Structure of Diffusion Flames from a Vertical Burner

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Abstract
Non-steady and turbulent flames are commonly observed to produce flame contacts with adjacent fuels during fire spread in a wide range of fuel bed depths. A stationary gas-fired burner (flame wall) was developed to begin study of flame edge variability along an analagous vertical fuel source. This flame wall is surrogate for a combustion interface at the edge of a deep (1.8 meters), vertically arranged fuel bed. Thermocouple and heat flux measurements along the flame wall indicate most of the variability in flame convection occurs at frequencies lower than 10-20 Hz. The variability and flame volume increased with increased height (turbulence) and fuel gas flow rate (flame mass).

Keywords: Flames, Turbulence, Vertical Burner, Wall Fire

1. Introduction

At the leading edge of a wildland fire, the interface between burning and unburned fuel is inclined at a positive angle in the direction of spread from the ground toward the top of the fuel bed (Hottel *et al*. 1971, Albini 1986, Baines 1990). The ignition interface has the same vertical dimension as the fuel bed, which can vary from a few centimeters in surface fuels to tens of meters in forest canopies and crown fires. Flame structure in buoyancy driven flow along this interface is typically turbulent (Thomas 1961, Yedinak et al. 2010) potentially with flow length scales as short as 10 centimeters (Delichatsios 1986). Turbulent/non-steady flow means fuel particles ahead of the burning zone likely experience intermittent flame contact prior to ignition (Thomas 1967, Nelson and Adkins 1987, Weber 1990, Baines 1990, Pitts 1991, Beer 1995, Finney *et al*. 2010). Given the questionable sufficiency of radiation for fine fuel heating prior to ignition (Cohen and Finney 2010), understanding convection heating through non-steady flame contact becomes important. Detailed measurements of the variability in flame convection are, however, difficult to obtain on spreading fires because of the moving interface, short residence time, variable burning rates, and fuel burnout. Thus, the use of a stationary vertical fuel source was thought to be useful for gaining understanding of the convective environment at the ignition interface.

Gas-panel burners have been used previously to study vertical flame structure and heat transfer to interior walls of buildings (de Ris and Orloff 1975, Ahmad and Faeth 1979, Wang et al. 2002). The primary interest of these studies has been the mean temperature and velocity profiles extending up and away from the wall (Delichatsios 1982, Bertin et al. 2002) and for the upward spread and burning rates of solid fuels on the walls (Quintiere et al. 1986). For wildland fire spread, it is the non-steady convection resulting in flame extensions normal to the vertical interface that is of interest due to its potential significance to the ignition process. This paper describes an experimental study of some aspects of variable flame structure along the vertical edge of a flame wall.

2. Methods

We developed a vertical flame source to study diffusion flame geometry and turbulence. The rectangular burner was constructed from a tubular steel frame with inside dimensions of 0.61 m wide, 1.83 m tall, and 0.15 m deep (**Figure 1**). The interior volume of the frame was enclosed by a solid back panel and a two-layer flow equalizer. The first flow equalizing panel was composed of fiberglass fabric and the second panel was ceramic foam 2.5 cm thick (porosity of 17.7 pores per centimeter (45 pores per inch)). A 2cm layer of fiberglass insulation was inserted between these two layers. The ceramic foam was made of Cordierite[1] ™ which has properties of low thermal expansion for use in burners and was coated with a silicon carbide spray for durability. The burner was supplied with ethylene gas by means of six inlets (3 on top and bottom) connected internally by a perforated tubing manifold. The open-chamber design and low pressure drop across the flow equalizers made the burner susceptible to uneven gas flow across the face of the burner. Low gas flow

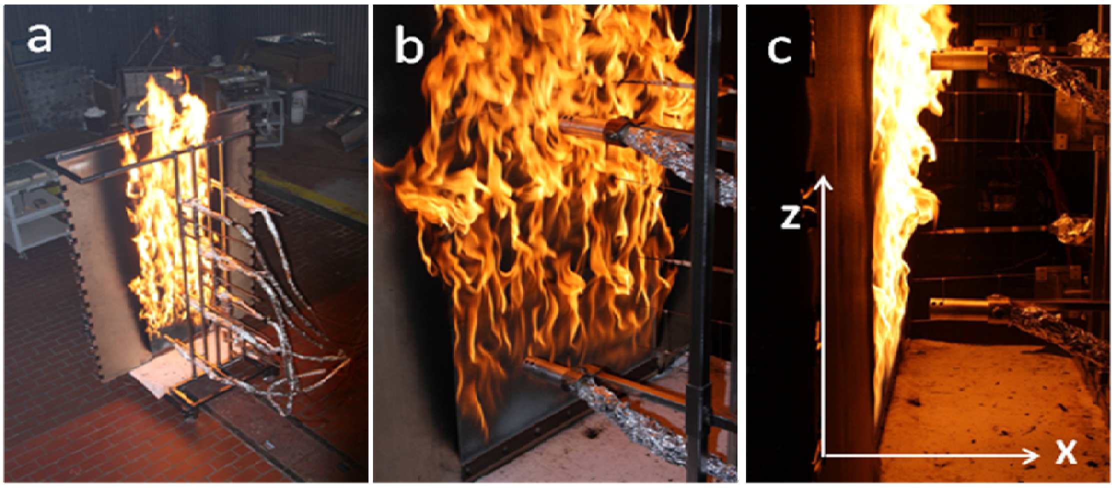

Figure 1. Photographs of flame wall apparatus showing (a) sensor placement, (b) transition from laminar to turbulent flame structure, (c) close-up of turbulent eddies intersecting heat flux sensor and thermocouple arrays. Axes labels are shown for reference as Z for vertical and X for horizontal dimensions.

occurred at the burner top for negatively buoyant propane and at the burner bottom for positively buoyant methane. We, therefore, chose ethylene (molecular weight 28.05) as the fuel gas due to its near neutral buoyancy compared to ambient air (molecular weight 28.96). Prior to ignition, the chamber was purged with nitrogen. Ethylene was introduced to the mixture until sustainable ignition occurred and the nitrogen flow could be halted.

The experiment was designed to examine the flame structure characteristics as a function of fuel-gas flow rate. Burning rates were controlled using a mass flow controller calibrated to ethylene gas. Flow rates were adjusted to pre-determined levels of 115, 155, 235, 315, 390 and 470 liters per minute. The flame properties of interest were:

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[1] Cordeirite is a trademark of Sud Chemie Hi-Tech Ceramics Corporation, Alfred, New York. Use of brand name does not constitute product endorsement.

1. The time-series of flame contacts relative to the horizontal distance and vertical position (X and Z) relative to the burner face (see axes in Figure 1);
2. The frequency spectra of heat flux and temperature for different horizontal distances and heights along the burner face; and,
3. The vertical profile showing the horizontal displacement of flame from the burner face.

Sensors and data acquisition

Two analog sensor systems were used during the experiment to measure heat flux and flame horizontal temperature profile. Analog flux and temperature data were sampled, digitized and recorded by a National Instruments Inc.[2] data acquisition system.

Heat Flux. Total heat flux was measured using Vatell Corporation[2] HFM-7 E/H high temperature flux sensor and signal conditioned with a Vatell AMP-10 amplifier. These sensors make two measurements, heat flux to the sensor and sensor core temperature. Core reference temperature is maintained relatively constant by water cooling. These flux sensors were designed to be water cooled and approximately 1.8 Liters per min. (½ gallon per min.) was circulated through the sensor during the experiment for this purpose.

Heat flux is measured by a thermopile heat flux sensor (HFS) on the sensor face while temperature is measured by a platinum thin film resistance temperature sensor (RTS) looped around the outer edge of the sensor face. The RTS measurement is used to reference the temperature dependence of the HFS measurement. The HFS was factory coated with a black paint giving the sensor an absorptivity of 0.94; however, this coating reduces the response time of the sensor to 300μs. Equation 1 can be used to determine the half power bandwidth of a system when given its response time:

$$BW = \frac{0.159}{\tau} \qquad [1]$$

where BW is the bandwidth of the system and τ is its response time. Equation 1 gives a 531 Hz bandwidth for the HFS.

Each AMP-10 amplifier is designed with two channels, one for the HFS and the other for the RTS. The AMP-10 amplifiers were operated at gain settings of 500 for the HFS measurement and 200 for the RTS measurement. At these gain settings the bandwidth of each channel is 50kHz and 100kHz respectively indicating that the sensor will limit the bandwidth of the system.

Horizontal Temperature Variations. The horizontal temperature profile of the flame was determined by using thermocouple sensors composed of six 0.00508 cm (0.002 in) diameter type K thermocouples spaced horizontally at 2 cm intervals extending out from the surface of the flame wall. Four sets of these thermocouple arrays were installed at heights of 35, 78, 123, and 169 cm above the base of the wall. Type K thermocouples were used due to their relatively high maximum temperature range (1300+°C), low cost and fine wire availability. The body of each sensor was composed of six pieces of 0.15748 cm (0.062 in) diameter,

[2] Brand name is provided for information and does not constitute endorsement.

metal sheathed and MgO filled type-K thermocouple wire bonded together to form a sensor 0.15748 cm (0.062 in) wide by 0.9488 cm (0.372 in) tall. The internal wires were extended 1.905 cm (0.75 in) beyond the ends of the sheathing and were bent at 90° to the sheath. Bare thermocouples 0.00508 cm (0.002 in) diameter were resistance welded to these wires. Type K connectors and extension wires were used to interface each sensor to a SCXI 1303 module in the data acquisition system. The measured response time of the diameter bare thermocouple wire in 5m/s moving air was found to be approximately 50ms. Equation 1 gives a sensor bandwidth of approximately 3 Hz.

Data acquisition. A National Instruments Inc.[2] SCXI data acquisition system was used to sample and digitize the analog data with 16 bit resolution at a rate of 500 Hz. It was necessary to band limit the analog signals to below the Nyquist frequency of 250 Hz before digitizing in order to prevent aliasing artifacts from appearing in the sampled data. HFS and RTS signals were band limited by a National Instruments SCXI 1141 8^{th} order elliptic low pass filter with a cutoff frequency (f_c) of 150Hz. This filter has 80 dB of stop band attenuation at $1.5*f_c$ or in this case, 225 Hz, just below the Nyquist frequency. Thermocouple signals were interfaced to the data acquisition system through a National Instruments SCXI 1102B module with a f_c of 200 Hz. Assuming a single pole transfer function for the thermocouple response, the thermocouple signal will roll off at a 20 dB/decade rate after f_c. Signals from the 0.00508 cm (0.002 cm) diameter thermocouples will be attenuated by approximately 44 dB at the Nyquist frequency and will be further attenuated at 20 dB/decade beyond 200 Hz by the 1102B module.

Analysis. For frequency domain collections, heat flux signals were processed by Fourier analysis to examine the frequency spectra at each X,Z position. Time-domain analysis examined the autocorrelation and intermittency statistics of the time-series.

3. Results and Discussion

The flame wall experiments were found to be very consistent and controllable. Figure 2 illustrates the comparison of temperature means and ranges for four replications each at different mass flow rates for the thermocouples positioned 169 cm in height and 4cm from the wall. Average velocity near the top of the flame wall was estimated at approximately 4 to 5 m s^{-1} using correlations of temperature between vertically paired thermocouples. This technique cannot give precise indications of flow field velocity or changes throughout the flame profle. Further work is planned for use of particle image velocimetry (PIV) to estimate flow velocity, similar to other work on flame structure on vertical walls (Annarumma et al. 1992).

The time-series of thermocouple temperature showed coincidence of

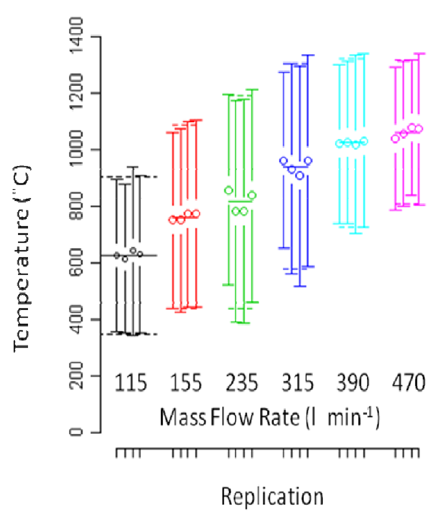

Figure 2. Graph showing the consistency among replications for means and ranges of thermocouple temperature measurements at a distance of 4 cm from the wall surface at 169 cm height for different ethylene gas mass flow rates.

fluctuations recorded at distances of 4 to 14 cm from the flame wall (Figure 3a). This likely reflects the coherent structure of turbulent flame eddies that sweep past the positions of the thermocouples in the linear array which extends perpendicularly away from the wall. The general shape of the time-series temperature fluctuations (Figure 3a) also suggested slower descent of temperature than ascent which might be produced by temperature and velocity gradients in the eddies or by intermittent presence of forced convection.

Thermocouples closer to the wall had noticeably higher frequencies than those farther from the wall because they were presumably affected by smaller eddies. This was verified by Fourier analysis of the temperature time series (Figure 3b) which revealed greater signal power at higher frequencies for thermocouples closer to the wall. Interestingly, there was no evidence along the wall of periodic or pulsating behavior found in pool fires (Malakasera et al. 1996). Probably, this is explained by the strong dependency of pulsation frequency on pool diameter which has a negligable dimension along the base of our wall fire. Frequency analysis suggested very little power at frequencies greater than about 10 Hz (Figure 3b) regardless of the height along the flame wall, distance from the wall, or mass flow rate of ethylene gas. This finding is partly a function of the relatively slow response time of the 0.00508 cm (0.002 in) thermocouples which reduces the power of signal detection at frequencies above the band width of 3 Hz (½ power at 6Hz and ¼ at 12 Hz). By comparison, spectral density plots of heat flux, obtained from sensors with much faster response times and a bandwidth of over 500 Hz, revealed greater signal power at frequencies above 10 Hz than the temperature data but also confirmed that most of the power is concentrated below about 20 Hz (Figure 3c). The critical question for our purposes is determined by the response time of fuel particles that would experience such intermittent flame bathing Undoubtedtly, all wildland fuel particles are thicker than the thermocouples used here. Fuel particles should, therefore, be largely insensitive to fluctuations in the thermal environment at frequencies higher than about 6 Hz, and logically, even lower than recorded by these thermocouples.

Two other features of the thermocouple temperature time-series (e.g. Figure 3a) were evident. First, the lower magnitude, amplitude, and frequency of the temperature-signals at increasing distances from the wall suggested only larger eddies with greater entrainment mixing with cooler air were present at greater distances. Second, there appeared to be an increasing time-lag between temperature peaks with distance between thermocouples. This could partly be related to the geometric effects of the sizes and shapes of eddies as they encounter the sensor array. For example, eddies with roughly circular cross-sections would hit thermocouples in a linear array at different times. Details of these features were examined by correlation analysis (Figure 4a) which showed reduced correlation with thermocouple separation distance (from about 0.75 between the 4 cm and 6 cm thermocouples to about 0.4 between the 4cm and 14cm thermocouples) and increasing lag between temperatures recorded at longer distances. Auto-correlation of temperature signals at all distances from the wall were very similar at a given height (Figure 4b) and suggested insignificant autocorrleation at lags longer than about 1/5th second.

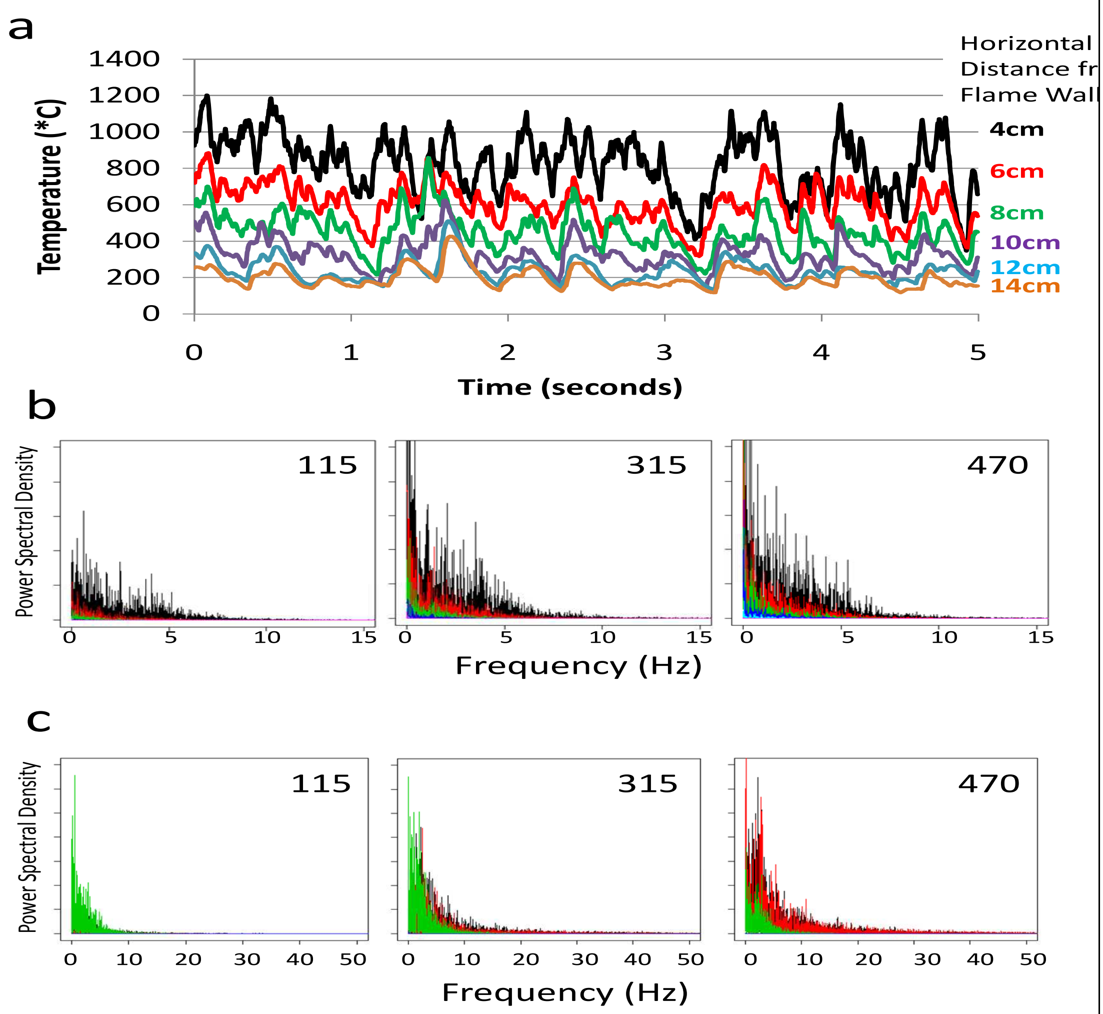

Figure 3. Time-series data from the flame wall suggest (a) temperature fluctuations are correlated at multiple distances but higher frequency fluctuations occur near the wall (4cm) compared to farther away (14cm). (b) Spectral density plots of thermocouple temperature data suggest little power in the signal at frequencies greater than about 10 Hz for mass flow rates of 115, 315 and 470 liters of ethylene burned per minute. This is partly caused by slow response time of the thermocouples compared to (c) heat flux sensors that inidcate more power in the spectrum at frequences up to about 20 Hz at the same ethylene mass flow rates. Colors in the frequency spectra are from thermocouples at different distances from the flame wall surface (as labeled in panel (a)). Data shown are from sensor positions of 169 cm in height along the wall.

The thermocouple and heat flux measurements revealed patterns of increasing variability with height and with mass flow rate (Figure 5). One way of characterizing the variability is through a level-crossing probability, in other words, a probability of temperature or heat flux above a specified level or threshold. For illustration purposes, Figure 5 shows the probability of visible "flame" as indicated by the temperature exceeding the nominal thermocouple temperature of 550 °C. The patterns clearly show a widening of the flame volume with height and flow rate. This means that taller fuel beds and greater burning rates should increase the horizontal flame extensions. The relevance of this flame structure to fire spread was discussed recently by Yedinak et al. (2010), and Finney et al. (2010). The wall-flames described here were studied as an abstraction of the combustion interface in a fuel bed where fluid flow would not be interrupted by dense vegetation matter. Vertical flame expansion and lateral excurisons from this interface into unburned fuel have been found to be responsible for convective heating and ignition of fuel particles. Similar processes for laminar flames were described by Weber (1990) and by Beer (1995) for wind tilted flames. However, further research is required for understanding flame structure on vertical fuel sources and options for its modeling, to understand flame structure in cross flow (with wind), and to understand particle heating and cooling response to variable convective environments.

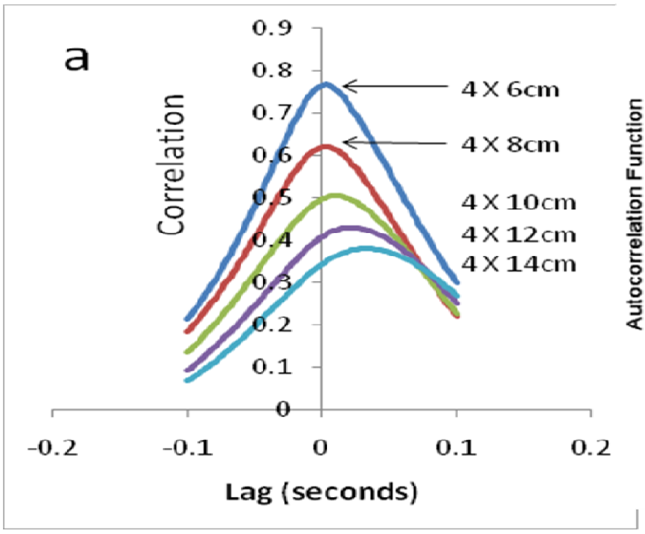

Figure 4. Graphs showing (a) that temperature time-series data are corrleated among different horizontal distances from the wall but with increasing time-lag, and (b) auto-correlation functions for time series data are nearly identical at all distances from the flame wall, suggesting little auto-correlation beyond about 1/5th of a second. All measurements are taken at a height of 169 cm along the wall.

4. Conclusions

Use of a stationary gas burner allows study of the statistical properties of flame structure that are difficult to sample from the short duration and non-stationary burning of solid and cellulosic fuels. Spectral analysis of heat flux found that most of the power occurs at relatively low frequencies, less than 10-20 Hz. The heat flux and temperature variability increases with height and indicates the expansion of the flame volume with height similar to experiments using spreading fires. The convective heating environment experienced by fuel particles in a wildland fuel bed is highly variable at short distances from the combustion interface. With the observed difficulty for radiation to sufficiently heat fine fuel particles to ignition, study of the high variability in convective heating will be necessary to describe fire spread and ignition processes.

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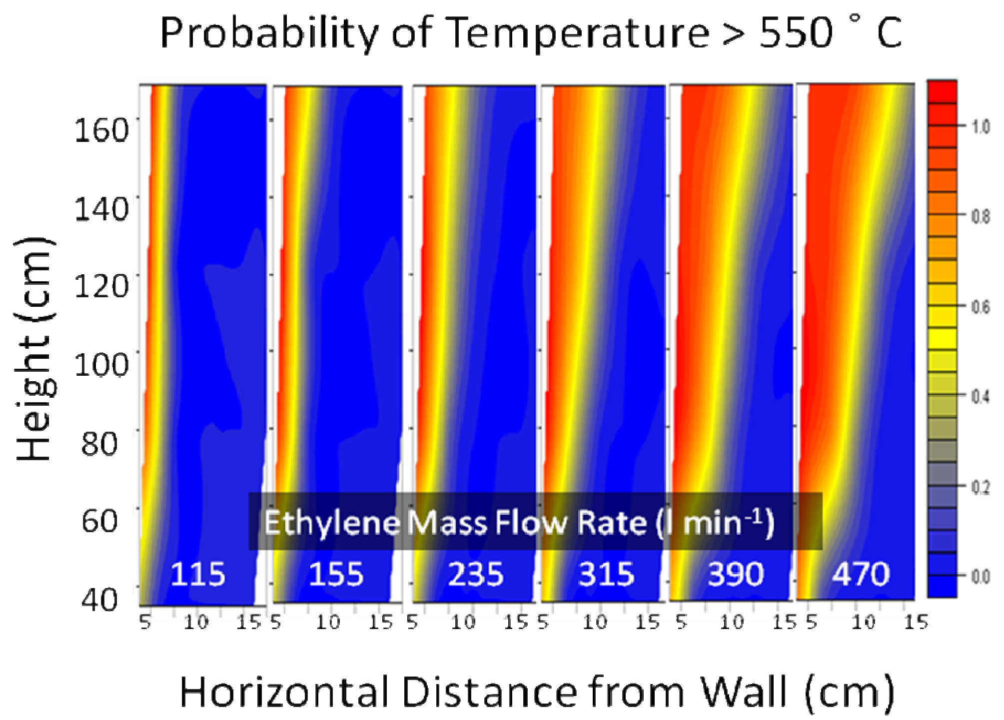

Figure 5. Contour plots showing probability of thermocouple-measured temperatures exceeding the nominal visible flame temperature of 550 C. Flame volume increased with height along the wall and with ethylene mass flow rate from 115 ot 470 liters per minute.

Literature Cited

Ahmad, T. and G. M. Faeth. 1979. Turbulent wall fires. 17th Symposium (International) on Combustion, The Combustion Institute, p. 11 49.

Albini FA (1986) Wildland fire spread by radiation – a model including fuel cooling by natural convection. Comb. Sci. and Tech. 45:101-113.

Annarumma, M., L. Audouin, J. Most, P. Joulain. 1992. Wall fire close to a horizontal surface: numerical modeling and experimental validation. Fire and Materials 16:1-13.

Baines, P.G. 1990. Physical mechanisms for the propagation of surface fires. Mathl. Comput. Modeling 13(12):83-94.

Beer, T. 1995. Fire propagation in vertical stick arrays: the effects of wind. Intl. J. Wildl Fire 5(1):43-49.

Bertin, G., J.M. Most, and M. Coutin. 2002. Wall fire behavior in an under-ventilated room. Fire Safety Journal 37:615-630.

Cohen, J.D. and M.A. Finney. 2010. An examination of fuel particle heating during fire spread. Proc. VI International Conference on Forest Fire Research.

De Ris, J. and L. Orloff. 1975. The role of buoyancy direction and radiation in turbulent diffusion flames on surfaces. 15th Symposium (International) on Combustion. The Combustion Institute. P 175-182.

Delichatsios, M.A. 1982. Turbulent convective flows and burning on vertical walls. 19th symposium (international) on Combustion. 855-868.

Delichatsios, M.A. 1986. A simple algebraic model for turbulent wall fires. 21st Symposium (International) on Combustion, The Combustion Institute 53-64.

Finney, M.A., J.D. Cohen, K.M. Yedinak, and I.C. Grenfell. 2010. An examination of fire spread thresholds in discontinuous fuelbeds. Intl. J. Wildl. Fire. 19: 163–170

Hottel, H.C., G.C. Williams, and G.K. Kwentus. 1971. Fuel preheating in free-burning fires. Thirteenth symposium (International) on Combustion, Thirteenth symposium (International) on Combustion 13(1): 963-970.

Malalaskera, W.M.G., H.K. Versteeg, and K. Gilchrist. 1996. A review of research and experimental study on the pulsation of buoyant diffusion flames and pool fires. Fire and Materials 20:261-271.

Orloff, L., J. De Ris and G. H. Markstein. 1975. Upward turbulent spread and burning of fuel surfaces. 15th Symposium (International) on Combustion, The Combustion Institute, p. 183.

Pitts, W.M. 1991. Wind effects on fires. Prog. Energy Comb. Sci. 17;83-134.

Quintiere, J.k M. Harkleroad, and Y. Hasemi. 1986. Wall flames and implications for upward flame spread. Comb. Sci. Tech. 48(3/4): 191-222.

Wang, H.Y., M. Coutin, and J.M. Most. 2002. Large-eddy-simulation of buoyancy-driven fire propagation behind a pyrolysis zone along a vertical wall. Fire Safety Journal 37:259–285

Weber RO (1990) A model for fire propagation in arrays. Mathl. Comput. Modeling 13(12):95-102.

Yedinak, K, J.D. Cohen, J. Forthofer, and M. Finney. 2010. An examination of flame shape related to convection heat transfer in deep-fuel beds. Intl. J. Wildl. Fire. 19:171-178