# Phosphorus Impact on Soot Formation in Flames of Condensed Phase Fuels

Haiqing Guo<sup>1</sup>, R. Walters<sup>2</sup>, R. Lyon<sup>2</sup>

<sup>1</sup>Diakon Solutions LLC

<sup>2</sup>FAA Technical Center

#### Background

- Phosphorous FR material promotes soot formation in fires and decreases the soot surface reactivity. (Guo et al. 2021)
- The soot ratio pyrometry has been widely used to simultaneously obtain flame temperature soot concentration in the flame.

#### Objectives

- Implement the ratio pyrometry for full-field temperature and soot concentration measurement.
- Develop a quasi-steady laminar diffusion flame system that can easily mix fuel with the flame retardant material.
- Quantify the flame temperature and soot volume fraction to reveal flame retardant material's impact.

## Ratio Pyrometry

- CMOS sensor (36 x 24mm) of a DSLR camera NIKON D750
- Broad-band technique based on CMOS's spectral response

$$\frac{S_{j1}}{S_{j2}} = \frac{\int \frac{\eta_{j1,\lambda}}{\lambda^6 [\exp(hc \ / \ \lambda kT) - 1]} d\lambda}{\int \frac{\eta_{j2,\lambda}}{\lambda^6 [\exp(hc \ / \ \lambda kT) - 1]} d\lambda}$$

- Blackbody furnace to calibrate the detector and inverse the detector's spectral response based on a Gaussian Profile assumption.
- Constant refractive index of m = 1.57 0.56*i* was assumed.
- Deconvolution to obtain local distribution.

## Ratio Pyrometry

Detector's Spectral Response



#### **Calibration Curve**



## Flame Retardancy Flame System

- 10 mm ceramic disk serving as wick.
- Flame surrounded by coflow air to straighten and stabilize the flame
- Liquid MMA monomer is used as fuel to emulate the burning of PMMA.
- Trimethyl phosphate (TMP) is added to the MMA to form an MMA+TMP mixture with 2% mass fraction of TMP.



#### **Temperature Results**

Temperature accuracy does not deteriorate much without deconvolution



#### **Temperature Comparison**



#### Soot Concentration Comparison



## Soot Mass Flux

$$\dot{m}_s = \rho_s \int_0^R 2\pi r f_v(r) v(r) dr$$

- Simplified with constant velocity assumption.
- Similar soot formation path below 22 mm height.
- Above 22 mm height, F<sub>v</sub> of the MMA flame drastically decreases due to oxidation.



## Summary

- The Ratio Pyrometry is implemented on a liquid-fueled (MMA) laminar diffusion flame to reveal the impact of phosphorus containing flame retardant material on the chemical kinetics within the fire.
- At lower flame height where soot formation normally occurs, the MMA+TMP flame involves slightly higher rate of soot formation.
- At upper heights where soot oxidation normally occurs, TMP significantly suppress the soot oxidation.
- The increased soot level results in a much higher energy radiation that cools the local flame temperature.
- As a result, flame extinguishes before fuel is completely burned and soot emits out of the flame tip.