

SOME OBSERVATIONS OF TWO-DIMENSIONAL SMOLDERING AND THE TRANSITION TO FLAMING

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ABSTRACT

Experiments have been conducted to study the upward smolder characteristics and the phenomenon of transition to flaming of a porous combustible material in the presence of an air/porous-solid interface. External air flow velocities ranging from 0 m/s to 2.5 m/s are forced upward and forward across the exposed, flat, vertical surface of a high void fraction, flexible, polyurethane foam to examine how a smoldering fuel responds to increased oxygen supply and heat transfer. The smolder results of varying the air flow velocity reveal three regimes. First, for no flow (natural convection) to 0.25 m/s, smoldering either dies almost immediately following the ignition period or propagates very slowly. Second, for flow velocities between 0.25 m/s and 2.0 m/s, transition to flaming occurs with decreasing smolder duration relative to increasing air flow velocity. Visual observations and thermocouple histories, when compared to analyses of differential shear interferometry images of the gas phase at the interface, indicate that transition to flaming occurs inside the hot char region below the smoldering front and not at the air/porous-solid interface. Finally, as the air velocity is increased further (> 2.0 m/s), the smolder reaction is initially strong following the ignition period but always ends in almost abrupt extinction, due ultimately to convective cooling. These results indicate that smolder propagation with transition to flaming is the result of increased oxidizer supply and reduced heat losses.

INTRODUCTION

Smoldering is defined as a non-flaming, self-sustaining, propagating, exothermic, surface reaction, deriving its principal heat from heterogeneous oxidation of the fuel (direct attack of oxygen on the surface of a solid phase fuel) [1]. Smoldering constitutes a serious fire risk because it typically yields a substantially higher conversion of fuel to toxic compounds than does flaming (though more slowly), is difficult to detect (and extinguish) in the interior of a porous material, and provides a pathway to flaming that can be initiated by heat sources much too weak

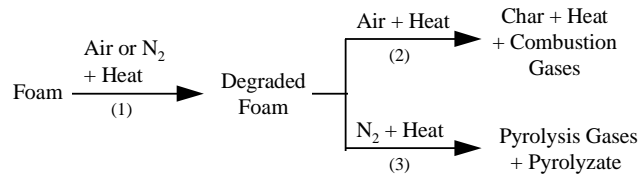
to cause a flame directly [2]. This transition process from slow smoldering to rapid flaming (fast, exothermic, gas-phase reactions) is also of particular interest as a fundamental combustion problem, with, surprisingly, very little information currently available.

Ortiz-Molina et al. [3] studied the relative smoldering tendency of different flexible polyurethane foams, in a horizontal configuration, by varying the ambient oxygen concentrations. A few experiments showed transition to flaming for very high oxygen concentrations. However, the work primarily concerned itself with the threshold conditions at which transition to extinguishment occurs. Chen et al. [4] examined the behavior of cellulosic materials (grain and wood byproducts and paper) in 20 cm layers at external air stream velocities up to 6 m/s. In this case, the fuel layer was set horizontally into the bottom of a flow tunnel so that its top surface was initially flush with the tunnel floor and the bottom surface was heated uniformly. Glowing combustion with subsequent transition to flaming occurred for air velocities less than 3 m/s. Ohlemiller's work [5] with cellulose remains the most detailed study on the matter to date. He examined smoldering of thick, horizontal layers of permeable fuel (cellulosic insulation) in the presence of flowing air and found that while opposed smolder responded only weakly to an increased air flow with no transition to flaming at flow velocities up to 5 m/s, forward smolder responded strongly to increased air flow and yielded transition to flaming at about 2 m/s.

It is well known that a forward, upward smoldering fuel responds to an increased oxygen supply by becoming faster and hotter until, eventually, flames erupt [5, 6, 7,]. This paper presents observations of two-dimensional, upward smoldering of open cell, flexible, polyurethane foam in the presence of forward, forced air flow at a vertical, air/porous-solid interface and the transition to flaming. In the particular smoldering configuration treated here, the foam is ignited at the bottom; and the smolder wave propagates upward. Thus, the resulting smolder may be termed forward smolder because the smolder wave propagates in the same direction as the forced air flow as well as the upward, buoyancy induced flow. In this work, the use of polyurethane foam, a very common material whose geometric structure tends to be preserved during and after the passage of a smolder wave [8], permits upward burning experiments without the fuel collapse and material erosion problems that occur with cellulose and other loose material. Ortiz-Molina et al. [3] finds that the smoldering behavior of flexible polyurethane foams can in large part be interpreted in terms of the mechanism postulated for cellulose. Therefore, the use of this material provides us with a degree of generality, in addition to advantageous thermophysical properties. Upward smolder is an intrinsically unsteady process controlled not only by the supply of oxidizer, but where the accumulation of heat in the foam, transported by the products of combustion, increases the smoldering velocity, and may lead eventually to gas phase pyrolysis and transition to flaming [6, 7]. Forward smolder, as described in Refs. [5, 6], responds strongly to increased air flow and is known to yield transition to flaming. Consequently, such an arrangement is employed in this work.

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From analyses of the physical transformations and temperature histories involved in the smoldering process, we can formulate the following broad model of the behavior of flexible polyurethane foams in the smolder process [9, 10, 11]:



For our upward, forward smolder configuration, as the heat from the product gases is convected downstream of the smolder front, the virgin foam becomes preheated, thereby reducing the additional thermal energy needed to pyrolyze the foam and initiate its oxidation. Consequently, local temperatures and smolder propagation velocities can increase, accelerating perhaps to a transition to flaming. Although this is a possible mechanism for the phenomenon [2, 6, 7], experiments indicate that transition from smoldering to flaming in the present arrangement proceeds by way of a different path.

Steps 1 and 2 comprise the smolder mechanism of flexible polyurethane foam, whereby a complex polymer, $C_{1.0}H_{1.7}N_{0.07}O_{0.3}$, is converted to a char-like material of approximately $C_{7.2}H_5NO$ (which is clearly not a simple carbonaceous char) [6]. Noteworthy, the char is also oxidizable, exhibiting experimentally that it is somewhat more resistant to oxidation than the original foam, but once reacted, is more exothermic. This process is documented in the literature, Ref. [2, 6-11], and is commonly referred to as secondary char oxidation. Ohlemiller [2] recognizes that the course of secondary char oxidation can be energetic enough to ignite flammable gases, initiating a transition to flaming. As it is shown below, it is this process that provides the pathway to flaming in the present experimental setup.

EXPERIMENTAL APPARATUS AND PROCEDURE

A schematic of the experimental setup is shown in Fig. 1. The experiments are conducted in a test facility that involves a small scale, vertically oriented, combustion wind-tunnel along with the supporting instrumentation. The wind tunnel test section is 610 mm long and has a rectangular cross section 127 mm wide and 70 mm deep. Three of the tunnel walls are made of quartz to enable visual observation and optical access. House compressed air, serving as oxidizer, flows through a converging nozzle and a settling chamber before entering the test section. The flow velocity is controlled with critical flow nozzles and measured with a TSI[®] VelociCheck[™] Model 8330 air velocity meter. All tests are run using open cell, unretarded, polyurethane foam samples, with 26.5 kg/m³ density and 0.975 void fraction, that are mounted flush in one of the test section walls, establishing the air/porous-solid interface. The top and remaining three side surfaces of the sample are insulated with 12.7 mm thick Fiberfrax[®] sheets that are

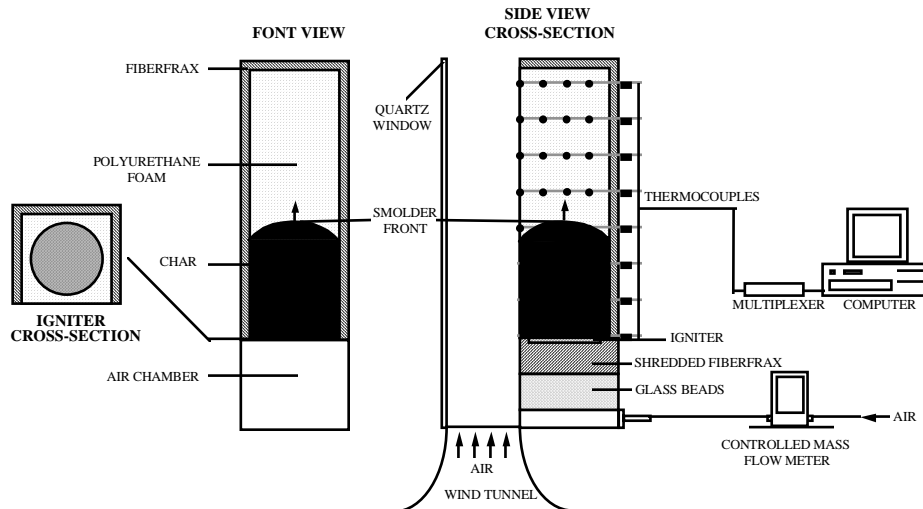


Figure 1. Schematic of experimental setup.

covered by aluminum foil to prevent species diffusion through the walls. Smolder ignition is accomplished with an electrically heated igniter placed in close contact with the foam at the upstream end (bottom) of the sample. The heater consists of a Nichrome wire placed in-between two, 5 mm thick, 101.6 mm diameter, flat, porous honeycomb, ceramic plates that provide rigidity to the igniter. During the ignition period, uniform air is forced upward through the igniter and subsequently through the foam at a very low velocity (0.124 mm/s). The air flow is supplied with bottled, dry air and controlled by a Tylan Model FC280S controlled mass flow meter. This flow aids ignition by adding oxidizer to the preheated virgin foam ahead of the reaction wave, and provides consistency to the ignition process. However, the flow rate cannot be too high because complete or almost complete oxidation of the insulative char can render the reaction zone exposed and subject to inevitable extinction. Shredded Fiberfrax[®] insulation is placed upstream of the igniter to insulate the smolder ignition zone.

Temperature, smolder propagation velocity, and transition to flaming location are obtained from the temperature histories of a 2-D matrix of thirty-two thermocouples (chromel/alumel in a 0.8 mm diameter stainless-steel sheath), which are embedded at predetermined positions in the foam with their junctions placed along the fuel centerline in the plane normal to the exposed foam surface. Ten thermocouples (chromel/alumel of 0.005 in diameter) measure the temperature at the air/porous-solid interface along the length of the sample. Differential shear interferometry (schlieren interferometry [12, 13]), recorded onto video tape and 35 mm film, is employed to provide qualitative information of the temperature evolution in the gas phase. Unburnt hydrocarbons, CO, and CO₂ species histories from gas analyzer sampling of mixed-aggregate exhaust gases provide comparison with temperature data, adding to qualitative diagnosis of the smolder behavior and enhancing the perceptibility of some pre-flaming phenomena.

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The experimental procedure is as follows. Foam samples are cut into rectangular-parallelepiped dimensions of 127 mm by 139.7 mm by 406.4 mm and compressed into a Fiberfrax[®] box of slightly smaller dimensions (127 mm by 127 mm by 381 mm), so as to ensure good heater/foam contact and no air gaps between the foam and the walls. A thin wire grid with 10 mm side square holes covers the bottom 101.6 mm exposed surface of the foam, preventing the foam surface from bulging outward during ignition. The heat losses and flow disturbances caused by the grid are negligible and do not affect the smolder downstream. The foam ignition requires a supply of 70 W along with 0.124 m/s, air flow forced upward through the igniter for 3000 s, heating the igniter to about 520°C and establishing a strong, self-sustained smolder. At this time, the heater and igniter flow are turned off; and the external air flow is turned on and forced upward and parallel to the exposed foam surface.

RESULTS AND DISCUSSION

Initial experiments indicate that self-sustained, upward smoldering with subsequent transition to flaming is very sensitive to sample size, ignition power and duration, and air flow velocity. Samples with square cross-sectional areas smaller than 161 cm² evince a smolder reaction that propagates upward initially at an increased velocity, becoming hotter and producing considerable amounts of smoke, but that eventually extinguishes itself. For samples with square cross-sectional areas larger than 161 cm² and subject to relatively low flow velocities (~0.25 m/s), transition to flaming is observed consistently. Analyses suggest that larger sample sizes provide not only more fuel but also better self-insulation, resulting in stronger reaction fronts with less heat losses per unit volume of smoldering material to the surrounding tunnel walls and air at the interface.

For smolder ignition, the basic requirement is the provision of a source of heat which will initiate the foam oxidation, but the temperature of the source and/or the rate of supply of heat are important [14]. Proper external heating power must be supplied so that endothermic degradation of the material without char formation (due to very low heating rates) and smolder inhibiting tar formation (“melting” of the material due to high heating rates) are avoided. This agrees with the finding of Ohlemiller et al. [15] that there is a variable induction period for heat up of the upper part of the solid to the point where the smolder reaction takes off; if the igniting flux is too low, the solid will not reach the point of reaction runaway in any reasonable time. Ohlemiller and Rogers [10] finds that with high heating rates, pyrolysis to tar dominates; this liquid, tar-like material may then flow away from the heated zone and block air access to that zone thus inhibiting the propagation of a smolder wave. In addition, the heating period must be long enough to support the smolder propagation, when enough char has been created and left behind to insulate the smolder reaction zone. Consequently, the sample size and ignition parameters that are used for this study have been chosen so that the smolder reaction can propagate along the whole length of the sample

and transition to flaming occurs consistently within the range of air flow rates examined.

The smolder results of varying the air flow velocity reveal three regimes: 1) for no flow (natural convection) to 0.25 m/s, smoldering either dies almost immediately following the ignition period or propagates extremely slowly; 2) for flow velocities from 0.25 m/s to 2.0 m/s, transition to flaming occurs inside the hot char region upstream of the smolder front; 3) for flow velocities above 2.0 m/s, the smolder reaction is initially strong following the ignition period, but always ends in an eventual, abrupt extinguishment, without flaming, despite elevated temperatures indicating exothermic secondary char oxidation and observations of substantial gas phase pyrolysis. For a flow velocity of 2.5 m/s, the smolder reaction dies promptly after the ignition period.

Smoldering and Extinction Regimes

In regime 1, for the natural convection case, smoldering is on the verge of being self-sustaining, but most of the tests result in extinction. However, a few experiments exhibit self-sustaining smolder, with indications of a slight accelerating trend, ensuing in extinguishment only due to the smolder wave reaching the end of the sample. Nonetheless, transition to flaming does not take place for sample lengths of 381 mm, although Torero and Fernandez-Pello [7] observes transition to flaming for polyurethane samples with lengths of 300 mm in upward, free convection smolder. Notwithstanding, this difference can be attributed to the fact that the work of Ref. [7] consists of a one-dimensional geometry; while in this work, the exposed foam surface presents a two-dimensional problem, with different oxidizer transport routes and heat losses to the ambient air. For forced, flow velocities above 0 m/s and below 0.25 m/s, smolder propagates very slowly, without transition to flaming, for the lengths of our samples.

In regime 3, for flow velocities larger than 2.0 m/s, smoldering extinction happens soon after the ignition period, although there does seem to exist significant fuel gasification just before extinguishment. Perhaps the increased oxidizer supply initially enhances smolder of the foam in the igniter vicinity enough to increase local temperature and rate of pyrolysis gas generation; but at the same time, the smolder front retreats so far back into the foam (due to heat losses at the air/porous-solid interface) that oxidizer can no longer be transported to the reaction front fast enough to sustain smolder. The mechanism for this extinguishment should be studied in more detail; nonetheless, cooling due to convection appears to be the dominant factor for the event.

It should be noted that 2.5 m/s is the maximum flow velocity allowed by our present apparatus; however, from our observations, we believe that this extinguishment regime should occur for flow velocities above this value.

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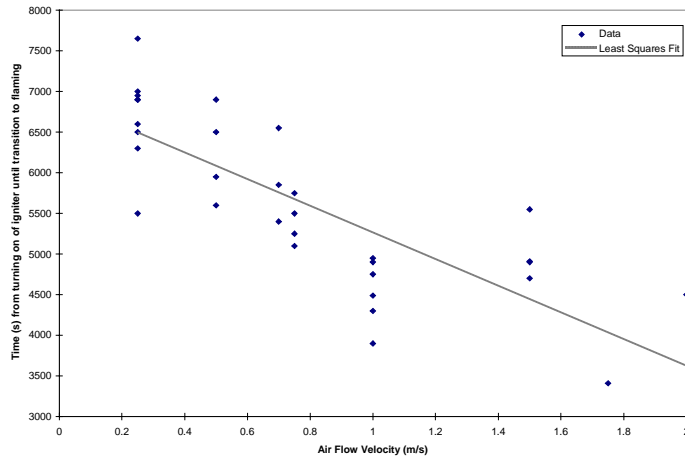


Figure 2. Smolder duration until transition to flaming.

Smolder with Transition to Flaming Regime

In regime 2 (0.25 m/s to 2.0 m/s), consistent transition from smoldering to flaming is observed. Smolder duration until transition to flaming decreases with increasing air flow velocity, as shown in Fig. 2, suggesting that oxidizer supply and not heat losses is the controlling factor in this regime. There exists quite a bit of scatter in the data of Fig. 2, which is most likely due to deformation of the foam and void formation during the smoldering process, influencing the paths of local oxidizer flow and heat transfer. Nevertheless, the trend of decreasing smolder duration until transition to flaming versus air flow velocity is evident and insightful.

A characteristic example of the temperature history (along the centerline of the fuel sample) for this regime is given in Fig. 3. The first thermocouple is in contact with the igniter; the others are spaced 25.4 mm apart, spanning the length of the sample. The rapid drop in temperature of the igniter thermocouple at 3000 s marks the switching off of the igniter power. As evinced by Fig. 3, thermocouple traces higher than 50.8 mm above the igniter divulge an overall trend of continual temperature increase for the remainder of the experiment. The unsteady oscillations in the temperature curves (occurring above 400°C) reflect secondary char oxidation reactions that propagate intermittently in seemingly random directions throughout the char region left by the main smolder front. These secondary char reactions are generally characterized by faster propagation rates and higher temperatures than the primary smolder reaction [6]. Due to the immediate initiation of secondary char oxidation by the original smolder front, it is difficult to define from the thermocouple histories the smolder temperature and smolder wave thickness. With no clearly defined maximum in the temperature profile, the arrival of the smolder front is determined by drawing tangents to the temperature curves and cutting them by a line at a predetermined temperature, 350°C here. Characteristic smoldering temperatures for flexible polyurethane

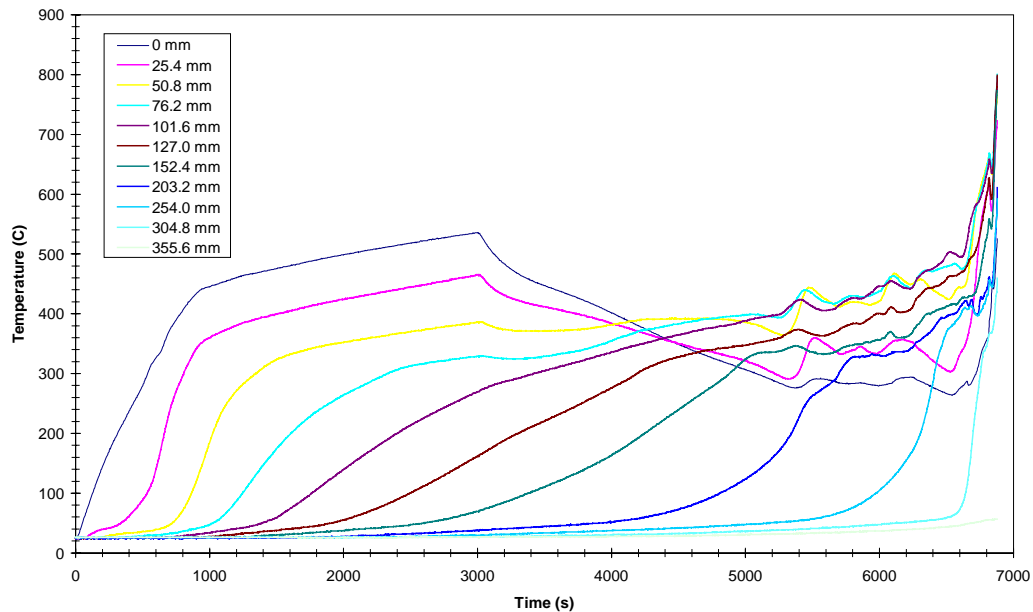


Figure 3. Characteristic temperature history for a forced air flow velocity of 0.25 m/s. The legend shows locations of thermocouples above the igniter, along the centerline of the foam sample.

foam have been observed by several authors [1, 9, 10] to be approximately 350°C to 400°C. The smolder velocity is calculated from the time lapse between two consecutive intersections. In this regime, the smolder velocities of experiments with the same air flow velocity do not follow a typical trend towards transition to flaming. In some cases, smolder velocity increases; and in others, it decreases, as transition to flaming is approached. There does not seem to exist the behavior of monotonically increasing average smolder velocity per experiment with increasing air flow velocity found in Ref. [5], suggesting that increasing smolder velocity is not the direct cause for transition to flaming.

Visual observations and thermocouple histories, when compared to analyses of differential shear interferometry images of the gas phase at the air/porous-solid interface, reveal that transition to flaming occurs inside the hot char region below the smoldering zone and not at the interface. Although one might expect flaming ignition to occur at the interface where exhausted pyrolysis gases meet fresh oxidizer, thermocouple measurements indicate that the interface is too cold (rarely exceeds little more than 400°C prior to flaming). Transition to flaming requires both a mixture of combustible gases and air that are within their flammability limits and a sufficient heat source or heat insulation to ignite this mixture; additionally, these two requirements must be realized at the same locus in space and at the same time [2]. Apparently, for these air flow velocities, oxidizer can be sufficiently transported to the char, such that its oxidation

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generates enough heat flux to compensate for any heat losses due to the entrainment.

Preliminary analysis of the convection aspects of the experimental setup reveals that oxidizer is best transported to the char region near the igniter upstream of the smolder front. The high temperatures and varying smolder velocities leading up to flaming imply that secondary char reactions and not the primary smolder reaction provide the main driving force for the event. Although the char is most likely also an oxygen limited region that consumes as much of the available oxidizer as it can, oxidizer can still be transported to the smolder front above and ahead of it. This is because, in our two-dimensional arrangement with an air/porous-solid interface, oxidizer can be transported normal to the upward direction, thus allowing for a combination of forward and reverse reactions. The two-dimensional array of thermocouples reveals that the smolder front surface is fairly symmetric about the fuel centerline and for the most part propagates forwards and upwards (see Fig. 1). Although there exists additional oxidizer at the interface, it also presents more heat losses; and despite better insulation at the back of the foam, there is less oxidizer. Oxidizer does not have to traverse the entire char region to reach the smolder zone. Therefore, the smolder front can propagate almost independently of oxidative consumption in the lower char region without a complete shift to endothermic pyrolysis; but aided by additional heat flux from transition to flaming effects in the char, the primary smolder reaction can become more intense and generate substantial amounts of pyrolysis gases. Presumably, the enhanced air supply accelerates local secondary char oxidation, heating the char to the point where it can then ignite pyrolysis gases that are circulating in convection currents within it.

Figures 4 and 5 show the temperature distribution along the length of the sample for increasing time for a single experiment, elucidating the absence of a

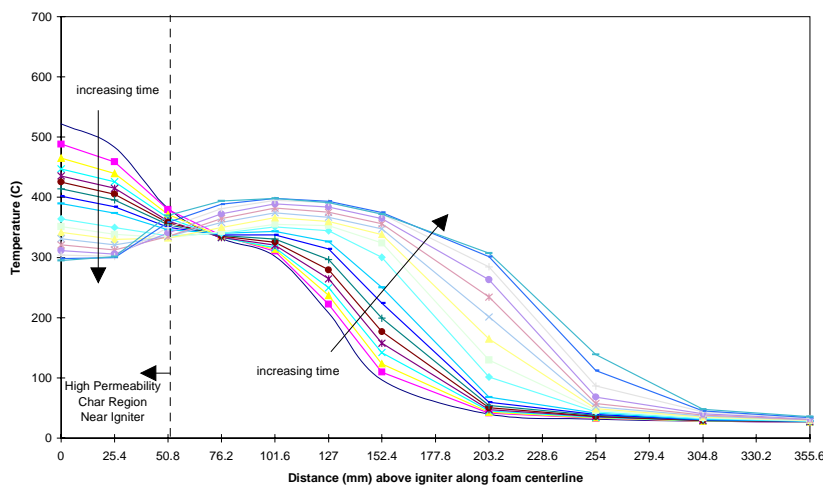


Figure 4. Domain 1 of the temperature distribution along the length of a sample with increasing time (3000 s to 4800 s at 100 s intervals). Note: 3000 s is the time that the igniter is turned off and that the smolder is self-propagating. The forced air flow velocity is 0.75 m/s.

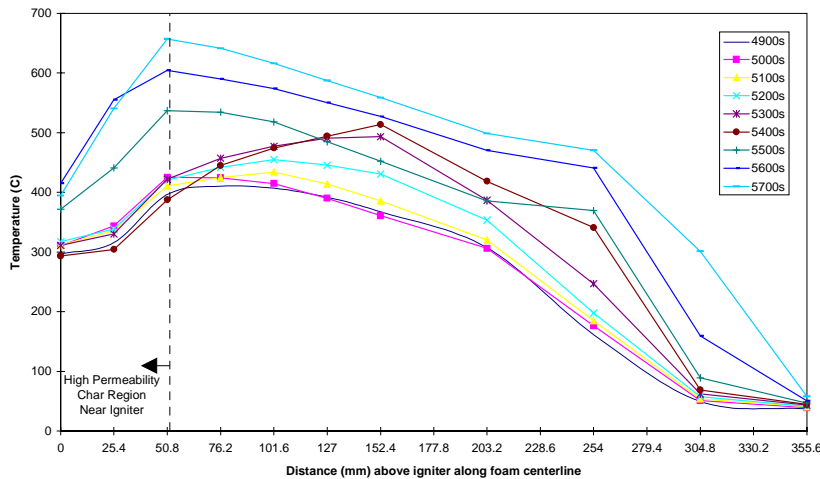


Figure 5. Domain 2 of the temperature distribution along the length of a sample with increasing time (4900 s to 5700 s at 100 s intervals). Note: the sample transitions to flaming at 5752 s. The forced air flow velocity is 0.75 m/s.

well defined smolder temperature and the blurring of the smolder zone, but definitely manifesting the propagating smolder front. Note that Figs. 4 and 5 are presented separately to better explicate the results of the experiment; Fig. 4 elucidates a domain of smolder propagation along with an initial secondary char oxidation wave, and Fig. 5 reveals a domain of intense secondary char oxidation. In the first domain (Fig. 4) the temperature of the sample increases regularly with time, as the smolder reaction propagates and as the secondary char oxidation zone expands gradually and propagates down to the igniter from the smoldering zone. Once the char temperature at the igniter starts to increase, the second domain (Fig. 5) prevails. Here, the temperature profiles often fluctuate with time, but with a general disposition of significant temperature increase. The reactions seem to be more exothermic than those in the preceding domain.

In this second domain, the char below the smolder front increases in temperature fairly uniformly along the length of the region; nonetheless, the hottest region of the sample is consistently found within 76 mm of the igniter (raising questions about the effect of the igniter on the development of the permeability of the char near it), with temperatures around 600°C. At this point, another interesting phenomenon is encountered. Extremely localized, high temperature rises (up to 1200°C) in the char region, which are virtually unnoticed by thermocouples just 25.4 mm away, well precede flaming at the interface. Yet, the time scale for this ignition delay seems to be too long (on the order of 100 s) to be the induction time normally associated with the ignition of a combustible mixture. A possible explanation is that a well-insulated, exothermic surface reaction proceeds within the oxygen limited char until a sudden influx of oxidizer, brought to this location by void formation in the char, triggers the transition to flaming.

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At first glance, one might suspect that the large voids (on the order of centimeters) formed in the char by the secondary char oxidation would expose the char to more convective heat losses. However, this is empirically not the case. Thus, gas-phase oxidation of volatilized fuel must provide a significant portion of the exothermicity in the region, although flaming ignition may have not yet occurred. The larger pore size in the char favors gas-phase radical chain reactions; in contrast, the smaller pore size ($\sim 500 \mu\text{m}$) near the smolder front tends to suppress gas-phase reactions by surface quenching of the free radicals, encouraging solid surface attack of oxygen [1]. These gas-phase reactions in the char can then act to “insulate” the intense heterogeneous reactions occurring at the char surface. Although a localized char surface may be at a high temperature and surrounded by a combustible mixture where gas-phase reactions are occurring, flaming ignition is not requisite. Temperature gradients in a reacting mixture are always accompanied by composition gradients [16]. In the immediate vicinity of the local char surface, the concentration of oxygen will be the lowest (compounded by the fact that the surface reactions are competing with the gas-phase reactions for oxidizer) and that of the fuel and products will be the highest. Thus, within this oxygen limited region, as long as there exists solid phase fuel to be reacted, we can expect high temperatures (perhaps even superadiabatic) to be reached without transition to flaming. The proposed sudden influx of oxidizer, allowed in by the increased permeability (a result of the heterogeneous reactions) in the char, provides the impetus needed for the transition.

Once transition to flaming occurs in the char, it propagates outward to the interface, where it anchors itself and engulfs the entire sample with flames. This phenomenon can be viewed as a true transition from smoldering to flaming because the flames move into virgin fuel, consuming self-generated pyrolysis-vapors [5]. Gas analyzer data of mixed-aggregate exhaust gases show notable increases in HC, CO, and CO_2 production as the smolder nears transition to flaming. The aforementioned gas-phase reactions which precede transition to flaming are probably CO burning. Ohlemiller [15] recognizes the importance of the inclusion of this process in any attempt at describing transition from smoldering into flaming. However, hydrocarbon pyrolysis-vapor reactions are most likely responsible for the initiation of flaming. We do not observe any of the blue CO flames that Ohlemiller [5] does; nevertheless, Ohlemiller [5] does not deem them a necessary precursor to the initiation of pyrolysis-vapor flames. Because the spread of the flames over the entire sample is so fast (a matter of seconds), we believe that we are encountering a true transition from smoldering to flaming combustion of pyrolysis-vapors.

CONCLUDING REMARKS

The present work, although preliminary in nature, divulges additional information about smoldering with an air/porous-solid interface and the transition to flaming. The experimental results seem to indicate that smolder propagation is strongly

influenced by heat losses to the air flowing past the porous material at the interface, while the transition to flaming is influenced by the transport of oxidizer to the char interior. In the present experiment, transition to flaming is not the result of an accelerating smolder, but of the onset of gas-phase reactions in the char produced by the propagating smolder reaction. The higher porosity of the char favors the flow of oxidizer to the sample interior, which, in conjunction with the reduced heat losses, results in the transition to flaming.

The complexity of the chemistry as well as the unclear understanding of heat and mass transfer in porous media makes the task of modeling transition from smoldering to flaming a complicated one. Furthermore, to describe the transition to flaming, it may be necessary to abandon a spatial averaging technique and adopt a "single particle" treatment due to the large voids in the char region, making the modeling of this phenomenon difficult at best. Nonetheless, the research stands at a very promising stage.

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