Monte Carlo Model of Laser Induced Solid Fuel Pyrolysis

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ABSTRACT

Soot is formed through solid fuel pyrolysis during wildfires, waste incineration, and aerospace applications. Solid fuel combustion is controlled by radiation feedback from the flame to the fuel surface which induces fuel pyrolysis. Pyrolysis is the process of thermal decomposition of fuels at high temperatures. The significance of pyrolysis during solid fuel combustion has motivated various studies. These studies utilize a CO_2 laser to emulate thermal radiation of a flame during solid fuel combustion and study pyrolysis and soot formation from varying energy inputs. However, the presence of soot will alter the amount of laser energy reaching the surface through scattering and absorption, thus providing unknown conditions. The goal of this work is to understand the influence soot produced has on experimental conditions. In this study, a Monte Carlo Rayleigh scattering model of a CO_2 laser experiment is developed to determine how much energy is reaching the solid fuel surface in the presence of a soot cloud. This model can be applied to different solid fuel combustion experiments where wavelength, distance to fuel surface, and soot volume fraction varies. A more accurate correlation between heat flux and pyrolysis can be produced through this method, and in turn, a better characterization and understanding of soot formation. Understanding soot formation is crucial to working on improving the efficiency, and health and environmental effects of solid fuel combustion events and applications.

Nomenclature

κ: absorption coefficient

σ: scattering coefficient

l: characteristic length

R: randomly generated number

I: intensity

Subscripts

λ: spectral dependence

κ: absorption value

σ: scattering value

abs: absorption value

sca: scattering value

INTRODUCTION

Solid Fuel Pyrolysis

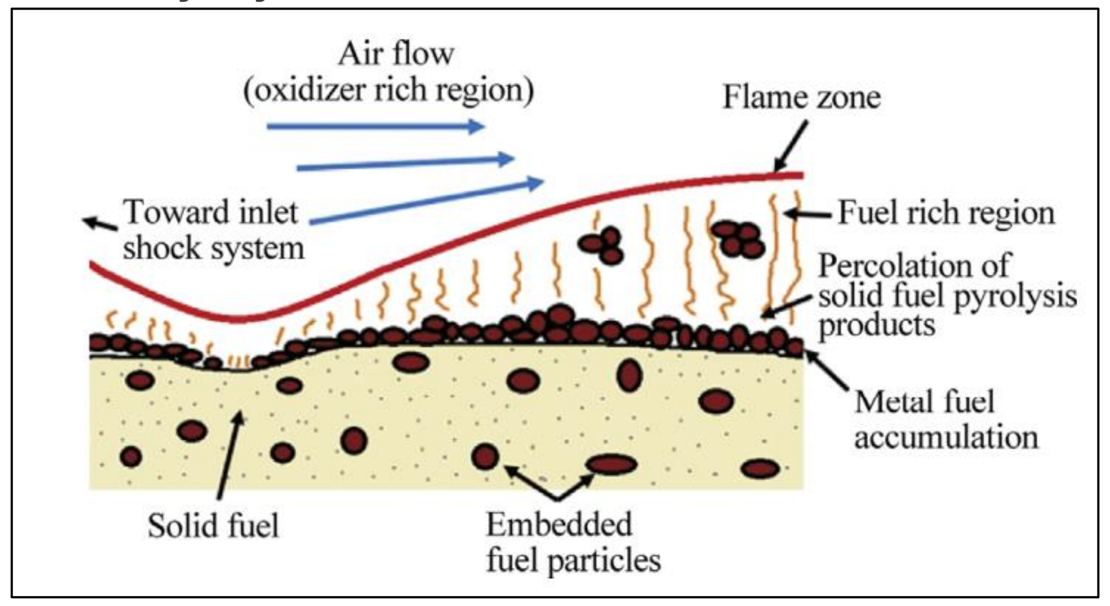

Figure 1: Combustion environment of a solid fuel ramjet. [1]

CO_2 Laser Experiment

- To study the pyrolysis mechanism of solid fuels, a CO_2 laser is used to mimic the thermal radiation of a flame [1-2].
- **Objective: Determine influence of soot during CO_2 laser induced solid fuel pyrolysis experiments.**

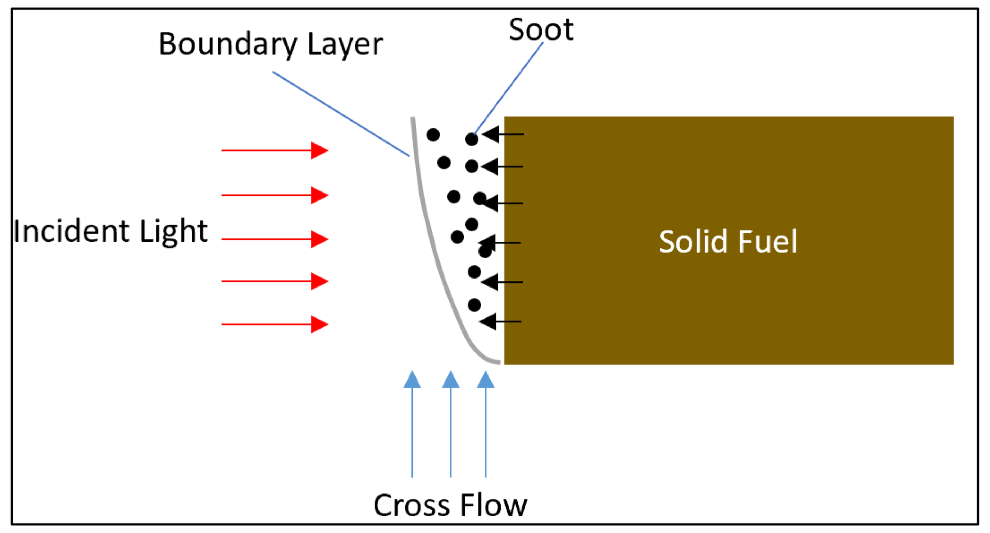

Figure 2: CO_2 laser experiment schematic

METHODS

Monte Carlo Method

- Due to the small size parameter, Rayleigh scattering theory is used [6].
- Based on characteristic absorption and scattering lengths [Eq. 1-2] calculated from spectral properties [Fig. 3] and a random number generator, the photon bundle is either absorbed, scattered, or reaches a boundary [3-6].

Verification Experiments

- A simplified CO_2 laser experiment is simulated to determine the influence soot cloud length has on light reaching the fuel surface for varying constant volume fractions [Fig. 4].
- Verify the Monte Carlo model scatters light following the Rayleigh scattering phase function [Eq. 4].
- Verify the Monte Carlo model follows Beer's Law [Eq. 3].

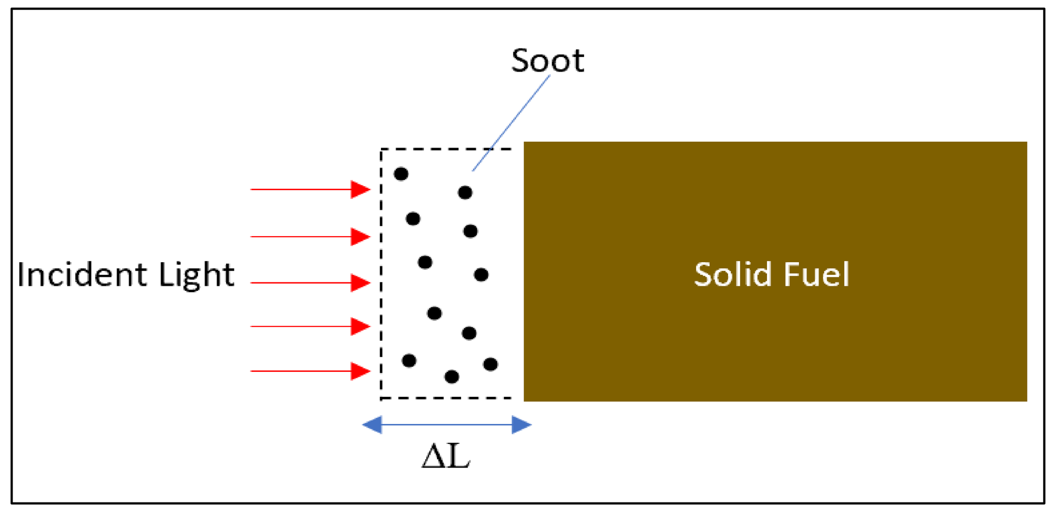

Figure 4: Preliminary experiment schematic.

$$l_{abs,\lambda} = \frac{1}{\kappa_\lambda} \ln\left(\frac{1}{R_{\kappa,\lambda}}\right)$$

Equation 1

$$l_{sca,\lambda} = \frac{1}{\sigma_\lambda} \ln\left(\frac{1}{R_{\sigma,\lambda}}\right)$$

Equation 2

$$I = I_0 e^{-\kappa_\lambda * l}$$

Equation 3

$$\varphi(\theta) = \frac{3}{4}(1 + \cos^2\theta)$$

Equation 4

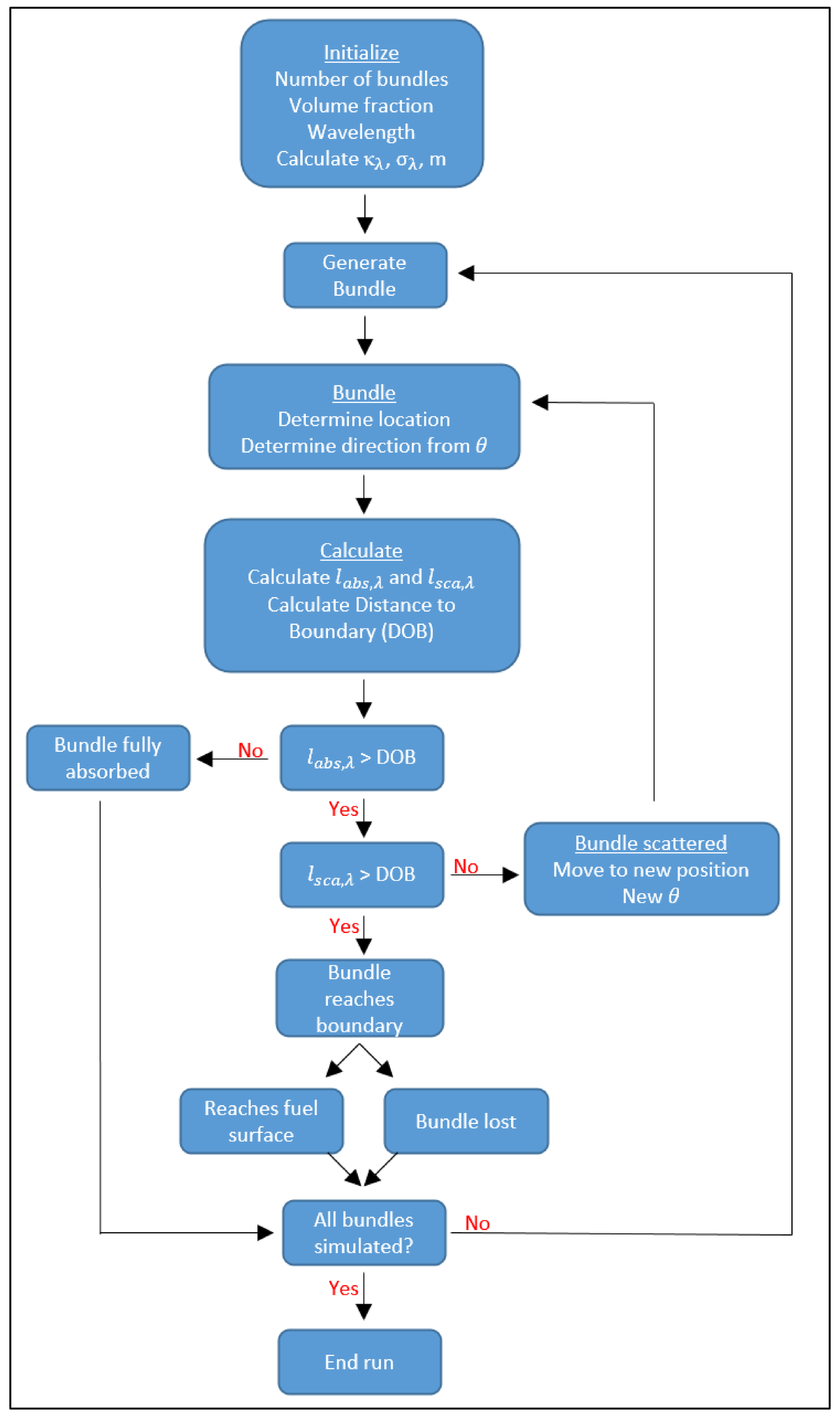

Figure 3: Flowchart of logic in the Monte Carlo Model.

RESULTS

Phase Function Verification (2D Scattering)

- Probability scattering matrix is verified through sampling using MATLAB and an actual plot of the Rayleigh scattering phase function [Fig. 5a, 5b; Eq. 4].

Experiment Results

- As soot cloud length increases, light reaching fuel surface exponentially decays [Fig. 6].
- Data was fit to an exponential decay (Beer's Law) and produced absorption coefficients (κ_λ) similar to calculated inputs [Table 1].

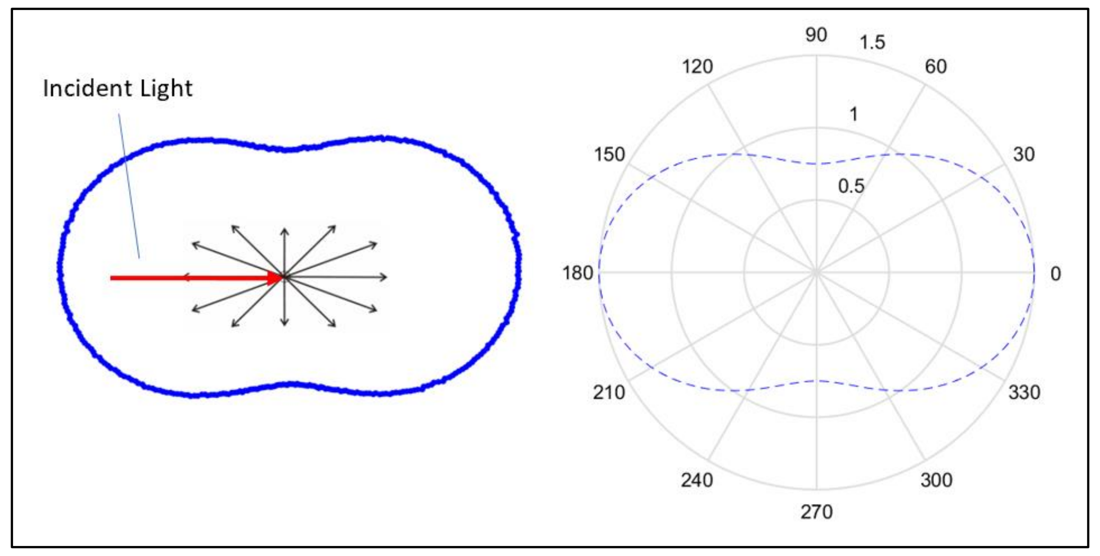

Figure 5a (left): Results from MATLAB sampling of probability matrix.
Figure 5b (right): Rayleigh scattering phase function plotted in polar coordinates.

Table 1
Preliminary Experiment Results

Constant Volume Fraction (ppm)	Exponential Fit	Fit Absorption Coefficient (1/cm)	Input Absorption Coefficient (1/cm)
25	$I = 1.00e^{-0.0931*l}$	0.0931	0.0931
100	$I = 1.00e^{-0.3723*l}$	0.3723	0.3724

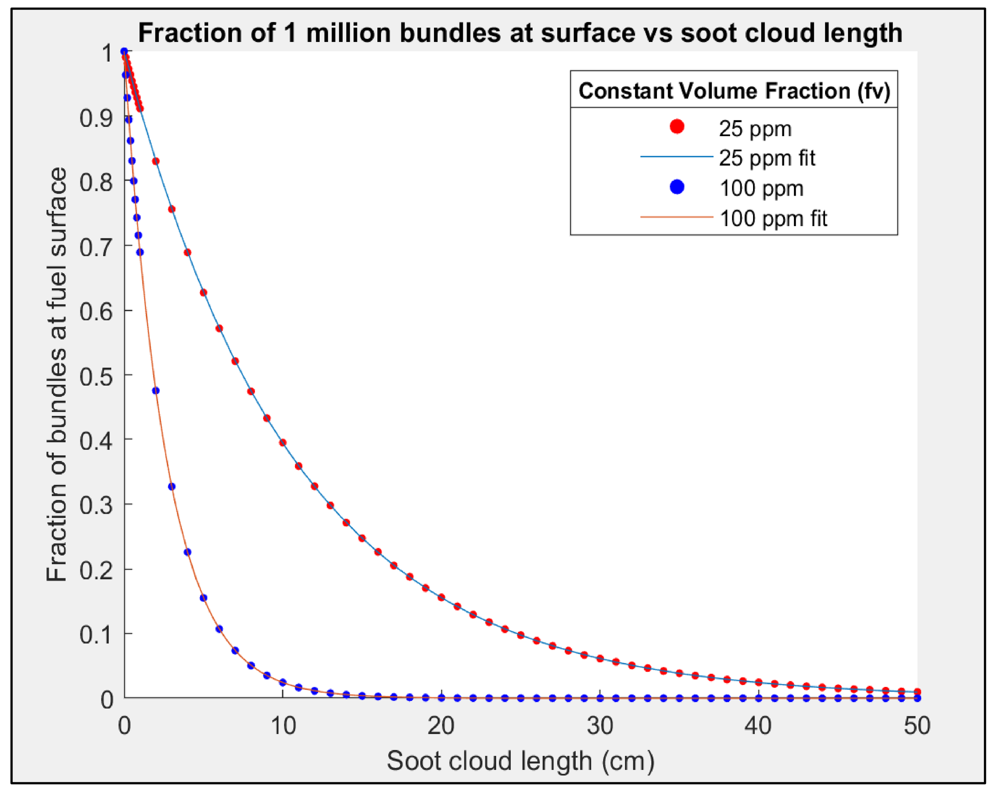

Figure 6: Preliminary experiment results.

CONCLUSION

- To better understand soot formation during solid fuel combustion, the solid fuel pyrolysis mechanism is studied.
- A Monte Carlo model was developed to determine soot influence during laser induced solid fuel pyrolysis.
- Rayleigh scattering theory was used to model the interaction between laser light and soot.
- Rayleigh scattering phase function and Beer's Law were verified for the Monte Carlo Model.

FUTURE WORK

Monte Carlo Model

- Implement mass flux from cross flow and fuel sample to determine its influence of heat transfer to the fuel.
- Simulate full experiments (mass flux, boundary layer, heat transfer).

Experimentation

- Perform CO_2 laser experiments in laboratory.
- Verify Monte Carlo model using CO_2 laser experimental data.
- Experimentally measure soot concentrations.
- Experimentally measure light intensity through a soot cloud.

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