Fiscal Year:	FY 2019	**Task Last Updated:**	FY 05/03/2019
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Project Title:	Residence Time Driven Flame Spread Over Solid Fuels		
Division Name:	Physical Sciences		
Program/Discipline:			
Program/Discipline--Element/Subdiscipline:	COMBUSTION SCIENCE--Combustion science		
Joint Agency Name:		**TechPort:**	No
Human Research Program Elements:	None		
Human Research Program Risks:	None		
Space Biology Element:	None		
Space Biology Cross-Element Discipline:	None		
Space Biology Special Category:	None		
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Zip Code:	92182-0001	**Congressional District:**	53
Comments:			
Project Type:	Flight	**Solicitation / Funding Source:**	2009 Combustion Science NNH09ZTT001N
Start Date:	04/06/2015	**End Date:**	04/30/2022
No. of Post Docs:	0	**No. of PhD Degrees:**	0
No. of PhD Candidates:	1	**No. of Master' Degrees:**	5
No. of Master's Candidates:	7	**No. of Bachelor's Degrees:**	4
No. of Bachelor's Candidates:	7	**Monitoring Center:**	NASA GRC
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Flight Program:	ISS		
Flight Assignment:	ISS NOTE: End date changed to 4/30/2022 per S. Olson/GRC (Ed., 1/9/2020)		
Key Personnel Changes/Previous PI:			
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Grant/Contract No.:	NNX15AG11G		
Performance Goal No.:			
Performance Goal Text:			

Task Description:	NOTE: Continuation of "Residence Time Driven Flame Spread Over Solid Fuels," grant # NNX10AE03G, Principal Investigator Subrata Bhattacharjee, PhD. Flame spread over solid fuels in an opposed-flow environment has been investigated for over four decades for understanding the fundamental nature of hazardous fire spread. The appeal for this configuration stems from the fact that flame spread rate remains steady, even if the flame itself may grow in size. For practical fire safety issues, however, wind-assisted flame spread is more relevant. However, these two regimes have always been studied in isolation without much effort to establish a connection, even though the underlying mechanism of flame spread is the same in all regimes. Sitting between the two regimes are high-residence time flames, as found in a low-velocity or quiescent microgravity environment. Residence time is the time spent by an oxidizer in the combustion zone. Such flames, which are of interest on their own merit due to fire safety issues in spacecraft, offer some unique characteristics because of the high residence time. Radiation becomes dominant and, based on previous space experiments and analysis, we contend that a vigorously spreading flame on Earth becomes self-extinguishing in a microgravity environment under certain conditions such as the fuel thickness being greater than a critical value. The proposed research uses a comprehensive approach-- a novel experimental set up and a theoretical framework based on scaling and numerical modeling-- to investigate flame spread driven by varying residence time, from blow-off extinction in an opposed-flow configuration through high residence time flame to blow-off extinction in a concurrent-flow configuration. At the heart of this proposal is a novel but simple experiment where the residence time of the oxidizer can be controlled and high residence time flames can be established for a long duration (compared to drop towers). As a proof of concept, we have constructed a flame tower at San Diego State University (SDSU) in which, after a sample is ignited, the sample holder, placed in an open moveable cart, can be traversed at any desired speed upward or downward, creating an external flow that can augment or mitigate the buoyancy-induced flow. Preliminary results show that we can control the residence time and create flames in different regimes, including a transition between a wind-aided and wind-opposed configuration. At Gifu University in Japan, we have been developing an interferometry based imaging system which we intend to enhance to capture the thermal footprint of a flame's leading edge. The leading edge is central to our understanding of mechanism of flame extinction. Further development of this technology will enable us to integrate diagnostics in future space based experiments and provide validation data to a comprehensive numerical model. The comprehensive model, to be built upon our existing two-dimensional model, will solve an unsteady, three-dimensional, Navier stokes equation with finite rate kinetics in the gas and solid phases and radiation in the gas phase. The software implementation will be object-oriented and utilize a new technology called Web Services that will decouple various sub-models and enhance parallel execution. The radiation model will also be refined by including the equilibrium composition of species for finding radiative properties in high residence-time flames. The comprehensive model, tested against available theory, data in literature, and data generated at SDSU and Gifu, was applied to test the three hypotheses presented in the preceding grant regarding flame extinguishment in a microgravity environment. A successful outcome of that project is leading to a well thought out space-based experiment on the mechanism of flame extinction in a gravity free environment. We have received authority to proceed to Preliminary Design Review.
Rationale for HRP Directed Research:	
Research Impact/Earth Benefits:	Our research has four components. (a) We have built three experimental setups at SDSU: Flame Tower where a test sample can be traversed up or down at any desired velocity; Flame Stabilizer where the motion of the flame can be arrested by moving the sample exactly at the speed of the flame spread in the opposite direction; and a rotating Flame Tunnel where a combustion tunnel can be oriented at any desired angle to study the interaction of buoyancy and forced flow; (b) Theoretical and computational work that explores the similarity and differences between the mechanisms flame spread in a zero gravity space environment and on Earth; (c) Support the space based experiment (in the SoFIE project) to establish extinction mechanism of flames; (d) Develop software tools for data analysis and share those with the research community. The data that we are acquiring in the experiments provide the research community with a comprehensive set of results for testing different theories of flame spread in a normal gravity environment. Moreover, by controlling the residence time, various regimes of flame spread, including the microgravity regime, can be explored in the Flame Tower. Our theoretical work predicts a fuel thickness beyond which steady flame spread is unsustainable in a gravity free environment. If we are successful in establishing a critical thickness, this will have a powerful impact on making fire resistant environment for humans in space. As part of this project, we are developing thermodynamic calculators for combustion and equilibrium calculations, which has a significant educational component. These are available to the community through http://www.thermofluids.net/ . We have also developed a MATLAB based image processing tool named FIAT (Flame Image Analysis Tool), which is now available to the community from http://flame.sdsu.edu .
	The tasks we have performed to date can be separated into four different categories. Below, we list the progress we are making in each. A. Ground-Based Experimental Work: The goal of this work is to establish the role of residence time, time spent by an oxidizer in a flame leading edge, on the mechanism and control of flame spread. Towards this goal, we have been building a number of ground-based experiments involving flame spread over thin solid fuels in an opposed flow environment. A.1: SDSU Flame Tower: The flame tower is the centerpiece of our ground-based activities. We have finished the construction of a 10 m tall steel chamber (details on year-1 report--FY2011 report for predecessor grant NNX10AE03G) inside which a fuel sample mounted on a cart can be traversed up or down a vertical rail with a prescribed velocity. We have been successful in developing a completely remote controlled system to move a cart at any desired speed (from -3 m/s to + 3 m/s: details in year-2 report, FY2012 report for predecessor grant NNX10AE03G). We have conducted detailed velocity measurement to establish that the flow seen by the flame is uniform upstream over a 40 mm by 40 mm area upstream of the fuel sample (which is 20 mm wide). The design and operation of the micro flame tracker, which is housed inside the moving cart, has been described in the

Task Progress:

year-2 report (FY2012 report for predecessor grant NNX10AE03G). Once the flame is ignited, a gas phase thermocouple, attached to a linear motion system on the cart, tracks its motion of the leading edge of the flame, providing the instantaneous flame spread rate. The flame spread is also obtained by analyzing the side-view digital video of the flame, allowing us to verify the data from the automated tracking system.

Data on flame spread rate and flame shape were obtained for flame spread over ashless filter paper with the relative flow velocity varying from positive (opposed flow configuration) to negative (concurrent flow configuration). The spread rate behavior was consistent with theoretical prediction for the opposed flow configuration. When the cart was moved upward (in the same direction of the buoyancy driven flow), the flame spread rate remained fairly constant (or slightly increasing) until about a flow speed of -40 cm/s, when the flame converted itself into its concurrent-flow configuration (wind assisted flame spread). We are still analyzing the wealth of data produced by these experiments.

The flow velocity at which blow-off extinction occurs was found to be sensitive to the development length of the boundary layer. Using an air flow sensor, we characterized the velocity field seen by our moving sample. A detailed study using Fluent was used to relate that cart velocity with the velocity seen by the flame (see previous reporting).

The effect of the flow velocity and the boundary development lengths were experimentally studied using ashless filter paper and the results strongly support an effective velocity correlation that we developed from scale analysis (see details in phase-I, year-4 report).

We have begun new experiments with PMMA (polymethyl-methacrylate) samples. Results of these experiments will be reported in the next year's progress report.

A.2: Flame Stabilizer: One of the challenges in the experimental study of flame spread is that even if the flame spreads at a steady rate, the propagating flame creates an unsteady phenomenon with respect to the laboratory frame of reference. As a result, it is difficult to obtain detailed data, necessary for validating models, in a spreading flame. To remedy this situation, we have built a novel flame spread apparatus that moves the fuel in the opposite direction of the flame spread to keep the leading edge of the flame stationary with respect to the laboratory. A thermocouple, fixed to the laboratory frame of reference, in front of the leading edge of the flame senses the presence of the flame and a proportional–integral–derivative controller (PID controller) keeps its temperature constant by moving the sample holder, driven by a stepper motor, in the opposite direction at the velocity of the spread. Instantaneous flame spread rate and the visible flame structure are compared for a downward spreading flame over ashless filter paper with the corresponding stationary flame. The results indicate that the difference between the two configurations are within experimental uncertainties and the stabilized flame can represent a spreading flame adequately, including variability of flame spread rate and the flame geometry, for further observation.

We have presented this work in the 34th International Symposium on Combustion. With a spreading flame stabilized by this apparatus, we are in a position to measure gas phase temperature, including in the plume region, where fluctuations due to turbulence makes it very difficult to map out the thermal field of a spreading flame.

Using a K type thermocouple we mapped the gas phase temperature field of a stabilized flame. An infrared CO2 sensor was used to map out the CO2 concentrations.

When the temperature and CO2 concentrations are normalized by their equilibrium values (0 for ambient conditions and 1 for chemical equilibrium values), the similarity between the temperature and CO2 is remarkable (see FY2014 report for predecessor grant NNX10AE03G). Using the fluctuations in the signal, the pseudo-turbulence intensity was calculated for both the temperature and CO2 concentrations showing strong similarity. Turbulence is most intense at the far downstream of the flame and in the outer zone of entrainment.

In the subsequent years we have improved the flame stabilizer by replacing the thermocouple with a radiometer to sense the advancing flame. The data acquisition capabilities now include measurement of thermal radiation and gas phase temperature using S-type thermocouple.

A.3 The Flame Tunnel: We have designed and fabricated a wind tunnel for combustion experiments where we can create a prescribed flow of air over different types of fuel samples (flat or cylindrical). The unique design also allows us to change the orientation of the tunnel making it possible to create downward, opposed-flow, horizontal, and concurrent-flow flame spread. In addition, the angle of the tunnel with the vertical axis can be changed to study effect of inclination on flame spread.

A.4 The Ignition Delay Apparatus: The Burning and Suppression of Solids –II (BASS-II) experiments have generated a wealth of information on ignition time of solid fuels. Yet, almost none of these data have been analyzed. We have built a simple apparatus with the goal of accurately measuring ignition delay time of solid fuels. Two horizontal parallel cylindrical wires (Kanthal) are electrically heated in a symmetric fashion. Once they reach steady state, a sample is suddenly inserted in between the two ignition wires. An infra-red camera monitors the rise in temperature of the fuel and an inflexion point in the rise in temperature, which is followed by ignition, is used to identify the ignition time.

B. Preparation for Space-Based Experimental Work:

We have proposed an experimental matrix in the BASS-II project to that will help us (a) determine a suitable ignition method; (b) select an oxygen level suitable for flame spread over PMMA ; (c) estimate extinction time at lower oxygen level; and (d) evaluate the width effect to supplement our original experimental matrix in the SoFIE project.

Results from BASS-II experiments have been used in several archival journal publications. The results have reinforced our theoretical prediction that below a certain critical velocity, flame extinguishes due to radiative cooling.

C. Theoretical/Modeling Work: We are continuing to make progress in modeling flame spread over solid fuels under different conditions. Our modeling/theoretical effort can be summarized as follows:

1. We have been developing Web based tools for calculating equilibrium temperature of PMMA and Cellulose combustion. This calculation tool, which can be used by the community, helps us determine exactly how much sample burn is possible (under different conditions) in a closed chamber without significantly altering the oxygen level. It also predicts the equilibrium composition providing us with the thermodynamic limits of CO2 level and temperature in the gas phase to be expected.

2. We are using a two dimensional model with finite-rate one-step kinetics, and radiation to simulate opposed flow

flame spread. The model has been used to compare downward flame spread results with experiments conducted in the lab. The spread rate from the model for three different fuel thicknesses agreed quite well with the experimental results for downward spread over PMMA sheets under the ambient conditions.

3. The model was used to compare pure downward flame spread with the stabilized flame produced by our stabilizer device. The comparison of the numerical results as well as experimental data established the flame stabilizer does reproduce all the characteristics of a downward spreading flame, only the flame is now frozen in the laboratory coordinate ready for prolonged examination. This study established the flame stabilizer as a new viable platform for experimental studies of flame spread.

4. The data from the flame tower showed that the blow off velocity (of the opposing flow) was related to the boundary layer development length. The computational model, along with scale analysis, was used to quantify the effect of the development length in terms of an effective velocity. An effective velocity for a flame, embedded in a boundary layer, is defined as an equivalent velocity seen by the flame. The effective velocity is then correlated with free stream velocity, development length of the boundary layer, and fluid and fuel properties. The resulting correlations were remarkably accurate in explaining the blow off extinction velocity over a wide range of parametric conditions.

5. We have done detailed radiation calculations to establish the importance of radiation loss versus radiation feedback. Also, the radiation loss correction of thermocouple measurement has been computed taking into account both radiative loss and gain by the thermocouple bead.

6. We have developed a MATLAB based image analysis tool (FIAT (Flame Image Analysis Tool)) that can be used to analyze videos of any flame spread experiment.

D. Space Based Experiments (BASS-II): We have conducted three sets of experiments as part of the BASS-II project, burning twenty samples of PMMA. Computational and theoretical work in support of these experimental results have been published in several archival journal papers. The experimental matrix for the SoFIE experiments has been finalized.

E. Dissemination of Results: We have published a significant number of journal and conference papers, one textbook, and updated our research and outreach websites (http://www.thermofluids.net/ , http://flame.sdsu.edu). The MATLAB based application FIAT (Flame Image Analysis Tool) is available for download from our website flame.sdsu.edu .

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