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Effect of Far-Field Radiation on Freely Falling Droplet Burning Behavior

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Objectives

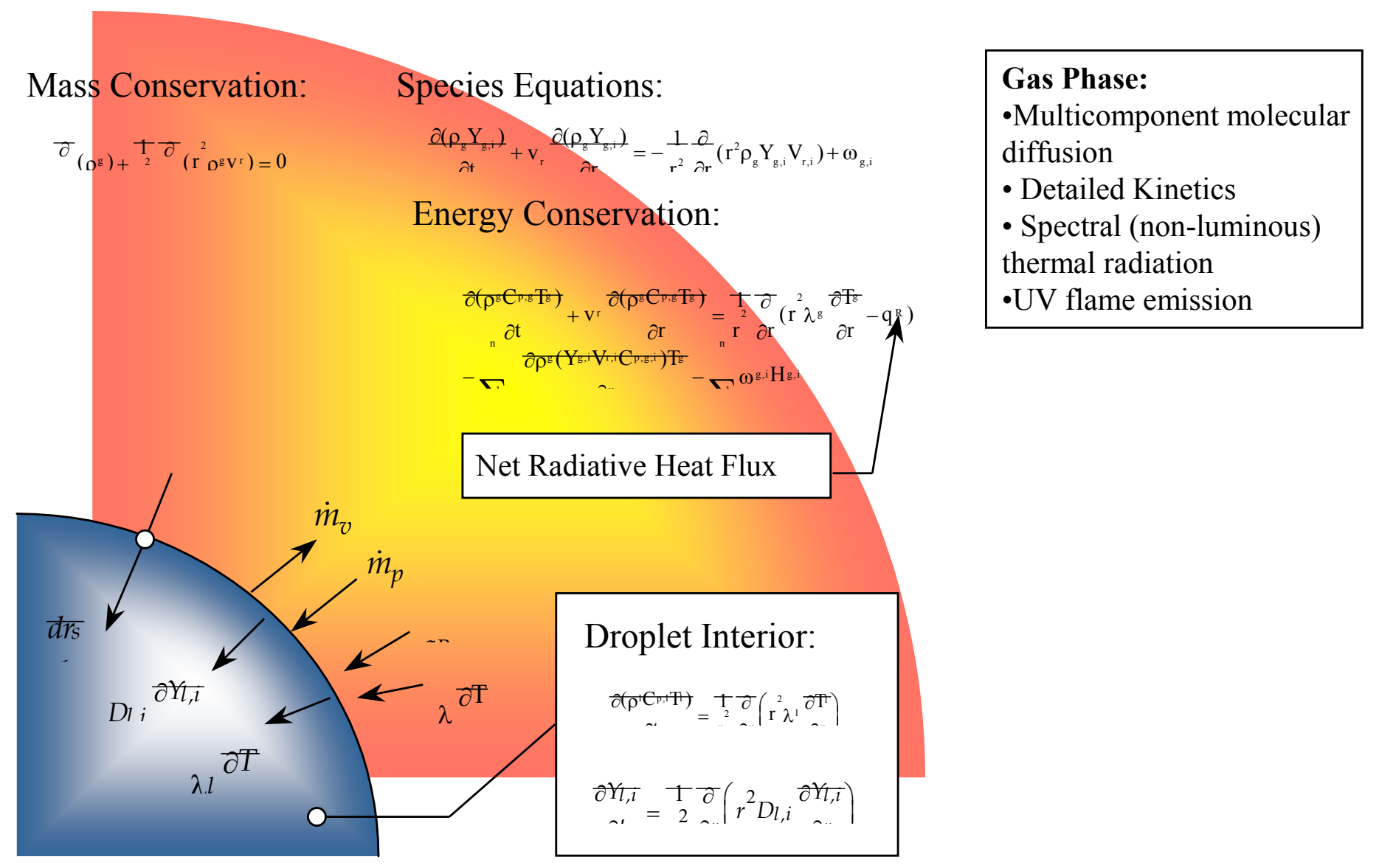
The combustion of heterogeneous media in general and liquid fuels in particular is an important topic of interest on both fundamental and practical grounds. On the practical side, most accidental fires and energy conversion systems rely upon condensed phase fuel. From a theoretical standpoint, there a physical processes associated with heterogeneous combustion, such as extinction, which are still not well understood. For this work in progress, experimental data were examined in order to gain additional knowledge regarding important physical processes in isolated droplet combustion. This understanding was then applied to the question of fire suppression and prevention in microgravity environments.

Background

Numerous studies have used ground-based, freely falling, isolated droplets to examine the combustion behavior of liquid fuels, fuel emulsions, and liquid-solid slurries[1,2,3]. Droplets of mono-disperse size formed repetitively are projected down a duct flow oriented parallel to the gravity vector. Typically, ignition of the individual droplets is achieved by exposure of the droplet stream to post-combustion gases issued from an inverted flat-flame burner and projected downward through the duct. The isolated droplets are subjected to both Stokes drag and body forces, causing a varying gas-drop relative velocity and local buoyancy disturbances of the flame structure surrounding each droplet. A novel method of further reducing both relative convection and buoyancy effects is to incorporate acceleration of the surrounding gases to match that of gravity, resulting in minimal Reynolds number and Grashof number based upon the characteristic length scales of droplet and flame diameter, respectively. A second consideration is that the post flame gas stream may have heat losses that result in centerline temperature gradients of more than 10 K per cm if the duct surfaces are not thermally buffered to reduce heat losses.

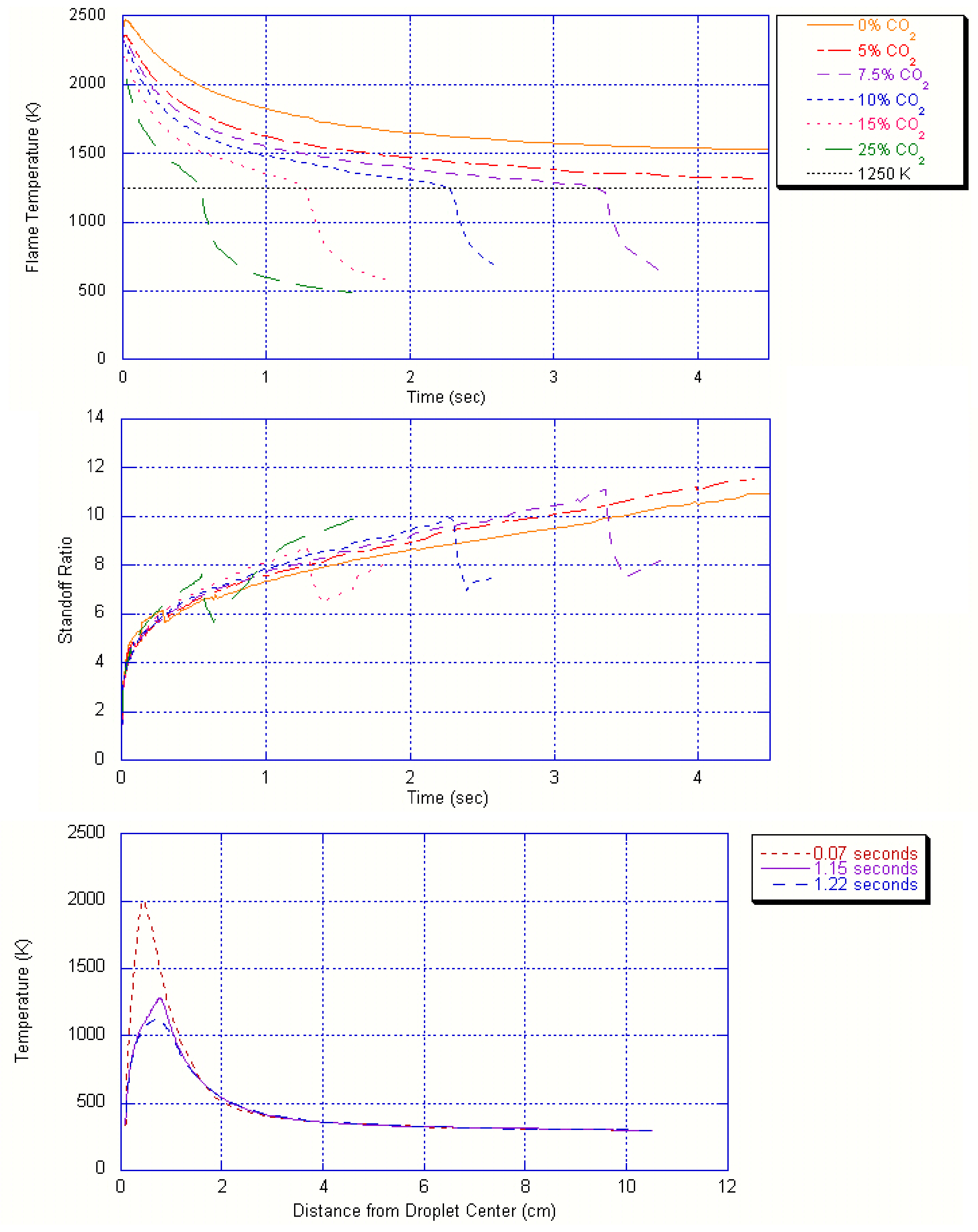
Shaw and co-workers have recently studied experimentally the combustion of isolated droplets of *n*-heptane, *n*-decane and *n*-hexadecane in these configurations, with both constant duct cross-section and with duct cross section properly shaped such that the post flame gases have an acceleration on the duct centerline equivalent to that of gravity[4,5]. The purpose of these experiments was to provide direct comparisons of droplet combustion parameters under the more common freely falling configuration with constant duct cross-section and the shaped duct configuration, which should achieve the low Grashof/Reynolds number characteristics similar to those found in typical drop tower experiments that require larger diameter droplets. To address the duct flow heat loss issue, the duct walls in both configurations were heated using electrical resistance heaters and insulation to approximate an isothermal field surrounding the droplet combustion event. Establishing minimal heat loss from the flow is also critical to determining the appropriate duct shape for achieving flow acceleration equivalent to gravity. The experimental measurements appear to support that the low Grashof/Reynolds number result differs from the straight duct result; however, the droplet combustion parameters in the low gravity configuration as directly measured appear to also differ from those found in actual drop tower experiments[6].

Transient Sphero-symmetric, Multi-component Droplet Combustion Model



Gas Phase:
- Multicomponent molecular diffusion
- Detailed Kinetics
- Spectral (non-luminous) thermal radiation
- UV flame emission

- Computational analysis based upon a previously developed and published model[7]
- Sphero-symmetry offers significant advantages in terms of numerical modeling and inclusion of robust physical and chemical models
- A source term of the form ^{4} ^{4} was added to the liquid-gas interface, assuming the gas phase species had little interaction with the broadband far-field radiation



Physical versus Kinetically-Limited Extinction

- Simulations of 2 mm *n*-heptane droplets in the listed mole fraction of CO_2 mixed with air (21% O_2/79% N_2).

- As CO_2 mole fraction is increased, extinction, as characterized by a region of high negative curvature, begins at higher temperatures. This time corresponds exactly with a rapid decrease in burning rate.

- The rapid decrease in standoff ratio which occurs near extinction corresponds exactly with 1250 K. It therefore decorrelates from extinction time as the mole fraction of CO_2 increases

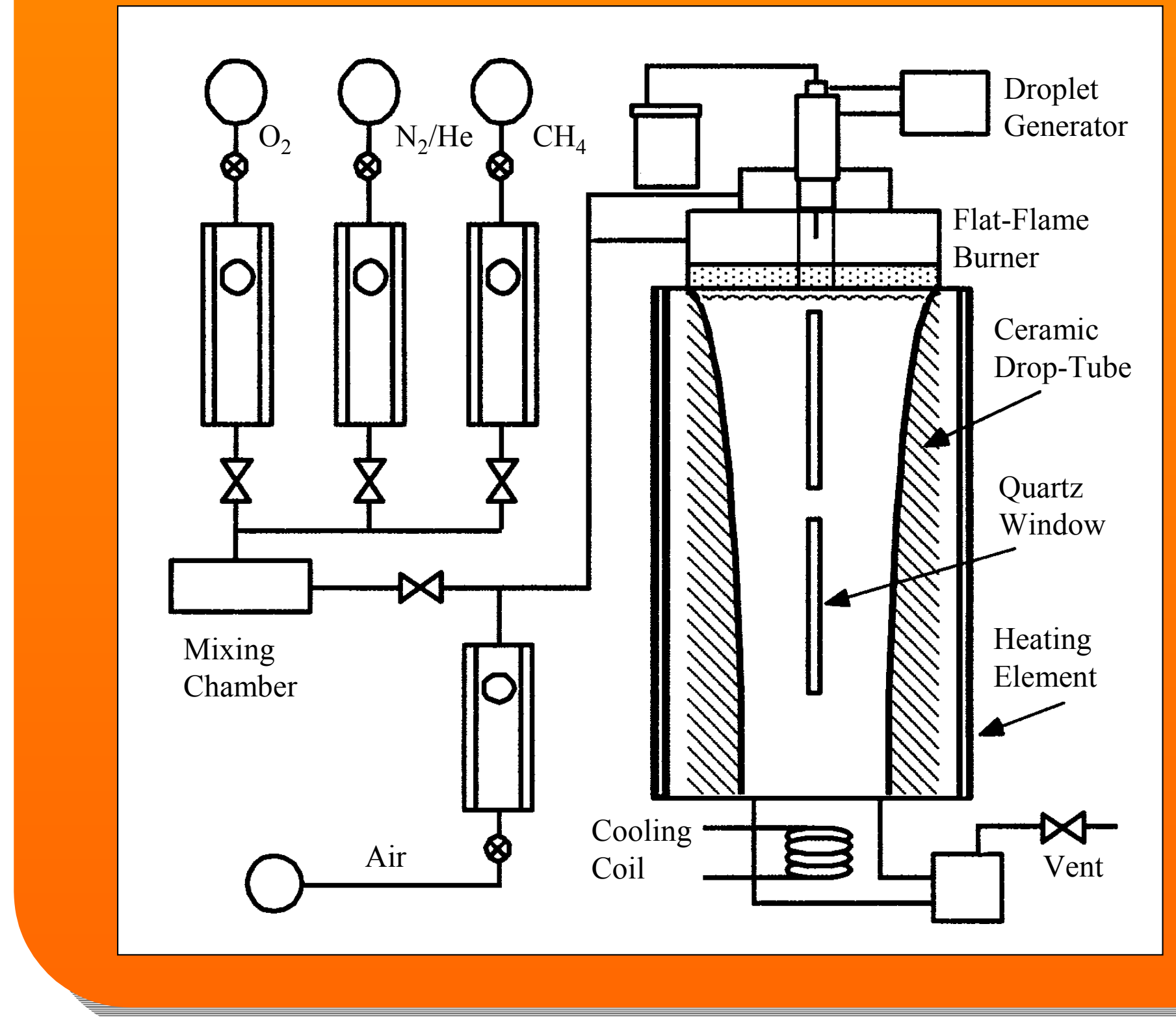
- As visible in the temperature profiles at differing times within a characteristic burning history, we see the fundamental difference between the temperature profile before the decrease in standoff and thereafter is the loss of a sharp peak. This peak is associated with local heat generation, and thus chemical reaction.

- We therefore have a simple technique for differentiating kinetically-limited extinction from extinction resulting from other effects.

- The suppressant effect of carbon dioxide is therefore not only because of an increase in local heat capacity, but also due to some more active source of heat loss. These losses could most easily be attributed to an increase in spectral radiative heat transfer from the flame zone.

Experiment

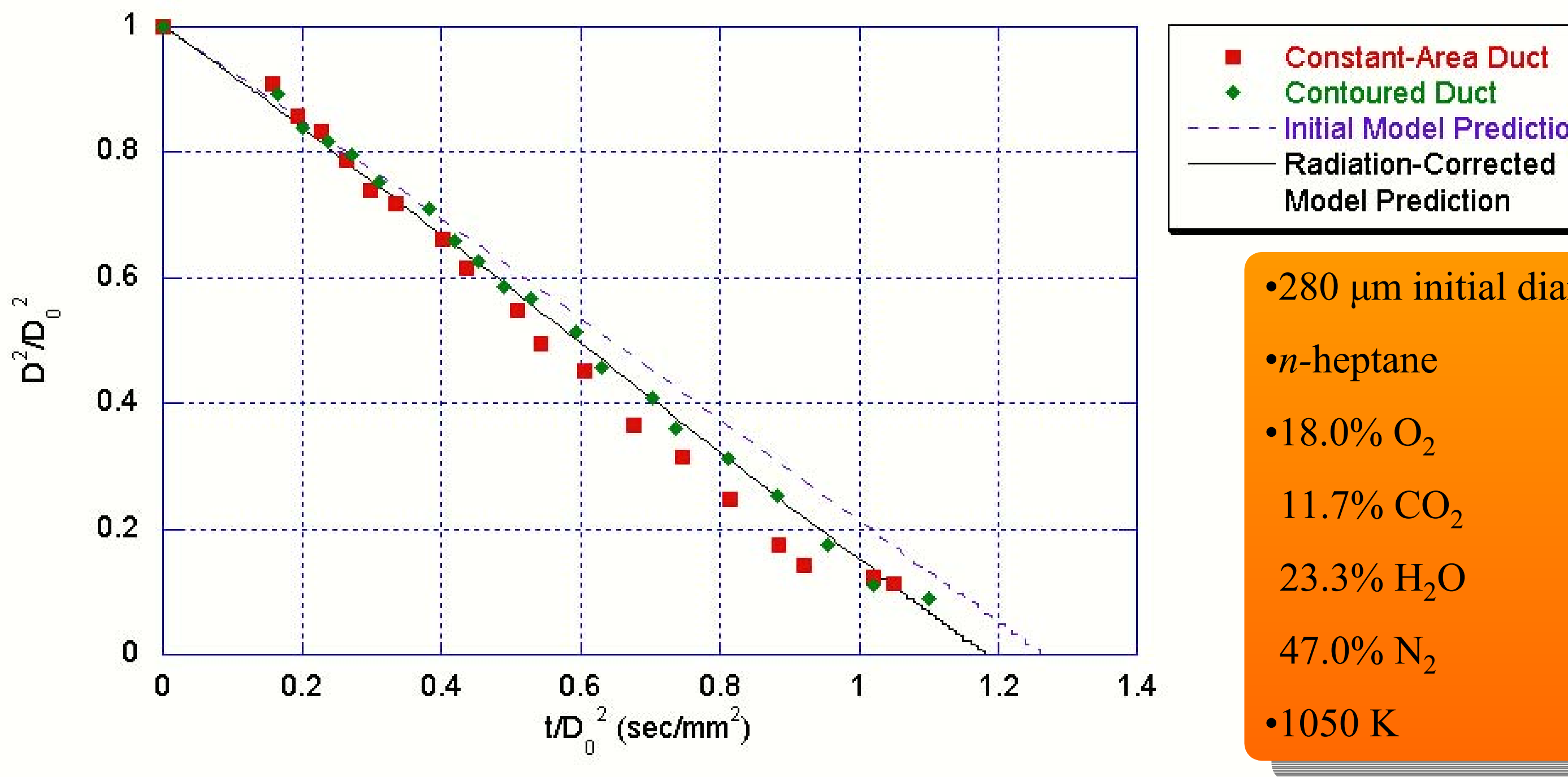
- Constructed and operated at the University of California, Davis.
- Droplets with diameters between 270 and 285 µm were generated using a cylindrical piezoelectric crystal.
- The ceramic liner of the apparatus was removable, allowing explicit comparison of constant-area and gravitational accelerative contoured ducts with the same apparatus.
- Quartz windows along the axis of the duct allowed for visual access and the capture of backlit images for determination of droplet surface regression rates.
- More technical details are available in the literature5.



Comparison

- Initial discrepancy attributed to thermal radiative transfer between the droplet surface and the duct walls. In some experimental configurations, the ratio of the estimated incident thermal radiation from the far-field as compared to the total energy flux of the unperturbed, simulated system reached 25%.
- By assuming the bath gas to be optically thin to thermal radiation wavelengths, an effective heat source term was introduced to the droplet surface to mimic the gray-body radiative exchange between the liquid surface and far-field solid boundary.
- This modified the burning rate by a nearly constant amount over the droplet lifetime, which is to be expected as the radiative influx scales with droplet surface area.
- Within the experimental accuracy, the emissivity of the liquid phase was estimated to be 1.0.

The modification was sufficient to account for the discrepancy in droplet behavior and to bring the experimental results in line with previous experimental work conducted under true microgravity conditions.



- 280 µm initial diameter
- *n*-heptane
- 18.0% O_2
  11.7% CO_2
  23.3% H_2O
  47.0% N_2
- 1050 K

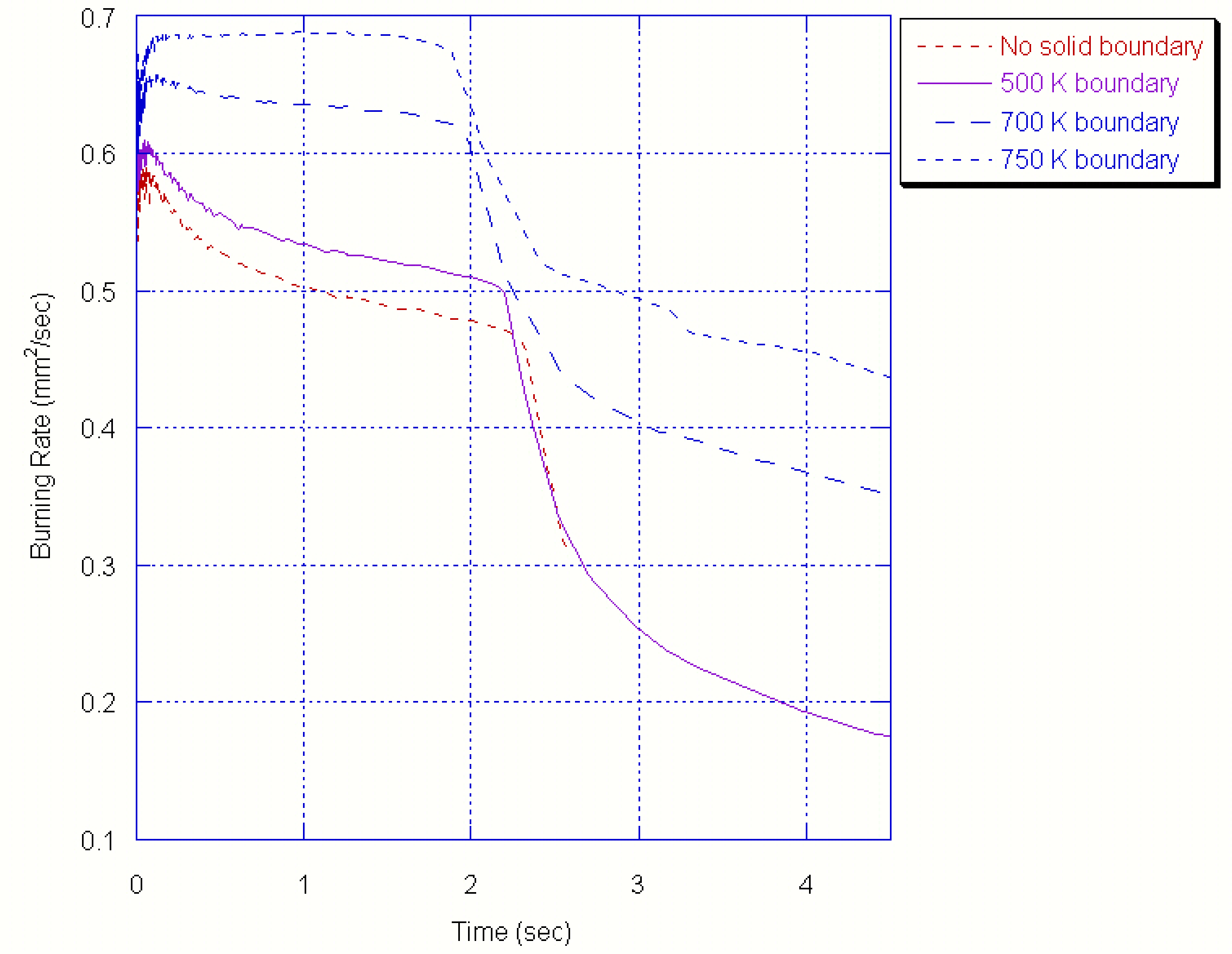
Effect of Far-Field Radiation on Flame Suppression by Carbon Dioxide

- The figures at right represent an *n*-heptane droplet in a 10% carbon dioxide in air with an initial diameter of 2 mm

- The temperature at infinity was held constant at 298 K while the equivalent blackbody temperature of the incoming radiation was modified.

- The increased energy flux into the system only couples with the liquid surface and thus, while significantly increasing the vaporization rate, has no effect upon flame zone temperature.

- Since the flame zone is largely unaffected, the extinction diameter is constant



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