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Transition from Forward Smoldering to Flaming in

Small Polyurethane Foam Samples

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Short running title: **Transition Smoldering-Flaming: Small Samples**

Abstract

Experimental observations are presented of the effect of flow velocity, oxygen concentration, and a thermal radiant flux, on the transition from smoldering to flaming in forward smoldering of small samples of polyurethane foam with a gas/solid interface. The experiments are part of a project studying the transition from smoldering to flaming under conditions encountered in spacecraft facilities, i.e., microgravity, low velocity variable oxygen concentration flows. Because the microgravity experiments are planned for the International Space Station, the foam samples had to be limited in size for safety and launch mass reasons. The feasible sample size is too small for smolder to self propagate because of heat losses to the surroundings. Thus, the smolder propagation and the transition to flaming had to be assisted by reducing heat losses to the surroundings and increasing the oxygen concentration. The experiments are conducted with small parallelepiped samples vertically placed in a wind tunnel. Three of the sample lateral-sides are maintained at elevated temperature and the fourth side is exposed to an upward flow and a radiant flux. It is found that decreasing the flow velocity and increasing its oxygen concentration, and/or increasing the radiant flux enhances the transition to flaming, and reduces the time delay to transition. Limiting external conditions for the transition to flaming are reported for this experimental configuration. The results show that smolder propagation and transition to flaming can occur in relatively small fuel samples if the external conditions are appropriate. The results also indicate that transition to flaming occurs in the char region left behind by the smolder reaction, and it has the characteristics of a gas-phase ignition induced by the smolder reaction, which acts as the source of both gaseous fuel and heat. A simplified energy balance analysis is able to predict the boundaries between the transition/no transition regions.

Keywords: smoldering; transition to flaming; polyurethane foam.

1. Introduction

The transition from smoldering to flaming is of interest both as a fundamental combustion problem and as a serious fire risk. It encompasses phenomena related to the ignition of a homogeneous gas phase reaction (flaming) that is induced by a heterogeneous surface reaction (smolder) that acts both as the source of gaseous fuel (pyrolyzate, CO, etc.) and the source of heat to initiate the homogeneous reaction [1-4]. That it is a fire hazard is confirmed by the fact that more than 40% of United States fire deaths can be attributed to smoldering [5]. The transition to flaming is also of concern in the space flight program; to date there have been a few minor incidents of overheated and charred cables and electrical components reported on Space Shuttle flights [1,6] and significant smolder-related incidents aboard the Russian space station Mir [7,8]. With the ongoing establishment of the International Space Station and the planning of other long-term space missions, there is an added need to study smoldering and transition to flaming in microgravity in order to prevent and minimize the effects of a smolder-initiated fire.

The configuration in which transition to flaming is more likely to occur is forward smolder, where the oxidizer flows in the same direction as that of smolder propagation [9,10]. Thus, the oxidizer reaches the reaction zone after passing through the hot char left behind by the propagating smolder reaction, and the transition to flaming may occur by vigorous oxidation of this char. The transition from smoldering to flaming in the presence of a porous-solid/gas interface is of interest since it is likely to occur in practical situations. In this case the transport processes at the interface may play an important role in the process [3, 4]. The flow of oxidizer at the solid/gas interface can enhance or deter the smolder process, depending on the balance between the oxygen supply to the reaction, and convective heat loss from the reaction. Furthermore, if an external heat flux is present, as could occur at the onset of a fire, the heat losses would be further counteracted, and the added supply of oxidizer flow would result in the enhancement of the smolder process.

While considerable work has been conducted to understand the smoldering combustion of porous fuels, there has been considerably less research conducted on the transition from smoldering to flaming. Prior work in transition from smoldering to flaming considered cellulosic materials or polyurethane foam

samples of different sizes and with different oxygen concentrations [3,4,11-15]. Most of the experiments were conducted with a solid/ gas interface, in a horizontal arrangement for loose materials, or vertical for materials that maintained their structure during smolder. The flows were either naturally induced or forced. A common observation of these works is that for the transition from smoldering to flaming to occur the fuel samples have to be fairly large, or the process must be assisted by increasing the oxygen concentration of the oxidizer flow and/or external heating.

The present work is part of a NASA funded project to study the transition from smolder to flaming of polyurethane foam in environmental conditions encountered in spacecraft facilities, i.e., microgravity, and low velocity and variable oxygen concentration oxidizer-flows [1]. Because the microgravity experiments are planned for the International Space Station, the polyurethane foam samples had to be limited in size for safety and launch mass reasons. The maximum sample size permitted for the experiments (50 mm x 50 mm side and 100 mm long) is too small for smolder to self propagate [16] due to heat losses to the surroundings. Thus, the smolder propagation had to be assisted by reducing the heat losses and by increasing the oxidizer oxygen concentration. This has resulted in a study of the effect of the heat loss reduction and of increasing the oxidizer flow oxygen concentration on the smolder propagation and its transition to flaming, presented here. The work has also demonstrated that both can occur with relatively small fuel samples if the external ambient conditions are appropriate.

2. Experiment

2.1. Experiment concept and protocol

The experimental configuration is similar to that employed by Tse et al [4] i.e. three-dimensional forward smolder with a solid/gas interface. The foam sample is a vertically-oriented parallelepiped insulated on three of its surfaces and with the fourth, free surface, exposed to an upward forced convective oxidizer flow parallel to the surface. Smolder ignition is induced at the bottom of the sample and smolder propagates upward in the same direction as the oxidizer flow (buoyant and forced), i.e., forward smolder. A schematic of the experiment is shown in Fig. 1.

As indicated above, the sample is limited in size to dimensions that are too small for smolder to self propagate even in microgravity [17] and for transition to flaming to occur [12]. Smolder is a weak reaction that is very sensitive to external heat losses, which increase as the sample size is reduced and can prevent smolder propagation. A simplified analysis of smolder propagation [10,18] helps to illustrate this aspect of the problem. Smolder often occurs under oxygen-limited conditions [9], and consequently the rate of heat release from the smolder reaction is directly proportional to the oxidizer mass-flux. The heat released by the reaction is in turn partially transferred ahead of the reaction and partially lost to the surrounding environment. Under these conditions, the smolder propagation velocity is given by:

$$
u_{sml} = \left(y_{O2} \rho_g u_i Q_{sml} - \dot{Q}''_{loss} {}^{A_L}\!/_{A_c} + \dot{Q}''_{ext} \right) \Big/
\left\{ \begin{array}{l} \left[(1-\phi)\rho_s c_s + \phi \rho_g c_{p,g} \right](T_{sml} - T_a) \\ -(1-\phi)\rho_s Q_P + y_{O2} \rho_g Q_{sml} \end{array} \right\} \quad (1)
$$

where Q_{sml} is the heat of smoldering per mass of oxygen consumed, Q_p is the heat of pyrolysis per mass of foam reacted, $\dot{Q}''_{loss}$ is the total heat loss per unit area to the surrounding environment, $\dot{Q}''_{ext}$ is the external heat addition per unit area, A_L is the lateral (peripheral) area of the smolder front, A_C is the cross-sectional area of the smolder front, ρ is the density, c is the specific heat, T_a is the ambient temperature, T_{sml} is the temperature of smolder, u_i is the velocity of the internal air going though the porous media, u_{sml} is the smolder propagation velocity, y_{O2} is the mass fraction of oxygen in the incoming air and ϕ is the porosity of the foam.

As the sample is made smaller, the ratio A_L/A_C (which is inversely proportional to the sample side length) increases, and the effect of the heat losses increases until smolder propagation cannot occur. Torero [16] studied the critical size of parallelepiped samples of polyurethane foam to smolder in natural convection air and identified a critical size of 140 mm side for the setup used in [16]. Thus for a sample size below this critical size, to sustain smolder, the heat losses must be reduced or the heat generated by the smolder reaction increased, or both. The former can be accomplished by insulating the sample or increasing the wall temperature and the latter by increasing the oxygen concentration of the oxidizer flow.

Similar arguments can be made for the transition to flaming, which can be viewed as a self-ignition process, and as such its occurrence requires the heat generated by the reaction to be larger than the heat losses to the surrounding environment. As in smolder propagation, the transition to flaming may require the reduction of heat losses, and/or the increase of the heat generated by the reaction. Both approaches are followed in the present study.

Controlling the wall temperature with guard heaters on the holder sides was found to be the most effective approach for limiting the heat losses. In order to avoid significant thermal decomposition by pyrolysis, the sample-holder walls are maintained at a minimum of 200 °C by the guard heaters, although the wall temperature during the tests exceeds 200 ºC due to the exothermic smoldering reaction.. At 200 ºC, the foam degradation in isothermal thermogravimetric experiments [20] is below 5% but rapidly increases if temperature rises (i.e. at 220 °C the foam conversion is 20 %). Also, the free sample surface was exposed to an external radiant flux kept below 10 kW/m^2, to avoid a smolder initiated by the radiant flux alone. The sample still loses heat at the free surface by convection to the oxidizer flow, whose velocity becomes a parameter of the problem.

To enhance the heat generated by the reaction, the transition to flaming experiments are conducted with oxidizer flows at oxygen concentrations above that for air, which also becomes a parameter of the problem. To ensure a transition process that is solely generated by the smolder reaction and not assisted by the igniter, smolder is initiated and allowed to propagate beyond the igniter influence in air initially. Once self-smolder propagation is established, the igniter is turned off, allowed to cool to temperatures below 250 °C and the internal and external oxidizer flows switched to the nominal oxygen concentration for the experiment. Transition to flaming is considered not to occur if smolder propagates through the whole sample without transition, or if smolder propagation does not occur beyond the region influenced by the igniter.

2.2 Experimental Apparatus

The experiments are conducted in a small vertically oriented aluminum flow duct (Fig. 1), 380 mm long and with a cross-sectional area of 135 mm by 80 mm. One wall of the flow duct consists of a pane of

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borosilicate glass for optical access. The opposite wall includes a calcium fluoride window (25 x 100 mm) for infrared imaging. The oxidizer flow entering the test section of the flow duct first passes through a settling chamber and a converging nozzle.

The sample holder is located 120 mm from the inlet to the flow duct and vertically oriented such that the front face of the fuel sample is flush with the interior wall of the flow duct. The sample holder is constructed of thin-walled (0.75 mm) brass sheets insulated with Fiberfrax™, with a central cavity to contain the fuel sample (50 mm x 50 mm cross section and 125 mm long), and the igniter holder assembly. The outer surfaces of the back and side walls of the sample holder each have a guard heater independently controlled by a Minco temperature controller.

An infrared radiant heater is mounted opposite the sample holder in the vertical wall of the flow duct to counter heat losses from the free surface of the fuel sample with a radiant flux perpendicular to the sample surface. The radiant heat flux from the heater was measured using air-cooled radiometers placed in the fuel sample.

In order to initiate the smolder reaction, the bottom face of the sample is in contact with an electrically heated ceramic honeycomb igniter of area 50 mm by 50 mm. The bottom face of the igniter is insulated with a layer of Fiberfrax™ of thickness 15 mm. During the tests, there is a forced flow of oxidizer through the Fiberfrax™ and the igniter, and into the fuel sample at a flow rate of 13.4 cc/s, which was determined to be the optimal internal flow rate for smolder ignition and propagation from previous testing.

The duct oxidizer flow is controlled using two identical sets of critical flow nozzles. Duct oxidizer flow velocities are uniform over the cross section of the flow duct, with minimal boundary layer growth. The internal oxidizer flow through the igniter is controlled using mass flow controllers.

In all testing, the fuel samples were open-celled, non-flame-retardant, flexible polyurethane foam. The fuel properties are listed in [19]. Five type-K thermocouples are located along the centerline of the sample at distances from the igniter/fuel interface of: 0 mm, 20 mm, 41 mm, 62 mm, and 94 mm. The

igniter thermocouple is a 0.14 mm diameter bare-wire thermocouple, while the other four are 0.84 mm diameter sheathed grounded thermocouple probes, inserted through the back of the sample. In addition, an infrared camera (FLIR Systems Model SC1000) monitors the surface temperature of the foam at an oblique angle of approximately 45°, and views the sample through the calcium fluoride window. Because the emissivity of the surface of the fuel sample is unknown and varies due to the changing molecular structure of the surface caused by the smolder reaction, all surface temperatures reported by the infrared camera are equivalent blackbody temperatures. A video camera views the sample through the borosilicate window.

2.3 Experiment Procedure

Tests are conducted varying the external radiant heat flux, duct oxidizer flow velocity and oxygen concentration of the duct and internal flows. In each test, a smolder reaction is first initiated using air in both the duct and internal flows, and the oxygen concentration is changed to the nominal value once self-smolder propagation is established. During the smolder ignition portion of the test, an internal air-flow of 13.4 cc/s was used, which has been determined as optimum to induce smolder ignition in the present experiments. After the duct and internal flows reached steady state, the radiant heater was turned on, and the Minco heater temperature controllers were set to a set point of 200 ºC. This set point temperature was chosen to prevent significant foam pyrolysis due to the guard heaters while reducing the heat losses from the reaction.

The igniter is activated when the guard heaters reached their set point temperature on to a power of 23.25 W, which was determined to be the optimal power for smolder ignition based on previous testing. The igniter is turned off after self-smolder propagation is observed (ranging from 450 to 600 s). When the igniter cooled to 250 °C, the internal and external flows were simultaneously enriched to the nominal oxygen mole fraction. The selection of 250 °C as a threshold temperature is consistent with the minimum pyrolysis temperature, below which no further reaction is expected. If the smolder reaction reached the top of the sample without a transition to flame, the test was stopped. If transition to flaming occurred, it was rapidly extinguished with a jet of CO_2 to preserve as much of the sample as possible.

3. Results

3.1 Thermocouple, Video and Infrared Results

Characteristic temperature time histories are shown in Fig. 2 comparing two tests with and without a transition to flame. The temperatures of Fig. 2(a) are typical of those observed in forward smolder [10], although once the flow is switched from air to the nominal oxygen concentration there is an increase in temperature upstream of the smolder reaction indicating an enhancement of the char oxidation reaction. Following the temperature histories in Fig. 2(b) it is seen that the temperatures of the thermocouples located at 41 mm and 62 mm from the igniter increase steadily and reach a peak of approximately 382 ºC, indicating the arrival of the smolder front at the thermocouple location. The temperature of the thermocouple located at 94 mm increases steadily indicating the approach of the smolder reaction. At 1019 s, the internal and duct flows are enriched to the nominal oxygen concentration, and at approximately 1035 s there occurs a noticeable change in the slope of the temperature history of the thermocouple at 94 mm. The thermocouples at 62 mm and 41 mm attain minimum values before increasing sharply. The transition to flame, indicated by the sharp temperature increase of these thermocouples, occurs at approximately 1054 s, which is confirmed by both video and infrared imaging. Enlargement of the temperature histories in the vicinity of the transition to flaming shows the transition occurring at a location between thermocouples at 41mm and 62 mm and foam burning rapidly propagating downstream and upstream along the foam.

In Fig. 3, characteristic video and infrared camera images of a transition from smoldering to flaming are presented. The first two video images show that the smolder reaction has been ignited and progressed approximately 95 mm through the sample height. The char structure on the free surface shows that the smolder reaction does not spread to the edges of the sample, due to heat losses to the holder walls. Once the oxidizer flow is switched to the nominal oxygen concentration an intensification of the reaction is observed, as shown in Fig. 3(a) by comparison of the second, third, and fourth images in the sequence. The reaction also spreads transversely toward the walls indicating that the stronger reaction helps in overcoming the heat losses to the holder walls. Simultaneously, the top portion of the char on the fuel

sample surface is burned away, opening a large hole in the char on the surface. The fifth image clearly shows a flame protruding into the duct from the upper half of the sample. It has been observed that the flame rapidly spreads upstream from the transition, towards the igniter, and engulfs the sample.

The infrared images (Fig. 3(b)) show that the smolder reaction has propagated away from the igniter and that the lower half of the sample has cooled. This is consistent with other smolder tests [3, 4, 10] and is due to heat losses to the surrounding. The second, third, and fourth infrared images correspond to the opening of a large hole on the sample surface as seen in the video imaging. The high temperatures in the char, shown in white, exceed the operating range of the camera. The fifth image clearly shows a flame protruding into the duct from the upper half of the sample.

3.2 Effect of External Flow Velocity and Oxygen Mole Fraction

A set of tests was run varying the duct flow velocity and oxygen mole fraction of the internal and duct flows, while holding the heat flux constant at 7.25 kW/m^2 to determine the conditions under which transition from smoldering to flaming occurs. The results of these tests are shown in Table 1. Transition tests are marked with the time delay between the flow oxygen enrichment and the transition to flaming, and failed transition tests are marked with an "N". Tests for which the smolder reaction did not self-propagate are marked with an "N*". The flow velocity reported is that of the forced flow as determined with cold samples. However, since as the sample heats up an upward natural convection flow is generated that adds to the forced flow, the actual flow velocity near the fuel surface is larger than that reported, particularly at low flow velocities. As can be seen from Table 1 transition to flaming was not observed below 35 % oxygen concentration. The tests run with 35% oxygen produced transition to flaming at a forced flow of 0.25 m/s, but not at 0.5 m/s. At 37.5% and 40% oxygen, transition to flaming was observed for forced flow velocities equal to or less than 1.5 m/s. At 2 m/s smolder did not self-propagate and transition to flaming did not occur. The results appear to indicate that as the flow velocity increases the time delay to transition also increases. The results also appear to indicate that as the oxygen mole fraction increases, the time delay to transition decreases.

3.3 Effect of External Heat Flux

Tests varying the external heat flux were conducted with duct flow velocities of 0.25, 0.5 and 1.0 and 1.5 m/s, and an oxygen mole fraction of 0.35. The nominal radiant heat fluxes tested in this series were 7.25, 8.00, 8.75 kW/m^2. As shown in Table 2, transition to flame was observed for all three heat fluxes at a forced flow velocity of 0.25 m/s. In the case of 0.5 and 1.0 m/s duct flow velocities, no transition to flame was observed for a radiant heat flux of 7.25 kW/m^2 but transition to flame was observed at 8.00 and 8.75 kW/m^2. The time delay for transition decreases as the radiant flux is increased.

4. Discussion

By studying the detailed temperature history depicted in Fig. 2(b), it is observed that the transition to flaming occurs somewhere in the vicinity of the thermocouples at 62 mm and 41 mm, since they are the first thermocouples to sharply increase in temperature. The fact that both thermocouples start to increase rapidly at almost the same time (1054.5 s) suggests that the transition occurs somewhere between these two thermocouples. At the time of transition, the temperature of the thermocouple at 94 mm is 446 ºC, indicating that the smolder front has already passed this location. These results indicate that the transition to flaming occurs in the char region behind the smolder front. These findings are consistent with those of Tse et al. [4], which reported that the transition to flaming occurred in voids that formed in the char region behind the smolder front. This is further confirmed by examination of the infrared imaging sequence in Fig. 3(b). In the third image in the sequence, it can be clearly seen that the char upstream of the smolder front exhibits higher temperatures than at any other location in the fuel sample at that time. The fourth image, just prior to the transition, shows that this region of high temperature char spreads counter to the flow direction while the smolder reaction continues to move in the flow direction.

Table 1 and Table 2 show a demarcation between the regions of transition and no transition, which is in qualitative agreement with Eq. 2. As the overall heat transfer coefficient for the heat losses increases due to convective cooling from the increased duct flow or lower radiant heat flux, the oxygen concentration must be increased for transition to occur. Thus the results presented above support the conclusion that the transition from smolder to flaming is a type of spontaneous gas phase ignition where the smolder reaction acts both as source of fuel and of heat for the reaction. They also indicate that in

order for the transition to occur the heat generated by the reaction has to overcome the heat losses to the surrounding environment. For example, it is expected that increasing the oxidizer flow velocity can enhance the reaction in the char by providing increased oxygen, but can also convectively cool the reaction. The results of Tables 1 and 2 indicate that the latter is dominant in the present experiments since transition does not occur at the higher velocities and the delay to transition increases as the flow velocity is increased. Similarly, it is expected that increasing the external heat fluxes will enhance the tendency to transition to flaming since the heat losses are reduced, as observed in the experiments. As per the effect of the oxidizer flow oxygen concentration, an increase in oxygen mole fraction for a constant radiant heat flux and constant duct flow velocity, will increase the reaction rate of the secondary char oxidation reaction and of the gas phase reaction, thus increasing their heat release rate. Thus it is expected that at a sufficient increase in oxygen concentration the heat generation will overcome the heat losses, which in turn will lead to the transition to flame. From the data presented in Tables 1 and 2 a threshold oxygen mole fraction between 0.325 and 0.35 has been identified below which the transition to flaming does not occur for the present experimental protocol and natural convection conditions.

For an oxygen mole fraction of 0.35, and duct flow velocities of 0.5 m/s and 1 m/s, there is a threshold radiant heat flux between 7.25 and 8.00 kW/m^2 below which a transition to flame is not observed. In addition, for an oxygen mole fraction of 0.35 and a duct flow velocity of 1.5 m/s, there is a threshold radiant heat flux between 8.00 and 8.75 kW/m^2 below which a transition to flame is not observed. Thus it appears that below these threshold heat fluxes, the radiant heat flux cannot overcome the heat losses and therefore transition to flame does not occur.

The transition to flaming can be viewed as an autoignition process in which the heat generated by the reaction overcomes the heat losses to the surroundings. Conducting a simplified energy balance, similar to that of Frank-Kamenetskii [21], on the smolder front region gives the following:

$$Q_{sml} y_{O2} \rho_g u_i = \left(\dot{Q}''_{free} + 3\dot{Q}''_{side} - \dot{Q}''_{rad} \right) A_L / A_C \qquad (2)$$

where $\dot{Q}''_{free}$ is the heat loss per unit area by convection from the exposed sample surface, $\dot{Q}''_{side}$ is the heat loss per unit area by conduction through the three unexposed sample sides, and $\dot{Q}''_{rad}$ is the external heat flux from the radiant heater. Estimates of the heat loss terms in Eq. 2 results in an expression for the critical duct flow velocity as a function of the oxygen mass fraction and the radiant heat flux as shown below:

$$u = (12y_{O2} + 0.4\dot{Q}''_{rad} - 6.7)^2 \; [m/s] \qquad (3)$$

The results of Eq. 3 are plotted versus the experimental results of transition/no transition tests in Fig. 4 (a) and (b). The analysis predicts well the boundaries between the transition/no transition regions, corroborating the concept that transition to flaming can be described as an autoignition process.

5. Conclusions

The presented experiments show strong evidence that a transition from smolder to flaming occurs in the char region upstream of the smolder reaction, in agreement with previous observations of the process. A combination of infrared and video imaging, with in-depth thermocouples adequately tracked the progress of the smolder reaction, and captured the transition to flaming event in sufficient detail to determine the approximate location of the transition and the time delay to the transition event.

The results show that transition from smoldering to flaming can occur in relatively small fuel samples if the external conditions are appropriate. It is shown that the transition to flaming is sensitive to the external heat losses, and the heat generated by the secondary char reactions occurring in the char upstream of the smolder reaction. The data shows that increasing the oxygen concentration of the oxidizer flow, reducing the velocity of the external flow, and/or increasing the external radiant flux increases the likelihood of a transition to flaming. These observations support the concept that the transition from smolder to flaming is basically a spontaneous gas phase ignition reaction that is supported by the smolder

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reaction, which acts both as the source of gaseous fuel (pyrolyzate) and of heat to support the reaction. The transition is more likely to occur when the heat released by both the heterogeneous smolder reaction and the homogeneous gas phase reaction is larger than the heat losses to the surrounding environment. These findings are supported by a simplified energy balance analysis that describes the transition as an autoignition process. The analysis is able to predict the boundaries between the transition/no transition regions. These findings are also supported by the observations that the transition occurs in the interior of the char, where it is more likely that the pyrolyzate be present since the smolder reactions are generally oxygen limited, and where the reactions are thermally insulated from the exterior by the char itself. Under these conditions a sudden surge of oxygen, due to openings in the char near the sample surface, or external increases in the oxygen supply, could trigger the onset of the gas phase reaction and consequently the transition to flaming.

Acknowledgements

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Tables

Table 1. Matrix of tests varying duct flow velocity and oxygen fraction of internal and duct flow, at 7.25 kW/m^2 radiant heat flux

Oxygen Mole Fraction	Duct Flow Velocity [m/s]				
	0.25	0.5	1.0	1.5	2.0
0.30	N	N			
0.325	N	N			
0.35	32 s	N	N	N	
0.375	29 s	32 s	34 s	44 s	N*
0.40	27 s	26 s	25 s	40 s	N*

Table 2. Matrix of tests varying duct flow velocity and radiant heat flux, at 0.35 oxygen mole fraction.

| Heat Flux [kW/m^2]	Duct Flow Velocity [m/s]			
	0.25	0.5	1.0	1.5
7.25	32 s	N	N	N
8.00	29 s	39 s	41 s	N
8.75	22 s	34 s	31 s	31 s

List of Figures Captions

Fig. 1 Schematic of the experimental apparatus.

Fig. 2 Characteristic temperature histories along sample; (a) smolder propagation without transition to flame. Test conditions: 0.5m/s duct flow, 0.35 oxygen mole-fraction, 7.25 kW/m^2 radiant flux, (b) with transition to flame at 1054.5s. Test conditions are 0.5 m/s, 0.35 oxygen mole fraction, and 8.75 kW/m^2.

Fig. 3. Photographic sequences of transition from smoldering to flaming, using (a) visible imaging, (b) infrared imaging. Test conditions are: 0.25 m/s duct flow, 0.35 oxygen mole fraction, and 8.00 kW/m^2 radiant heat flux. Images are taken at the times: t=900.0s, 1052.0s, 1057.0s, 1062.7s, and 1062.8s.

Fig. 4. Comparison of experimental results with the energy balance analysis predictions of transition/no transition regions as a function of (a) oxygen mole fraction. (b) radiant heat flux.
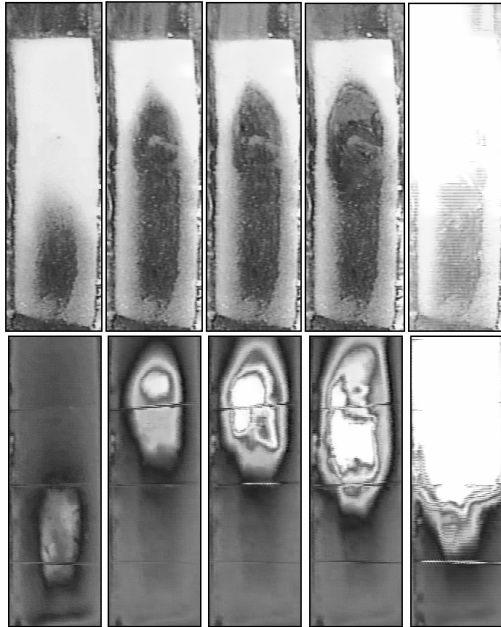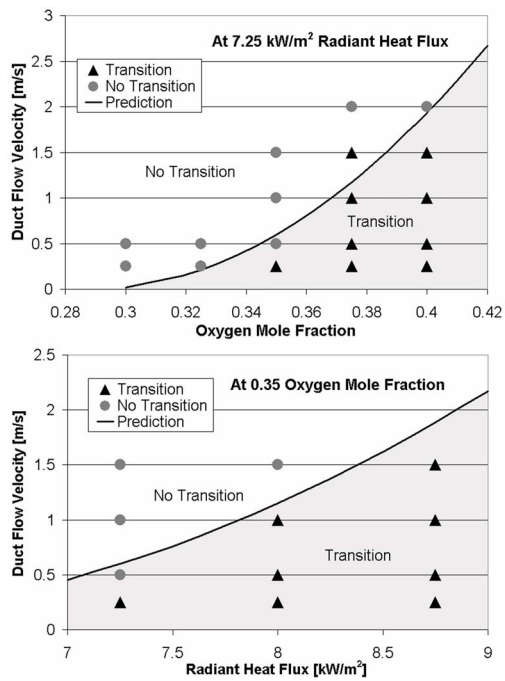
Figures
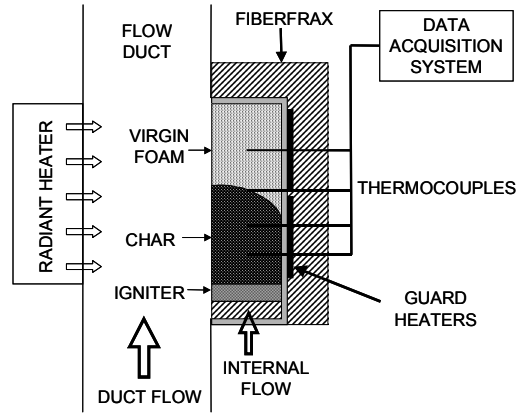
Fig. 1
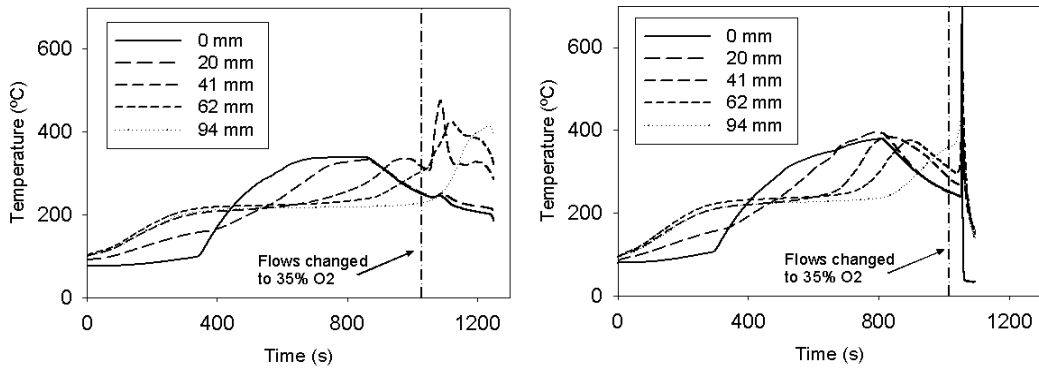
Fig. 2 (a) and (b)

Fig. 3 (a) and (b)

Fig. 4 (a) and (b)