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Authors

Walther, David C
Anthenien, Ralph A
Fernandez-Pello, Carlos

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**SMOLDER IGNITION OF POLYURETHANE FOAM: EFFECT OF OXYGEN
CONCENTRATION**

D.C. Walther, R.A. Anthenien[†], and A.C. Fernandez-Pello*

Department of Mechanical Engineering
University of California at Berkeley
Berkeley, CA 94720

*Author to whom correspondence should be directed.

Phone: (510) 642-6554

Fax: (510) 642-1850

[†]Current address: Air Force Research Laboratory / Propulsion Directorate
Wright-Patterson AFB, OH 45433

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ABSTRACT

Experiments have been conducted to study the ignition of both forward and opposed smolder of a high void fraction, flexible, polyurethane foam in a forced oxidizer flow. Tests are conducted in a small scale, vertically oriented, combustion chamber with supporting instrumentation. An electrically heated Nichrome wire heater placed between two porous ceramic disks, one of which is in complete contact with the foam surface, is used to supply the necessary power to ignite and sustain a smolder reaction. The gaseous oxidizer, metered via mass flow controllers, is forced through the foam and heater. A constant power is applied to the igniter for a given period of time and the resulting smolder is monitored to determine if smolder is sustained without the assistance of the heater, in which case smolder ignition is considered achieved. Reaction zone temperature and smolder propagation velocities are obtained from the temperature histories of thermocouples embedded at predetermined positions in the foam with junctions placed along the fuel centerline. Tests are conducted with oxygen mass fractions ranging from 0.109 to 1.0 at a velocity of 0.1 mm/s during the ignition period, and 0.7 or 3.0 mm/s during the self-sustained propagation period. The results show a well defined smolder ignition regime primarily determined by two parameters: igniter heat flux, and the time the igniter is powered. These two parameters determine a minimum igniter/foam temperature, and a minimum depth of smolder propagation (char), which are conditions required for ignition to occur. The former is needed to establish a strong smolder reaction, and the latter to reduce heat losses from the incipient smolder reaction to the surrounding environment. The ignition regime is shifted to shorter times for a given igniter heat flux with increasing oxygen mass fraction. A model based on concepts similar to those developed to describe the ignition of solid fuels has been developed that describes well the experimental ignition results.

INTRODUCTION

The objective of this work is to better understand the controlling mechanisms of smoldering, in particular the ignition process. Smoldering is defined as a non-flaming, self-sustaining, propagating, exothermic, surface reaction, deriving its principal heat from heterogeneous oxidation of the fuel [1,2]. Many materials can sustain smoldering and, if the material is sufficiently permeable, smoldering is not confined to the outer surface and can propagate as a reaction wave through the interior of the material. Due to its low reaction temperature (~600-700K), a smolder reaction is very weak, hovering between extinction and flaming. Heat losses to the ambient are therefore critical. The ignition, propagation, transition to flaming and extinction of the smolder reaction are controlled by complex, thermo-chemical mechanisms that are, as yet, not well understood.

Smoldering is a basic combustion phenomenon that encompasses a number of fundamental processes, including: heat and mass transfer in porous media, endothermic pyrolysis of the combustible, ignition, propagation, and extinction of heterogeneous exothermic reactions at the solid/gas pore interface, and the onset of gas phase reactions (flaming) which develop from the surface reactions [1,2]. From a practical point of view, smoldering occurs in processes ranging from smolder of porous insulating materials [3-8] to underground coal combustion [9-11]. Here, we are interested in smoldering in the context of fire safety through the prevention of a smolder initiated fire. Smoldering is of concern because it requires low heat fluxes for ignition, can propagate slowly in the material interior, going undetected for long times, and is difficult to extinguish. It also typically yields a substantially higher conversion of fuel to toxic compounds, notably CO and HCN [12,13], than does flaming (though more slowly), and may undergo a sudden transition to flaming [14-16]. Various fire studies since the early 1970's have shown that over 40% of United States fire deaths can be attributed to smoldering of household furniture [17].

There are two distinct classifications for one-dimensional propagation of a smolder reaction: opposed and forward [2,16], defined according to the relative directions in which the reaction zone and oxidizer propagate. In forward smolder, the oxidizer and smolder reaction propagate in the same direction in the laboratory reference frame, in opposed flow they propagate in opposite directions. Figure 1 shows a schematic of these smolder modes for one-dimensional propagation. Upward and downward smolder refers to the propagation direction of the reaction

zone relative to the gravity vector. The reader is referred to [2,18,19] for further information on smolder.

While much work has been done to date concerning smolder propagation, the ignition process itself is not well understood, with experimenters resorting to *ad hoc* methods of ignition in their propagation studies. An understanding of the smolder ignition process is important for the complete comprehension of the entire smoldering process, and as a practical matter in predicting and preventing smolder initiated fires. The factors that control smolder ignition and propagation need to be identified for fire safety applications as well as conceptual understanding. Of the few studies on smolder ignition, Ohlemiller [20] examined the effect of igniter geometry on smolder ignition of cellulose, simulating overheated wires and recessed lighting fixtures, finding that geometry had a substantial effect (differences in ignition temperature of up to 150°C). The study did not, however, investigate the amount or rate of energy deposition necessary for ignition of the smolder reaction. To the best knowledge of the authors, only two studies of the energetic requirements for the initiation of a self-sustaining smolder reaction have been conducted to date. Kitano and Nagano [21] examined the ignition of smolder under natural convection conditions, and Anthenien and Fernandez-Pello [22] studied the effects of forced oxidizer flow velocity on the ignition process for forward smolder; both studies utilizing polyurethane foam as the fuel. From this latter study it was found that the flow velocity during ignition has little, if any, effect on the ignition characteristics. It is the effort of this work to examine the effects of oxygen concentration on smolder ignition and propagation in both forward and opposed flow smolder. This work is in direct support of the Microgravity Smoldering Combustion (MSC) project being conducted by NASA; it's goal is to provide a well defined ignition protocol, as well as investigate the fundamental mechanisms controlling smolder ignition.

EXPERIMENT

A schematic of the experimental setup is shown in Fig. 2. The experiments are conducted in a small-scale combustion apparatus with supporting instrumentation. The test section for the opposed flow smolder experiments is a 300 mm long, vertically oriented, square cross-section duct with 130 mm side length. The test section walls are 3 mm thick Fiberfrax 970-J insulating board held within an aluminum frame. Aluminum tape is used along the outer surface of the test section to prevent species diffusion to/from the ambient. The forward flow test section is a

300 mm long, vertically oriented, 120 mm internal diameter 304 stainless steel cylinder insulated externally with 3 mm Fiberfrax 970-J insulating paper and internally with Fiberfrax QF-180 insulating cement. The differences between the two apparatuses are the result of the evolution of the project and the need to adapt the apparatus test section to that used in the Space Shuttle experiments [12]. Oxidizer is forced into the test section through a diffuser section to provide uniformity of the flow throughout the test section. Flow rate and oxygen concentration are controlled by Tylan[®] Model FC280S, Sierra Instruments[®] Model 840, and Brooks[®] Model 5858A mass flow controllers.

All tests are conducted using open-cell, unretarded, flexible, polyurethane foam (26.5 kg/m³ and 0.975 void fraction). The fuel samples for opposed flow smolder tests are 143 mm across and 150 mm long, and for forward smolder are 132 mm diameter and 300 mm long. The 10% dimensional oversizing is to ensure good contact between the fuel sample and the wall thereby preventing preferential oxidizer flow between the walls and sample. The sample is placed into the duct with approximately 5 mm protruding from the igniter end of the chamber for good igniter/fuel contact. The igniter consists of an electrically heated Nichrome wire sandwiched between two 5 mm thick honeycomb ceramic disks that provide rigidity to the igniter as well as diffuse the heat flow. Porous FiberFrax Durablanket-S[®] insulation, 50 mm thick, is placed behind the ceramic plate of the igniter to insulate the back of the igniter. During the ignition period, a constant power is supplied to the igniter for a given period of time. The igniter power is controlled by a Variac[®] transformer regulating AC voltage, and is monitored by measuring voltage across, and current through, the igniter wire. A symmetrical heat flux profile is assumed to exist on both sides of the igniter, *i.e.* half of the heat energy from the igniter enters the foam, half is transferred to the porous insulation located at the back side of the igniter. Oxidizer is supplied by mixing bottled dry air, oxygen, and nitrogen.

Reaction zone temperature and smolder propagation velocity are obtained from the temperature histories of 0.8 mm diameter K-type thermocouples in a 1.6 mm diameter stainless steel protective sleeve. The thermocouples are embedded in the foam with their junctions 20 mm apart along the fuel centerline with the first at the igniter-fuel interface. Thermocouple voltages are multiplexed, A/D converted and logged onto a personal computer.

The experimental procedure is as follows: during the ignition period the oxidizer flow rate is kept constant at 0.1 mm/s. The igniter is switched on to the prescribed input flux for the test

being run. Igniter heat flux is held constant within 2% during each test and is varied from test to test in the range of 2 kW/m² to 10 kW/m². At the prescribed time, (300 to 5000 sec ±5 sec), the igniter is switched off and, simultaneously, the air flow is switched to the forced oxidizer setting, 0.7 mm/s for the opposed flow and 3.0 mm/s in the forward tests. Flow velocities are based on the volumetric flow rate of oxidizer divided by the cross sectional area of the fuel sample. During the ignition phase of the tests, the oxidizer flow velocity (0.1 mm/s) is chosen to simulate the conditions observed during natural convection smolder ignition [23,24]. For forward flow smolder, the forced oxidizer velocity (3.0 mm/s) during the propagation phase of the test is chosen to be high enough such that the smolder reaction had the characteristics of forward smolder [23]. For the opposed flow tests, the forced oxidizer velocity (0.7 mm/s) is chosen to stay within the regime where the reaction will self-propagate [25]. All forward flow tests are conducted with the smolder reaction propagating upward, thereby avoiding confusion between the downward forward extinction regime [26] and a no-ignition result. All opposed flow tests are conducted in the downward smolder direction, thereby widening the range of forced oxidizer flow without entering the extinction regime [26]. Post combustion analyses include weighing the sample and residual char together, and weighing the remaining unburned foam with the char removed to obtain the mass loss of the char. Visual examinations of the sample as well as measurements of the char depth and diameter are also performed.

RESULTS

Ignition of the foam is said to occur when a self-sustaining smolder propagates beyond the influence of the igniter after the igniter has been switched off. Tests are considered to not result in ignition when a smoldering reaction initiated by the igniter does not propagate beyond the thermally assisted region near the igniter. Exemplar temperature histories of an ignition and a no-ignition case are presented in Fig. 3 and Fig. 4 for forward and opposed smolder respectively.

The ignition cases (Figs. 3a & 4a) are characterized by a reaction front that, after the igniter has been switched off, continues to propagate beyond the thermally assisted igniter region (the volume of the fuel sample in which the temperature has been raised during the time the igniter is powered). The char present near the igniter is very similar to that formed in the no ignition cases, but as the smolder propagates in a self-supported fashion, the char formed has a cylindrical shape with a hemispherically shaped leading edge. It approaches the walls and sample end in a manner dictated by the incoming oxidizer rate. As the oxidizer mass flow rate is

increased, the smolder reaction becomes more vigorous (higher reaction temperature and front velocity) and char is formed closer to the test section walls, indicating the increased ability to withstand heat losses to the surroundings.

In the no-ignition cases (Figs. 3b & 4b) the reaction does not propagate significantly beyond the influence of the igniter. Char is often present near the igniter indicating that, while a smolder reaction had been initiated, an insufficient volume of reacting fuel had been generated to overcome heat losses of the system and self-propagate. In these cases, the char has a hemispherical shape, typically small in diameter, (<100 mm opposed; <50 mm, forward) and does not penetrate deep into the sample (<50 mm, opposed; <30 mm, forward). For all of the no-ignition cases tested, the foam is discolored (browened) and often degraded by pyrolysis near the igniter.

Ignition diagrams for various oxygen concentrations for the forward smolder, and for the opposed smolder tests are presented in Figs. 5 and 6 respectively. The results, together with the theoretical analysis of the problem, suggest that ignition of a smoldering reaction is controlled primarily by two parameters: the heat flux supplied from the igniter and the amount of time the igniter is powered. Two regions with a well defined boundary, or ignition curve, are identified in Figs. 5 and 6: 1) a no-ignition region where for a given igniter flux there is an insufficient igniter activation time, and 2) an ignition region, where sufficient time is provided for the smoldering reaction to become self-sustaining. The ignition curve shows a critical heat flux for ignition, below which smolder ignition does not occur. For heat fluxes larger than the critical value, ignition occurs at shorter times as the igniter heat flux is increased. The other oxygen mass fractions that have been examined show identical trends, with a slight shift to shorter ignition times and reduced igniter fluxes for higher than ambient oxygen concentrations.

It is interesting to note that the ignition curves are very similar to those obtained for the piloted ignition delay (gas phase) of solid fuels heated by an external radiant flux [18,27,28]. They are also similar to those of spontaneous ignition (replacing heat flux by temperature) [29,30], which indicates that the controlling mechanisms of smolder and gas phase solid fuel ignition are similar. As in the case of gas phase ignition, it can be seen that if the igniter is activated for a given period of time, a minimum, igniter flux, $\dot{q}_{o,min}''$, exists for smolder ignition to occur. This minimum heat flux is attributed to the need for the foam to reach a minimum temperature near the igniter to initiate the smolder reaction. Attaining this temperature is

contingent to overcoming the heat losses from the reaction to the surrounding. For heat fluxes less than this minimum, the system reaches a steady state in which the reaction temperature near the igniter is too low for a continued reaction. As the oxygen mass fraction is increased the minimum igniter flux, $\dot{q}_{o,min}''$, decreases, although only slightly. The results for the different oxygen concentration tested are summarized in Table 1.

The small effect that the oxygen concentration has on the ignition process is in contrast to its effect on the smolder propagation itself, which is found to vary approximately linearly with the oxygen mass flux [2,31]. This indicates that the smolder ignition process is controlled primarily by thermal effects with chemical kinetic effects playing a secondary role. It should be noted that for the flow velocities used during ignition, the amount of energy convected out of the fuel sample by the forced oxidizer flow is small compared to the energy required to be transferred ahead of the reaction as it self-propagates. Additionally, the volumetric heat capacities of nitrogen and oxygen are virtually identical. Although not examined explicitly here, it can also be inferred that oxygen has little effect on the kinetics of the reaction at the low temperatures occurring during the long transient heating period prior to ignition, and that the minimum igniter flux required for ignition is largely dictated by the thermal characteristics of the fuel. This finding is important because this allows for these results to be extended to fuels other than flexible polyurethane foam-even those in which the chemical kinetics are not well understood.

The minimum igniter temperature ($T_{ign,min}$) that is required for ignition of a self-supporting smolder diminishes with increasing oxygen mass fraction for opposed smolder but appears to be independent of the oxygen mass fraction for forward smolder (see Table 1). This minimum igniter temperature was determined by comparing the igniter-fuel interface temperature for ignition and no-ignition cases. The reader will note that the minimum ignition temperatures reported in Table 1 are lower than in Figs. 3 and 4. These minimum ignition temperatures are evident primarily in the low power, long time ignition tests where heat losses from the experimental apparatus begin to become significant. They indirectly define a critical igniter flux for ignition for this particular geometry. The minimum temperature requirement is a necessary but insufficient condition for the initiation of smolder in polyurethane foam.

The minimum ignition times for forward flow are generally less than those, at the same heat flux, for opposed flow ignition. This is due to the direction of heated gases that preheat the virgin fuel ahead of the reaction in the forward mode, reducing the amount of energy required to

ignite the fuel. The extra time is needed for the natural convection flow to overcome the inertia of the gas within the foam. In opposed flow smolder, however, heat is carried out of the system by the combustion products therefore requiring greater energy input by the igniter. This is evidenced in the ignition boundary curves being shifted lower and to the left in Fig. 5 (forward flow) as compared to Fig. 6 (opposed flow). Data from Kitano and Nagano [21], shown in Figs. 5 & 6, agree well with the data obtained in this study. The slight shift toward longer times for a given power may occur because the data of [21] were obtained under natural convection conditions.

IGNITION MODEL

From the results described above it is inferred that for smolder ignition to occur the external heat source is required to: (a) raise the foam above a threshold ignition temperature, and (b) provide a minimum input heat flux for a sufficient time, as defined by the ignition diagram of Figs. 5 and 6. The minimum foam temperature is required to initiate the smolder reaction, and is consistent with an Arrhenius type smolder reaction rate. The minimum heat flux and time requirements indicate that for smolder to be self-sustained the thermal wave, and consequently the incipient smolder reaction must propagate a certain distance into the sample interior. This results in the generation of an insulating volume of pyrolyzed or smoldered fuel (char) that reduces the heat losses from the reaction to the ambient and helps establish a strong enough smolder reaction to sustain its propagation through the interior of the virgin fuel.

These requirements are similar to those encountered in the gas phase ignition of solid fuels [18,19], although the events leading to ignition are somewhat different. For example, in the case of the spontaneous ignition of a solid fuel, as described in a Semenov model [19,29,30,32,33], ignition is determined by the thermal run-away (flaming) of the incipient combustion reaction. The ambient temperature is increased to initiate the combustion reaction, and its critical value for ignition depends on the heat losses from the reaction to the ambient. In the piloted ignition of a solid under an externally applied heat flux, as in the LIFT apparatus [27,28], ignition is determined by the initiation of solid pyrolysis. A minimum, or critical, heat flux is required to overcome the heat losses from the solid to the environment. For heat fluxes above this minimum the time for ignition decreases as the heat flux is increased. In the present work, ignition is characterized by the onset of a self-propagating smolder reaction. As in the LIFT case, the external heat flux is used to increase the solid temperature such that a smolder

reaction (rather than a pyrolysis reaction) is established, and a minimum, or critical, heat flux is required to overcome the heat losses from the solid to the environment.

The above observations suggest that smolder ignition can be modeled following an approach similar to that used in thermal models of gas phase ignition of solid fuels, although adapting them to the specifics of smolder ignition, i.e. that ignition is determined by the onset of a self propagating smolder reaction. The chemical kinetic parameters determining an Arrhenius type reaction rate of the smolder reaction of polyurethane foam are, at this time, not well known, and consequently it is not possible to determine the rate of heat release as used in a Semenov theory of ignition [29,32,33]. However, significant experimental and theoretical information about the propagation of a smolder reaction exists, and the propagation is the result of a balance between the heat released by the reaction and the fuel heating requirements. It is therefore possible to extract the needed heat release information from the available data on smolder propagation. A model such as that of Dosanjh *et al.* [34-36] that describes the controlling heat transfer mechanisms of smolder propagation, should be applicable for this purpose.

In the present analysis, the smoldering sample is divided into two regions as illustrated in Fig. 7: a pyrolyzed fuel, or char, region (I), and a virgin fuel region (II), with the incipient smolder reaction separating both regions. In both regions the gas and solid are assumed to be in local thermal equilibrium [37,38], and the solid phase is considered continuous with a constant void fraction. Energy transport due to concentration gradients, viscous dissipation, and work done by body forces are considered negligible. Gas velocities are taken as known quantities at each location in the sample. It is assumed that the smolder process occurs in an infinitely thin region and under oxygen limited conditions [2]. Consequently, the heat released by the reaction is given by the product of the oxidizer mass flux at the reaction zone, and smolder heat of combustion (energy released per unit mass of oxidizer), Q , which is assumed constant and known. Pyrolysis also assumed to occur in an infinitely thin region, and is incorporated in the smolder analysis through a heat of pyrolysis, Q_P (energy absorbed per unit mass of fuel consumed). Radiation heat transfer is incorporated in the analysis using a diffusion approximation [39]. Oxygen depletion via char oxidation is assumed negligible. With these assumptions, and making use of the similarities between the formulation of the opposed and forward smolder in the laboratory reference frame the energy equation for both modes of smolder takes the form:

$$((1-\phi)\rho_F C_{PF} + \phi\rho_A C_{PA}) \frac{\partial T}{\partial t} \pm \rho_A C_{PA} U_g \frac{\partial T}{\partial x} = [\lambda_{eff} + \lambda_{rad}] \frac{\partial^2 T}{\partial x^2} + Q \frac{dm_O''}{dx} + Q_P \frac{dm_F''}{dx} \quad (1)$$

where the plus sign refers to forward smolder and the minus sign to opposed smolder, and the pyrolysis term appears only in forward smolder [34]. The pyrolysis term is incorporated into the heat release term in opposed smolder due to the singular reaction front. ρ_A and ρ_F are the densities of the air and foam, C_{PA} and C_{PF} are the specific heats of the air and foam, f is the porosity, $Y_{O,i}$ is the inlet oxygen mass fraction, U_g is the inlet gas (Darcy) velocity [37], m_O'' is the oxygen mass flux, m_F'' is the fuel mass depletion rate, and I_{eff} is an effective thermal conductivity defined by:

$$I_{eff} = fI_A + (1-f)I_F \quad (2)$$

We will first look at the propagation of a smoldering reaction in region II, which is assumed to be one-dimensional and steady. With the reference frame anchored at the reaction zone (note that in this reference frame the fuel and oxidizer enter the reaction in the same direction for opposed smolder and opposite direction for forward smolder) and making the corresponding change of coordinates in Eq. 1, we obtain:

$$[(1-\phi)\rho_F C_{PF} U_S + \phi\rho_A C_{PA} (U_g - U_S)] \frac{dT}{dx} = [\lambda_{eff} + \lambda_{rad}] \frac{d^2 T}{dx^2} + Q\phi\rho_A (U_g - U_S) \frac{dY_O}{dx} - Q_P \frac{dm_F''}{dx} \quad (\text{Forward}) \quad (3)$$

$$[(1-\phi)\rho_F C_{PF}] U_S + \phi\rho_A C_{PA} (U_g + U_S) \frac{dT}{dx} = [\lambda_{eff} + \lambda_{rad}] \frac{d^2 T}{dx^2} + Q\phi\rho_A (U_g + U_S) \frac{dY_O}{dx} \quad (\text{Opposed})$$

where the mass flux of oxygen entering the reaction zone is given by:

$$\dot{m}_O'' = Y_O \phi \rho_A (U_g - U_S) - \phi \rho_A D \frac{dY_O}{dx} \quad (\text{Forward}) \quad (4)$$

$$\dot{m}_O'' = Y_O \phi \rho_A (U_g + U_S) - \phi \rho_A D \frac{dY_O}{dx} \quad (\text{Opposed})$$

where D is the mass diffusivity. The mass flux of fuel entering the reaction zone is

$$\dot{m}_F'' = (1-\phi)\rho_F U_S \quad (5)$$

The boundary conditions that complete the problem can be identified from Fig. 1 and are; at

$x = x_S$, we have, $T = T_S$ (opposed) $T = T_P$ (forward), $\dot{m}_O'' = 0$, and $\frac{dT}{dx} = -\frac{\dot{q}_{ign}''(x)}{I_{eff} + I_{rad}}$, where

$\dot{q}_{ign}''(x)$ is the heat flux from the igniter. At $x = x_F$, we have, $T = T_i$, $\dot{m}_O'' = \dot{m}_{O,i}''$, $\frac{dT}{dx} = 0$. Integrating

Eq. 3 with respect to x from x_S to x_F , the following expression is obtained for the heat flux at the reaction front:

$$\dot{q}_{ign}''(x_S) + (U_g - U_s)\phi\rho_A QY_{o,i} = U_s [(1-\phi)\rho_F \{C_{PF}(T_P - T_i) + Q_P\}] + (U_g - U_s)[\phi\rho_A C_{PA}(T_P - T_i)] \quad (\text{Forward})$$

$$\dot{q}_{ign}''(x_S) + (U_g + U_s)\phi\rho_A QY_{o,i} = U_s [(1-\phi)\rho_F \{C_{PF}(T_S - T_i)\}] + (U_g + U_s)[\phi\rho_A C_{PA}(T_S - T_i)] \quad (\text{Opposed}) \quad (6)$$

where, T_S , T_P , T_i are the smolder, pyrolysis and inlet air temperatures. Although the pyrolysis front in forward flow smolder may propagate at a higher velocity than the reaction front [36], it is assumed here that during ignition the two fronts are close enough together to be treated as a singular front.

It should be noted that Eq. 6 is the equivalent of the energy equation in the Semenov model of spontaneous ignition [18], but accounting for the fact that the thermal and reaction fronts are propagating along the porous fuel. That is, in addition to the standard heat losses to the surrounding environment, there are the heat losses associated with heating the virgin fuel to the smolder temperature. Thus, Eq. 6 basically states that the heat released by the smolder reaction together with that provided by the igniter is used to heat the incoming fuel and oxidizer to the ignition (smolder) temperature and to overcome the heat losses to the surrounding environment.

In order to calculate the heat flux necessary for ignition, we look again at Eq. 1, now considering region I, *i.e.* the heating by the igniter of the pyrolyzed foam or char left behind by the smolder reaction. Experimental evidence has shown that the ignition process itself is relatively insensitive to oxidizer velocity, therefore the gas convective term is neglected [22]. Thermal transport in the foam is further described by a semi-infinite solid solution with effective properties of the foam and heated by a constant surface heat flux as provided by the igniter. The semi-infinite solid assumption is justified because the ignition time is less than the characteristic

time for the thermal wave to travel the entire length of the sample (order of 10^3 s vs. 10^5 s). With these assumptions, Eq. 1 becomes:

$$\left((1-\phi)\rho_F C_{PF} + \phi\rho C_{PA} \right) \frac{\partial T}{\partial t} = [\lambda_{\text{eff}} + \lambda_{\text{rad}}] \frac{\partial^2 T}{\partial x^2} \quad (7)$$

The boundary conditions are: at $x = 0$, $\frac{\partial T}{\partial x} = -\frac{\dot{q}_o''}{\lambda_{\text{eff}} + \lambda_{\text{rad}}}$, where \dot{q}_o'' is the constant surface heat flux provided by the igniter, and at $x = x_{\text{min}}$, $\frac{\partial T}{\partial x} = 0$. The initial condition is $T = T_i$ at $t = 0$. The solution of Eq. 7 in terms of the heat flux takes the form:

$$\dot{q}_{\text{ign}}''(x_{\text{min}}) = \dot{q}_o'' \operatorname{erfc} \left(\frac{x_{\text{min}}}{\sqrt{4\alpha_{\text{eff}} t_{\text{ign}}}} \right) \quad (8)$$

Matching the heat flux at the interface between regions I and II, as given by Eqs. 6 & 8 provides the required heat flux at the igniter for smolder ignition to occur.

An undetermined parameter in Eq. 8 is the location of the interface between regions I and II, i.e. x_{min} . Experimentally it is observed that in order for the smolder reaction to occur, a minimum char depth must be achieved before the smolder reaction can be self-sustaining. This layer of char provides insulation and thus reduces the heat losses from the smolder reaction to the external environment once the igniter is turned off. Thus, the minimum char depth, x_{min} , can be determined by assuming that, once the heater is turned off and has cooled down, the heat losses from the smolder reaction to the igniter (environment) cannot be larger than the minimum heat needed for the smolder to propagate, i.e.

$$\frac{\lambda(T_S - T_A)}{x_{\text{min}}} \leq \rho C_P U_S (T_S - T_o) \quad (9)$$

With the foam properties given in Tables 2 and 3, and the minimum value for the smolder velocity observed experimentally, Eq. 9 gives a value of $x_{\text{min}} = 50$ mm. This agrees with experimental observation, where forward smolder requires a minimum depth of 40 mm, and opposed smolder requires a minimum depth of 55 mm.

With the value of x_{min} , obtained from Eq. 9, and equating Eqs. 6 & 8 to solve for the ignition time as a function of igniter heat flux generates the predicted ignition curves presented in

Figs. 5 and 6. The data used in the equations are listed in Tables 2 and 3. The values for the smolder velocities are adjusted to obtain optimum fitting of the theory and experiments, but agree well with experimentally observed minimum smolder velocities. As the reaction and pyrolysis fronts coincide for the opposed flow configuration, the heat of pyrolysis, Q_P , is incorporated into the smolder heat of combustion. As it can be seen from Figs. 5 and 6 the model results are in good agreement with the experimental results for all of the experimentally tested oxygen concentrations.

From the above analysis it can be stated that for smolder ignition to occur, the heat transferred from the igniter to the fuel should be large enough to increase the temperature of the fuel to its smolder temperature, and thus initiate the smolder reaction. Furthermore, this heat flux must also overcome the heat losses to the surrounding environment, and be applied for a sufficiently long time period to form an insulating char layer that prevents the extinction of the reaction due to heat losses once the heater is turned off. Depending on the heat flux at the igniter, these conditions will be reached after a period of time given by the ignition curve, and referred here to as the ignition time, t_{ign} . If the heat flux at the igniter is below a minimum (critical) value, ignition will not occur. This critical heat flux for ignition is obtained from Eq. 8 by setting t_{ign} equal to infinite. It is seen that the critical heat flux for ignition is $q''_{crit,ign}$, and consequently given by Eq. 6. Thus, the critical heat flux for ignition is approximately equal to the enthalpy flow needed to increase the temperature of the fuel approaching the smolder front at the minimum smolder velocity to its smolder temperature. If the igniter heat flux is larger than the critical heat flux for ignition, smolder ignition will occur if the time of igniter actuation is larger than that given by Eq. 8. The ignition regime is shifted to shorter times for a given igniter heat flux with increasing oxygen mass fraction. This is due to the larger heat contribution of the incipient smolder reaction.

CONCLUDING REMARKS

This work represents one of the few available studies on smolder ignition. The experimental results together with the theoretical predictions show the requirements for ignition of a self-sustaining smoldering reaction of a porous combustible such as open-cell, unretarded, polyurethane foam. It has been found that smolder ignition is primarily determined by two parameters: igniter heat flux and the time the igniter is powered. These two parameters

determine a minimum igniter/foam temperature, and a minimum depth of smolder propagation (char) that are required for ignition to occur. The former is needed to establish a strong smolder reaction, and the later to reduce heat losses from the incipient reaction to the environment. The ignition regime is shifted to shorter times for a given igniter heat flux with increasing oxygen mass fraction.

A smolder ignition diagram with a well-defined boundary between the ignition and no-ignition regimes has been developed with the results of these experiments. The smolder ignition diagram is similar to the ignition diagrams that describe the piloted ignition of a solid fuel heated by an external radiant flux [27]. It also reproduces the trends observed in the spontaneous ignition of gaseous and solid fuels, if the heat flux is replaced by the external temperature [18,40]. Based on this similarity, a theoretical analysis containing the basic concepts included in models of the above ignition processes but that describes the characteristics that determine smolder ignition has been developed that predicts well the smolder ignition diagram, and critical conditions for smolder. The results show that the minimum igniter flux required for ignition is largely dictated by the thermal characteristics of the fuel and only secondarily dependent on moderate oxidizer flow differences. This finding is important because this allows for these results to be extended to fuels other than flexible polyurethane foam, even those in which the chemical kinetics are not well understood. It should also be noted that the ignition boundary found in this work is not independent of geometry as no correction for heat losses is made. Future work should examine the effect of oxidizer velocities and different geometry on the ignition process.

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