A FUNDAMENTAL STUDY OF SMOLDERING COMBUSTION IN MICROGRAVITY

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ABSTRACT

A research program is being conducted to study smoldering combustion in microgravity. The program's final objective is to design and conduct smolder experiments in a space based laboratory, which will complement normal gravity ones, and that will help to: increase the current fundamental understanding of smoldering; predict smolder behavior in a space-based installation; and prevent and control smolder originated, ground or space based, fires.

I. INTRODUCTION

Smoldering is defined as a non-flaming, surface combustion reaction, that propagates through the interior of porous combustible materials. The propagation of the smolder reaction is a complex phenomena involving processes related to the transport of heat and mass in a porous media, together with surface chemical reactions. Smoldering is a weakly reacting phenomena, and generally propagates very slowly. The products of smoldering combustion are, however, often toxic and consequently hazardous. Smoldering can also play an important role in the initiation of unwanted fires because of the potential rapid transition from the slow smoldering reaction to the flaming combustion of the material. Furthermore, smoldering is often difficult to detect and suppress because it may take place in the material interior and the porosity of the material may prevent the access of the extinguishing agent to the reaction zone. Thus, understanding of the physical and chemical mechanisms controlling smoldering is important not only because smoldering is a fundamental combustion process, but because such understanding can be critical to the prevention and control of unwanted fires.

Gravity influences smoldering by affecting the transport controlling propagation mechanisms, the stability of the propagation front, the structure of the porous material and the flow of particulates through the material. Conducting smolder experiments in microgravity will simplify the study of the phenomena by eliminating some of these effects. Furthermore, to date there is no experimental information about smoldering behavior in microgravity. This is important since such information and complementary theoretical foundation are necessary to asses the fire risk of a space based installation.

The project's overall objective is the understanding and prediction of smoldering combustion under normal and microgravity conditions. This is accomplished by conducting smolder experiments on the ground and in a space based laboratory, and developing theoretical models of the process.

II. RESEARCH PROGRESS

II.1 Normal Gravity Smoldering:

A series of experiments of forced flow smoldering, opposed and forward, have been conducted. In addition to providing information about smoldering, the experiments have the objective of determining the effect of buoyancy in the smolder process. This is accomplished by comparing the experimental results for upward and downward smoldering, and by comparing the data with the predictions of theoretical models of the process. Measurements conducted in these experiments included the smolder propagation velocity and the reaction zone temperature as a function of some of the parameters that affect them. The data are correlated with non-dimensional parameters that are derived from a theoretical analysis of the problem.

The experimental apparatus consists of a square cross section duct containing the fuel and through which the oxidizer gas flows to produce a one-dimensional, forced flow, smolder, and the supporting instrumentation. The test section containing the porous fuel consists of a 0.3 m long vertical duct with a 0.15 m side square cross section. Metered air flows into the test section through a diffuser and a 50 mm long settling section filled with glass beads. All the tests are conducted with 150mm side cubes of open cell, unretarded, white flexible polyurethane foam. The rate of smolder propagation is obtained from the temperature histories of eight Chromel-Alumel thermocouples 0.8 mm in diameter that are embedded at predetermined positions in the porous fuel with their junction placed in the fuel centerline. The smolder velocity is calculated from the time lapse of the reaction zone arrival to two consecutive thermocouples, and the known distance between the thermocouples. These thermocouples are also used to measure the reaction zone temperature which is characterized by a maximum in the temperature profile.

All the experiments showed that three zones with distinct smolder characteristics can be identified along the foam sample. An initial zone near the igniter where the smolder process is influenced by heat from the igniter, an intermediate zone where smolder is relatively free from external effects, and a third zone near the sample end that is strongly affected by the external environment. The smolder reaction propagation velocity and temperature generally have a direct correspondence and vary in each one of these three zones.

Opposed Smolder: Characteristics results of opposed smolder are presented in Fig. 1, which shows the variation of the downward smolder propagation velocity through the sample length for several representative opposed air flow velocities. Tests were also conducted at other flow velocities, but the results are not presented to avoid crowding of the figure. The data is the average from five tests, and the error bars describe the maximum deviations from the mean. These data plus other obtained with different foam lengths, initial temperature and orientation are correlated in Fig. 2 in terms of a non-dimensional smolder velocity that is derived from a theoretical analysis of the problem previously developed under this grant. The analysis basically balances the energy needed to heat the foam to the smolder temperature and the energy generated by the smolder reaction, which is assumed to be in thermodynamic equilibrium. By assuming that all the oxygen is consumed at the reaction zone (smolder is oxygen limited), the analysis predicts that the smolder velocity is proportional to the mass flux of oxygen at the reaction zone. The mass flux of oxidizer to the reaction zone is obtained in its turn from an analysis of the mixed, forced and free, flow through the porous fuel. From the correlation of Fig. 2 it is seen that the model predicts well the measurements, except at conditions were extinction or transition to flaming occur. In these limiting conditions solid or gas chemical kinetics play an important role, and the smolder velocity is no longer singly controlled by the oxidizer mass flux. An interesting result of correlating the experimental data with the model prediction is that the effect of buoyancy can be extracted by simply comparing the pure forced flow and mixed flow correlations. Such comparison shows that buoyancy has an influence over the hole range of velocities tested.

These results point out to a smolder process that is controlled by the competition between the supply of oxidizer to the reaction zone and the loss of heat from the reaction zone. For example analyzing the data in zone II of Fig. 1, it is seen that at very low flow velocities (< 0.5 mm/s) the smolder propagation velocity is very small, indicating the presence of a weak smolder reaction. As the air flow velocity is increased, the smolder reaction velocity first increase, reaches a maximum (at approximately 2.5 mm/s), and then start to decrease. The initial increase in the smolder temperature and velocity is due to the increased supply of oxidizer to the reaction zone which enhances the heat production, as predicted by the model. As the air velocity is increased further, the heat generated at the reaction and the convective heat losses eventually balance each other and the smolder reaction velocity reaches a maximum. If the air flow rate is increased even further the heat losses overcome the heat generation and the smolder temperature and velocity start to decrease. For air flow rates larger than 2.8 mm/s, the heat losses dominate and cause the weakening and final extinction of the smolder reaction. The above discussed controlling mechanisms also apply to the other two zones, although the external effects modify somewhat the balance between them.

Forward Smoldering: The measurements show that in this type of smolder, as the flow velocity is increased the smolder velocity increases but the reaction temperature decreases, regardless of the sample location. These trends are the result of the hot post-combustion gases being convected ahead of the smolder front. Although they preheat the virgin material downstream of the reaction favoring the propagation of the smolder reaction, they also dilute the oxidizer ahead of the reaction weakening it and reducing its temperature. The smolder velocity data are also correlated well with the predictions of a theoretical model of this mode of smolder. For upward smoldering, transition to flaming was observed to occur in the char at the zone closer to the sample end and for air velocities of 15 mm/sec or larger. Comparison between upward and downward smoldering also showed that the effect of gravity takes place for air flow rates smaller than 3 mm/sec.

Transition to Flaming: Experiments are currently being conducted to study smoldering in the presence of a gas/solid interface, and the phenomenon of the transition to flaming. The experiments are conducted in a test facility that includes a small scale combustion tunnel and the supporting instrumentation. The tunnel test section is 0.61m long with a cross section 0.15m wide and 0.07m deep, and is vertically oriented. Pre-metered compressed air flows through a settling chamber and a converging nozzle prior to entering the test section. Foam samples with a 0.15m side square cross section and with variable lengths are mounted flush in one of the test section walls. A flat type igniter is mounted in the upstream end of the fuel sample. The experiments show that transition to flaming is very sensitive to sample size, probably because of heat losses to the surrounding ambient. Samples with lengths smaller than 0.15m showed a smolder reaction that would propagate upward at an increased velocity, and that would became hotter and produce considerable amounts of smoke, but that eventually would extinguish itself apparently because of the dilution of the available oxidizer by the post-combustion gases. For samples larger than 0.15 m and at relatively low flow velocities (of the order of 0.3 m/s), transition to flaming is consistently observed initially in the upper part of the foam near the interface, after which the whole sample is rapidly involved in flames and burns completely. A parametric study is currently being conducted to study the mechanisms controlling the transition to flaming.

II.2 Ground Based Microgravity Smoldering:

A series of smolder experiments were conducted at the NASA LeRC 2.2 seconds drop tower to observe trends in the ignition characteristics of the foam, and to attempt to infer how smoldering will behave in microgravity. The parameter analyzed was the time derivative of the smolder reaction temperature, because the temperature itself, or the smolder velocity, do not change enough in 2.2 seconds to observe significant differences. The temperature gradients measured in the foam ahead of the reaction zone showed that microgravity favors the initial heating of the virgin fuel by the smolder reaction, and that the upper range of flow velocities at which buoyancy plays a significant role on smoldering is around 3 mm/s, in approximate agreement with the normal gravity experiments.

A series of opposed flow, downward and upward, smoldering experiments were also conducted in a NASA KC-135 aircraft (30 s of micro-g for up to 40 parabolas) to observe the effects of the variation of the gravity on the smolder process. The experimental apparatus is a small scale version of that described in the normal gravity forced flow experiments. Although the microgravity period was too short to study steady smoldering in micro-gravity, the tests provided initial information about the process and permitted the observation of smolder trends as the gravity changes. The tests also complement the Drop Tower tests summarized above. As with those tests, the variation of the smolder reaction temperature with time was the parameter used to infer the effect of gravity on the smolder process.

A characteristic example of the measurements made is given in Fig. 3, where the variation with time of the temperature in the three zones of the foam identified above (near igniter, middle, and free end) is plotted together with the gravity level variation. The results show that buoyancy affects the temperature differently according to the location of the measurement with respect to the reaction zone. In the virgin foam ahead of the reaction zone and in the char behind of it, the temperature increases as the gravity is reduced, but the opposite is observed around the reaction zone. This indicates that buoyancy affects both the species transport and transfer of heat to and from the reaction zone. At the reaction zone the former is dominant, which results in a decrease of the smolder temperature in microgravity. Away from the reaction zone the latter is dominant and the temperature increases due to the lack of convective cooling. All these effects are less noticeable as the flow velocity is increased, and as the reaction propagates toward the sample interior confirming that buoyancy is important at low flow velocities and near the sample ends.

II.3 Space Based Experiment:

Work on this aspect of the program has included the design of a small scale smolder experiment that was successfully carried out in the glovebox in Spacelab on USML-1, during the June 25 - July 11, 1992 mission of the Space Shuttle Columbia, and the preparation of the Science Requirement Document and Conceptual Design Review for a larger scale space based experiment to be conducted in the mid-deck or one of the gas-cans of the Space Shuttle in the mid-nineties.

The glovebox experiment hardware consists of four modules each containing an instrumented fuel sample, with an embedded igniter and an internal fan to induce forced convection. The test variables of the experiment are the igniter geometry and the convective environment. Through the use of an axial igniter and a plate igniter, both radial and axial smolder is investigated. For each igniter geometry, a test is conducted with a quiescent environment and with a low velocity flow, for a total of four test conditions. The modules are sealed, lexan boxes, nominally 0.15m by 0.20m, filled with air. A cylinder of open-cell polyurethane foam, 50mm in diameter and 80mm length is positioned in the center of the box. The igniters are resistively heated ceramic elements. The fuel sample is instrumented with 6 thermocouples, located at various positions to measure the smolder reaction temperature and its propagation throughout the sample. The temperature and igniter current measurements are displayed on two digital displays and recorded with a video camera.

Currently we are in the process of analyzing the data from the experiment, and we expect to completed the analysis within the next few months. However, preliminary temperature histories such as that of Fig. 4, which correspond to a test with the axial igniter and the fan on, indicate that although incipient smolder occurred, and seemed to be more intense than in normal gravity, the smolder reaction itself was not self-sustained and did not propagate beyond the vicinity of the igniter. A possible reason for this is that the incipient smolder reaction chokes itself with its own products by diluting the surrounding air. In microgravity, diffusion of oxidizer toward the reaction zone seem to be too slow to counteract this dilution process. Although we believe that for the same igniter conditions the smolder reaction would not propagate in normal gravity either. we think that this will be due to convective cooling effects and no to chemical reaction effects.

III. FUTURE RESEARCH PROGRAM

The future research program maintains the general guidelines established during the current research program. It contains two major tasks; one that concentrates on the space based experiments; and the other on the ground based experiments, and on the development and verification of theoretical models.

III.1 Ground Based Smoldering Experiments

III.1.1 Effect of Buoyancy on Forced Flow Smoldering

The experiments on the effect of buoyancy on forced flow smoldering will be continued. A parametric study will be made of the influence of parameters such as the fuel type and void fraction, the oxidizer oxygen concentration. ambient temperature and pressure, on the gravity effects. Experiments to study the effects of oxidizer temperature and oxygen concentration will be conducted first. The former will affect the rate of heat losses from the reaction, and the latter the rate of heat release. These are two competing mechanisms that determine the characteristics of the smolder reaction.

III.1.2 Transition Processes in Smoldering

This is a very interesting task of the research program because transition processes such as ignition, flaming and extinction are issues of great importance in the fire safety field. These processes are also interesting as a fundamental combustion problem, and very little information is currently available on them.

The experiments will concentrate initially in the determination of the conditions leading to smolder initiation (or ignition), and to flaming. Smolder ignition is very sensitive to porous fuel type, rate of heat addition, geometry of the experiment and igniter, and temperature, among others, and there is a need to characterize the process. There is also a need to come up with a protocol for the ignition of the foam that is reliable so that an automatized ignition system can be designed for its use in the space experiments. Concerning the transition to flaming, the parametric study currently being conducted will be continued to determine the conditions leading to transition to flaming. As the program progresses drop tower and parabolic flight tests will be planned to study these process under microgravity conditions. Since the characteristic time of the transition process is small (particularly flaming) it is expected that the ground base microgravity experiments will give useful information.

Concurrent with the above experiments, the analyses already developed of forced flow opposed and forward smoldering will be extended to include finite rate kinetics. The objective is to predict those conditions were extinction of the reaction was observed experimentally. The modeling of the transition to flaming both in one-dimensional and smoldering in an interface will also be continued.

III.2 Space Experiments

This task will consist primarily in the interaction with the NASA LeRC engineers in the design and construction of the space based experimental apparatus. Also the data from the USML-1 smolder experiments will be analyzed and compared with the ground data. The results will be used to finalize the design of the large scale space experiments

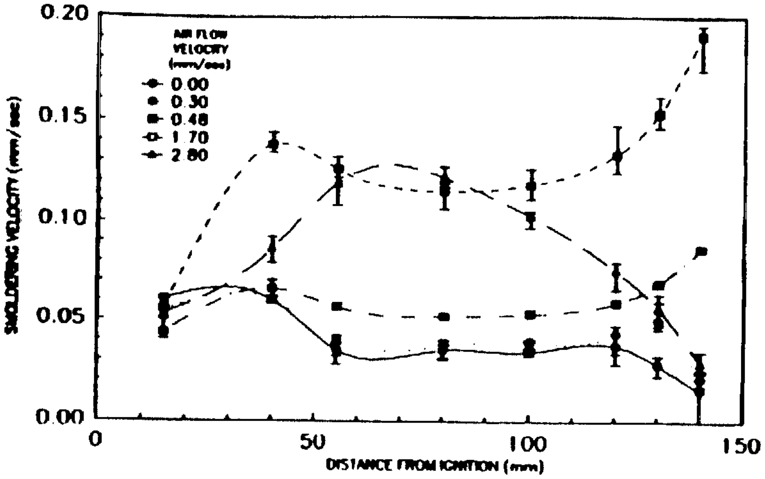

Fig. 1. Variation of the downward smolder velocity along the foam sample for several opposed air flow rates.

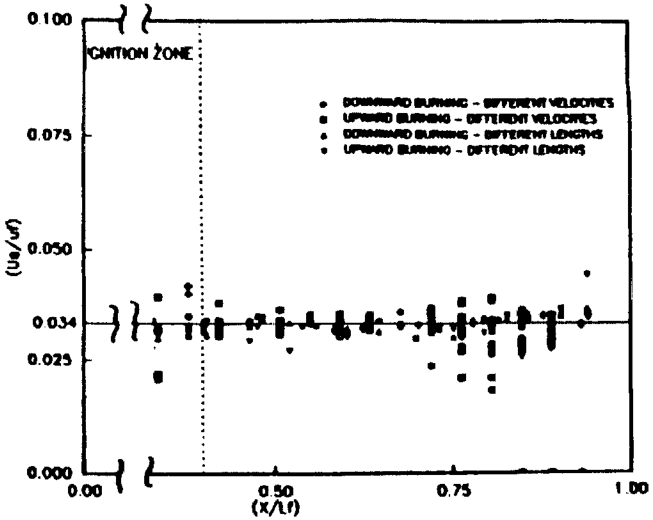

Fig. 2. Correlation of the opposed flow smolder data in terms of the theoretically calculated nondimensional smolder velocity.

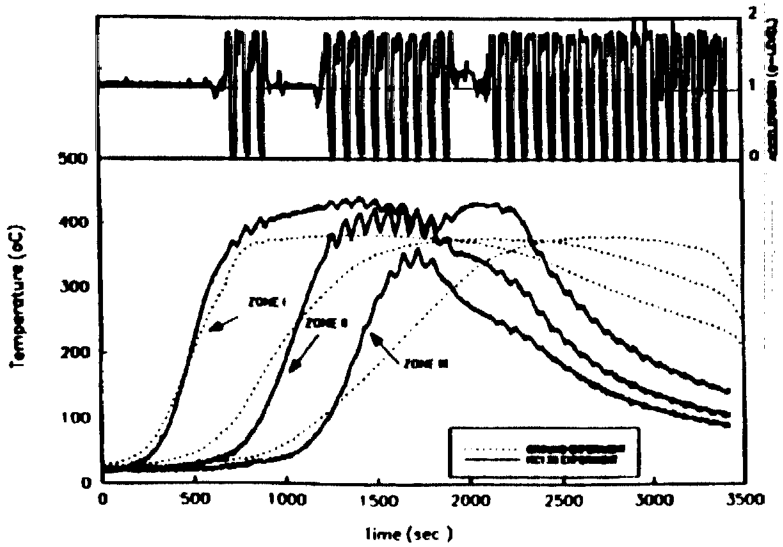

Fig. 3. Foam temperature histories in natural convection, downward smolder from experiments conducted in a KC-135 aircraft (acceleration level is indicated for reference).

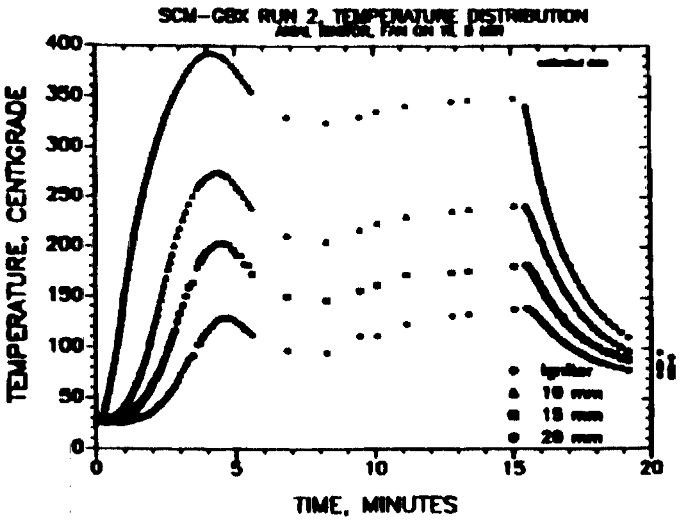

Fig. 4. Temperature histories at several locations of the foam sample from experiment conducted in the USML-1 of the Space Shuttle Columbia.