nor significantly char the fine excelsior fuels (Figures 4d and 4e). These results are inconsistent with the unqualified assumption that radiation heat transfer dominates fuel particle ignition and strongly suggests the need for describing fuel particle heating processes. Our observations of actual fires and exploratory experiments in conjunction with the literature has led us to ask questions about fuel particle heating processes and initiate research to describe and model the processes leading to ignition.

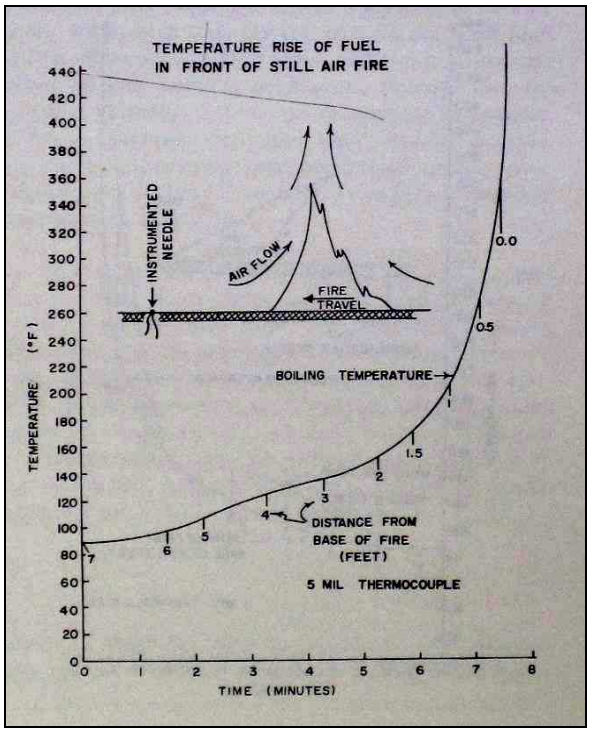


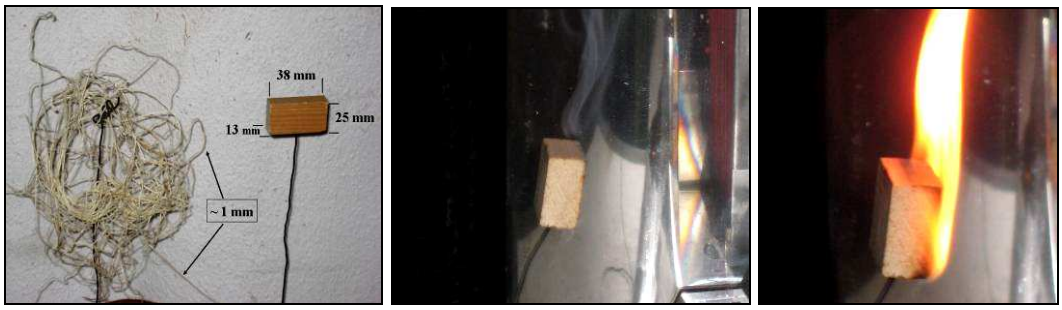
Figure 3 The fuel particle temperature (deg. F) is shown with fire proximity noted below the line. The fuel particle temperature at fire arrival (0 distance) is ~350 F (177 C) and well below significant pyrolysis temperatures (> 275 C). [from Rothermel and Anderson 1966]

2. Preliminary Experiment Describing Fuel Particle Heat Exchange

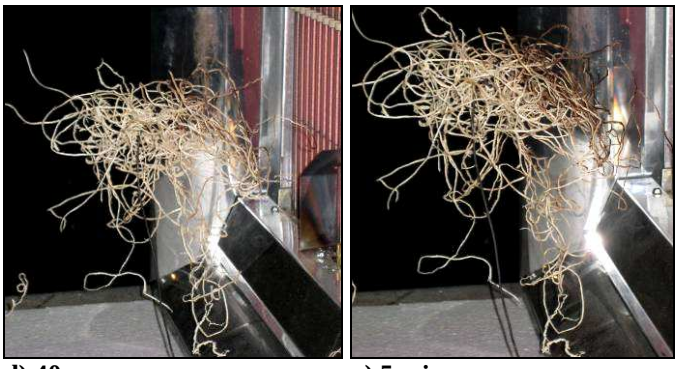
Fuel particle heating studies were conducted as part of an overall research effort directed toward understanding how the living foliage of shrub and tree canopies ignites and sustains fire spread (McAllister et al. 2010; Finney et al. 2010). We are conducting this research to establish a physical basis for reliably estimating the potential for intense fire spread in shrub and tree canopies (crown fires).

Methods

These methods are for a preliminary examination of fuel particle preheating due to thermal radiation exposure. Two different sized fuel particles were made from a single piece of relatively uniform grained "yellow poplar" wood (*Liriodendron tulipifera*) and precisely machined to square cross-sections of 1 mm and 12 mm and had a length of 120 mm (Figure 5a). Both fuel particle sizes were dried before exposure to less than one-percent moisture content (dry mass basis). The fuel particles were exposed to a gas fired, ceramic element radiant panel (.486 m wide x .375 m high) (Figure 5b). Using a .076 mm thermocouple, the average ceramic surface temperature from several locations was 1238 K.

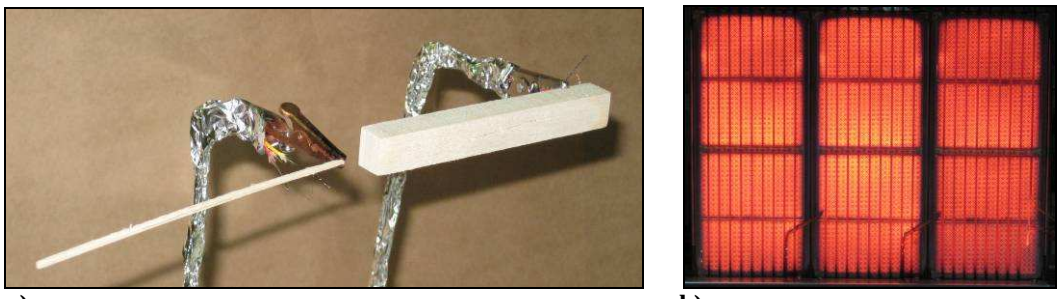


a) Exposed fuels **b) 20 secs** **c) 35 secs**



d) 40 secs **e) 5 mins**

Figure 4 a) The excelsior (*Populus spp*.) on the left with less than a 1 mm cross-section and the Douglas-fir (*Pseudotsuga menziesii*) wood block with dimensions 25 mm x 38 mm x 13 mm (height, width, depth) were equally exposed to radiant heat; b) The wood block quickly started pyrolyzing (20 secs) and; c) Pilot ignition at 35 seconds; d and e) The excelsior did not ignite nor significantly pyrolyze at 40 seconds or at 5 minutes.



a) **b)**

Figure 5 a) Experimental fuel particles having 1 mm (left) and 12 mm (right) square cross-sections and 120 mm in length; b) Ceramic element, gas-fired radiant panel having a radiating surface of .486 meter wide and .375 meter high with an average surface temperature of 1238 K.

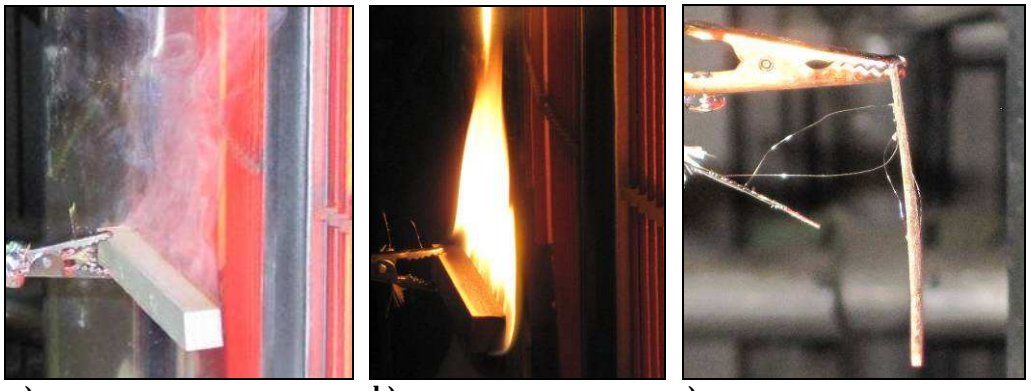
The radiant panel temperatures were within the general range of wildland flame temperatures at the spreading fire front (Butler et al. 2004; Taylor et al. 2004). Assuming burning vegetation and the radiant panel radiate as gray bodies, the panel spectral characteristics are similar to actual flames and can serve as a reasonable facsimile for vegetation fire.

We separately exposed the two different sized fuel particles (Figure 5a) to an incident radiation flux of 41 kW/m^2 in quiescent air. The incident radiation flux was measured prior to fuel particle exposures using a Medtherm® Schmidt-Boelter, water

cooled total heat flux sensor (Medtherm 1997). We assumed the sensor measured the incident radiation as it was positioned 0.10 meters from the radiating surface and beyond the panel flame convection. Fuel particles were placed at the sensor position during exposure. The initial radiation exposure was virtually instantaneous by using a radiation shield during fuel particle placement and then quickly removing it. Each particle was instrumented with a thermocouple (Type K, .076 mm diameter wire) imbedded at the surface center such that the highest radiation exposure produced a cross-grain thermal gradient into the fuel. After heating produced observable pyrolyzates, a small, premixed gas pilot flame was introduced immediately above the top surface of the fuel particle, forward of the front surface.

Results

The results of the fuel particle radiation heating experiment were consistent with prior results; the fine particles did not ignite or significantly pyrolyze during a radiation exposure that resulted in coarser particles igniting. We observed the 12-mm fuel particle significantly emitting pyrolyzates shortly after the initial exposure (Figure 6a) with piloted ignition shortly thereafter (Figure 6b). By comparison, the 1-mm particle had not produced observable pyrolyzates or significant particle charring after 2 minutes when the exposure was terminated (Figure 6c). The fuel particle surface temperatures (exposed face) as shown



a) b) c)

Figure 6 a) The 12 mm fuel particle pyrolyzing after 15 seconds of exposure to a 41 kW/m^2 incident radiation heat flux. b) The same 12 mm fuel particle pilot ignited after 26 seconds. c) The 1 mm fuel particle after 2 minutes at the 41kW/m^2 radiation exposure without ignition or significant pyrolysis.

in Figure 7 are consistent with and help explain the visual observations. Although the 12-mm and 1-mm particle surface temperatures initially increased similarly, they diverged after less than 2 seconds of exposure at a surface temperature of about 130 C. The 12-mm fuel particle surface temperature continued to monotonically increase. The observable pyrolysis shown after 15 seconds of exposure in Figure 6a corresponds to a measured surface temperature of 314 C (Figure 7). Piloted ignition occurred at a measured temperature of 425 C as indicated by the abrupt temperature jump 26 seconds after the initial exposure (Figure 7). The 1-mm particle temperatures largely varied between 160 C and 200 C after the initial temperature increase (Figure 7). Importantly, this temperature range neither produces significant pyrolysis rates nor flammable pyrolyzates (Fairbridge et al. 1978; Tillman et al. 1981; Simmons 1995; Drysdale 1998).

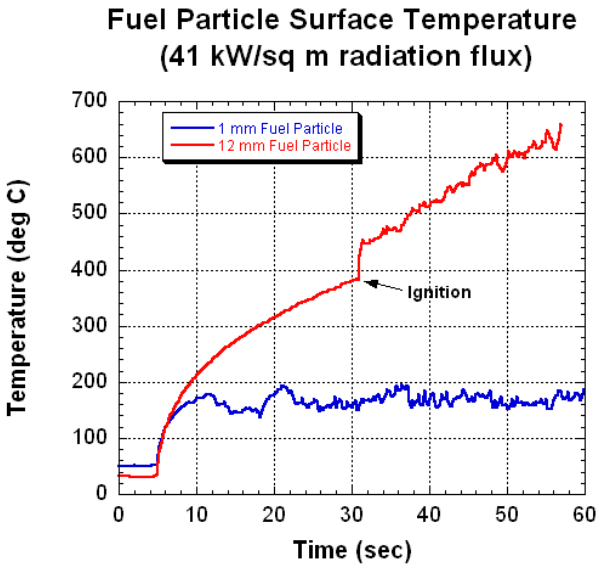


Figure 7 The 1 mm and 12 mm particles were separately exposed to an incident radiation heat flux of 41 kW/m^2. Fuel particle surface temperatures were measured with an imbedded thermocouple in the radiated surface. The 12 mm particle pilot ignited at the time as indicated by the arrow – 26 seconds after the initial exposure.

Discussion

The fuel particle surface temperatures and resulting ignition of only the coarse particle (12mm) are consistent with prior fire spread and fuel particle experiments. Our recent experiments reduced and controlled the factors influencing particle heat exchange as well as measured the resulting temperature of the radiantly heated surface. From these experiments, a pattern of fuel particle transient heat exchange emerges that is consistent with heat transfer theory; fuel temperature is a function of the net radiation and convection heat transfer at particle surfaces and the thermal diffusivity within the particle interior. Two different sized fuel particles will therefore heat at different rates because their surface (boundary) conditions produce different levels of convection cooling. For example, our 12-mm particle (SA/V = 333 m^{-1}) produces a thicker boundary layer than the 1-mm particle (SA/V=4000 m^{-1}). The greater boundary layer development (Incropera and DeWitt 2002) of the 12-mm particle was sufficient to result in its ignition only. This contrasts with the trend expected based on SA/V where higher combustion rates are known to occur for smaller particles. It is true that higher SA/V results in more rapid thermal response of the particle interior (per unit mass) to a change in surface temperature, but SA/V *per se* does not determine boundary conditions. Thus, SA/V does not determine the convective cooling by forced or natural convection of particles receiving radiant fluxes.

Only by considering the particle boundary layer and associated convection cooling can the the non-ignition of the 1-mm particle be explained in contrast to the ignition of the 12-mm particle and even much larger wall sections (Tran et al. 1992; Cohen 2004). Our use of an appropriate laminar free convection heat transfer coefficient correlation (Incopera and DeWitt, Equation 9.27) revealed the effect of a heated vertical surface length (L) on free convection heat exchange. In terms of fuel particle size, this is the vertical length of a fuel particle side exposed to radiation heating. The actual fire context is simplified to an

experimental analogy of a flame source radiantly preheating adjacent fuels. The experimental boundary condition is one of a constant incident radiation heat flux at the vertical face of a wood fuel particle. As the radiation is absorbed, the fuel particle surface temperature increases and thereby induces a buoyant/free convection boundary layer of ambient air at the surface resulting in cooling. Our analysis used a measured, mid-length (*L/2*) 1-mm fuel particle surface temperature of 470K (197 C) to calculate a free convection heat transfer coefficient. We chose this specific temperature because the 1-mm particle fluctuated at or below this near maximum surface temperature while the 12-mm particle continued heating to ignition (Figure 7). We show the relationship between particle size and the free convection heat transfer coefficient in Figure 8.

Our analysis of the free convection heat transfer coefficient revealed significant potential heat exchange differences as a function of surface length in general and specifically for the 1-mm and 12-mm fuel particles used in our experiment. Inspection of our free convection analysis (Figure 8) agrees with the experimental results. The 1-mm particle has a significantly higher (more than 3-times) free convection coefficient than the 12-mm particle. This is consistent with the 12-mm particle igniting but not the 1-mm particle. In addition, the resulting free convection coefficients (Figure 8) are consistent with the empirical ignition model (Tran et al. 1992; Cohen 2004) predicting the 12-mm particle ignition. The 12-mm and larger particles (longer surface lengths) are on the low sensitivity portion of the function and thus, the convection coefficients are not significantly different for a wide range of vertical surfaces from a 12-mm particle to a wood-wall panel. Notably, the experimental 1-mm particle is at the coarse end of fine fuels (Scott and Burgan 2005) and particularly some western U.S. coniferous and shrub foliage known for active crown fire (Rothermel and Anderson 1966; Philpot and Rothermel 1973). Based on Figure 8, we would expect fuel particles finer than 1-mm (with non-elongated cross-sections) to have greater convection cooling during a flame radiation exposure.

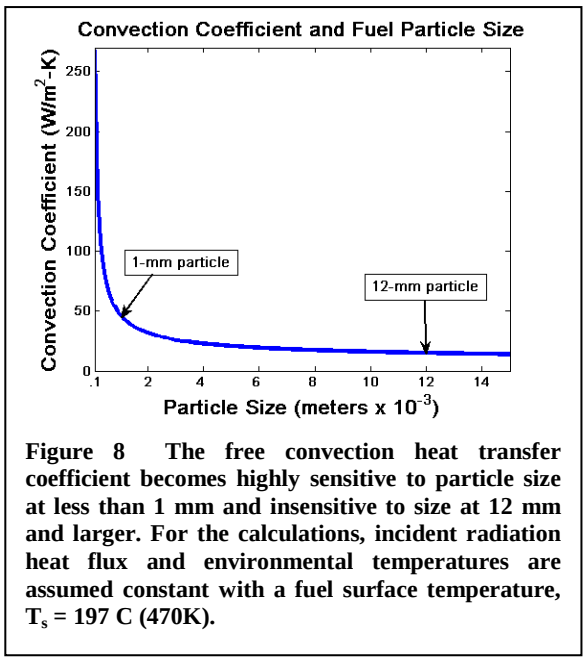


Figure 8 The free convection heat transfer coefficient becomes highly sensitive to particle size at less than 1 mm and insensitive to size at 12 mm and larger. For the calculations, incident radiation heat flux and environmental temperatures are assumed constant with a fuel surface temperature, T_s = 197 C (470K).

We examined post crown fire burn patterns to check consistency with our laboratory findings. The necessity of flame contact (convection heating) for ignition would indicate that radiation and convection preheating sufficient for ignition would occur over a few meters distance. This is the possible scale of lateral flame extensions from the flaming front across gaps to adjacent fuels. If this is the case then evidence from actual crown fires should be found revealing intense burning as indicated by complete canopy fine fuel consumption adjacent to unconsumed, largely uncharred foliage. An examination of post-burn evidence would reveal a crown fire with an abrupt transition from complete foliage consumption juxtaposed to unconsumed canopy (Figure 9). Although surface fire and associated canopy foliage mortality might be evident an extended gradient of foliage

consumption and charring laterally through the canopy would be absent. We readily found such post-burn patterns in burned areas of active crown fire (Figure 9).

a) **b)**

Figure 9 a) A crown fire spread from right to left at nearly a right angle to the road. The gap of 10 to 15 meters not only ceased canopy fire spread but inspection revealed no significant charring/pyrolysis of the left side canopy (Rodeo-Chediski Fire, June 2003, Arizona, USA); b) The consumed canopy foliage (black) and the uncharred/unpyrolyzed but needle-killed canopy foliage (brown border) are separated by less than a canopy width (Alder Creek Fire, August 2000, Montana, USA).

Our experiments and analyses suggest convection as a principal heat transfer mechanism particularly in low density shrub and tree canopy foliage. The different degree of convection cooling demonstrated by our experiments was principally due to increasing boundary layer thickness with flow length (Incopera and DeWitt 2002; Kays et al. 2005). This will occur for free and forced convection. Thus, the convection heat exchange whether cooling or heating will be primarily governed by the fuel configuration (surface flow length) rather than its SA/V. Future research is necessary for explicitly and comprehensively determining fuel particle heat exchange for fuel particle geometries and clusters.

3. Conclusions

We cannot assume the nature of fuel particle heat exchange during wildland fire spread without a comprehensive experimental and theoretical basis. Our preliminary experimental results concurred with previous experimental demonstrations of coarse fuel particles igniting while finer fuels did not. Our results were also consistent with studies resulting in fine fuels reaching ignition level temperatures only after flames reached preheating fuels. Our analysis of the free convection heat transfer coefficient as a function of fuel particle size suggests convection cooling as the principal physical mechanism explaining the experimental results. This additionally suggests fuel shape, the particle side lengths (e.g. needles vs leaves), to be as important to fuel particle heating as the SA/V. Our preliminary results reveal the need to represent heat transfer mechanisms in physical fire models based on explicit fuel particle experiments and a fundamental theory of fire spread.

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