Characterization of convective heating in full scale wildland fires

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Abstract

Data collected in the International Crown Fire modeling Experiment during 1999 are evaluated to characterize the magnitude and duration of convective energy heating in full scale crown fires. To accomplish this objective data on total and radiant incident heat flux, air temperature, and horizontal and vertical gas velocities were evaluated. Total and radiant energy fluxes were measured. Temperatures were measured using bare Type K 0.13 mm wire diameter thermocouples. Gas velocities were measured using pitot-static type sensors designed specifically for velocity measurements in fires. The experiments occurred in 14 m tall jack pine stands. Flames were 18-25 m tall, fire spread rates were between 0.5 and 1.0 m-s^{-1}. The magnitudes of the temperatures presented are representative of those found in naturally occurring wildland fires. The measured peak gas temperatures varied from 1000 to 2000 K, and gas velocities of 10 to 20 m-s^{-1}. Convective heating rates reached 150 kW-m^{-2} for short durations (5 to 10 seconds) with sustained flux rates of 40 to 80 kW-m^{-2} for durations of (~20 to 40 s). The data suggest that maximum convective heat transfer coefficients to the sensor face range from 30 to 50 W-m^{-2}-K^{-1}.

Keywords: Fire Behavior, Fire Intensity

## 1.	Introduction

Many questions exist regarding how energy is released and transported from wildland fires to the surroundings. In the past it has been stated that, at least for crown fires, radiant energy transport dominates the energy exchange process (Albini 1986). More recently, laboratory and field studies have indicated that convection may be just as critical to the energy transport as radiation (Anderson, et al. 2010; Finney, et al. 2010; Frankman, et al. 2010). A set of experiments conducted in a controlled laboratory environment suggest that the heating can be divided into roughly two regimes: The first is characterized as heating that occurs far from the flame (i.e. greater than one flame length) and is dominated by radiant energy transport. As the flame approaches within one flame length and closer a second regime develops where radiant energy transport increases exponentially, but convective energy transport plays a duel role. At first convection generally acts in a cooling mode, counteracting the radiant driven heating, however just prior to arrival of the flame front convective heating reverse and contributes substantial energy to the heating process (Anderson, et al. 2010). Extrapolation of these results to naturally burning fires can be difficult. Anecdotal observations suggest that some cases exist were

radiation indeed dominates the energy transport process, for example a fire spreading through grass in the absence of wind would seem to be driven by radiant heating ahead of the flaming front, or a large crown fire with minimal wind would also be characterized by radiant heating. However, in the case of the crown fire it is difficult to separate the radiant heating from the advective influence of lofting and ignition from burning embers. The opposite side of the spectrum would be a fire burning through grass in the presence of a very strong ambient wind. The wind causes the flames to reach far head of the burning front igniting stems far in advance of the fire. Intuitively it seems that in this case convective energy transport would be significant and potentially dominate the energy transport and fire spread.

In this study data collected from the International Crown Fire modeling Experiment during 1999 (Stocks, et al. 2004) are evaluated to characterize the magnitude and duration of convective energy heating in full scale crown fires. 13.6 m tall towers were placed approximately 10 m inside the downwind edge of the burn unit with sensors located 3.3, 6, 9, 12.1, and 13.6 m above the ground surface (Butler, et al. 2004). The experiments occurred in 14 m tall jack pine stands. Flames were 18 to 25 m tall, fire spread rates were between 0.5 and 1.0 m-s^{-1} (Taylor, et al. 2004).

2.   Methods

Characterization of energy transport in a wildland fire environment can be difficult due to high temperatures, remote locations, wide variation in environments, and variability in fire behavior at relatively small temporal and spatial scales. The data presented here were gathered in a set of experiments that required the design of a unique set of sensors (Butler, et al. 2004). To summarize total and radiant energy fluxes were measured using dual window schmidt-boelter thermopile sensors. Flame emissive power was measured using a custom designed sensor (Butler 1993). Temperatures were measured using bare Type K 0.13 mm wire diameter thermocouples. Gas velocities were measured using pitot-static type sensors (McCaffrey and Heskestad 1976) designed specifically for velocity measurements in fires. The radiant energy is separated from the total energy by placing an identical sensor adjacent to the first and covering it with a sapphire window to prevent convective heating. Both sensors are mounted in 2.5 cm diameter brass bodies which is then secured in 7.5 cm diameter aluminum bodies that act as heat sinks. The entire package is insulated with only the sensor surfaces exposed to the environment. The temperature measurements can include significant uncertainty (i.e. hundreds of degrees) but in the environment of a full scale crown fire where flames are optically thick and contain significant soot then the uncertainty due to radiative cooling or heating is reduced, especially for small diameter new (shiny) sensors. The error for the measurements reported here is estimated at ±40 K. The flame emissive power measurements were made using a narrow angle radiometer with an associated measurement uncertainty of ±3%. The total flux measurements are assumed to have a similar uncertainty. The radiant flux sensors; however, are subject to a set of relatively severe assumptions. They are calibrated using a high temperature source that may not approximate that produced by a wildland flame. The manufacturer suggests that error is reduced as the effective radiant temperature of the source increases. An error of ±20% is assigned to the radiant heat flux measurements, albeit based on somewhat arbitrary assumptions. For the purposes of this discussion a rough measure of the convective energy incident on the face of the

sensor is defined to be the difference between the total and radiative energy sensors. Clearly, it is acknowledged that significant uncertainty exists due to the difference in the spectral properties of the calibration source and a naturally burning fire relative to the transmission properties of the sapphire windows used on the radiation sensors. Butler et al. (2010) provides a in-depth discussion of these sensors and implies that such an assumption may include significant error.

3.   Data Analysis and Discussion

Figures 1 presents representative measurements of total and radiant thermal energy flux incident on sensors located within the forest stand. The data indicate that as the flame approaches (prior to time 573 s) the dominant mode of energy transfer is by thermal radiation. At the time of ignition at the sensor location (~572 s) radiant energy accounts for approximately 90 % of the total energy transfer. However, during ignition (time 572-575 s) convective energy heating (difference between total and radiant) increases dramatically accounting for nearly 50% of the total energy load. As the flame passes, the proportion changes to approximately 50 percent radiant and 50 percent convective energy.
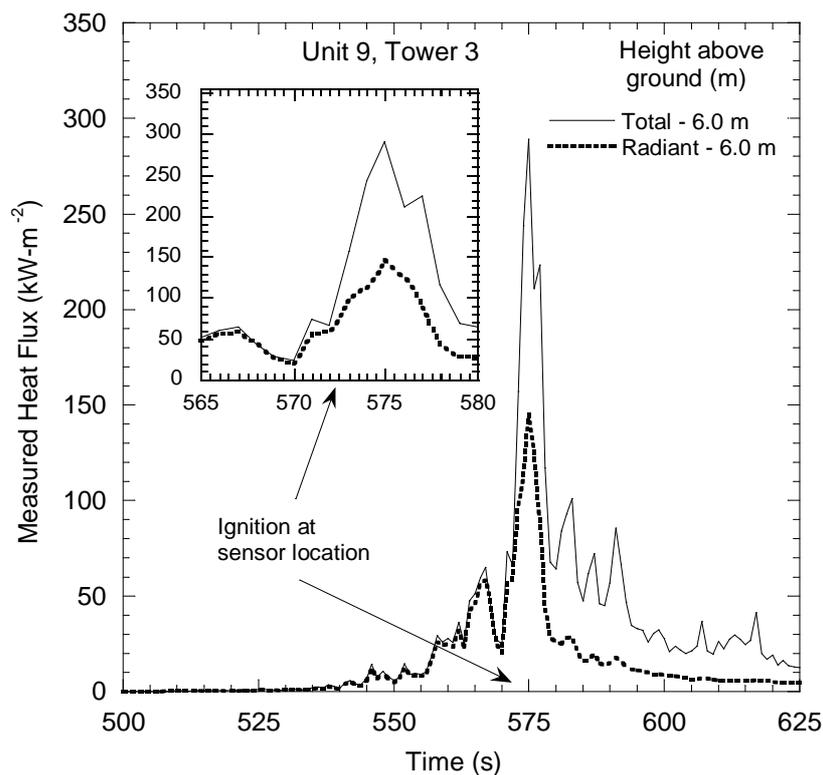

Figure 1—Representative time trace of measured incident total and radiant energy flux collected 6.0 m above the ground.

Figure 2 presents the calculated convective energy flux (the difference between the total and radiant energy) for all of the sensors on the tower. Ignition is defined to occur at the time that a heating trace shows a rapid and significant rise (e.g. 572 s for 9.0 m location). However it is

unclear if the rise at 570 s for the 6.0 m location is a heating pulse or actual ignition. Likely it indicates the passage of a high temperature gas pulse (i.e. flame). Some convective cooling is indicated in the period 5 to 10 s prior to ignition. The inset graph provides a "close-up" of the heating immediately prior to and during the ignition event. The data suggest that ignition occurs first in the mid story locations (i.e. 6 and 9 m at 570 and 572 s respectively) and then the upper portion of the canopy (~576 s) followed last by ignition at in the lower (<3.3 m) portion of the stand (~580 s). This seems to agree with the observations made by others in laboratory experiments (Finney, et al. 2010), and suggests that laboratory scale experiments may indeed provide insight into the physical mechanisms governing wildland fire spread at the scales characteristic of crown fires. The maximum magnitude of the convective energy transfer to be approximately 195 kW-m^{-2} but only for a relatively short duration (<5 s) at occurred in at the 3.3 m sensor, suggesting that maximum heating occurs in the lower portion of the stand. This has potential implications into how ignition occurs in these types of fires.
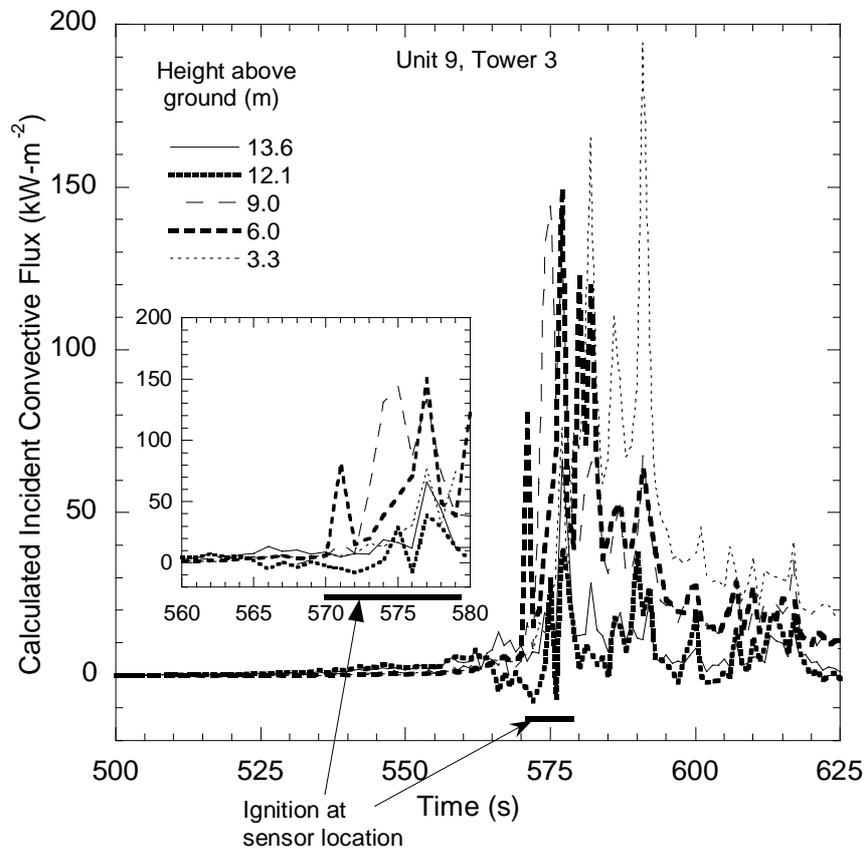

Figure 2—Convective energy flux calculated as the difference between the measured total and radiant energy fluxes for all sensor locations on Tower 3 in Burn Unit 9. Inset plot is close-up of heating history prior to and during ignition. Heavy bars indicate assumed ignition times.
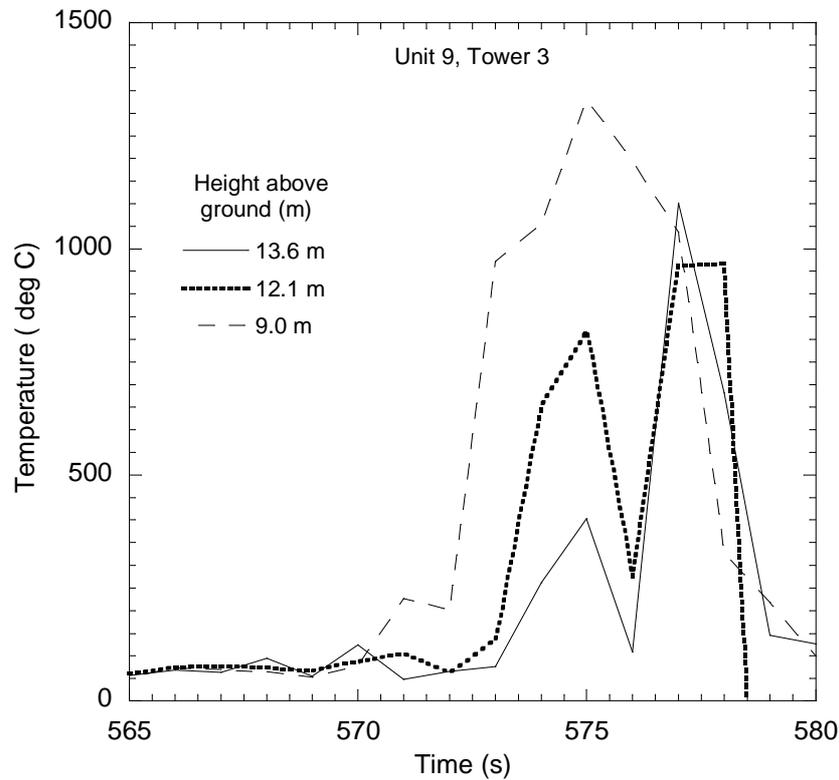
Figure 3—Measured air temperatures collected during the crown fire experiments.

Measured air temperatures are shown in figure 3. Unfortunately, sensors at 3.3 and 6.0 m failed prior to the ignition event and the sensor at 12.1 m failed during ignition. Temperatures immediately prior to ignition indicate some short convective heating pulses, but they seem to be characterized by relatively low temperatures until 2 to 4 s prior to ignition. Data reported earlier from all of the burn units suggests that maximum air temperatures occur in the lower portion of the forest stand and are about 1400K (Butler, et al. 2004) which seems to correspond with the data shown here. The temperature data support our earlier supposition that ignition occurred at 572 s at the 9.0 m height. It is not clear if the first temperature pulse shown at 573 s for the 12.1 and 13.6 locations is ignition or indicates "flame bathing" with ignition occurring at 576 s. The fact that subsequent rise is steeper and reaches higher maximums indicates that indeed the first pulse is a flame bathing but ignition. The temperature rise rates vary from 333 to 980 K-s^{-1} with the greatest occurring in the upper portion of the canopy.

Figures 4 presents measured vertical and horizontal air flow velocities 9 m above the ground within the forest stand. The data indicate the magnitude of the gas velocities that could be expected under relatively intense burning conditions. As indicated in figures 1-3 the ignition occurs at approximately 572 s. Prior to ignition the vertical flow environment is characterized by intermittent upward pulses with a strong downward pulse at ignition and very strong (~10 m-s^{-1}) upward pulse during ignition. The horizontal flow is characterized by It is interesting to note that the horizontal flow reverses and is directed into the oncoming flame approximately 1 minute before the flame arrives. As the flame passes the flow reverses and is relatively strong in

direction of the flame travel and upward. It is intended that this data provide some indication of the magnitude of air flow velocities that would be driving the convective energy transfer.
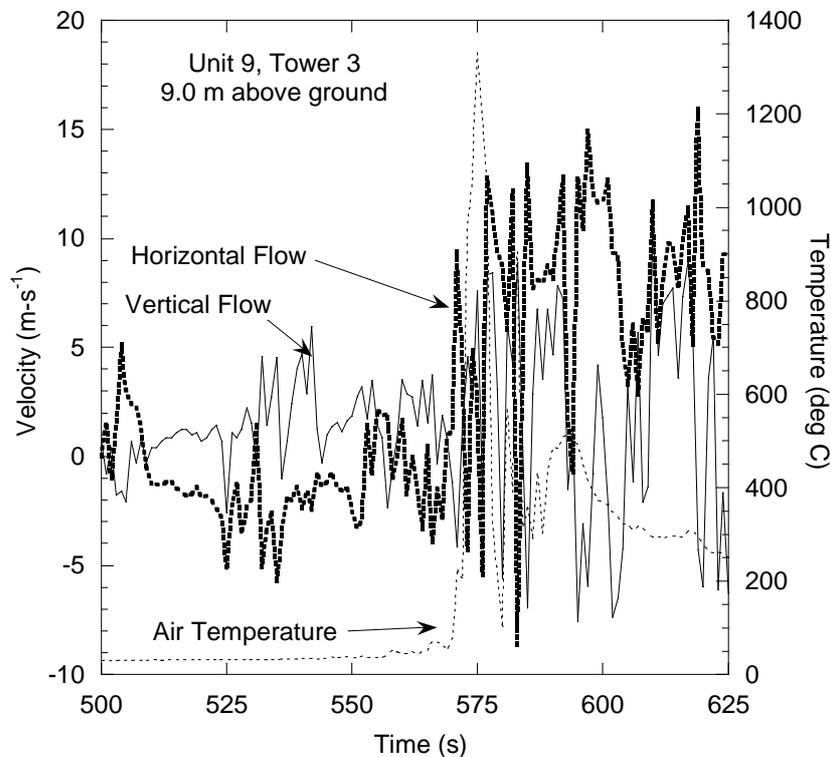

Figure 4- Horizontal and vertical gas velocities measured 9 m above the ground surface. Positive values indicate flow in the direct of the flame movement or upward flow for the horizontal and vertical sensors respectively. Temperature is included to indicate ignition.

The local convective heat flux can be expressed as q=h(Ts-Tf) where h is the local convective coefficient. Ts is the surface temperature and Tf is the fluid temperature. Assuming that the surface temperature of the sensor remains relatively low (near ambient) and constant at least up to ignition, we can estimate the heat transfer coefficient (h) from our data by dividing the calculated convective heat flux (represented by q) by the absolute temperature of the fluid (see figure 5). Figure 5 suggests convective heat transfer coefficient can reach 120W-m^{-2}-K^{-1} during the peak heating period at ignition. Referring to published equations for flat plates and impinging jets and using values for air temperature of 1200 K, air velocity of 10 m-s^{-1}, and characteristic lengths of 0.5 m we obtain heat transfer coefficients of between 15 and 100 W-m^{-2}-K^{-1} (Incropera and Dewitt, 2002), suggesting that these measurements are in the range of published data. An average heat transfer coefficient for the heating period up to ignition would be approximately 50 W-m^{-2}-K^{-1}.
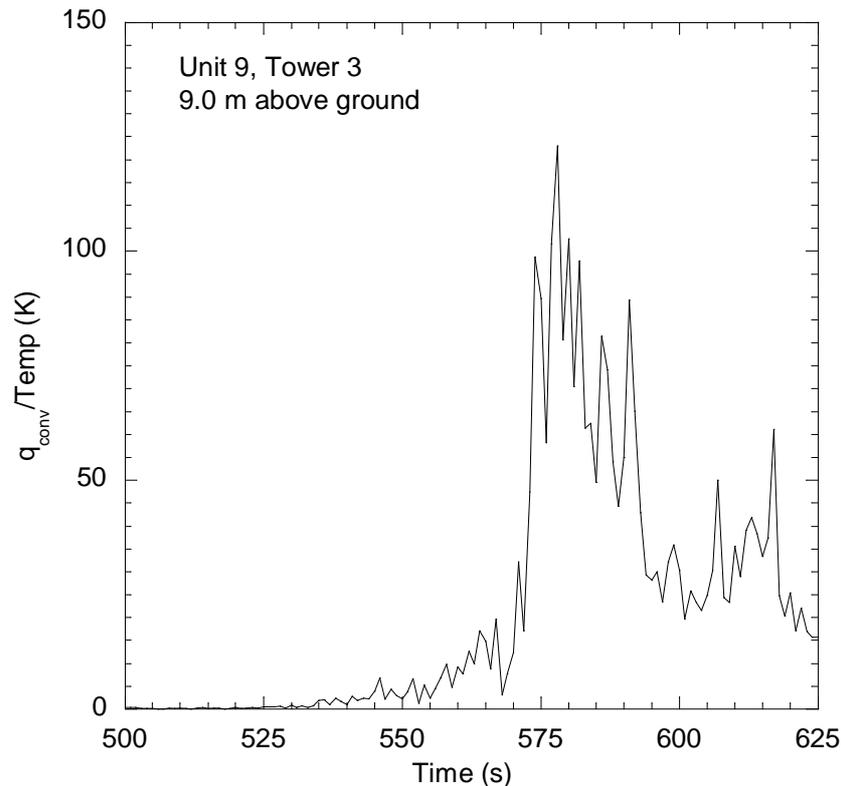
Figure 5—Calculated convective heat transfer coefficient obtained by dividing convective flux by measured air temperature.

While this analysis is fraught with many gross assumptions for the sensors and associated heat transfer analysis, it suggests that convective energy transport may be as important as radiant energy transport to the overall ignition and fire spread process in crown fires. The data qualitatively match observations from the work of others performed in relatively small scale laboratory experiments (Anderson, et al. 2010; Babrauskas 2001; Finney, et al. 2010). The analysis described above is simple and based on many assumptions; however it seems that some conclusions can be drawn from these data. It is the opinion of the author that the magnitudes of the temperatures presented are representative of those found in naturally occurring wildland fires. The measured radiant and total heat fluxes are also representative of those occurring in wildland fires. These data suggest that a wildland fire convective heating environment can be characterized by gas temperatures between 1000 and 2000 K, with associated maximum gas velocities of 10 to 20 m-s^{-1}. Convective heating fluxes at the sensor face can reach 120 kW-m^{-2} for short durations (5 to 10 s) and 40 to 80 kW-m^{-2} over longer time periods (i.e. 20 to 40 s). Maximum calculated convective heat transfer coefficients based on these measurements reach 120 W-m^{-2}-K^{-1}.

4. Conclusions

A simple analysis has been performed examining the relative contribution of convective and radiant heating to the fire ignition process in full-scale crown fires. The findings suggest that convective cooling can be significant prior to ignition and that convective heating at the immediately prior to and at the time of ignition is extreme. Fossil fuel combustion suggests that convective energy transport is a significant factor in transferring energy from the flames to their surroundings (Butler, et al. 1992). It is logical that similar implications apply to wildland fire. These data support that assumption. Additionally the data indicate ignition is characterized by extremely fast rises in temperature ($\sim$ 333 to 980 K-s^{-1}) and that temperature and heat flux data compare relatively well as indicators of ignition. To conclude, it is generally acknowledge that wood combustion is highly complex, the development of any models of fire ignition and spread must depend on generalizations of the complex energy, chemical and fluid dynamic processes (Babrauskas, 2001). This simple analysis suggests that given the rapid temperature rises indicated by the measurements reported here, it would be difficult to identify a specific ignition temperature (i.e. the traditional ignition model). This implies that perhaps a more relevant approach to modeling fire ignition and spread would be to characterize ignition as a function of fuel descriptors (i.e. particle size, moisture content, shape, chemical properties, etc) and heating rate or cumulative heat load.

5. Acknowledgements

6. References

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