In-situ characterization of wildland fire behavior

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Abstract
A system consisting of two enclosures has been developed to characterize wildand fire behavior: The first enclosure is a sensor/data logger combination that measures and records convective/radiant energy released by the fire. The second is a digital video camera housed in a fire proof enclosure that records visual images of fire behavior. Together this system provides a robust relatively inexpensive, system for characterizing wildland fire behavior.

Additional keywords: Fire behavior, fire documentation, fire instrumentation

Introduction

Computer models that are used for day-to-day fire management are largely empirical (Rothermel 1972); examples include BEHAVE(Andrews 1986), Farsite (Finney 1998). Wildland fire researchers have recognized the benefit of insitu measurements of fire intensity and behavior as one critical component of efforts to develop improved fire decision support models. Actual measurements of fire intensity benefit wildland fire behavior research and modeling by providing data for evaluating and developing fire models. Past measurements consisted primarily of observations of rate of spread, gas temperatures and fuel consumption and have been both field based (Barrows 1951; Cheney *et al.* 1993; Fons 1946) and laboratory based (Catchpole *et al.* 1998; Fons 1946; Rothermel 1972) . Such studies provided useful data and observations; however with the advent of modern numerical computers, the complexity of wildland fire models has increased (Call and Albini 1997; Linn *et al.* 2002; Mell *et al.* 2007). New mathematical models include additional physics which led to the need for additional measurements, particularly of the basic heat and chemical processes occurring in fire. This need has been addressed through both field (Alexander 1990; Hiers *et al.* 2009; Stocks *et al.* 2004) and laboratory experiments (Catchpole *et al.* 1998)

However quantitative measurements of energy and mass transport in wildland fire have been relatively sparse. The reasons are likely related to the risks and hazards to humans and equipment associated with wildland fires as well as the high degree of uncertainty in the weather and fuel conditions. Additionally, only recently has the technology become readily available at a cost that allows scientists to capture the desired measurements over the range of possible conditions. Some studies have been published that focus on relating fire intensity to emissions (Ward and Radke 1993), others on statistical modeling of fire behavior (Stocks *et al.* 1989).

Based on experience from an array of field experiments (Butler *et al.* 2004; Putnam and Butler 2004; Stocks *et al.* 2004) a field deployable, fire resistant, programmable sensor array mounted in a fire resistant enclosure and coupled with a video imaging system has been developed. This system reduces the safety risks to research team members and improves utility and reliability of the instruments. The development of this technology occurred over a significant amount of time involving multiple designs and tests. The sensor system has been coupled with a digital video system. The video system includes a programmable trigger linked to the fire sensors that allows the system to automatically initiate data and video recording when a fire is sensed (Jimenez *et al.* 2007).

In the following paragraphs we describe the system and some of the typical measurements provided by it.

Discussion

Two enclosures comprise the system. The primary sensor package is termed the Fire Behavior Flux Package (FBP). It measures 27 cm by 15 cm by 18 cm and in its current configuration weighs approximately 5.3 kg (fig. 1). Various enclosure materials have been used from mild steel, stainless steel and aluminum, the latest design consists of 3.7mm thick aluminum welded at the seams. A 12 volt 2.2Ah sealed lead acid battery or 8 AA dry cells provide power to the logger. A separate 8 AA dry cell battery array provides power for the flow sensors. Wiring and circuit diagrams can be found at www.firelab.org

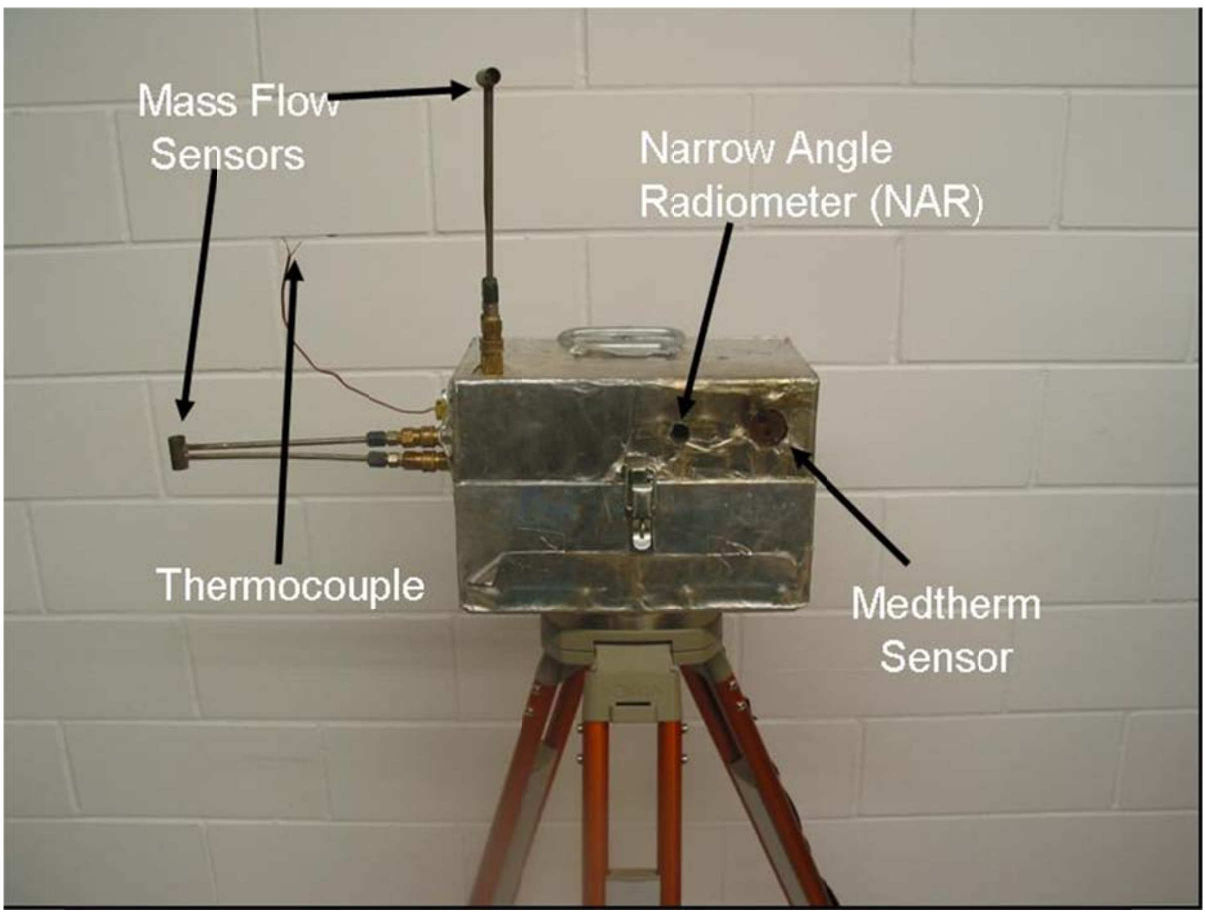

Fig. 1--Photograph of Fire Behavior Package.

The dataloggers used are Campbell Scientific® model CR1000. The dataloggers are capable of logging over one million samples, providing 20 hours of continuous data logging at 1hz. This logger is user-programmable and accepts a wide range of analog and digital inputs and outputs. It is thermally stable and has been relatively insensitive to damage incurred in shipping and handling. Alternative and lower cost dataloggers are available but generally do not have all of the features found in the aforementioned. Currently, all FBP's incorporate a Medtherm® Dual Sensor Heat Flux sensor (Model 64-20T) that provide incident total and radiant energy flux, a type K fine wire thermocouple (nominally 0.13 mm diameter wire) for measuring gas temperature, a custom designed narrow angle radiometer (Butler 1993) to characterize flame emissive power, and two pressure based flow sensors (McCaffrey and Heskestad 1976) to characterize air flow. Table 1 provides details about individual sensors and their engineering specifications.

Table 1. Insitu Fire Behavior Package (FBP) Specifications

Narrow Angle Radiometer	
Sensor	20-40 element thermopile
Spectral Band of Sensor	0.15 – 7.0 μm with sapphire window
Field of View	~4.5º controlled by aperture in sensor housing
Transient Response	Time constant of sensor nominally 30msec
Units of Measurement	Calibrated to provide emissive power of volume in FOV in $kW\text{-}m^{-2}$
Total Energy Sensor	Medtherm Corp® Model 64-20T Dual total Heat Flux Sensor/Radiometer
Sensor	Schmidt-Boelter Thermopile
Spectral Band of Sensor	All incident thermal energy
Field of View	~130º controlled by aperture in sensor housing
Transient Response	< 290msec
Units of Measurement	Total heat flux incident on sensor face in $kW\text{-}m^{-2}$
Hemispherical Radiometer	Medtherm Corp® Model 64-20T Dual total Heat Flux Sensor/Radiometer
Sensor	Schmidt-Boelter Thermopile (Medtherm Inc)
Spectral Band of Sensor	0.15 – 7.0 μm with sapphire window
Field of View	~130º controlled by window aperture
Transient Response	< 290msec
Units of Measurement	Radiant energy incident on sensor face in $kW\text{-}m^{-2}$
Air Temperature	
Sensor	Type K bare wire butt welded thermocouple, new, shiny, connected to 27ga lead wire
Wire Diameter	0.13mm
Bead Diameter	~0.16-0.20mm
Units of Measurement	Degrees Celsius
Air Mass Flow	
Sensor	SDXL005D4 temperature compensated differential pressure sensor
Pressure Range	0-5 in H_2O
Sensor Design	Pressure sensor is coupled to custom designed bidirectional probe with ±60º directional sensitivity.
Units of Measurement	Calibrated to convert dynamic pressure to velocity in $m\text{-}s^{-1}$ assuming incompressible flow
Sensor Housing Dimensions	150× 180 × 270 (mm)
Housing Weight	7.7 kg
Insulation Material	Cotronics Corp® 2.5cm thick ceramic blanket
Tripod Mount	½ inch female NCT fitting permantly mounted to base of enclosure.
Power Requirements	12V DC
Power Supply	Rechargeable Internal Battery
Data Logging	Campbell Scientific Model CR1000
Sampling Frequency	Variable but generally set at 1 Hz
File Format	ASCII

The second part of the system is a fire proof enclosure housing a video camera and is termed the In-situ Video Camera (IVC). The IVC measures 10 cm by 18 cm by 19 cm and is constructed of 1.6 mm aluminum with a weight of approximately 1.8 kg (fig. 2). The front of the IVC has two circular windows nominally 45 and 20 mm in diameter. A double lens configuration of high temperature pyrex glass and a second lens of hot mirror coated glass (Edmund Optics) is mounted in the ports. This multi-layer dielectric coating reflects harmful infrared radiation (heat), while allowing visible light to pass through. The system is designed to be turned on manually or can be set to trigger and record through a wireless link to the FBP data loggers (Jimenez *et al.* 2007). The system allows users to trigger the recording mechanism of the camcorder remotely by using its own unique internal computer source code. Once the FBP and IVC boxes are deployed the trigger system is armed from readily accessible switches in the respective enclosures.

Fig. 2--Insitu Video Camera package.

Both the FBP and IVC are designed to be mounted tripods. The preferred tripods consist of wall galvanized 2.5 cm diameter mild steel pipe with one extendable leg to facilitate deployment on slopes. Once mounted on the tripods a layer of 2.5 cm thick ceramic blanket enclosed in a single layer of fiberglass reinforced aluminum foil is wrapped around the boxes to provide further thermal protection.

Estimated material and construction costs for the FBP enclosures is $500 USD per box plus cost of data loggers, and sensors $700 USD per box plus cost of cameras for the IVC.

Typically each FBP is coupled with an IVC for simultaneous recording of video and in-situ measurements allowing researchers to better evaluate fire behavior measurements relative to flame size and local spread rate.

The packages are typically deployed so that the sensors are directed towards the oncoming fire front. The FBP is oriented to “look” at the expected fire approach direction, while the IVC is positioned to image both the FBP and approaching fire front (fig. 3). Once the FBP and IVC’s are mounted on tripods, they are powered up. The FBP’s have LED’s to indicate that the logger is indeed running, the IVC’s also have an LED to indicate that they are running and have entered “sleep” mode when they are being used with the remote automatic trigger system.

Fig.3--Insitu Video Camera mounted on tripod in wildland fire.

Other data typically recorded include the GPS location of each box, including reference orientation (compass direction), height above the ground, and any other local vegetation, or environment information deemed relevant.

Fig. 4 presents typical heat flux measurements from the total and radiant sensors. The sensors are calibrated to provide total incident energy flux and total radiant incident flux. In theory the convective heat flux at the sensor face would be the difference between the two sensors. The flux on the sensor face may not necessarily represent that incident on a nearby vegetation component. Surface incident energy flux is highly dependent on the properties of the surface itself. The sensors come from the factory calibrated against a high temperature source that emits the bulk of its energy in the near infrared. This source does not represent the spectral energy source produced by a typical wildland fire. The thermal transmission of the window on the radiometer has specific spectral properties. Thus the energy transmitted to the sensor in the calibration environment is not the same as that transmitted in the fire environment. Without additional calibration using a spectrally broad source, all that can be deduced from the radiometer data is that they represent the energy that would be incident on the face of the sensor

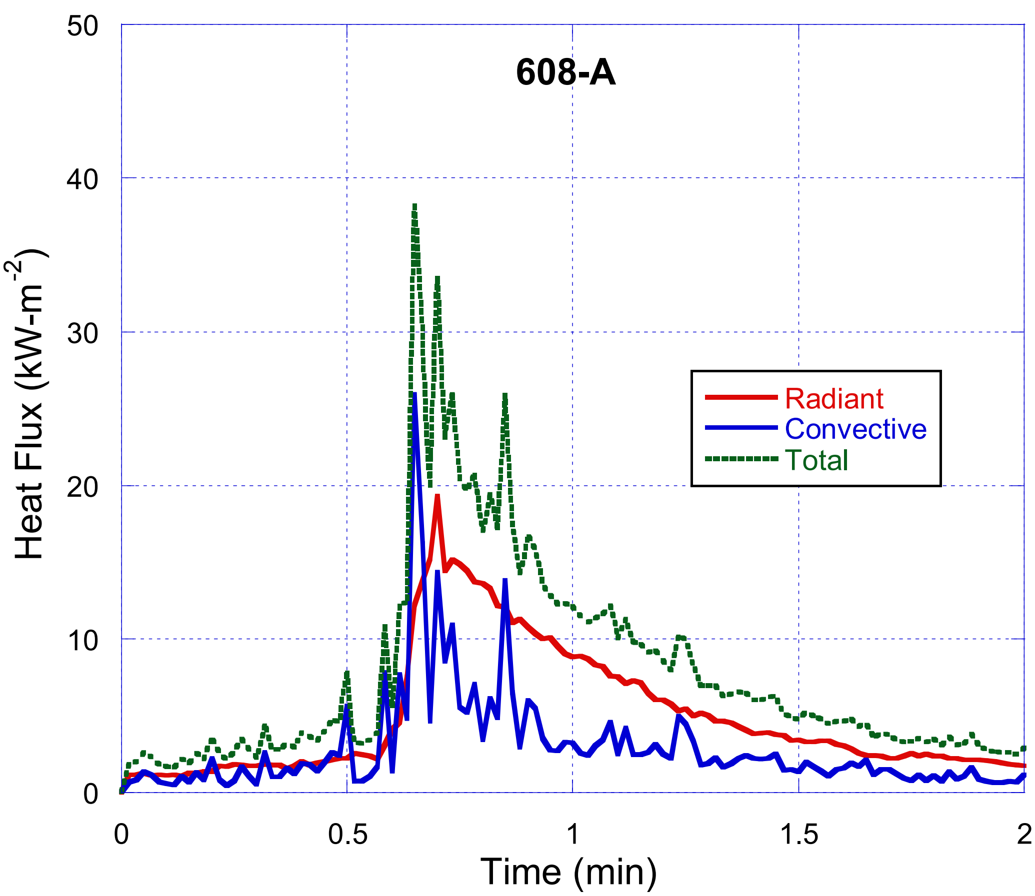

Fig. 4—Heat flux data from the FBP system.

if the source were similar to the calibration source. It is recommended that the radiometers be calibrated using a blackbody source over the expected range of energy flux to minimize error due to the spectral differences between the manufacturer calibration and that of a typical wildland fire source. However, ultimately, unless one uses a correction term determined from a known source (Frankman *et al.* 2010), uncertainty exists in the radiation measurement.

Type K fine wire thermocouples are used to measure air temperature (fig. 5). The use of new (shiny therefore low emissivity), small diameter (reduces radiant energy absorption), thermocouples can decrease measurement uncertainty (Ballantyne and Moss 1977; Satymurthy *et al.* 1979; Shaddix 1998). It is estimated that the measurements collected insitu using the 0.13mm diameter thermocouples specified above are subject to a measurement uncertainty of nominally ±50K but measurement uncertainty can be much larger depending on the temperature of the gas, the surroundings and the radiative properties of the local environment. For small or thin flames the uncertainty can be hundreds of degrees depending on the condition and size of the thermocouple (Pitts *et al.* 1999).

Fig. 5 presents typical flow measurements using differential pressure sensors (McCaffrey and Heskestad 1976). These sensors have been used extensively in laboratory experiments to characterize the flow field in and around flames generated by woody fuels (Anderson *et al.*

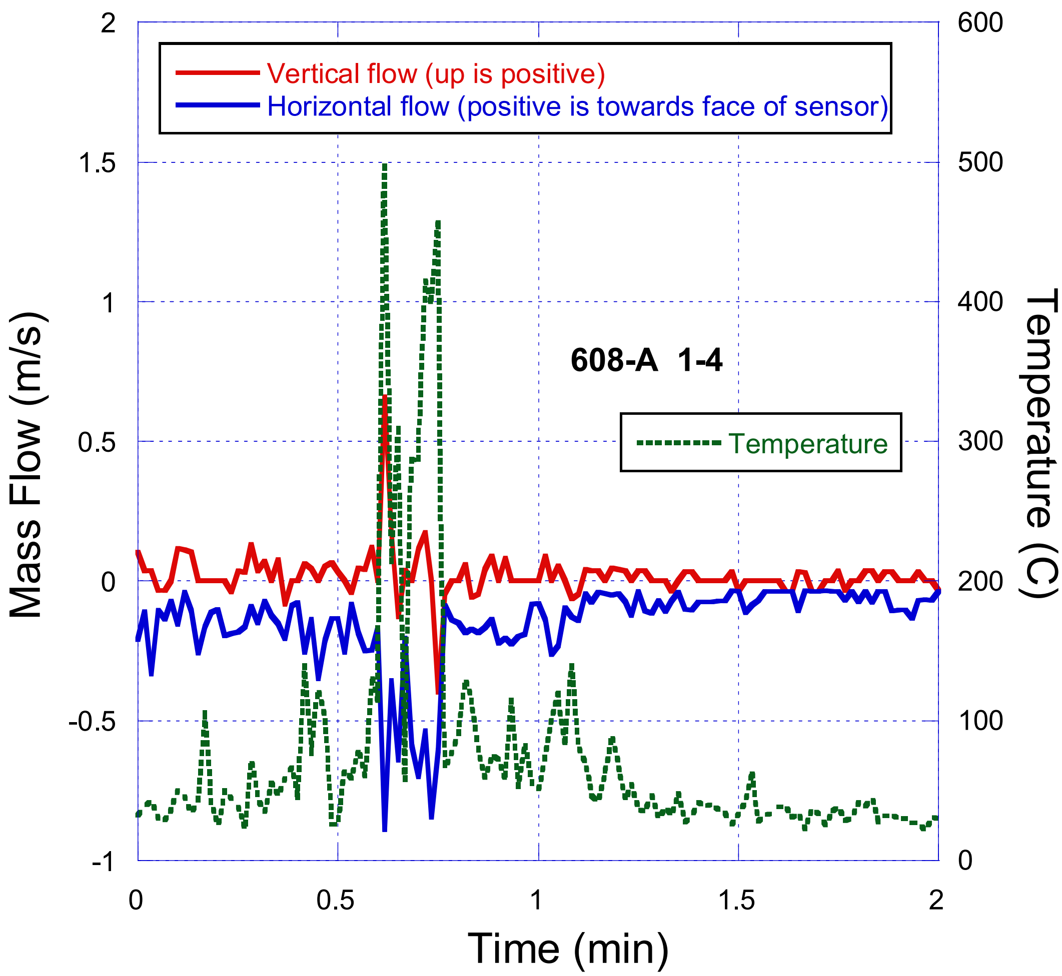

Fig. 5—Flow and temperature data from the FBP system.

2010). They are designed to capture the general horizontal or vertical flow given a nominally ±30 degree acceptance angle. The sensors are calibrated by comparison to a known sensor in a controlled flow. Because these sensors are based on pressure differences between the dynamic and static ports they are sensitive to changes in gas density as would occur due to temperature variations. Therefore the flow measurements require an air temperature measurement for determination of density. Additionally no correction is made for changes in the relative humidity of the air flow. Given the uncertainty associated with the air temperature measurement, it is estimated that the flow measurement uncertainty is approximately ±30% and may be larger.

In practice these measurement systems should be deployed with careful measurements of pre and post fire vegetation consumption. One of the challenges associated with characterizing physical processes in fire is the spatial heterogeneity introduced by variations in vegetation, terrain and weather. The sensors described here sense energy and mass transport at a very small scale relative to that of wildland fires. Consequently, another challenge is how to interpret data from these systems over the broad spatial scales characteristic of wildland fire. One approach is to deploy enough sensors to collect a statistically representative distribution. Alternatively, ground based sensors can be used to evaluate and correct remotely sensed data that represent spatial scales. Measurement success depends on a number of factors, including equipment reliability and weather. The automatic trigger option has increased the success of research efforts to quantify fire behavior; however, even in ideal conditions a realistic success rate of 50-80% is likely.

Conclusions

The FBP and IVC from a relatively low cost, light weight, ruggedized, portable, and programmable sensor system designed to provide measurements of energy and mass transport in wildland fires. The designs are flexible and can be adapted to fit other sensors and data loggers. When a fire is sensed, the fire behavior sensor package begins logging data and sends a wireless signal to activate the video package. This system can be constructed from readily available materials using basic tools and techniques. It seems that the use of sensors like those described here is the only practical solution to gathering quantitative information about energy and mass transport in wildland fires, at least in the near term.

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