

Forward Smolder of Polyurethane Foam in a Forced Air Flow

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An experimental study is conducted of forward smolder of polyurethane foam. Air is used as oxidizer, and is forced in the direction of smolder propagation under conditions that produce approximately one-dimensional forward smolder propagation. The objective of the study is to provide further understanding of the mechanisms controlling forward smolder and verification of theoretical models of the problem. Upward and downward forward smolder are compared to also observe the effect of buoyancy on the process. Measurements of the temperature histories at several locations throughout the foam sample are used to infer the characteristics of the smolder process, and to calculate the smolder propagation velocity along the sample length as a function of the air flow velocity and gravitational orientation. It is found that as the flow velocity is increased, there is a transition in the smolder characteristics from a smolder process that is characterized by the propagation of a single exothermic oxidation (smolder) reaction to one characterized by the propagation of two reactions, an oxidative smolder reaction preceded by an endothermic pyrolysis reaction. Buoyancy is observed to affect this mode of smolder at very low air velocities, or when the smolder front approaches the sample end. The smolder velocity data are correlated well in terms of a nondimensional smolder velocity derived from previously developed theoretical models of forward smolder. The good agreement between theory and experiments verifies that the smolder controlling mechanisms and simplifying assumptions implicit in the models are appropriate at least for the present experimental conditions.

NOMENCLATURE

C_p	specific heat capacity
D	mass diffusivity of oxygen in air
Gr	Grashof number
g	gravitational acceleration
K	permeability
L	length
M	mass
P	pressure
Q	energy released per mass of O_2 consumed
\dot{q}''_{ig}	heat flux from the igniter
Ra	Rayleigh number
Re	Reynolds number
t	time
T	temperature
U_s	smoldering velocity
u_b	mixed gas flow velocity
u_D	velocity induced by natural draft
u_f	forced air flow velocity
u_g	total average air flow velocity
W	width of sample

x	longitudinal coordinate
Y	mass fraction
y	normal coordinate

Greek Symbols

α	thermal diffusivity
β	volume expansion coefficient at constant pressure
δ	boundary layer thickness
λ	thermal conductivity
μ	dynamic viscosity
ϕ	void fraction
ρ	density
ν	stoichiometric coefficient

Subscripts

A	air
b	buoyant
C	char
D	diffusion
F	foam
f	forced flow
g	gas
gp	gaseous products
i	initial
O	oxygen

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P pyrolysis
S smoldering
W wall

INTRODUCTION

Smoldering is a surface combustion reaction that propagates through a porous combustible material [1, 2]. The heat released in smoldering is characteristically low [3], and stable smoldering is possible in some circumstances at air/fuel ratios that are a few percent of stoichiometric [1]. Smolder involves complex processes related to fluid flow and heat and mass transfer in porous media, together with surface chemical reactions. The interaction between these physical and chemical processes determines the final characteristics of the smolder reaction. Heat losses, temperature and oxidizer availability are restrictive parameters for the successful ignition and propagation of a smolder reaction [4–6].

One-dimensional smolder is normally defined as propagating in two distinctive modes, forward and opposed smolder. In forward smolder, the reaction zone moves in the same direction as the oxidizer flow, while in opposed (reverse) smolder moves in the opposite direction. Most real smolder situations are a combination of these two modes, but since one of these two modes is, in general, dominant, these configurations provide a very useful framework to study smolder. Opposed smoldering has been studied to a certain extent, both theoretically and experimentally [1, 2, 6, 7]. Less attention has been given to smoldering combustion in the forward configuration. Studies of forward smolder related to cigarette burning provided the initial basic information on this type of combustion. A description of the thermal and chemical characteristics of cigarette burning was given by Egerton et al. [8] and Summerfield et al. [9]. The geometrical configuration used was, for both cases, permeable paper cylinders filled with the porous fuel. The permeability of the paper together with the natural flow surrounding the samples resulted in a complicated geometry that prevented the determination of an adequate one-dimensional model for forward smolder.

Later studies aimed at assessing the potential risk of forward smolder as a fire initiator provided further understanding of the process [1, 10, 11]. Notable is the work of Ohlemiller and Lucca [10] that compared the characteristics of opposed and forward smolder of cellulose. The packed cellulose was always ignited at the top and the air flow direction was changed to obtain opposed and forward smolder. Two distinctive reactions were observed for forward smolder, a nonoxidative pyrolysis reaction (condensed phase pyrolysis) and a char oxidation reaction (smoldering). The presence of these two reactions was explained by the characteristics of the chemical decomposition of polymeric materials, which can follow one of these two pathways depending on heating and ambient conditions. For pyrolysis to occur the oxygen concentrations have to be low, and since pyrolysis is endothermic, heat must also be available. These are two conditions that can be encountered in forward smolder where the products of the oxidation reaction, which can be depleted of oxygen, flow ahead of it diluting the oxygen contained in the virgin material pores. The resulting low oxygen concentration together with the heat transferred from the oxidation reaction zone, provide the necessary conditions for the onset of the pyrolysis reaction ahead of the oxidation reaction. Dosanjh and Pagni [11] developed a theoretical model of forward smolder that included two reaction zones, a nonoxidative pyrolysis reaction that decomposed the fuel into a char, followed by a char oxidation reaction. Two different modes of char oxidation were considered in the model, one characterized by total fuel consumption and another characterized by total oxygen depletion. Recently, Buckmaster and Lozinski [12] following the work of the above authors [11] have developed a late time solution of the problem that provides a more elaborated description of the structure of the pyrolysis and oxidation fronts.

In a more recent work, Torero and Fernandez-Pello [13] also found two clearly defined reactions, pyrolysis and oxidation, when conducting natural convection, upward (forward) smolder experiments with polyurethane foam (natural convection forward smolder). The pro-

pagation velocity of both reaction zones was found to be similar and of the same order of magnitude as those previously reported for downward (opposed) smolder [14]. Upward smolder was found to be a nonstationary process that could lead to transition to flaming. If the sample was long enough, both the temperature and the propagation velocity attained values significantly higher than those observed for downward smolder. The role of buoyancy as a transport mechanism in forward smolder was studied by Torero et al. [15] by conducting experiments in an aircraft following a parabolic flight. It was observed that flows induced by buoyancy inside the char can play an important role in the heat and mass transport mechanisms that affect smolder. The experiments also show that forward smolder is a combustion process where exothermic oxidation coexists with nonoxidative endothermic pyrolysis, and where conduction, radiation, forced and natural convection are all important heat transport mechanisms.

An area of research that has many similar characteristics to those of smoldering combustion is the self-propagating, high-temperature, synthesis of ceramic and metallic materials (SHS) [16, 17]. This is an area of research where a significant amount of work, both theoretical and experimental, has been conducted, and given the similarity between the two processes it is possible that some of the resulting findings can be applied to the study of smolder combustion or vice-versa. However, both processes have some marked differences (in SHS the materials are generally less porous, melting plays an important role, combustion chemistry is generally significantly different, etc.), and the transfer of information from one area of research to the other is not straightforward. The recent theoretical model of forced forward smolder of Schultz et al. [18] is a good example of the application of some of the mathematical techniques initially developed to model SHS to the description of smolder propagation. In that work [18], the authors used asymptotic methods to determine the structure of the smolder front, and to predict the rate of smolder propagation when non-oxidative pyrolysis of the fuel does not play a significant role in the process.

The studies referred to above provide significant information about forward smolder. However, systematic experiments are still needed to determine the relative importance of the different mechanisms controlling forward smolder, and for model verification. In this work, systematic experiments are conducted to study the influence of the air velocity on the characteristics of forward smolder of polyurethane foam, and to determine the effect of buoyancy on the process. In the experiments, the air is introduced into the foam at the same sample end where smolder is initiated (ignition) so that the air flows in the same direction as the smolder reaction propagation. To assess the effect of buoyancy on forward smolder, the experiments are conducted for both upward and downward smolder propagation, so that the gravity vector is in the opposite or same direction as the forced flow, respectively. By comparing the smolder characteristics from both cases, the observed differences can be attributed to gravity effects. The sample size is selected to attain one-dimensional propagation at the core of the foam sample. The evolution of the fuel centerline temperature is obtained with the help of thermocouples, and this information is used to determine the propagation velocity of the reaction front. Polyurethane foam is a common insulation material and is also used extensively in the manufacture of furniture. Therefore, the results of these experiments can be used directly in the fire safety field and can also serve to validate theoretical works.

EXPERIMENT

Experimental Apparatus

A schematic diagram of the experimental apparatus in the upward smolder configuration is shown in Fig. 1. The test section consists of a 0.6-m-long vertical duct with a 0.15-m side square cross section, which is divided into three sections as follows: a 0.15-m-long gas settling section that is filled with glass beads to keep the flow uniform and has a gas inlet diffuser attached at its bottom end; a 0.15-m-long igniter section that is attached to the settling

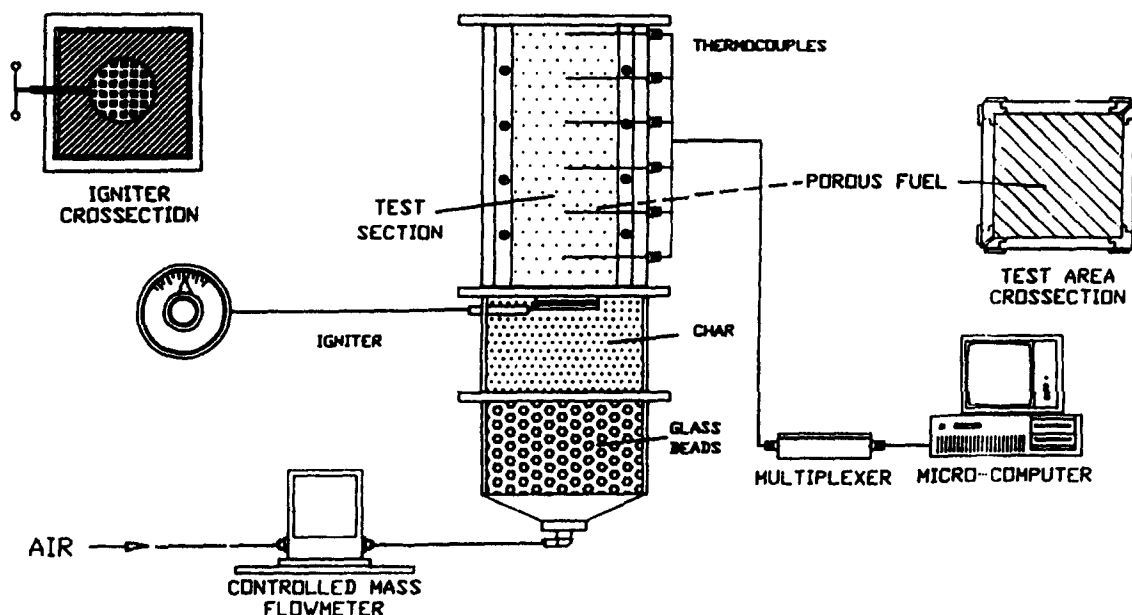


Fig. 1. Schematic of experimental apparatus.

section and contains the igniter and insulating char; and a 0.3 m long fuel section that contains the fuel. The duct walls are made of insulating 10 mm thick Fiberfrax sheets mounted on an Aluminum frame, and are covered with aluminum tape to prevent mass diffusion through the porous Fiberfrax. The foam sample is a parallelepiped of square cross section (0.16 m on the side) and 0.15 m long. The porous fuel is tightly fitted in the test section in an attempt to avoid the flow of oxidizer between the foam and the wall. The width was selected to reduce the effect of the cold walls on the smoldering reaction, and to obtain one-dimensional smolder propagation in a region of at least 50 mm in diameter at the core of the sample. Some tests were conducted with a radial array of thermocouples to verify the one-dimensionality of the reaction front. The length is enough to permit the observation of self propagating smolder without the influence of the igniter and end effects. Compressed house air is used as oxidizer. The air flow rate is metered with a Tylan FC280S mass flow meter/controller prior to entering the test duct. Controlling the mass flow rate is important in these experiments because the pressure drop through the porous material decrease with time as the smolder reaction propagates, and

nonactive flow controllers may not prevent the resulting increase in flow rate. The char is from the initial zone of an already smoldered sample and is used to insulate the ignition zone and somewhat simulate an ongoing smolder process. A gap is set between the char and the igniter to avoid the latter igniting the char and initiating an opposed type smolder through the char. The cold air flowing through the char further prevents its ignition.

The igniter consists of a Nichrome wire sandwiched between two 5-mm-thick porous ceramic honeycomb plates that provide rigidity to the igniter and heating uniformity. The foam ignition is accomplished by bringing the temperature of the igniter up to approximately 500°C. For these specific experiments the power needed was of approximately 1.7 KW/m² during a period of 900 s. However, most of the energy is used to heat the igniter ceramic plates to their operating temperature. Since the air flows through the igniter before reaching the fuel, the air flow is turned off during the heating period to avoid extending the igniter influence to a large region of the virgin material. This procedure also helps standardize the ignition process that, if performed with the air flow on, would depend on the flow rate. The heating period is selected to ensure the

self-supported propagation of the smolder reaction. Once the ignition heating period is completed, the igniter current is turned off and the flow of air is turned on, initiating the flow assisted smolder process. For the downward smolder experiments the apparatus is simply rotated 180 degrees.

The rate of smolder propagation is obtained from the temperature histories of eight Chromel-Alumel thermocouples 0.8 mm in diameter that are embedded at predetermined positions in the porous fuel with their junctions placed on the fuel centerline. The smolder velocity is calculated from the time lapse of the reaction zone arrival at two consecutive thermocouples, and the known distance between the thermocouples. Although the arrival of the reaction zone is characterized by a maximum in the temperature profile, under most experimental conditions this maximum is not sharply defined. The location of the pyrolysis front is defined by the intersection of the tangent to the temperature curve at the inflection point and a horizontal line at a temperature near the pyrolysis temperature (300°C in this work). The location of the oxidation front is defined by the intersection of a horizontal line at a temperature near the maximum temperature (380°C in this work) and a tangent to the temperature curve drawn after the pyrolysis front has passed the thermocouple and the temperature has started to increase again.

Experimental Results

All the experiments are conducted with an open cell, unretarded, polyurethane foam with a 26.5 Kg/m³ density and 0.975 void fraction. Its thermophysical properties are given in Table 1. Analysis of the temperature profiles along the foam sample and at the different air flow velocities shows that the characteristics of the smolder reaction vary depending on the magnitude of the air flow and the location of the reaction in the foam sample. Thus, the results will be reported here by first presenting characteristic temperature histories along the foam sample for several forced air flow velocities. Then the variation of the smoldering propagation velocity and maximum reaction temperature along the foam sample, obtained from

TABLE 1

Properties

$C_{pA} = 1.088 \text{ kJ/kg}$	$T_i = 293 \text{ K}$
$C_{pF} = 1.700 \text{ kJ/kg}$	$T_w = 483 \text{ K}$
$D = 4.53 \times 10^{-5} \text{ m}^2/\text{s}$	$Y_{O,i} = 0.235$
$d_p = 0.05 \text{ mm}$	$\alpha = 1.122 \times 10^{-4} \text{ m}^2/\text{s}$
$K_{CH} = 8.40 \times 10^{-7}$	$\beta = 1.684 \times 10^{-3} \text{ K}^{-1}$
$K_F = 2.76 \times 10^{-9}$	$\lambda_{\text{eff}} = 0.047 \text{ W/mK}$
$L_C = 150 \text{ mm}$	$\mu = 2.50 \times 10^{-5} \text{ kg/ms}$
$W = 150 \text{ mm}$	$\phi = 0.9750$
$Q_1 = 3,200 \text{ kJ/kg}$	$\rho_A = 1.225 \text{ kg/m}^3$
$Q_2 = 3,900 \text{ kJ/kg}$	$\rho_F = 1,034.0 \text{ kg/m}^3$
$Q_P = 300 \text{ kJ/kg}$	

these or similar temperature profiles, are presented for different air flow velocities. To describe the characteristics of the smolder reaction as it propagates through the foam sample, the analysis of the data is done by dividing the foam sample in three different zones. An initial zone near the igniter (I) whose length depends on the flow rate but that is never more than 50 mm long, where the smolder is affected by the ignition process. A second zone (II) covering approximately the central 60 mm of the sample where the smolder process is relatively free from end effects. A third zone (III) at the end of the sample where smolder is affected by the external environment.

Since during the period of ignition there is no forced air flow through the foam, smolder in region (I) is not representative of the type of smoldering studied here, thus only limited data from this region will be presented. The smolder propagation in zone II is the most representative of forced flow forward smoldering, at least from the point of view of modeling, since external effects are limited. Smolder in zone III is of particular interest from the point of view of observing the effect of buoyancy. As it will be shown later, it is found that buoyancy plays a significant role, particularly at low air flow velocities, and as the smolder reaction reaches the end of the sample.

Forced Upward Smolder

Experiments of upward smolder propagation were conducted for forced flow air velocities ranging from 0 to 8.0 mm/s and were repeated, on average, five times for each air flow

velocity. The series of temperature histories of Figs. 2a–4a describe the evolution of the smolder characteristics as the air flow velocity is increased. Each profile represents the temperature history at a specific location along the sample as recorded by a thermocouple. The distance between thermocouples is known but is not necessarily the same between different consecutive thermocouples. To avoid unnecessary crowding of the figures, all eight thermocouples are not presented unless considered necessary. These temperature histories can also be used to produce spatial temperature distributions as those presented in Figs. 2b–4b, which help in understanding the evolution of the smolder reaction, and facilitate the comparison with the results from theoretical models.

For air flow rates smaller than 0.5 mm/s, the general characteristics of the smolder process are very similar to those observed in opposed flow smolder [6]. From Fig. 2a, it is seen that as the smolder reaction approaches a specific location within the foam sample, the foam temperature increases monotonically, reaches a maximum and levels off until eventually it starts to decrease rather sharply. The increase in the foam temperature is due to heat transfer from the reaction zone to the virgin fuel ahead, which at these low flow velocities appears to be dominated by conduction and radiation, with convection having a secondary role. It should be noted that with a foam thermal diffusivity of 45.3 mm²/s and the sample length (150 mm) as characteristic length scale, the resulting velocity of the conduction thermal wave is

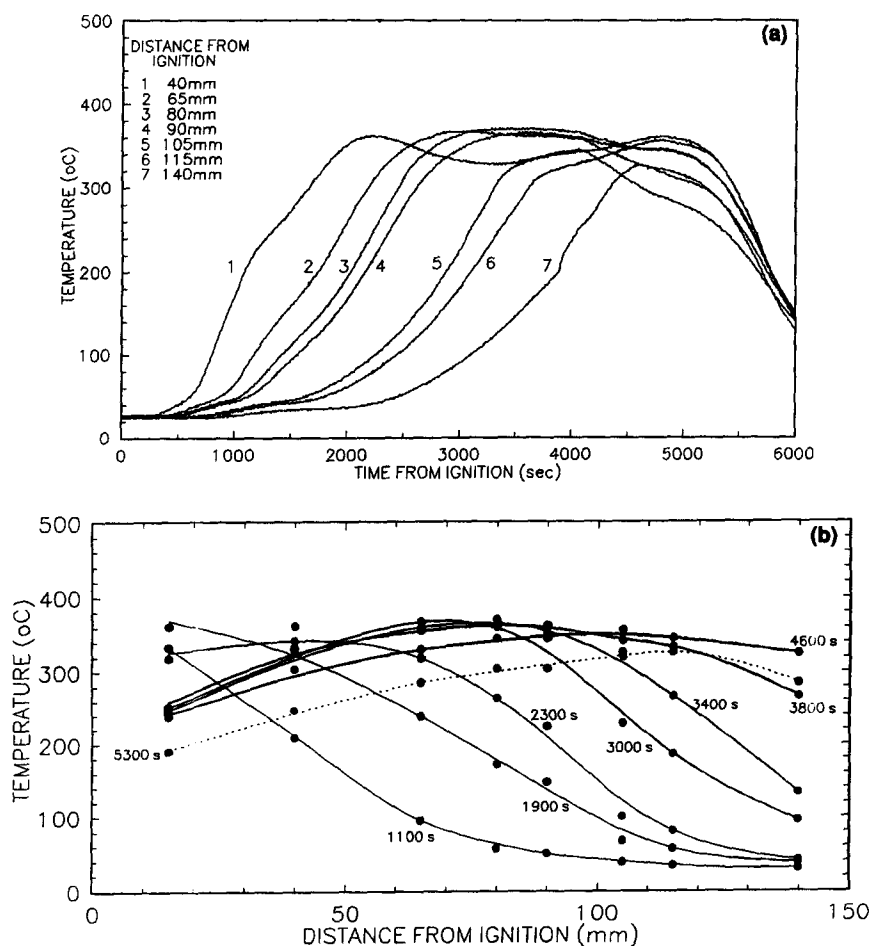


Fig. 2. (a) Temperature histories at several locations along the foam sample. (b) Evolution of the temperature profiles with time. Upward forward smoldering at an air flow rate of 0.30 mm/s.

larger than the gas flow velocity (0.3 mm/s in this case). This, together with the similarity between the temperature profiles for forward and opposed smolder, seems to indicate that at this low flow velocity, foam heating ahead of the reaction zone by convection is not significant. The arrival of the smolder reaction at a particular location is determined approximately by the leveling of the temperature, and is due to a balance between the heat generated by the exothermic oxidation of the fuel (smolder reaction) and the transfer of heat to the foam ahead of the reaction. The maximum temperature is observed to remain almost constant as the reaction propagates through the sample, with its value approximately 10°–20°C

lower than the maximum temperature measured in opposed flow [6].

As the air flow velocity is increased, the smolder reaction becomes more vigorous with larger propagation velocities and higher maximum temperatures. At velocities larger than 0.5 mm/s, a pyrolysis front, characterized by the onset of a plateau in the temperature profile at a temperature of approximately 320 °C, appears ahead of the smolder front (Figs. 3a, 4a). This plateau seems to be caused by the endothermic pyrolysis of the foam which occurs when the foam is heated in a non-oxidative environment [10]. Since the gas flow velocity is larger than the conduction wave velocity, the foam is heated by convection, in addition

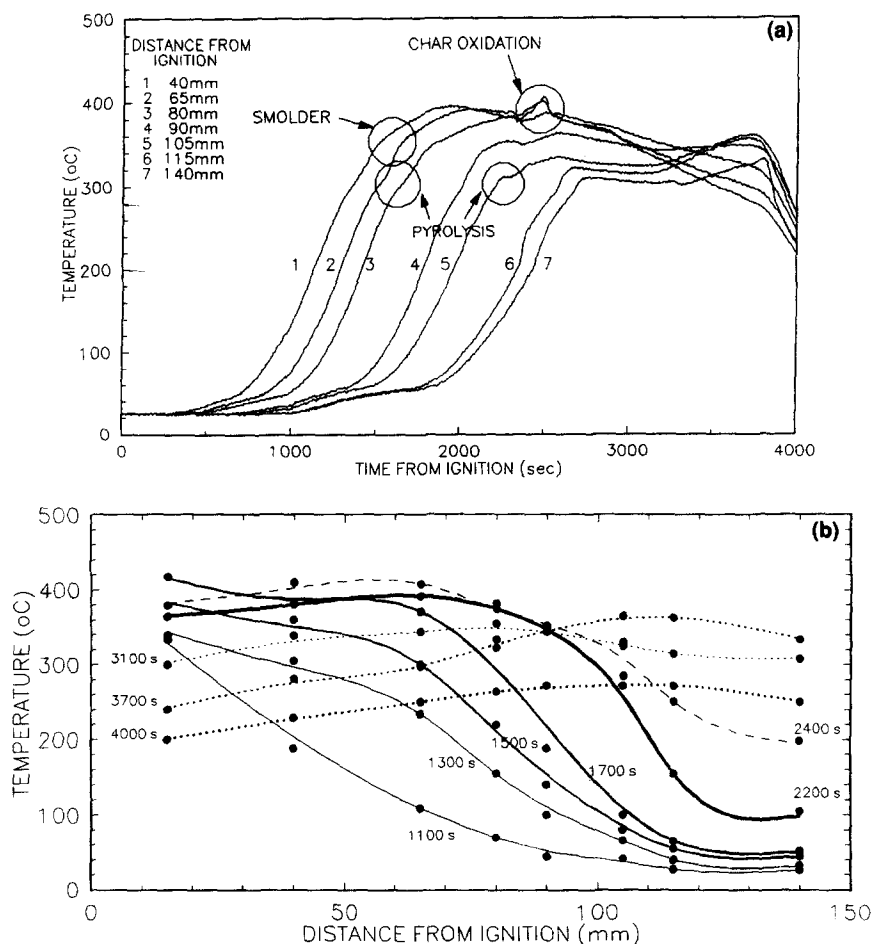


Fig. 3. (a) Temperature histories at several locations along the foam sample. (b) Evolution of the temperature profiles with time. Upward forward smoldering at an air flow rate of 0.90 mm/s.

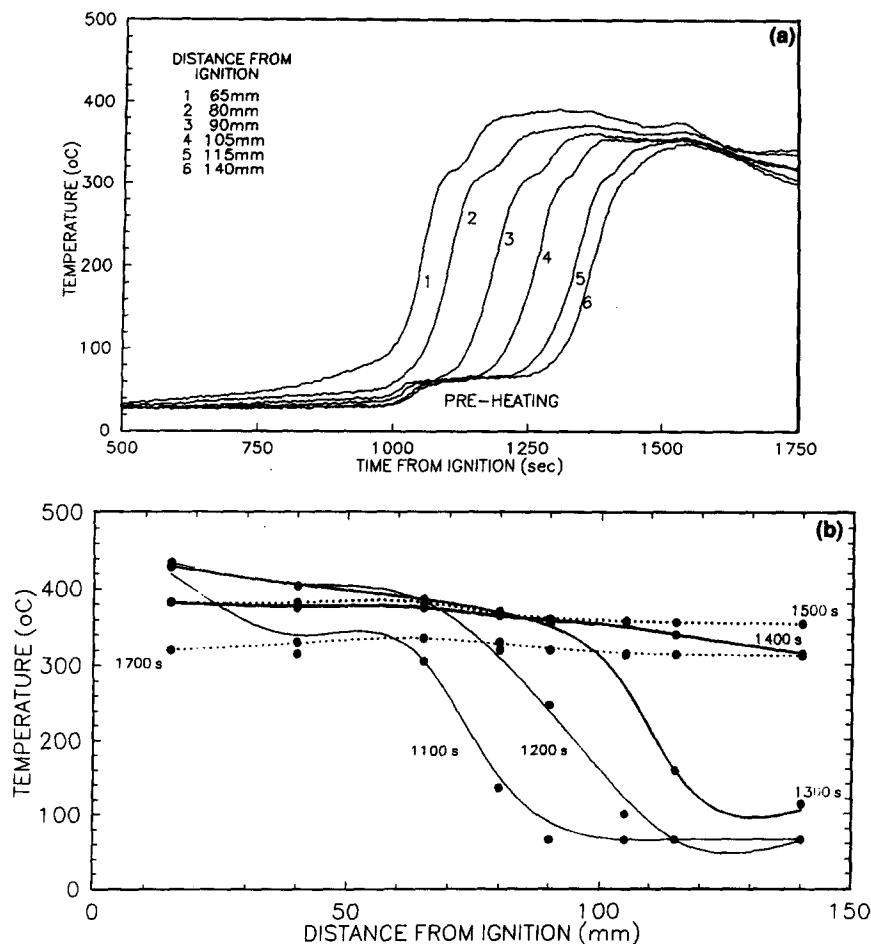


Fig. 4. (a) Temperature histories at several locations along the foam sample. (b) Evolution of the temperature profiles with time. Upward forward smoldering at an air flow rate of 2.80 mm/s.

to conduction and radiation, in an ambient that is determined primarily by the composition of the postcombustion gases. If the smolder reaction is oxygen limited, the postcombustion gas will be depleted of oxygen, which will favor the onset of a foam pyrolysis reaction ahead of the smolder oxidation. The time gap between the pyrolysis and smolder reaction increases as the air velocity is increased but, at least within the present experimental conditions, their propagation velocities are approximately the same for a given air flow rate.

Also evident from the temperature profiles for the larger air flow velocity cases is the convective preheating of the foam ahead of the pyrolysis front by the hot postcombustion gases. This is characterized by a temperature plateau

of the virgin foam at an almost constant value of approximately 60°C (Fig. 4a). The relatively low temperature increase is due to the large difference in the heat capacity of the foam and air. As the velocity of the flow is increased, the time at which this temperature is attained at a particular location in the sample decreases, and the extent of the sample preheat increases. The large difference between the preheat and smolder temperatures indicates that at least for the present experiments, the convective heating of the foam is secondary to the conductive heating and consequently should not have a strong effect on the characteristics of the forward smolder process. However, convection could become more important if the oxidizer had a larger heat capacity.

An interesting effect that can be observed from the temperature profiles of Fig. 3a is the presence of sharp temperature peaks behind the smolder front (TC's 2 and 3). These peaks are observed primarily for large flow velocities and indicate the onset of an oxidation reaction in the char left behind by the smolder reaction at a specific sample location and time. The onset of the char oxidation reaction coincides with a temperature dip in the next two downstream thermocouples (TC's 4 and 5) that are in the vicinity of the smolder reaction, and an increase in the temperature of the following two thermocouples (TC's 6 and 7) that are ahead of the pyrolysis front. It also coincides with a delay in the onset of the smolder reaction in the region downstream from the location where the char oxidation occurs. The sequence of events taking place after the onset of these secondary char oxidation reactions seem to be the result of the depletion of oxidizer by the reaction, and the resulting generation of additional heat at the reaction. Depletion of oxidizer by the char reaction hampers the propagation of the smolder reaction, while the additional generation of heat in the char region results in an increase in the temperature of the foam ahead of the smolder front. The char oxidation reaction is vigorous and leaves behind a rather porous material that is cooled fairly quickly by the incoming fresh air. After the pyrolysis and smolder fronts have reached the end of the sample, a secondary oxidation reaction that is quite strong propagates very quickly through the char, consuming most of the remaining char. Transition to flaming was observed in some experiments for air velocities larger than 15 mm/s. Experimental data for the secondary reactions and transition to flaming is not reported here because it is beyond the scope of this work.

The above interpretation of the characteristics of forward smolder is somewhat different from that given by Ohlemiller and Lucca [10], who interpreted the temperature profiles as the result of a thermal wave followed by a char oxidation reaction. The propagation of the oxidation reaction was determined by the total consumption of the char. The discrepancy in the observations may be the result of the different fuel used in each study, i.e., cellulose vs.

polyurethane foam, or the actual experimental conditions. As indicated above, in the present experiments a significant amount of char is left behind by the initial smolder wave. However, in a few experiments conducted at larger air flow velocities trends were observed that indicate that conditions may be reached where all the char would be consumed by the incoming oxidizer, as observed by Ohlemiller and Lucca [10]. In addition to their observations, these last authors argue that since the oxidizer flows through the char, it has to be totally consumed for the reaction to propagate. An explanation for the char not being totally consumed by the flowing oxidizer, as observed here, is that the char has a different reactivity (higher activation energy, higher heat of reaction) to that of the virgin, or pyrolyzed, foam, and requires different conditions of air supply or temperature for its oxidation [10]. When these conditions are reached, then the char oxidizes partially or totally, as observed in some of our experiments.

The variation of the smolder propagation velocity along the foam sample length is presented in Fig. 5 for different air flow velocities. The propagation velocities of the pyrolysis and oxidation fronts are similar, and constant along the middle of the sample (zone II), but increase and differ as the smoldering front reaches the end of the sample (zone III). For air flow velocities larger than 6 mm/s, as the reaction reaches the end of the sample, the oxidation front starts to propagate faster than the pyrolysis front probably due to an inflow of fresh oxidizer from the external environment. The variation of the smolder velocity with the forced air flow rate, averaged in each of the three sample zones, is presented in Fig. 6.

The variation of the maximum smoldering temperature along the foam sample is presented in Fig. 7 for several air flow velocities. It can be observed that for small flow velocities the temperatures are constant through zone II but decay through zone III. Temperatures cease to decay towards the end of the sample for air velocities larger than 4 mm/s, and start to increase for larger flow velocities. The temperatures increase with the flow velocity throughout the sample. It should be noted that the values plotted are average values for each

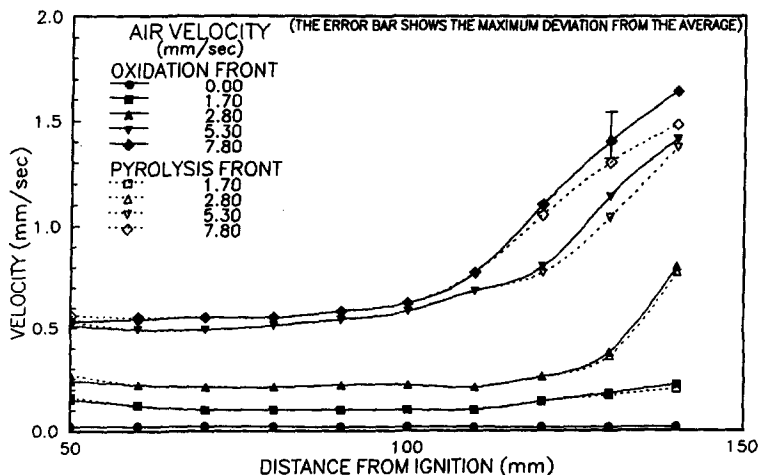


Fig. 5. Variation of the upward forward smolder propagation velocity along the foam sample for several air flow velocities.

zone, and therefore do not provide local detailed information about the process. Smoldering temperatures for polyurethane foam have been observed by several authors to be of the order of 360°–380°C [4, 5, 19]. The result of Fig. 7 shows higher temperatures, particularly at high flow velocities. This is due primarily to the oxidation of the char behind the reaction front, which is generally more energetic than that of the virgin foam.

The permeability of the char left behind by the propagating reaction depends on the

strength of the reaction and on the char structure itself and provides qualitative information about the degree of fuel consumption. This is reflected in the measured dependence of the char permeability on the forced flow velocity for upward smolder, presented in Fig. 8. Since increasing the forced flow velocity enhances the smolder reaction, the char permeability also increases. The increase, however, is not linear because at small flow rates the char keeps its structure [19]. However, as the smolder reaction becomes more vigorous, the fila-

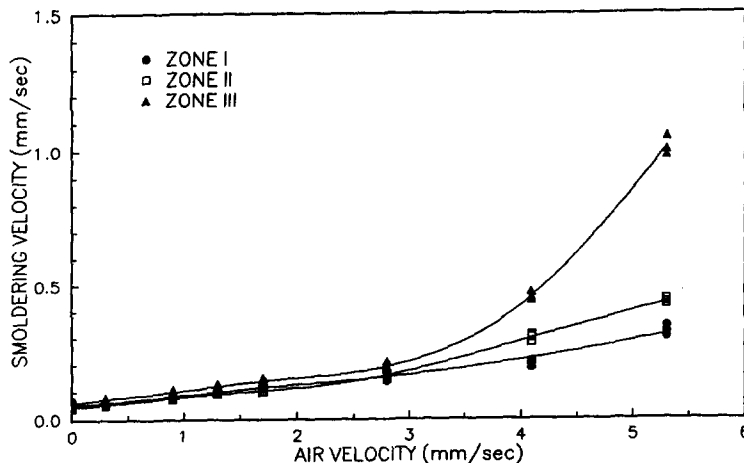


Fig. 6. Dependence on the air flow rate of the upward forward smolder velocity at three different sample zones.

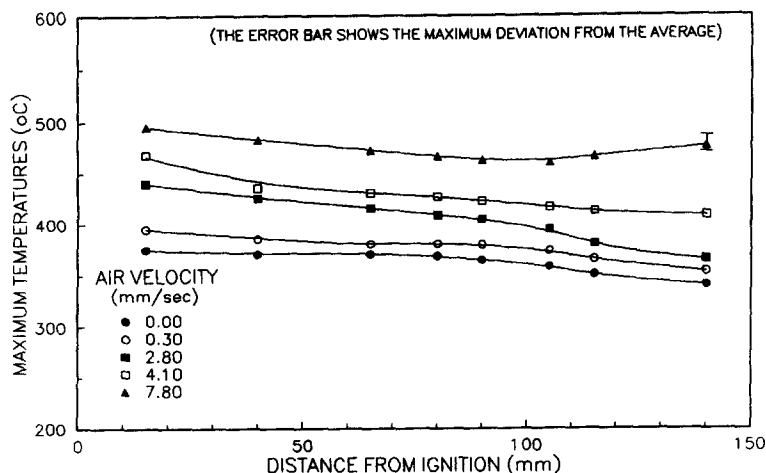


Fig. 7. Variation of the upward forward smolder reaction maximum temperature along the foam sample for several air flow velocities.

ments that form the microstructure of the foam break down [11], which results in a sudden increase in the permeability, as it is seen in Fig. 8.

Forced Downward Smolder

The downward smolder experiments were conducted in the same experimental apparatus as that for upward smolder, but rotated 180 degrees, and for the same experimental conditions. The objective of the experiments is to obtain additional information on the effect of

gravity on smolder. Comparison between the upward and downward results showed that the general characteristics of the respective smolder processes were similar, and that the major differences observed were primarily at low flow velocities. Thus, for brevity of presentation, emphasis will be given here to the discussion of low flow velocity results and the observed differences. The reader is referred to Ref. 7 for more detailed information.

The major differences between the upward and downward smolder configurations are easily observed by comparing the dependencies of the smolder propagation velocity and maximum temperature on the air flow velocity. For this purpose, the data for downward smolder are presented in Figs. 9 and 10, respectively. The smolder velocities are averaged values of the smolder velocities in each zone. The most important difference between the upward and downward smolder configurations is the presence of a nonpropagation regime in downward smolder at flow velocities between 0.3 and 1.2 mm/s (Fig. 9). At larger air velocities, the smolder propagation velocity increases monotonically with the flow velocity in a similar way as observed in upward smolder.

Analysis of the temperature profiles along the foam sample provides the following general characteristics of the downward smolder process as the flow velocity is increased. For very low flow rates (< 0.30 mm/s), the general

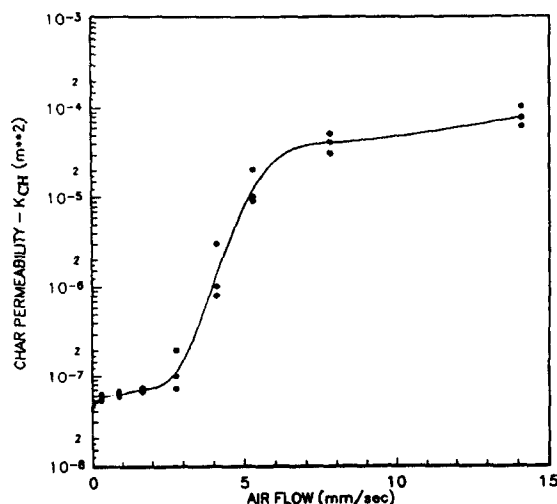


Fig. 8. Variation of the average char permeability with the air flow velocity, downward forward smolder.

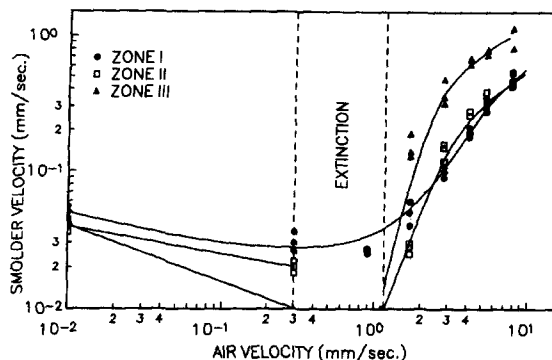


Fig. 9. Dependence on the air flow rate of the downward forward smolder velocity at three different sample zones.

smolder characteristics are similar to those observed for upward smolder at similar flow velocities. As indicated above, these characteristics resemble those for opposed flow smolder, and show that conduction and radiation are the dominant modes of heat transfer at these low flow velocities. When the air flow is increased to 0.3 mm/s, extinction (no self propagation) is observed very early in the sample, with the temperature dropping along the sample length. A further increase in the flow velocity to 0.9 mm/s shows again a slowly propagating reaction that stops propagating in the last 60 mm of the sample. For air flow velocities larger than 1.2 mm/s, the smolder wave propagates throughout the sample and the smolder

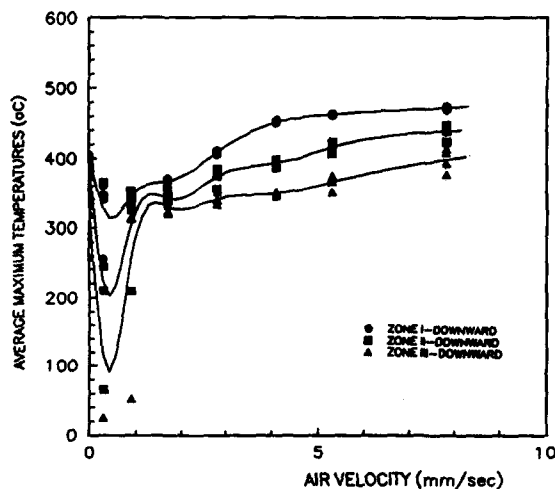


Fig. 10. Dependence on the air flow velocity of the downward forward smolder maximum reaction temperature at three sample zones.

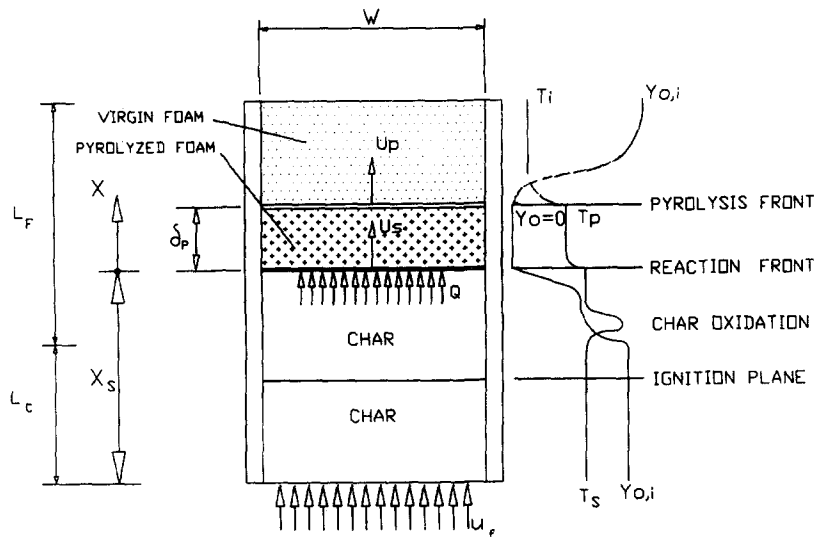
characteristics become more and more similar to those described above for upward smolder; i.e., the smolder reaction is preceded by a pyrolysis reaction and a preheat zone. At these larger flow velocities, forced convection of the postcombustion gases ahead of the smolder front has an important role in the characteristics of smolder propagation. As explained below, the nonpropagating regime is caused by buoyancy effects. In this configuration, buoyancy induces gas flows in the sample interior that are of the same magnitude, but opposite direction, to the forced ones. The result is the generation of a stagnation, or recirculation, region in the sample interior that hampers the flow of oxidizer to the reaction zone, and consequently the propagation of the reaction.

SMOLDERING MODEL

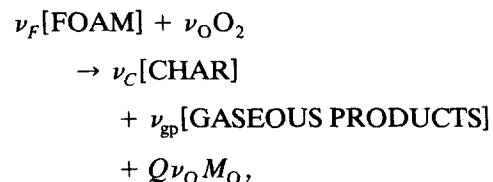
The above experimental results suggest the presence of two major regimes of forward smolder propagation. For air flow velocities smaller than approximately 1.0 mm/s, the smolder propagation appears to be controlled by diffusion of heat and mass, and the smolder characteristics are similar to those observed in opposed flow smolder propagation. For air flow velocities larger than 1.0 mm/s, convection of postcombustion products ahead of the smolder front appears to have an increasingly important role, and the smolder process is characterized by the propagation of an endothermic pyrolysis front preceding the oxidation smolder front. Thus, two different models will be used to describe the above experimental observations, one that considers only char and foam oxidation and that applies to flow velocities lower than 1.0 mm/s, and another that considers both pyrolysis of the virgin foam and oxidation of the char/foam, and that applies to higher flow velocities.

Energy Analysis

Previously developed models for forward smolder will be used as the basis for the development of simplified expressions for the smolder propagation velocity [11, 12, 18, 20]. The general characteristics of these models are as follows (see schematic in Fig. 11). In forward



For low flow velocities, before the appearance of fuel pyrolysis, the theoretical models developed by Schultz et al. [18] for forward smolder and by Johnson et al. [20] for the forward propagation of a regeneration reaction through a catalyst are applied here. The models provide a solution for forward propagation of an exothermic reaction in the absence of pyrolysis as a heat sink. Assuming that the oxidation reaction is described by a one step chemical reaction of the form

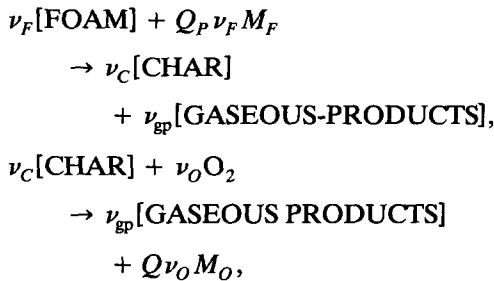


and that the oxidizer entering the upstream edge of the sample is totally consumed at the smolder reaction front, the solution of the appropriate energy conservation equation provides the following expression for the smolder velocity.

$$U_S = \frac{\rho_A Q Y_{O,i} u_g + \dot{q}_{ig}''(x)}{[\rho_A C p_A \phi + \rho_F C p_F (1 - \phi)](T_S - T_i) - (1 - \phi) Q \rho_A Y_{O,i}} \quad (1)$$

It should be noted that this equation is basically the same as that derived by Dosanjh et al. [20] for opposed flow smolder [6].

For velocities larger than 1.0 mm/s, a pyrolysis front is considered to propagate ahead of the char oxidation front, and a modified version of the models of Dosanjh and Pagni [11] and of Buckmaster and Lozinski [12] are used here. Assuming a two step chemical reaction consisting of a nonoxidative, endothermic first step (pyrolysis) followed by an exothermic oxidation of the char, as described by



and solving the one-dimensional energy equation assuming that pyrolysis and smoldering propagation velocities are equal, and that the pyrolysis reaction occurs at a constant temperature [4, 7, 9] the following expression for the smolder velocity is obtained:

$$U_s = \frac{\rho_A Q Y_{O,i} u_g + \dot{q}_{ig}''(x)}{[\rho_A C_{pA} \phi + \rho_F C_{pF} (1 - \phi)](T_s - T_i) - [Q_p \rho_F + Q \rho_A Y_{O,i}](1 - \phi)} \quad (2)$$

Unknowns in Eqs. 1 and 2 are the smolder temperature T_s , the initial temperature T_i , the heat of combustion for smoldering Q , and the heat of pyrolysis Q_p . Although the above theoretical analyses [11, 12, 18] provide expressions for the smolder temperature T_s , the corresponding asymptotic analyses leading to those expression impose a number of restrictive conditions that are often not applicable to the experiments or are difficult to implement. For this reason, in this work the value of the smolder reaction temperature is obtained from the experimental data. An integral solution for a semi-infinite slab with constant heat boundary condition [7, 14] is used to calculate the heat conducted from the igniter ($\dot{q}_{ig}''(x)$) and the

initial foam temperature $T_i(x)$ as a function of the distance from the igniter. Away from the igniter influence the initial temperature of the foam is obtained from the measured temperature histories. The heats of oxidation, Q , and pyrolysis, Q_p are not well determined for smoldering combustion [1], in this work they are selected so that the correlation of the experimental data with the above equation is optimized. The resulting values of Q and Q_p are presented in Table 1. The value of Q that fits the data best is smaller when only oxidation is present (Q_1) than when both pyrolysis and oxidation are present (Q_2). This difference may be due to the presence of strong char oxidation reactions in the latter case. Both values, however, agree fairly well with those previously reported for smolder combustion [4–7, 10, 19]. Finally, the oxidizer velocity u_g , is the forced flow of oxidizer plus the contribution from the air in the foam pores, and any buoyant flow. Significant buoyancy induced flows may occur in the char, since it is generally very porous. The potential generation of buoyant flows inside the char is studied below.

Flow Induced Through the Char by Buoyancy

The onset of buoyant flow inside a porous medium depends strongly on the permeability of the material [23]. The polyurethane foam used in the present experiments has a relatively low permeability in spite of the high void fraction, and no buoyant flows are expected to be generated inside the foam. However, the char left behind by the propagating smolder reaction is quite permeable, and buoyant recirculation flows can be induced in the char region by the natural convection boundary layer that is generated at the test section walls by the difference in the wall and char/post-combustion gases temperatures. A schematic of these potential recirculating flows is shown in Fig. 12. In downward smolder, cold air flows downward along the cold walls (in the char region) towards the reaction zone, here it encounters the unburned foam, which has a much smaller permeability and consequently prevents the air from flowing through, causing it to turn around and to move upward along the foam centerline opposing the forced air flow.

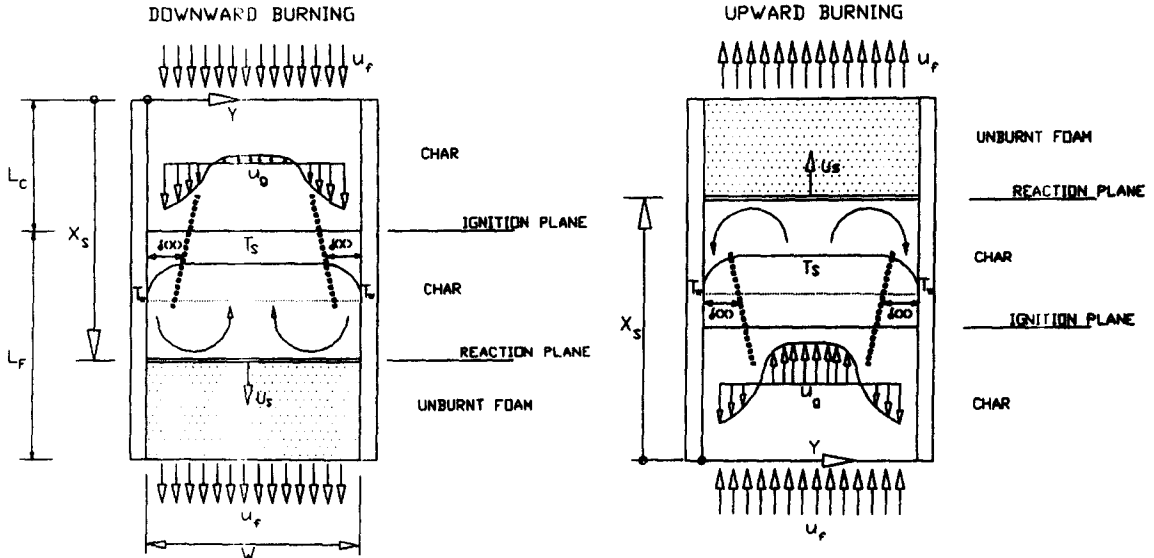


Fig. 12. Schematic of the flow field inside foam and char during a forward smoldering reaction for upward and downward smolder.

Thus, the net result is that the total air flow through the sample centerline decreases which, as it will be seen below, may be important at low forced flow velocities. For upward smolder the cold air moves down the walls and upward along the duct centerline in the same direction of the forced flow. Thus, in this case the net air flow increases through the sample centerline.

Few works have been conducted on the mixed, free and forced, flow in a porous media. The analysis developed here is based on the works of Refs. 23–27. The numerical analysis of the problem developed by Lai et al. [25] shows that for aiding boundary layer flows the mixed flow solution is valid for values of Ra/Pe smaller than 50, and the pure natural convection solution for values greater than 50. For downward smolder (aiding flow) and for the present experimental conditions it is found that for flow rates smaller than 1 mm/s, the Ra/Pe is larger than 50. Thus, the natural convection solution prevails for air velocities smaller than 1 mm/s, and the mixed convection solution for greater air velocities. For upward smolder (opposing flows), the mixed flow solution is found to give a more accurate description of the problem for values of Ra/Pe smaller than 500, which covers the whole range of flows used in the present experiments. Thus, both free and mixed flow conditions take place in the present

experiments and an analysis of the flow is necessary to determine the oxidizer mass flux at the reaction zone. A summary of the mixed and natural convection flow analyses used in this work follows.

Mixed Convection Flow

The analysis of Neild and Bejan [27] is followed here. With the assumptions that the fluid and porous media are in thermodynamical equilibrium, that there is no phase change in the solid, that the properties of the porous media and fluid are homogeneous and isotropic, and applying Darcy's Law together with the Boussinesq approximation, the solution of the resulting governing equations for mass, momentum and energy, provide the following expression for the averaged velocity of the air flow along the center region of the char [27]:

$$u_b = \frac{2\delta}{W} \left(\frac{Gr_K}{Re_K} \right) u_f, \quad (3)$$

where

$$\delta = x Ra_x^{-0.5},$$

$$Ra_x = \frac{K_C g \rho_A \beta (T_W - T_S) x}{\alpha \mu},$$

$$Re_K = \frac{\rho_A u_f K_C^{0.5}}{\mu},$$

and

$$Gr_K = \frac{K_C^{1.5} g \rho_A^2 \beta (T_w - T_s)}{\mu^2}.$$

The characteristic length scale used when evaluating the relative effects of buoyancy and inertia is $K^{0.5}$ (where K is the permeability) therefore both Reynolds and Grashof numbers are subindexed "K." The Rayleigh number is primarily a function of the distance from the ignition plane therefore is subindexed "x." All air properties are calculated at an average temperature 440 K.

Natural Convection Boundary Layer Flow

The analysis of Burns et al. [24] for buoyancy-induced flows in vertical ducts with different wall temperatures is used here. Application of the analysis to the present problem gives the following expression for the averaged air flow velocity at the char centerline

$$u_b = \frac{\alpha Ra_x}{4W}. \quad (4)$$

The final form of Eq. 4 results from the integration across the whole sample section of the flow induced by the temperature gradient close to the wall assuming a constant average velocity (u_b) outside the boundary layer [7].

Convective Flow Velocity at the Sample Centerline

A comparison of the magnitude of the free, or mixed, convection air velocity, relative to the pure forced flow velocity, as the smolder reaction propagates through the sample is presented in Fig. 13. It is seen that there is a range of conditions where the buoyancy induced air velocity is larger than the forced flow velocity. This is particularly important in downward smolder where both flows opposed each other at the char centerline region. It corroborates the above argument that the extinction, or nonpropagation, observed in downward smolder for forced air flow velocities ranging between 0.3 mm/s and 1.2 mm/s as due to buoyancy effects.

Diffusion of Oxidizer into the Reaction Zone

Another possible transport mechanism of oxidizer to the reaction zone is by diffusion from

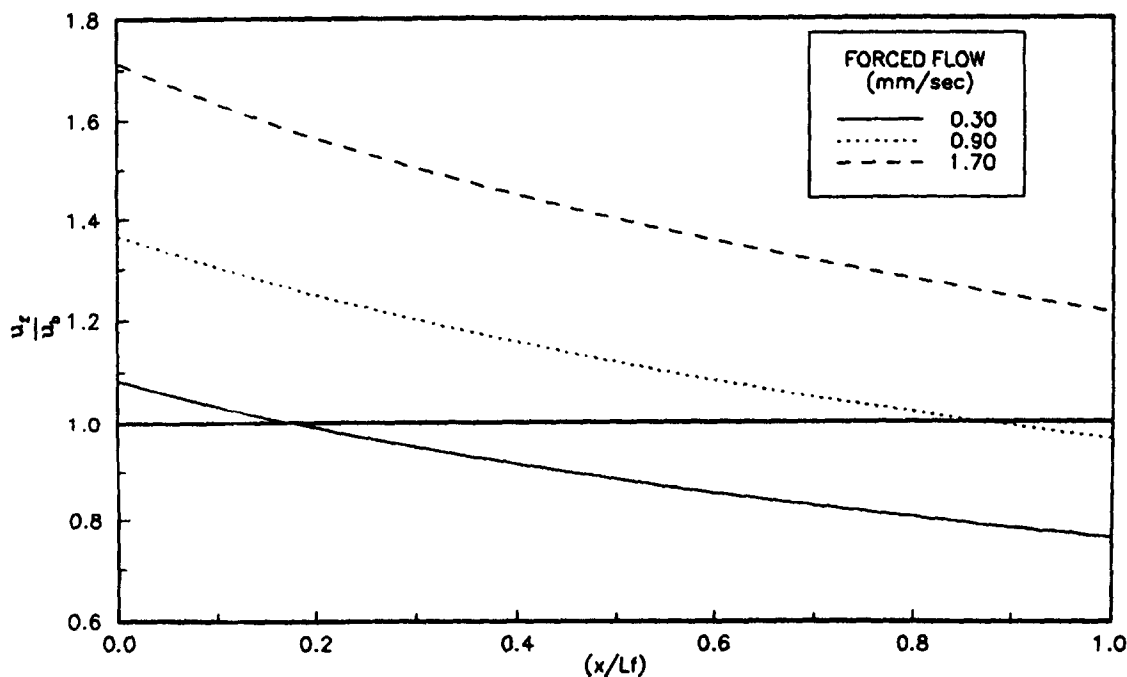


Fig. 13. Variation of the forced flow/buoyancy induced average flow ratio for different forced flow velocities and locations in the sample.

the external environment through the foam. From the governing species conservation equation, the following characteristic diffusion length is deduced

$$\delta_D = \frac{D}{u_f + u_b + \phi U_s}. \quad (5)$$

For the present experimental conditions it can be shown that this characteristic length is much smaller than the characteristic length of the problem, and that consequently diffusion can be neglected as a transport mechanism in this problem, when compared to the forced and natural convection flows.

Overall Oxidizer Flow into the Reaction Zone

The total mass flux of oxidizer at the smolder reaction zone is a combination of the mixed flow and the oxidizer flow resulting from the propagation of the reaction into the porous fuel, i.e.,

Upward Smolder

$$u_g = u_f + u_b + \phi U_s \quad (6)$$

Downward Smolder

$$u_g = u_f - u_b + \phi U_s, \quad (7)$$

where it is assumed that the buoyant recirculation flow induces a gas flow in the centerline region of the foam that moves in the same direction than the forced flow in upward smolder, and in the opposite direction in downward smolder.

DATA CORRELATION

Equations 1 or 2 together with Eqs. 6 or 7 are used to correlate the smolder velocity experimental data. The ratio of the experimentally measured and theoretically calculated smolder velocities, as a function of the nondimensional distance from the igniter is presented in Fig. 14, for forced air flow velocities smaller than 1.0 mm/s, and in Fig. 15, for larger flow velocities. The theoretical smolder velocity is calculated with Eqs. 1 and 2, respectively, and with the values of the fuel and oxidizer properties given in Table 1. The experimental data are that obtained for upward and downward smolder, partially presented in Figs. 5 and 9.

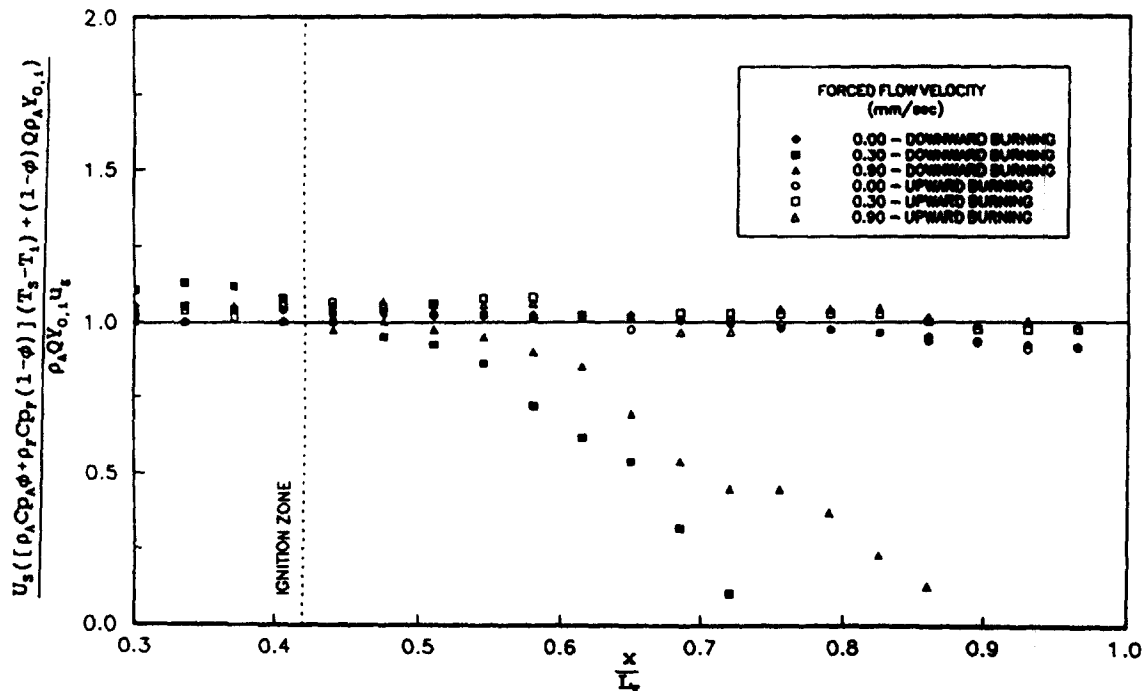


Fig. 14. Correlation of experimental and theoretical forward smoldering propagation velocities for different air flow velocities as a function of the distance from ignition. Air flow velocities smaller than 1.0 mm/s.

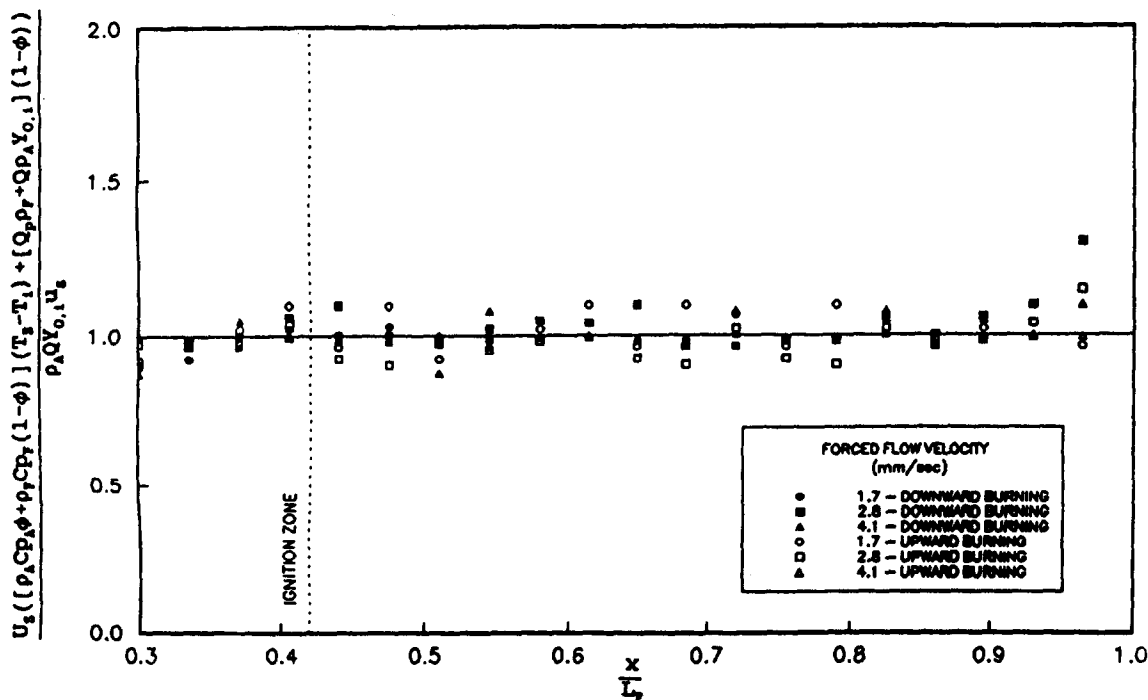


Fig. 15. Correlation of experimental and theoretical forward smoldering propagation velocities for different air flow velocities as a function of the distance from ignition. Air flow velocities greater than 1.0 mm/s.

The data correlation of Fig. 14 shows that Eq. 1 predicts well the smolder velocity, except for downward smolder in the extinction regime, where the analysis is not applicable. To improve the correlation, the oxygen concentration was selected as $Y_{O,i} = 0.188$, which is lower than the oxygen mass fraction of air. This is reasonable since Eq. 1 basically describes an opposed flow type smolder, and assumes that all the oxidizer reaches the reaction zone. In the experiments, however, the fresh air moves through the hot char before reaching the reaction zone, and even though weakly, the air is expected to react with the char, thus diminishing the oxygen concentration of the gases reaching the reaction. The observed slow down of the reaction after the initiation of vigorous char oxidation reactions seems to corroborate this hypothesis. Analysis of the composition of the gases reaching the reaction zone could corroborate this assumption, unfortunately our attempts to measure them were unsuccessful because the tar resulting from the reaction clogged the sampling lines. From the correlation of Fig. 15, it is seen that the model

predicts very well the present data for flow velocities larger than 1 mm/s. Since the heat generation term in Eq. 2 incorporates both the char and pyrolyzed foam (solid) oxidation, there is no need to reduce the oxygen concentration reaching the reaction to improve the correlation of the data in this case.

The success in correlating the experimental smolder velocity data with expressions derived from simple, heat transfer based, theoretical models of the problem corroborates that, at least within the present experimental conditions, smoldering is controlled by the heat transfer from the oxidation reaction to the adjacent material, and the mass transfer of oxidizer to the reaction. Chemical kinetics still has an important role in the process, and in these models appears through the magnitude of the heat of reaction, the smolder reaction temperature, and the assumption that the oxygen is totally consumed by the reaction.

DISCUSSION

The above experimental and theoretical results provide further understanding about some of

the mechanisms controlling forward smolder. Within the range of forced air flow velocities tested, two distinctive smoldering regimes can be identified. One at very small air flow velocities (smaller than the diffusion velocity), that is characterized by the propagation of a single oxidation reaction (smolder), and another at larger air flow velocities that is characterized by the propagation of two reactions, an oxidative charring reaction (smolder) and a nonoxidative pyrolysis reaction (condensed phase pyrolysis).

For small air flow velocities, the smolder reaction propagates through the virgin foam by transferring heat, by conduction and radiation, to the virgin fuel ahead, with convection of heat and mass playing only a secondary role. Furthermore, it appears that as the smolder reaction propagates through the sample, it leaves behind a weakly reacting char that does not consume much of the oxygen in the air flowing through it. Thus, the smolder controlling mechanisms at these low flow velocities are similar to those of opposed flow smolder, and when smoldering is self-sustained, the smolder propagation velocity is predicted well by an expression such as Eq. 1, which is basically an energy balance between the energy released at the reaction and the energy needed to heat the foam to the smolder temperature.

At low flow velocities buoyancy plays a significant role in the magnitude of the oxidizer flow reaching the reaction, that is determined by the combination of the forced flow and the buoyancy-induced flow. In upward smolder, where both flows add to each other, buoyancy enhances smolder by increasing the overall oxidizer flow reaching the reaction at the foam centerline, and in turn its heat release rate. In downward smolder, however, where both flows oppose each other, buoyancy hampers the smolder propagation. Furthermore, if the buoyant and forced flows have similar velocities, they tend to cancel each other near the centerline of the sample and to drive the oxidizer towards the walls where the temperatures are lower, which slows down the chemical reaction and causes its extinction.

The second smolder regime is more representative of forward smolder. At larger oxidizer flow velocities the smolder process

becomes one where convective effects are increasingly important. The postcombustion gases, which are depleted of oxygen due to the char and pyrolyzed foam (solid) oxidation reactions, displace the oxygen contained in the foam pores as they flow ahead of the oxidation front. As a consequence the virgin foam is heated, by convection, conduction and radiation, in the absence of oxygen, which favors the pyrolysis of the foam. The foam pyrolysis, which is endothermic, is also helped by the larger heat release resulting from the more vigorous oxidation reaction that takes place at larger oxidizer flow rates. Also it appears that in this regime the oxidation of the char left behind by the smolder reaction is significant, and since the oxidation of the char is characterized by a stronger energy release, the temperatures behind the smolder front are higher than those obtained during the smoldering of the virgin foam. This helps the onset of the pyrolysis reaction since the resulting transfer of heat to the foam ahead is larger. The final result is the generation of the two reactions, the endothermic, nonoxidative pyrolysis of the virgin foam, and the exothermic oxidation of the pyrolyzed foam (solid) and the char, that propagate at approximately the same velocity, at least for the present experimental conditions. In this regime, the smolder propagation velocity is predicted well by an energy balance between the energy released at the oxidation reaction, and the energy needed to pyrolyze the foam and to heat it to the smolder temperature, as expressed by Eq. 2. It should be noted that in Eq. 2 there is no distinction on whether the heat is released by the oxidation of the pyrolyzed foam or the char, all that it assumes is that all the oxygen is consumed by an overall oxidation reaction with an overall heat of combustion. At these larger flow velocities buoyancy effects are small, at least away from the sample ends, and the oxidizer flow velocity is that of the forced flow.

As the smolder reaction approaches the end of the sample, the resistance to buoyancy induced flows in the foam is reduced, and buoyancy affects the smolder process, at least for the flow velocities tested in this work. It has been shown that natural drafts near the end of the sample are capable of inducing flow veloci-

ties of a few mm/s [7, 13, 14]. These buoyancy induced flows can bring fresh cold air from the outside to the reaction, which can enhance the reaction by oxygen addition if it is vigorous, or deter it by cooling if it is weak. Buoyantly generated flows can also initiate and induce a reverse reaction through the char that can be very vigorous and even result in the transition to flaming.

CONCLUDING REMARKS

The present experimental observations have provided further understanding of the mechanisms controlling forward smoldering, and are consistent with already available models of the process. The good agreement between theory and experiments supports the simplifying assumptions implicit in the models at least for the present experimental conditions.

In forward smolder, as the air flow velocity is increased, there is a transition from an initial smolder process that is characterized by the propagation of a single oxidation (smolder) reaction to one that consists of an endothermic pyrolysis reaction that precedes the oxidation reaction. This change in smolder pattern appears to be generated by the onset of oxidation reactions in the char which deplete the oxygen from the oxidizer gas flow, together with the displacement of oxidizer from the foam pores by the post-combustion gases, which favor the pyrolysis of the foam heated ahead of the oxidation reaction. This type of smolder is only characteristic of forward smolder with relatively large oxidizer flow velocities, since for the above mechanisms to happen the oxidizer must flow ahead of the oxidation reaction and have velocities larger than the corresponding diffusion velocity.

The fact that simple, heat transfer based, theoretical models of the problem are able to predict well the smolder propagation velocity, does not imply that chemical kinetics are not important, but only that the problem is controlled by the rate of heat released (and absorbed) by the reactions. The heat released is the result of complex thermochemical reactions, and in this work, it is not calculated but selected to maximize the fitting of the data with the theory. Furthermore, the models have

the underlying assumption that all the oxidizer is consumed by the fuel and char oxidation reactions. Thus they will not be able to predict smolder under conditions where there is leakage of oxidizer through the reaction, i.e., weak or near extinction smolder.

Some preliminary experiments conducted with air flow rates larger than 8 mm/s seem to indicate that the oxidation reaction consumes a large percentage of the char, thus it is possible that for high air flow rates the total consumption of the fuel may be the parameter determining the rate of propagation of the smolder reaction. Also, the transition to flaming appears to be generated through the onset of strong oxidation reactions in the char.

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