# Transport and Chemical Effects on Concurrent and Opposed-Flow Flame Spread at Microgravity

**Y. Son, G. Zouein, P. D. Ronney**
University of Southern California, Los Angeles, CA 90089-1453

**S. Gokoglu**
NASA Glenn Research Center, Cleveland OH 44135

## INTRODUCTION

Flame spread over flat solid fuel beds is a useful means of understanding more complex two-phase non-premixed spreading flames, such as those that may occur due to accidents in inhabited buildings and orbiting spacecraft. The role of buoyant convection on flame spread is substantial, especially for thermally-thick fuels. With suitable assumptions, deRis [1] showed that the spread rate ($S_f$) is proportional to the buoyant or forced convection velocity (U) and thus suggests that $S_f$ is indeterminate at $\mu$g (since $S_f = U$) unless a forced flow is applied. (In contrast, for thermally thin fuels, the ideal $S_f$ is independent of U [1].) The conventional view [2], as supported by computations and space experiments, is that for quiescent $\mu$g conditions, $S_f$ must be unsteady and decreasing until extinction occurs due to radiative losses. However, this view does not consider that radiative transfer to the fuel surface can enhance flame spread. In recent work [3] we have found evidence that radiative transfer from the flame itself can lead to steady flame spread at $\mu$g over thick fuel beds. Our current work focuses on refining these experiments and a companion modeling effort toward the goal of a space flight experiment called Radiative Enhancement Effects on Flame Spread (REEFS) planned for the International Space Station (ISS) c. 2007.

## OPPOSED FLOW EXPERIMENTS AND MODELING

Microgravity experiments on flame spread over thermally-thick fuels were conducted using foam fuels to obtain low density and thermal conductivity, and thus large spread rate ($S_f$) over thermally-thick fuels compared to dense fuels such as PMMA. This scheme enabled meaningful results to be obtained even in 2.2 second drop tower experiments. After evaluating numerous candidate materials, we chose open-cell polyphenolic foams primarily because they have lower sooting tendency and negligible melting or dripping tendency compared to other foams such as polystyrene or polyurethane. Experiments were conducted in an apparatus consisting of a 20 liter combustion chamber that was filled with the desired atmosphere by a computer-controlled partial pressure gas mixing system. The samples are ignited by an electrically heated wire than in turn ignited a sheet of nitrocellulose. The flames were imaged using CCD cameras whose signals were connected via fiber-optic cables to ground-based S-VHS video recorders. Both direct video and interferometry were employed. The igniter was controlled and the radiometer data were collected by a microcomputer data acquisition and control system.

Figure 1 shows that for $CO_2$-diluted atmospheres the steady values of $S_f$ could be higher at μg than 1g, especially at low $O_2$ concentrations, but for $N_2$-diluted atmospheres $S_f$ was always higher at 1g than μg. At μg, $S_f$ can actually be higher in $CO_2$ than $N_2$ at the same $O_2$ concentration even though $CO_2$ has a larger $C_P$ and thus yields lower $T_f$ than $N_2$ for the same $O_2$ concentration. Figure 1 also shows that for $CO_2$ diluent the minimum $O_2$ concentration supporting combustion is substantially lower at μg than 1g, whereas for $N_2$ the minimum $O_2$ concentration is higher at μg. All of these results show that flames in $CO_2$-diluted atmospheres burn more robustly at μg than 1g whereas the opposite trend is found for $N_2$. This is likely due to three factors. First, □ is larger for $O_2$-$CO_2$ atmospheres (since both the combustion products and ambient atmosphere contain radiant species, whereas for $O_2$-$N_2$ only the combustion products radiate) which increases the heat flux to the fuel bed and thus $S_f$. Second, without buoyant convection (U = 0), the flame thickness □$_g$=□$_g$/($U+S_f$) is much thicker at μg than at 1g, thus μg flames have more volume and can transfer more radiation to fuel bed. Interferometer images (not shown) confirm that flames are much thicker at μg. This effect is more important for lower $O_2$ concentrations (thus lower $S_f$) which explains why the difference between 1g and μg spread rates in $O_2$-$CO_2$ atmospheres is larger at lower $O_2$

concentrations. Third, $O_2$-$CO_2$ atmospheres can reabsorb and re-radiate emitted radiation whereas $O_2$-$N_2$ atmospheres cannot, thus substantial radiative heat losses that would otherwise occur at μg with thick flames in strongly radiating $O_2$-$CO_2$ atmospheres are at least partially suppressed.

Figure 2 shows predicted pressure effects on $S_f$ [3] for $O_2$-$CO_2$ atmospheres at μg. Two different assumed values of $T_f$ are shown. All gas properties are evaluated at the average temperature $(T_f+T_\infty)/2$. The model provides reasonable $S_f$ estimates except near the low-pressure extinction limit, where heat losses may dominate, leading to slower than predicted flame spread, and at high pressure where there may be a transition to nearly opaque conditions. The opacity at high pressure causes less radiative transfer thus less fuel bed preheating than predicted by our optically-thin model, which leads to lower $S_f$ than the optically-thin predictions. (Neither of these effects can be predicted by the simple optically-thin, loss-free model developed in [3].)

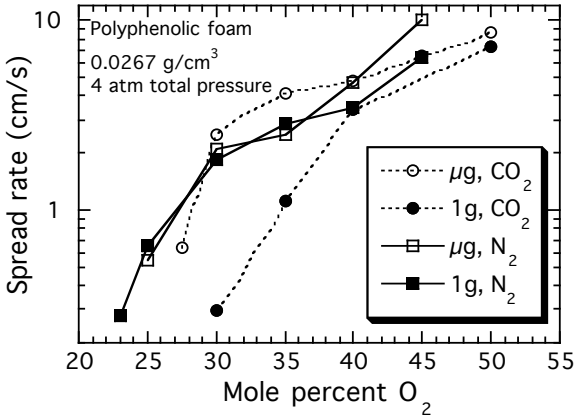


*Figure 1. Effect of oxygen concentration on spread rates over thick solid fuel beds at microgravity and earth gravity, polyphenolic foam, density: 0.0267 g/cm³, 4 atm pressure*

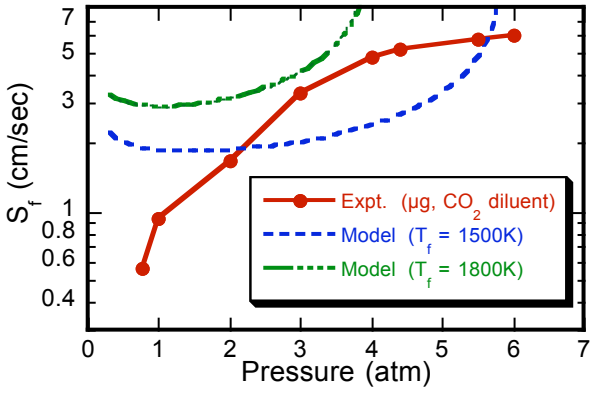


*Figure 2. Effect of pressure on spread rate over thick solid fuel beds at microgravity for polyphenolic foam, density: 0.0267 g/cm³, 40%$O_2$-60%$CO_2$.*

Figures 3a and 3b show the radiative characteristics of flame spread in $O_2$-$CO_2$ mixtures at 1g and μg, respectively. Narrow-angle thermopile-type radiometers mounted 10 cm from the fuel bed were used to determine radiative emissions from the flames. Three radiometers were used: (1) a front-side (burning side) radiometer viewing a hole in the fuel bed to measure only the outward gas-phase radiative loss, (2) another front-side radiometer viewing the fuel surface to measure both the outward gas-phase and surface radiative fluxes, thus total radiative loss, (3) a back-side radiometer viewing through the hole to measures the inward gas-phase radiative heat flux, thus the fuel bed heating due to gas-phase radiation. The only case where the back-side radiometer (which measures the gas-phase radiant heat flux to the fuel bed) shows comparable intensity and timing with two front radiometers is for the $O_2$-$CO_2$ atmosphere at μg (Fig. 3b). This is likely because only in this case is there substantial emission, absorption and re-emission, which is the only means to obtain substantial radiative flux to the rear-side radiometer. $O_2$-$N_2$ atmospheres (not shown) do not show this behavior at all, and even for $O_2$-$CO_2$ atmospheres this is seen only at μg (Fig. 3b) where the flame thickness is larger and thus the total radiative flux is greater. Note also that the gas-phase radiative loss ("Front, gas only" curves) at μg is actually lower for $O_2$-$CO_2$ than $O_2$-$N_2$ atmospheres due to reabsorption by the ambient atmosphere for $O_2$-$CO_2$. At 1g, (Fig. 3a) the surface radiation is much larger than gas-phase radiation due to the decreased flame thickness thus decreased volume of radiating gas at 1g. These results confirm our hypotheses concerning radiative transfer effects on μg flame spread, in particular that (1) radiative preheating of the fuel bed by the gas is significant in radiatively-active atmospheres at μg, (2) reabsorption effects can prevent massive heat losses (thus extinction) in radiatively-active atmospheres at μg and (3) these effects are less important at 1g due to substantial U caused by buoyancy which leads to smaller flame thicknesses thus less volume of radiating gas.

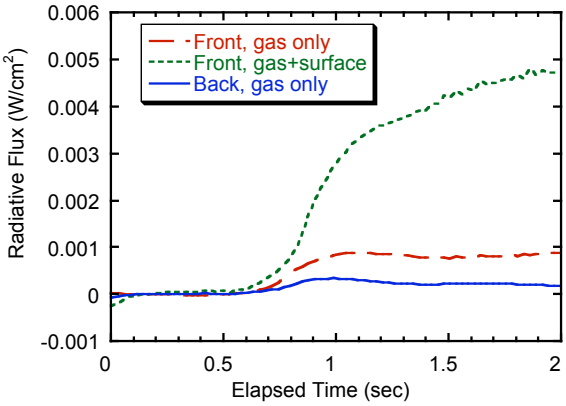


*Figure 3. Radiative flux characteristics of flames spreading over polyphenolic foam fuel. (a) 40%% $O_2$ - 60% $CO_2$, earth gravity.*

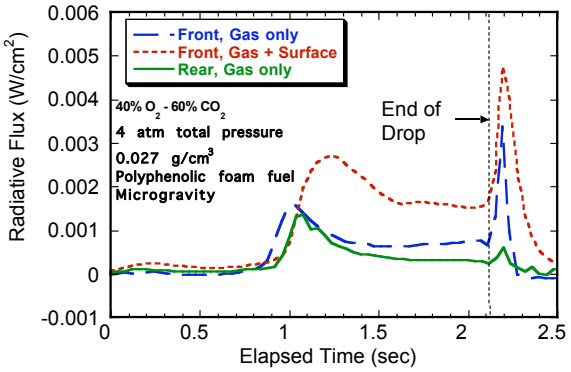


*Figure 3. Radiative flux characteristics of flames spreading over polyphenolic foam fuel. (b) 40%% $O_2$ - 60% $CO_2$, microgravity.*

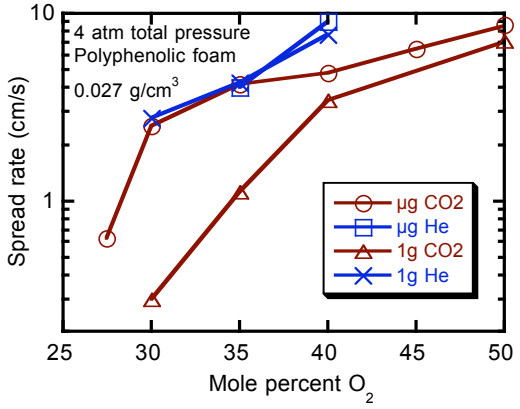


*Figure 4. Effect of oxygen concentration on spread rates over thick solid fuel beds at μg and earth gravity – comparison of $CO_2$ and helium as a fire extinguishing agent.*

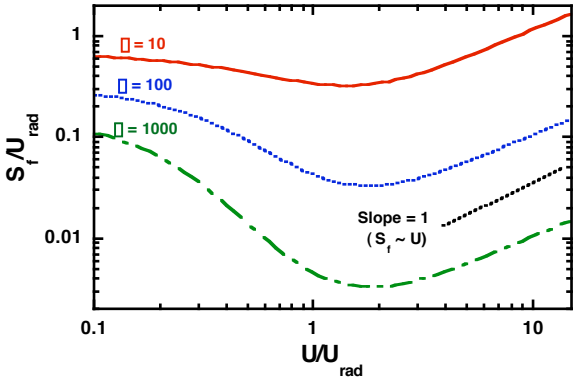


*Figure 5. Predicted combined effects of convection and radiation on flame spread rates over thick solid fuel beds*

Several tests were conducted using He diluent at 4 atm (Fig. 4). It was found that He- and $CO_2$-diluted atmospheres exhibit nearly the same $S_f$, for a given $O_2$ mole fraction even though $CO_2$ has a mole-based $C_P$ at 300K that is 1.8 times higher than He, and at 2000K is 3.9 times higher. Also, He has a thermal conductivity ($\lambda_g$) 9.4 times higher than $CO_2$. Both of these factors should lead to higher $T_f$ and $S_f$ in He than in $CO_2$-diluted atmospheres at the same $O_2$ concentration. Furthermore, at 1g the minimum $O_2$ mole fraction supporting combustion was nearly the same (30%) in He and $CO_2$-diluted atmospheres whereas at μg the minimum $O_2$ mole fraction was much higher for He (35%) than $CO_2$ (27%). There are at least three reasons for the observed behavior. First, the Lewis number of $O_2$ in He is much higher than $O_2$ in $CO_2$ (≈1.20 vs. ≈0.84), which leads to lower spread rates for He [4]. Second, the higher $\lambda_g$ and $\rho_g$ of He leads to thicker flames and thus greater radiative loss for the same $S_f$ since the heat loss per unit volume depends only on the radiating combustion products whose concentrations are not significantly different (at fixed ambient $O_2$ concentration) from $O_2$-$CO_2$ atmospheres. Third, unlike $CO_2$, He is radiatively non-participating and thus no reabsorption or re-emission occurs. Consequently, we conclude that He may be a superior inerting agent at μg on several bases. First, at μg He is more effective than $CO_2$ on a mole basis (thus pressure times storage volume basis), meaning that the size and weight of storage bottles would be smaller for the same fire-fighting capability. Second, He is much more effective on a mass basis (by about 11x) at μg. Third, He has no physiological activity, unlike $CO_2$ which affects human respiration. These results are relevant to fire safety in manned spacecraft, particularly the International Space Station that uses $CO_2$ fire extinguishers.

A model was developed that included the combined effects of convection and radiation on flame spread rates over thick solid fuel beds. Figure 5 shows model predictions in terms of the thick-fuel

flame spread parameter □ and the opposed forced flow velocity U referenced to a characteristic radiative velocity $U_{rad}$. It can be seen that there is an intermediate velocity U that minimizes the spread rate. At high U the classical thick-fuel behavior predicted by deRis is observed and at sufficiently low U, the spread rate becomes independent of U (the radiation-dominated regime). Note that in the high-U limit, $S_f$ is proportional to 1/□ whereas at low U, the effect of □ is much weaker.

## CONCURRENT FLOW RESULTS AT EARTH GRAVITY

Buoyancy-driven upward flame spread over thermally thick fuels is of great practical importance because it is a paradigm for the main mechanism of fire spread in most building fires. Previously a model for upward flame spread over thermally-thin fuels, including the effects of transverse heat and momentum losses to the sides of the fuel samples and surface radiative losses was developed. Such losses were necessary to yield steady flame lengths and spread rates and with such losses, model predictions were found to agree well with experiments [5]. Recently we conducted analogous experiments using low-density but thermally-thick foam fuels, but instead of steady spread, these tests yielded, for reasons still not clear to us, unsteady behavior due to a "jumping" mode of flame spread. These behaviors were found to occur for a wide range of fuel types, pressures, oxygen mole fractions and sample widths and were found not only near extinction limit but also far from the limit conditions. The spatial and temporal intervals of hopping were very regular for moderately narrow samples, whereas wider samples exhibited an unsteady "walking" or "ratcheting" mode and flames ignited on narrower samples extinguished. For thermally-thin fuels similar behavior was found but only near extinction limits. Figure 6 shows a sequence of images illustrating the "jumping" behavior for a narrow sample. Fig. 7 shows the corresponding temporal history of the leading and trailing edges of the flame. It can be seen that the leading edge progresses at a relatively constant rate as if a "source" of flame length, with the trailing edge pausing then "jumping" to catch up. Current work is focused on determine the mechanism(s) responsible for this unusual behavior.

*Figure 6. "Jumping" Flame spread, at 45%$O_2$-$CO_2$, 1atm, width=10mm, thickness=12mm*

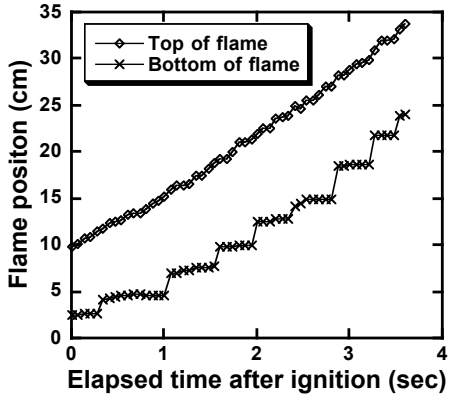


*Figure 7. Flame Top and Bottom position as Elapsed time at 45%$O_2$-$CO_2$, 1atm, width=10mm, thickness=12mm*

## REFERENCES


1. deRis, J. N., *Twelfth Symposium (International) on Combustion*, Combustion Institute, Pittsburgh, 1969, p.241.
2. Bhattacharjee, S., West, J., Altenkirch, R. A. *Twenty-Sixth Symposium (International) on Combustion,* Combustion Institute, Pittsburgh, 1996, p. 1477; Altenkirch, R.A., Tang, L., Sacksteder, K., Bhattacharjee, S., Delichatsios, M. A., *Twenty-Seventh Symposium (International) on Combustion,* Combustion Institute, Pittsburgh, 1998, p. 2515.
3. Son, Y., Ronney, P. D., to appear in *Proc. Combust. Inst.*, Vol. 29 (2003).
4. Zhang, Y., Ronney, P. D., Roegner, E., Greenberg, J.B., *Combust. Flame* 90:71 (1992).
5. Honda, L. K., Ronney, P. D., *Proc. Combust. Inst.* 28:2793-2801 (2000).