Opposed Forced Flow Smoldering of Polyurethane Foam

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J. L. TORERO, A.C. FERNANDEZ-PELLO   *Department of Mechanical Engineering, University of California, Berkeley, CA 94720*
and M. KITANO   *Department of Mechanical Engineering, Tohoku University, Sendai 980 Japan*

Abstract—An experimental study is carried out of the effect on the propagation of a smolder reaction through the interior of a porous fuel of a forced flow of oxidizer opposing the direction of smolder propagation. The potential effect of buoyancy in the process is also analyzed by conducting the experiments in the upward and downward propagation, and comparing the respective results. The experiments are conducted with a high void fraction flexible polyurethane foam as fuel and air as oxidizer, in a geometry that approximately produces a one-dimensional smolder propagation. Measurements are performed of the smolder reaction propagation velocity and temperature as a function of the location in the sample interior, the foam and air initial temperature, the direction of propagation, and the air flow velocity. For both downward and upward smoldering three zones with distinct smolder characteristics are identified along the foam sample. An initial zone near the igniter were the smolder process is influenced by heat from the igniter, an intermediate zone where smolder is free from external effects, and a third zone near the sample end that is affected by the external environment. The smolder velocity data are correlated in terms of a nondimensional smolder velocity derived from a theoretical model of the process previously developed. The analysis of the results confirm that the smolder process is controlled by the competition between the supply of oxidizer and the transfer of heat to and from the reaction zone. At low flow velocities oxygen depletion is the dominant factor controlling the smolder process, and the smolder velocity and temperatures are relatively small. Increasing the flow velocity strengthens the smolder reaction due to the oxygen addition resulting in increased smolder velocities and temperatures. These parameters, however, reach a maximum and as the air velocity is increased further the smolder reaction becomes weaker and eventually dies out due to convective cooling.

NOMENCLATURE

Cp	specific heat capacity
D	mass diffusivity of oxygen in air
d_p	pore diameter
g	gravitational acceleration
Gr_K	Grashof number
K	permeability
L	length
$\dot{m}''$	mass flux per unit area
P	pressure
Q	energy released per mass of O_2 consumed
$\dot{q}$	heat flux
$\dot{r}'''$	reaction rate
Ra_x	Raleigh number
Re_K	Reynolds number
t	time
T	temperature
U_s	smoldering velocity
u_b	buoyant velocity in x direction
u_D	velocity induced by natural draft
u_f	forced velocity
u_g	total average air flow velocity

v_b	buoyant velocity in y direction
W	width
x	x coordinate
Y	mass fraction
y	y coordinate

Greek Symbols

α	thermal diffusivity
β	volume expansion coefficient at constant pressure
ν	stoichiometric coefficients
δ	boundary layer thickness
δ_D	diffusion boundary layer thickness
λ	thermal conductivity
μ	dynamic viscosity
ϕ	void fraction
ϕ_C	char void fraction
ρ	density
σ	Stephan-Boltzmann constant

Subscripts

A	air
C	char
D	draft
F	foam
gp	gaseous products
i	initial
O	oxygen
P	pyrolysis
S	smoldering
W	wall
∞	infinity

Superscripts

$''$	per unit area
$'''$	per unit volume
$\cdot$	per unit time

INTRODUCTION

Smoldering is defined as a non-flaming, surface combustion reaction propagating through a porous fuel (Ohlemiller, 1986). For the smolder reaction to propagate, enough heat must be transferred from the exothermic reaction to the virgin fuel ahead to bring its temperature to high enough levels to initiate the surface combustion reaction. At the same time enough oxygen must be present in the fuel porous, or transported to the reaction zone from outside to sustain the reaction. Thus, smolder involves complex processes related to fluid flow and heat and mass transfer in a porous media, together with surface chemical reactions. The interaction between these physical and chemical processes determines the final characteristics of the smolder reaction. In addition to the thermochemical properties that are important in determining the combustion reaction characteristics, other fuel physical properties like void fraction, permeability to gas flow, and thermal properties are relevant. External factors like insulation from the environment,

buoyant flows, and the nature of the ignition source are also important factors in the smolder reaction characteristics and its propagation rate.

Although smoldering is present in a variety of combustion processes, it is of particular interest in the fire safety field because of its role as a potential fire initiation source. Smoldering combustion is a weakly reacting phenomenon which can propagate slowly for long periods of time, and suddenly transiting to flaming initiating a rapidly propagating and potentially hazardous fire. Furthermore, once established it is difficult to detect and extinguish because it can propagate through the interior of the porous combustible material. In comparison with other combustion processes, relatively small amount of fundamental work has been done to date on smoldering combustion. Studies that are relevant to the present work in that they aim to the identification of the mechanisms controlling the propagation of the smolder reaction are those of Moussa et al. (1976), Ohlemiller and Rogers (1978, 1979), Rogers and Ohlemiller (1978, 1980), Summerfield and Mesina (1981), Ohlemiller and Lucca (1983), Ohlemiller (1986, 1990).

The present work is part of an ongoing study that has as objective understanding the controlling mechanisms in smoldering propagation, with particular emphasis to understanding the effect of buoyancy on the smolder process. It extends the works of Dosanjh et. al. (1987) and Newhall et al. (1989) on opposed smoldering of powder cellulose, by using flexible polyurethane foam as fuel. The interest of using this material is two fold; it is a commonly used material, and its structure permits upward burning experiments without collapsing problems as it occurs with cellulose and other loose materials. In the above works the smolder propagation was only downward, and the effect of buoyancy on the process was studied by changing the ambient pressure. Here the effect of buoyancy is partially observed by comparing the smolder parameters in downward and upward propagation. The experiments are conducted in the opposed smolder configuration, for both downward and upward smolder propagation. In this configuration the reaction zone and the forced oxidizer flow move in opposite directions. This type of smoldering is also referred to as co-current smoldering because if the reaction zone is considered as stationary both the fuel and oxidizer reach the reaction zone in the same direction. In the downward smoldering experiments the foam is ignited at its top and the smolder reaction propagates downwards, in the same direction as that of gravitational acceleration, and for upward smoldering in opposite directions. Therefore, when the upward and downward experiments are compared, the difference between the two can be attributed to gravity effects. The smolder parameters that are compared in this work are the propagation velocity and reaction temperature.

EXPERIMENT

A schematic diagram of the experimental installation is shown in Fig. 1. The test section containing the porous fuel consists of a 300 mm long vertical duct with a 150 mm side square cross section. The duct walls are made of insulating 10 mm thick Fiberfax sheet mounted on an aluminum frame. The exterior surface of the Fiberfax sheets are sealed with Aluminum tape to prevent diffusion of air through the walls to the foam in the test section. The fuel is fitted tight to the test section walls to prevent preferential flow of air through the gap between the foam and the wall. For fuel lengths less than 300 mm, the fuel is positioned at the end of the test section where the igniter is located. The oxidizer gas flows into the test section through a diffuser and a 150 mm long settling section filled with glass beads that is fitted at one end of the duct. The gas flow rate is controlled and metered with a Tyland type FC280S controlled mass flow meter. Controlling the mass flow rate is important in these experiments because the pressure losses through the porous material decrease with time as the smolder reaction propagates, and conventional
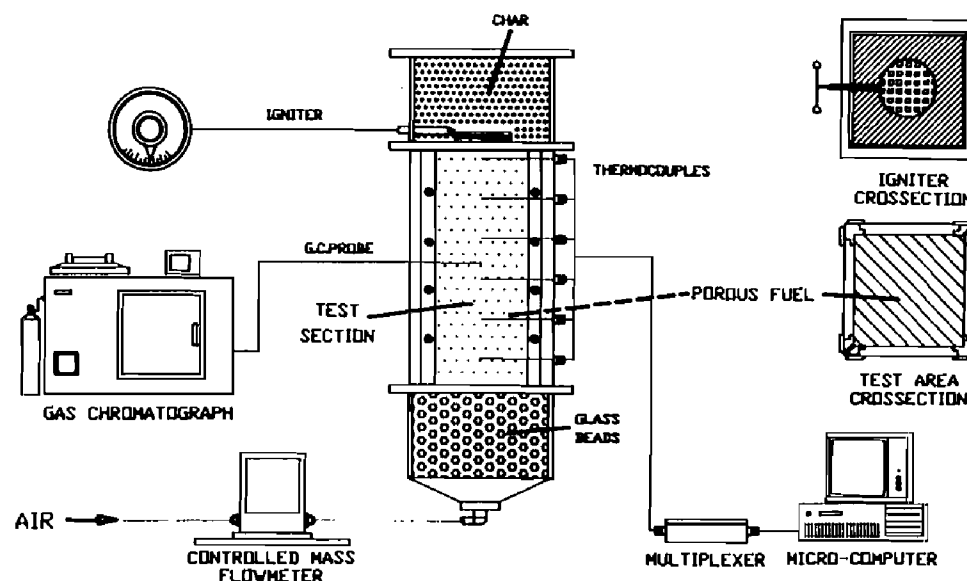
FIGURE 1   Schematic of forced flow smoldering experimental apparatus.

flow meters would not prevent the resulting increase in flow rate. The igniter and a 150 mm insulating char section are fitted at the other end of the duct. 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. To insulate the ignition zone and simulate an ongoing smolder process, a layer of char from an already smoldered foam is placed at the other side of the igniter, such that the igniter is in contact with the virgin fuel in one side and the char in the other. Heat losses to the environment and lack of oxidizer prevent the initiation by the igniter of a forward smolder reaction in the char.

The porous combustible used in the experiments is open cell, unretarded, white flexible polyurethane foam, with a 26.5 Kg/m^3 density and 0.975 void fraction. Most of the tests are conducted with samples 150mm side cubes. To observe the effect on smolder of the sample length, a few tests are conducted with foam samples 150, 175, 200, and 300 mm long, and a fixed air velocity of 1.7 mm/s. The foam sample width is selected to ensure a one dimensional smolder propagation in a region of at least 50 mm in diameter from the sample center line, and the length to permit the observation of self propagating smolder without the influence of end effects (Torero et al. (1990)). Filtered, house compressed air is used as oxidizer. The foam smolder initiation (ignition) is accomplished by applying an electrical power of 1.7 KW/m^2 for approximately 15 min, which for our igniter is the energy required to heat up the igniter ceramic plates to an approximate temperature of 500°C. During the course of this work it was found that the onset of foam smoldering occurs only under very restrictive conditions of igniter type, temperature and time. Too high a temperature results in the melting or flaming of the foam, and too low in its pyrolytic decomposition. The ceramic heater, temperature and heating period used in these experiments were selected to ensure the self supported propagation of the smolder

reaction in the foam. The above observations concerning the restrictive conditions for smolder initiation agree with those discussed by Ohlemiller and Rogers (1978).

Ignition is performed without air flow to ensure a uniform ignition procedure in all the tests. Once the ignition period is completed, the igniter current is turned off and the flow of air is turned on, thus starting the forced flow smolder of the foam. For the downward smolder experiments, the igniter and char are mounted on top of the foam sample and the air is introduced at the bottom of the test chamber. For the upward experiments the entire apparatus is simply rotated 180 degrees. A few characteristic tests in the downward configuration are conducted with the foam and air at temperatures above ambient. In these tests an in line air heater mounted at the diffuser entrance is used to heat the air and the foam to a uniform predetermined temperature prior to turning on the ignitor.

The rate of smolder propagation is obtained from the temperature histories of eight Chromel-Alumel thermocouples 0.8 mm in diameter that are embedded at predetermined positions in the porous fuel with their junction placed in the fuel centerline. The smolder velocity is calculated from the time lapse of the reaction zone arrival to two consecutive thermocouples, and the known distance between the thermocouples. The location of the reaction zone is characterized by a maximum in the temperature profile. However, in many of the tests this maximum is not sharply defined, thus to reduce uncertainties the location of the smolder reaction front is defined here by the intersection of the tangent to the temperature curve at the inflexion point and a horizontal line at a temperature near to the maximum ($350°C$ in this work). These thermocouples are also used to measure the reaction zone temperature. This temperature is used only for comparative purposes, and it is not considered to be the actual smolder temperature, since it is not possible to determine whether the thermocouples are measuring the foam or air temperature. Another important source of information in the smolder process is the species concentrations near the reaction zone. Our attempts to measure them using gas chromatography have failed so far due to the clogging of the sampling lines by the tars and heavy hydrocarbons produced during the smolder of the foam.

RESULTS

Downward Smoldering

The variation of the downward smolder propagation velocity through the sample length is presented in Fig. 2 for several representative opposed air flow velocities. Tests were also conducted at other flow velocities, but the results are not presented here to avoid crowding of the figure. The data is the average from five tests, and the error bars describe the maximum deviations from the mean. From these data, three zones with different smolder characteristics are identifiable along the foam sample. An initial zone (I) approximately 60 mm in length from the igniter where the smolder process is affected by the heat transferred from the igniter, and the smolder velocity is elevated. A second zone (II) approximately 50mm long in the middle of the sample where the smolder process is relatively free from end effects, and the smolder velocity is approximately constant if the smolder is self sustained, or decays if smolder is at near extinction. A third zone (III) at the end of the sample where the smolder is affected by the external environment, and its velocity increases if the smolder is self sustained, or decays if at near extinction. The characteristics of the smolder reaction at each zone depend on the air flow rate. Varying the sample length does not affect the smolder characteristics in each region, or the extent of regions I and III. The extent of region II, however, increases as
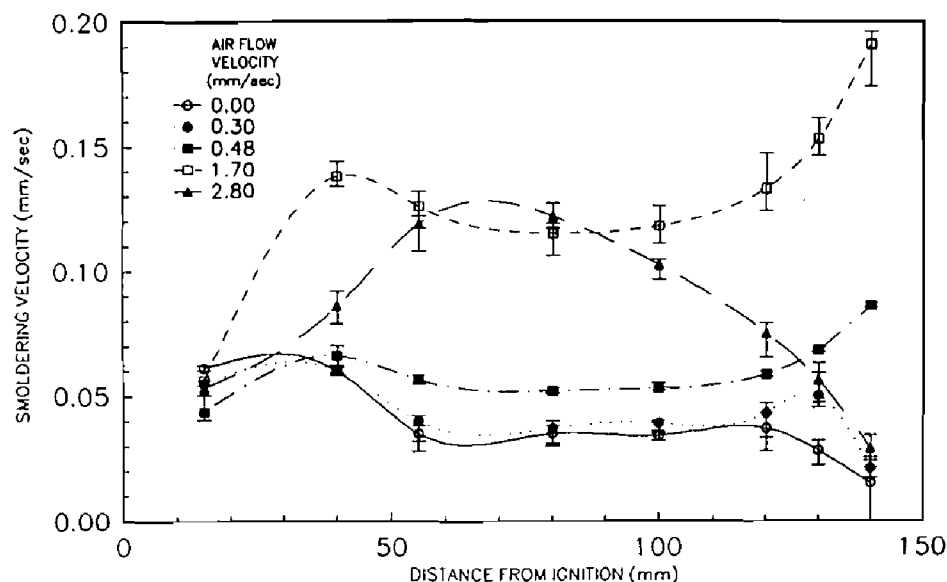
FIGURE 2   Variation of the smolder velocity along the polyurethane foam sample for downward propagation in an opposed air flow, for several representative air flow rates.

the sample length is increased. The smoldering in zone II is the most representative of a forced flow opposed smoldering, at least from the point of view of modeling, since is free from external effects. The smoldering in the other zones are also interesting, however, because they provide additional information about the process, and describe situations that may occur in practice. The smolder in zone I is representative of a situation where smoldering is supported by an external heat source. The smolder in zone III is of interest from the point of view of external ambient effects on smoldering. The measured smolder velocities are of the same order of magnitude to those reported by Ohlemiller (1986), Rogers and Ohlemiller (1978) and Ohlemiller et al. (1979). However, it is difficult to compare quantitatively the actual values because the above authors report average smolder velocities rather than local velocities as it is done here.

The variation of the maximum smolder reaction zone temperature along the foam sample is presented in Fig. 3 for the same air flow velocities of Fig. 2. Although less well defined, the data also indicates the presence of the three zones described above. The temperatures in zone I are generally higher due to the igniter influence. In region II are approximately constant except under extinction conditions. In region III the temperature variation depends on the strength of the smolder reaction itself. Comparison between the results of Figs. 2 and 3 shows that under forced flow conditions, there is a fairly well defined correspondence between the smolder reaction temperature and the smolder velocity, with the smolder velocity being higher when the smolder temperature is higher. It is also observed that small variations in smolder reaction temperature often result in large variations on the smolder propagation velocity. These observations are in qualitative agreement with those of Moussa et al. (1976), even though the fuel used
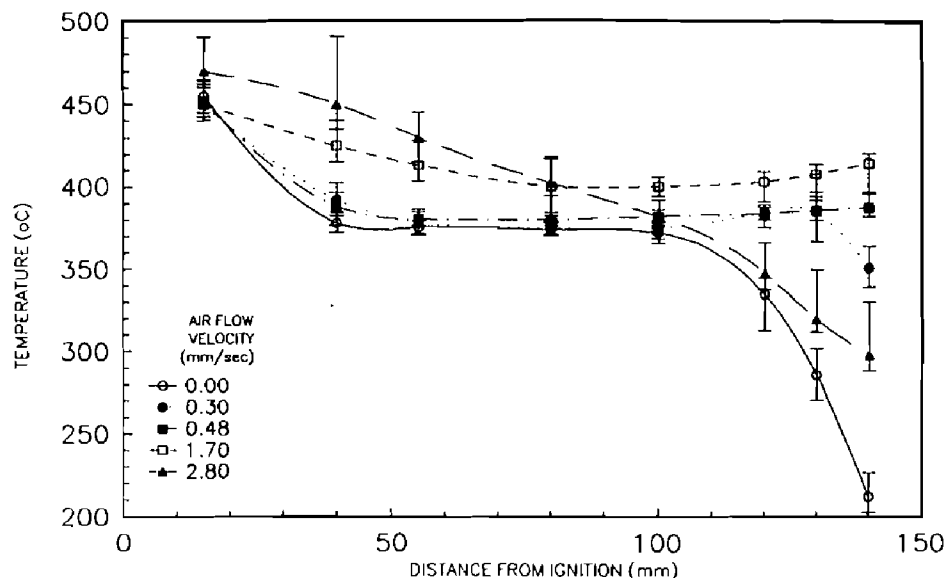
FIGURE 3   Variation of the maximum smolder reaction temperature along the polyurethane foam sample for downward propagation in an opposed air flow, for several representative air flow rates.

in those experiments was cellulose, and they did not contemplate flow inside the foam, but diffusion of oxidizer through a natural boundary layer around the fuel sample.

The variation with the forced air flow velocity of the smolder propagation rate is presented in Fig. 4, for the three zones indicated above. The smolder velocities are obtained from the results of Fig. 2 and are averaged values of the smolder velocities at each zone. It is seen that the smolder velocity in the three zones presents a maximum at air flow rates between 1 and 3 mm/s depending on the zone under consideration. The variation of the maximum smolder reaction temperature with the air flow rate is presented in Fig. 5, for the three zones. It is seen that the smolder temperature also presents a maximum at air velocities that approximately correspond to those of the smolder velocities, again corroborating the correspondence between the temperature of the smolder reaction and the propagation velocity.

Increasing the foam and air initial temperature results in smolder trends similar to those reported above, although for a given air velocity the smolder propagation velocity is larger at higher temperature, and the extinction conditions take place at higher air velocities. A representative example of the effect of the initial foam/air temperature on the smolder velocity is given in Fig. 6. The data is for downward smolder with an opposed flow velocity of 2.8 mm/s. It is seen that the smolder velocity increases as the initial temperature is increased, as it could be expected. What is more interesting, however, is that the initial temperature can also affect the characteristics of the smolder reaction itself. In this case, for example, at the standard temperature of 20°C, the smolder reaction weakens and tends to extinction in zone III as it approaches the sample end. At 110°C, however, the extinction regime has basically disappeared, and at 140°C the trend is reversed, and an enhancement of the smolder propagation velocity takes place as the smolder reaction approaches the sample end.
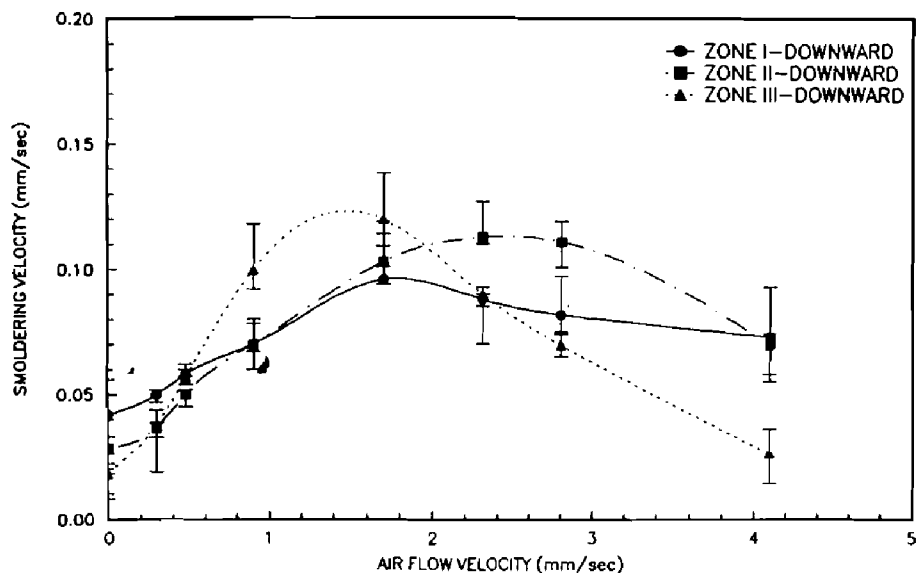
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FIGURE 4   Dependence of the downward propagating smolder velocity on the opposed air flow rate in the three identified regions of the polyurethane foam sample. The smolder velocities are averaged values in each region.

Upward Smoldering

The objective of these experiments is to further determine the effect of buoyancy on the smolder process. In upward propagation, buoyancy induces an upward flow of the hot postcombustion gases that opposes the downward moving forced air flow, while in downward smolder both the buoyant and forced flows would flow in the same direction. Thus, the buoyancy effect on the smolder process should appear through the differences between the downward and upward smolder characteristics. These differences should decrease as the forced air velocity is increased and becomes significantly larger than the buoyant induced flow velocity. The apparatus and experimental procedure for the upward smolder experiments are the same as those of the above described downward experiments, except that the apparatus is positioned upside down.

The variation of the upward smoldering propagation velocity through the foam sample length is presented in Fig. 7, and of the smolder reaction temperature in Fig. 8, for a few representative opposed air flow velocities. Here also three zones with particular smolder characteristics can be identified. The extent of the zones and the smolder characteristics in each zone are similar to those observed in downward smoldering, although there are some noticeable differences. As in downward smolder, region I occupies the first 60 mm of the sample, and is influenced by the heat transferred from the igniter. In this region the smolder velocity and temperature increase with the air velocity due to the increased supply of oxidizer to the reaction zone. Region II (middle of the sample) is narrower and less defined, with smolder velocities that at some air velocities change throughout the region. Another notable difference is that smolder occurs at larger air velocities than
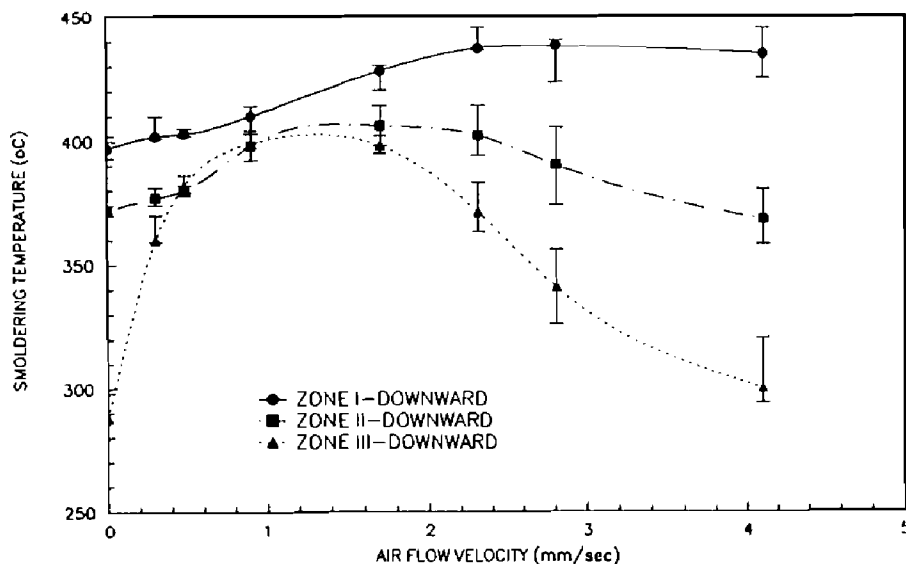
FIGURE 5   Dependence of the downward propagating maximum smolder reaction temperature on the opposed air flow rate in the three identified regions of the polyurethane foam sample. The smolder temperatures are averaged values in each region.

in downward propagation. In region III the end effects are more marked with strong variations of the smolder velocity in some cases.

The variation of the averaged upward smolder velocity with the opposed forced air flow rate in each zone is presented in Fig. 9, and the averaged maximum smolder temperature in Fig. 10. It is seen that the effect of the forced air flow on the upward smolder velocity is similar to that of the downward smoldering (Fig. 4) with the smolder velocity first increasing and then decreasing as the air velocity is increased. The air velocity at which the smolder velocity reaches a maximum is, however, higher than in downward smolder. Comparison of Figs. 5 and 10, shows less differences in the smolder temperatures, although it should be taken into account that the data are averaged values, and since small changes in temperature result in large changes in the smolder velocity, the average values may not be too representative of the process in certain cases.

SMOLDERING MODEL

The theoretical model of opposed flow smolder developed by Dosanjh et al. (1987) is used in this work to correlate the above reported data. To facilitate the understanding and discussion of the correlation, a brief description of the model is given here.

In opposed smoldering, with frame of reference anchored at the reaction zone, the fuel and oxidizer enter the reaction zone in the same direction. Since smoldering is generally oxygen limited, the heat released by the smolder reaction can be expressed in terms of the mass flux of oxidizer at the reaction zone. This heat is transported by conduction and radiation upstream of the reaction zone, and sustains the propagation
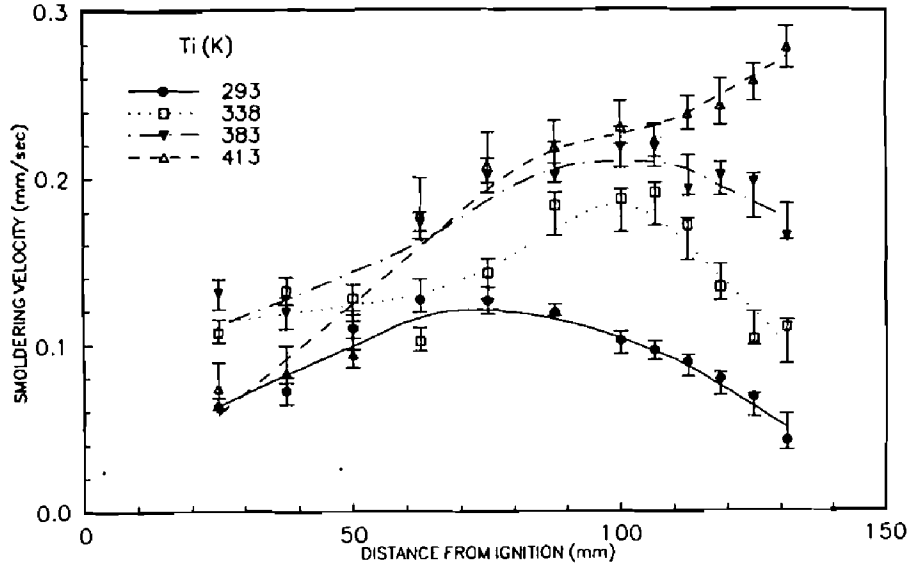
FIGURE 6   Variation of the smolder velocity along the polyurethane foam sample for downward propagation in an opposed air flow, for several representative initial temperatures.

of the smolder front. It should be noted that the fuels of interest in smolder are very porous, and consequently conduction is a relatively poor mode of heat transfer (Kansa et al. (1977)). Thus radiation heat transfer is important despite the relatively small temperatures encountered in smoldering combustion.

In the model of Dosanjh et al. (1987) smoldering is modeled as a finite rate, one-step reaction, of the form

$$\nu_F[\text{FOAM}] + \nu_O\ O_2 \rightarrow \nu_C[\text{CHAR}] + \nu_{gp}[\text{GaseousProducts}] + Q\nu_O M_O \tag{1}$$
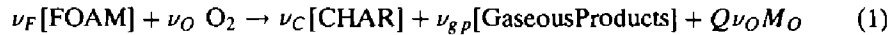
Smoldering is assumed to be one-dimensional and steady in a frame of reference fixed to the smolder wave. The gas and solid are presumed to be in local thermal equilibrium, and the solid phase is considered continuous with a constant void volume fraction. Energy transport due to concentration gradients, energy dissipated by viscosity, work done by the body forces, and the kinetic energy of the gas phase are ignored. Furthermore, since smoldering velocities are much smaller than flow velocities, flow velocities can be taken as known quantities at each location in the sample, x_s.

With the above assumptions, and neglecting heat losses to the environment, the one dimensional form of the energy conservation equation becomes

$$\left[\dot{m}_F''C_{pF} + \dot{m}_A''C_{pA}\right]\frac{dT}{dx} = \left[\lambda_{eff} + \lambda_{rad}\right]\frac{d^2T}{dx^2} + Q\frac{d\dot{m}_o''}{dx} \tag{2}$$

where the mass fluxes of fuel and oxidizer entering the reaction zone are given by,
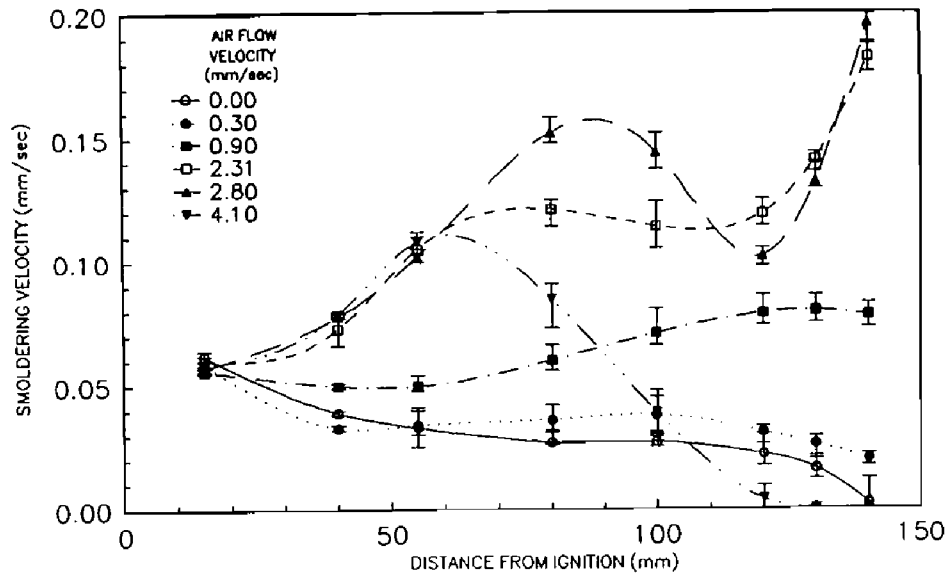
$$\dot{m}_F'' = (1 - \phi)\rho_F U_s$$

FIGURE 7   Variation of the smolder velocity along the polyurethane foam sample for upward propagation in an opposed air flow, for several representative air flow rates.

$$\dot{m}_A'' = \rho_A u_F \tag{3}$$

$$\dot{m}_O'' = Y_O \dot{m}_A'' - \phi \rho_A D \frac{\partial Y_O}{\partial x}$$

λ is an effective thermal conductivity of the form

$$\lambda_{eff} = \phi \lambda_A + (1 - \phi) \lambda_F \tag{4}$$

Radiation is incorporated in the analysis using a diffusion approximation with an equivalent thermal conductivity given by

$$\lambda_{rad} = \frac{16 \sigma d_p T^3}{3} \tag{5}$$

The boundary conditions for the above equation are

$$\text{at} \quad x = x_s \quad \frac{\partial T}{\partial x} = 0$$

$$T = T_s$$

$$\dot{m}_O'' = 0$$

$$\text{at} \quad x \rightarrow \infty \quad \frac{\partial T}{\partial x} = 0 \tag{6}$$
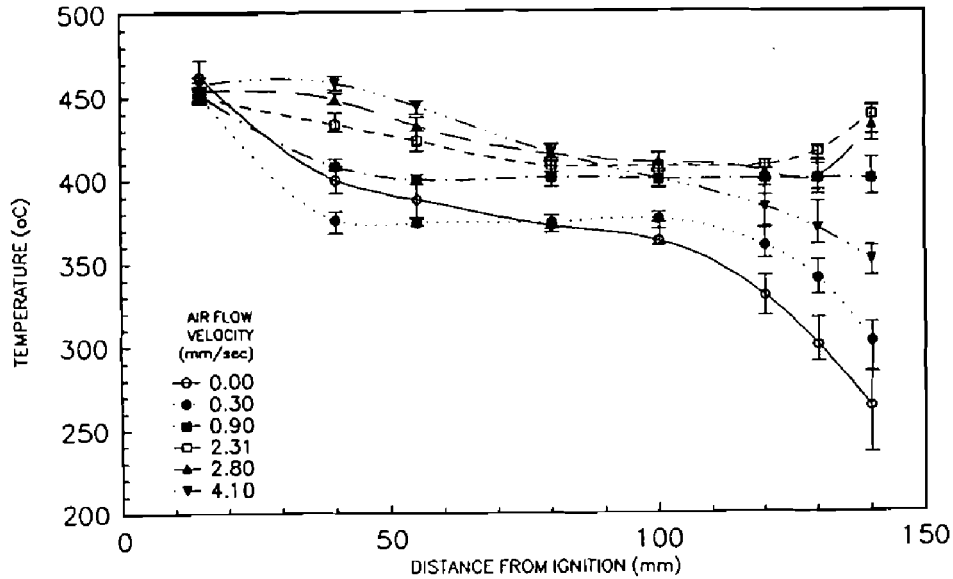
$$T = T_i$$

FIGURE 8   Variation of the maximum smolder reaction temperature along the polyurethane foam sample for upward propagation in an opposed air flow, for several representative air flow rates.

$$\dot{m}_O'' = \dot{m}_{O,i}''$$

Integrating with respect to x from x_s to ∞, the following expression is obtained for the smolder propagation velocity

$$U_s = \frac{\rho_A \left[QY_{o,i} - CP_A(T_s - T_i)\right]}{\rho_F C p_F (1 - \phi)(T_s - T_i)} u_g \tag{7}$$

The analysis of Dosanjh et al. (1987) also provides an expression for the smolder temperature Ts. However, the asymptotic analysis leading to that expression imposes a number of restrictive conditions that are often not applicable to the experiments. For this reason, in this work the value of the smolder reaction temperature is obtained from the experimental data of Figs. 3 and 8. The heat of combustion Q, is not well determined for smoldering combustion (Ohlemiller (1986)). In this work it will be selected such that the correlation of the data with the above equation is optimized. As it will be shown later, the resulting value for the heat of combustion agrees well with that previously reported in other works (Ohlemiller et al. (1979), Ohlemiller (1986), Summerfield and Mesina (1981), Dosanjh (1986), Dosanjh et al. (1987)). Finally, the oxidizer velocity u_g, is known if there is only a forced flow of oxidizer. However, the forced flow velocities at which smolder can progress through the foam are so small (Fig. 2), that under normal gravity conditions, buoyancy induced flows can become important as a means of oxidizer transport to the reaction zone. Thus, the potential generation of buoyant flows inside the foam requires the treatment of the flow through the foam as a mixed, forced and free, flow problem. This is done in the following section.
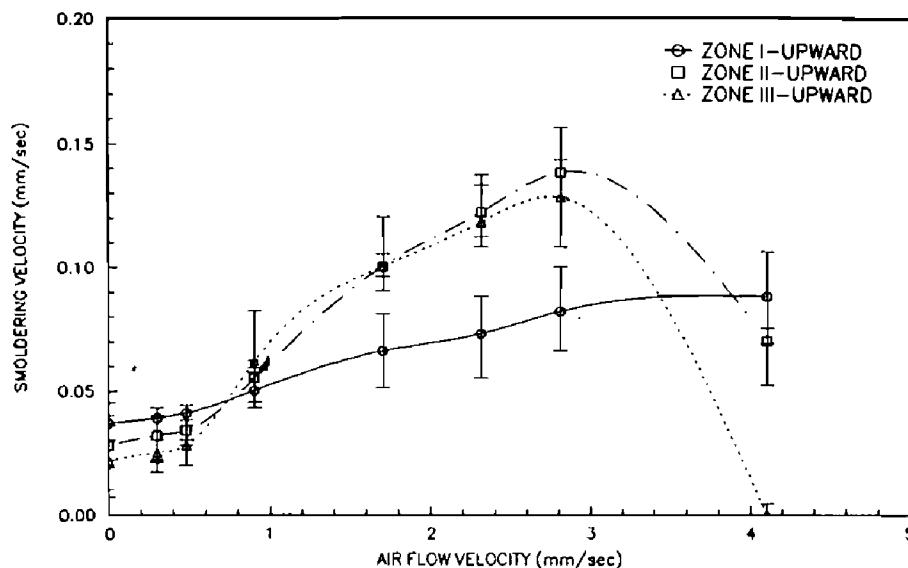
FIGURE 9   Dependence of the upward propagating smolder velocity on the opposed air flow rate in the three identified regions of the polyurethane foam sample. The smolder velocities are averaged values in each region.

Buoyantly Induced Flow Through the Foam

The onset of buoyant flows inside a porous media depends strongly on the permeability of the material (Bejan (1984)). 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 unless a chimney type, natural draft, is induced by the hot postcombustion gases. However, the char left behind by the propagating smolder reaction is quite permeable, and buoyant recirculation flows can be easily generated downstream from the smolder front. The permeability of the char depends on the strength of the smolder reaction, because more of the fuel is consumed when the reaction is vigorous, and on the char structure itself. This is reflected in the measured dependence of the char permeability on the forced flow velocity for downward smolder that is presented in Fig. 11. Since increasing the forced flow velocity enhances the smolder reaction (Figs. 2 and 3), the char permeability also increases. The increase however is not linear because at small flow rates the char keeps its structure (Rogers and Ohlemiller (1978)), but as the smolder reaction strengthen the filaments that form the micro-structure of the foam break down (Dosanjh (1986)), thus resulting in a sudden increase in the permeability as it is seen in Fig. 11.

The recirculating flows in the char region are induced by the natural convection boundary layer that is generated at the tests section walls by the difference in the wall and char/postcombustion gases temperatures. A schematic of these recirculating flow is shown in Fig. 12. In downward smolder, fresh air flows downward along the cold walls of the char region toward the reaction zone where it encounters the unburned foam that
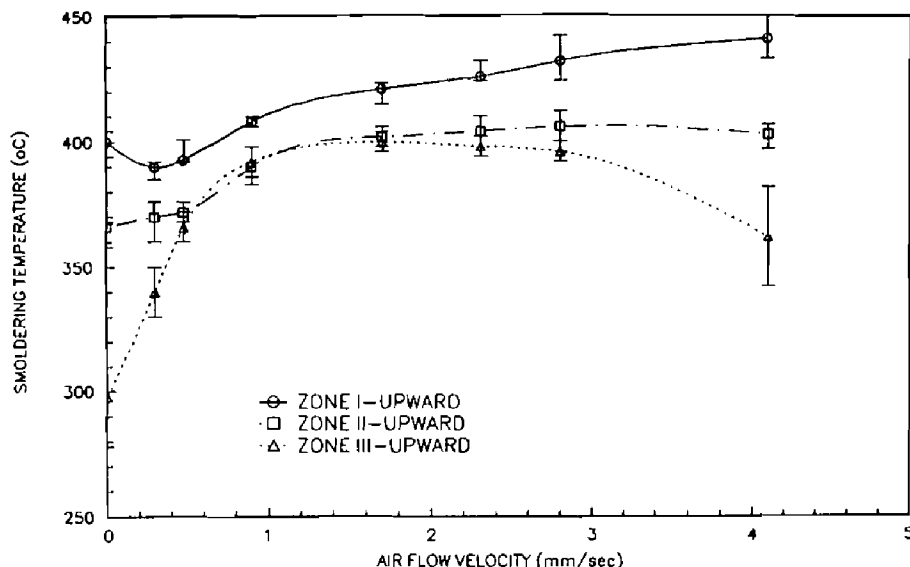
FIGURE 10   Dependence of the upward propagating maximum smolder reaction temperature on the opposed air flow rate in the three identified regions of the polyurethane foam sample. The smolder temperatures are averaged values in each region.

since it has a much smaller permeability prevents the air from flowing through. Instead, the air turns around at the reaction zone and moves upward along the centerline together with the gases being forced through the foam by forced convection. From the point of view of the smolder reaction, the net result is the added flux of air that tends to enhance the reaction but also tends to cool it off. If the air velocity is in the range that the smolder reaction is strong, the addition of the free flow air will result in the enhancement of the reaction. However, if it is in a range where the reaction is already weak, the cooling effect becomes dominant and the reaction will tend to extinction. In upward smolder, the direction of the recirculating flow is reversed, but the net result is the same.

The natural convection problem has been studied extensively, (Horton (145), Bejan (1984), Burns et al. (1977), Nield and Bejan (1992)). Particularly relevant for the present work is the analysis of Burns et al. (1977) for buoyantly induced flows in vertical ducts with different temperature walls. Application of that analysis to the present problem gives the following expression for the averaged flow velocity at the char centerline (Torero (1992)).

$$U_b = \frac{\alpha Ra_x}{4W} \qquad (8)$$

with

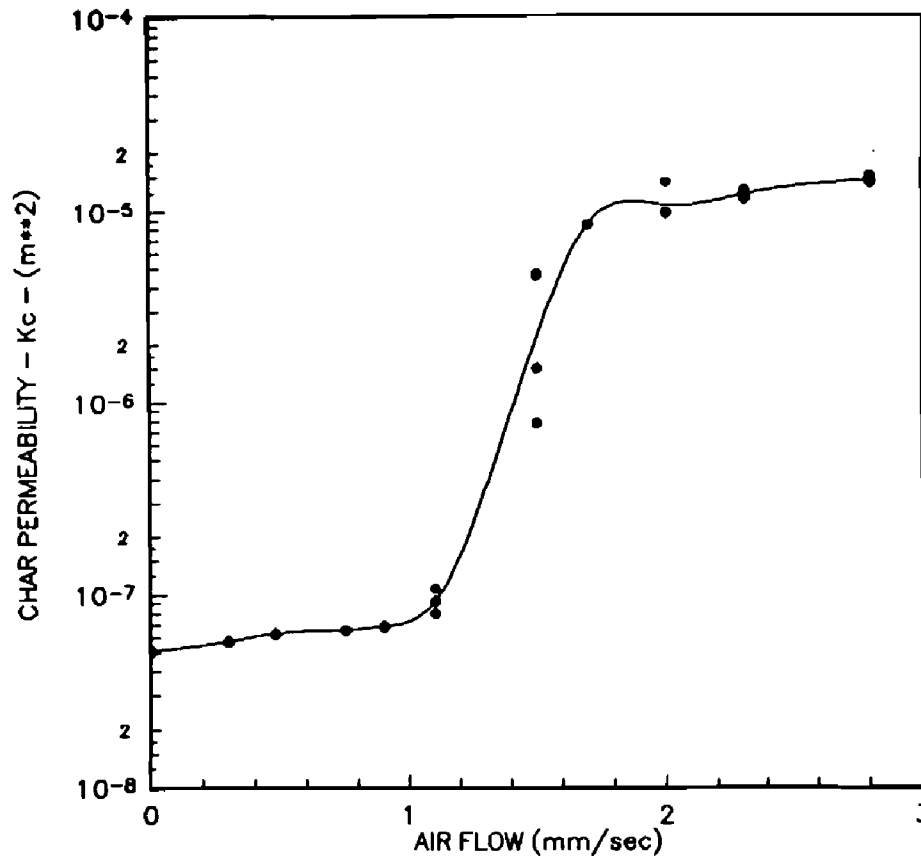$$Ra_x = \frac{K_C g \rho_A \beta (T_w - T_S)x}{\alpha\mu} \qquad (9)$$

FIGURE 11   Variation of the average permeability of the char left after smoldering at different flow rates.

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 Burns et al. (1977), Bejan (1984), Lai et al. (1988), Hadim and Govindarajan (1988) and Nield and Bejan (1992). For the mixed flow problem other considerations have to be taken on account. In the char, the recirculating flow moves from top to bottom near the walls and from bottom to top near the sample centerline; therefore, for downward burning, forced and buoyantly induced flows add at the centerline (aiding flows), while for upward burning, the flows oppose at the centerline region (opposing flows). A numerical analysis of the problem (Lai et al. (1988)) shows that for aiding flows the mixed flow solution is valid for values of the Ra/Pe smaller than 50, and that for values greater than 50 the solution resembles more the pure natural convection solution. 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.
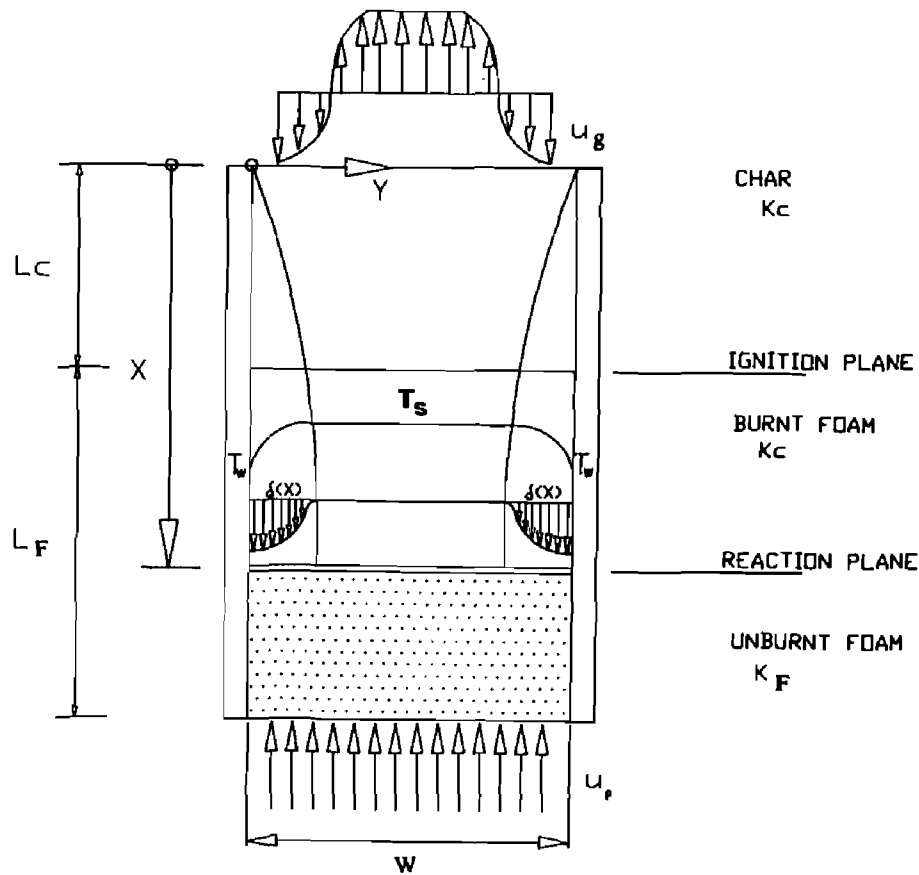
FIGURE 12   Schematic of the mixed flow occurring inside the sample.

In the analysis of the mixed flow through the foam it is assumed that the convective fluid and the porous medium are everywhere in thermodynamical equilibrium (Dosanjh (1986)), that there is no phase change in the solid, and that the properties of the fluid and the porous medium are homogeneous and isotropic. With the governing equations of mass, momentum and energy, and applying Darcy's Law together with the Boussinesq approximation, the following expression is obtained for the flow averaged velocity along the center region of the foam (Darcy (1856), Lai et al. (1988), Nield and Bejan (1984), Torero (1992)).

$$u_b = \frac{2\delta}{W}\left(\frac{Gr_K}{Re_K}\right)u_f \tag{10}$$

with

$$\delta = xRa_x^{-0.5} \tag{11}$$

$$Re_K = \frac{\rho_A u_f K_C^{0.5}}{\mu} \qquad (12)$$

and

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

Another possible transport mechanism of oxidizer to the reaction zone is by diffusion from the external environment through the char. From the governing species conservation equation, the following characteristic diffusion length is deduced

$$\delta_D = \frac{D}{u_f + u_b + \phi U_s} \qquad (13)$$

For the present experimental conditions it can be shown (Torero (1992)) 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 Transport to the Reaction Zone

From the above analysis, and in a frame of reference anchored at the reaction zone, it is deduced that the overall transport of oxidizer to the reaction zone is given by an overall velocity that includes the forced flow velocity, u_f, as given by the test condition; the buoyant velocity, u_b, as deduced from either of the above mixed or natural convection flow analyses, and the smolder velocity times the void fraction, to account for the oxidizer that is contained in the foam pores and that enters the reaction zone as it progresses through the sample. Thus, this velocity is given by

$$u_g = u_f + u_b + \phi U_s \qquad (14)$$

which is then used in Eq.(7) to correlate the smolder velocity experimental data.

DATA CORRELATION

In this section, Eq. (7) for the smolder velocity together with Eq. (14) for the oxidizer velocity, are used to correlate the opposed smolder velocity data obtained in the present experiments. The values of the fuel and oxidizer properties used in the equation are given in Table 1. The results of the correlation of the smolder velocity data of Fig. 2 is presented in Fig. 13. It is seen that the model predicts very well the smolder velocity data except when the smolder process is weak and approaching extinction, i.e., at very low, or very high, flow velocities and near the sample end. This is understandable since the model assumes fast chemistry, and that the energy released by the reaction is sufficient to heat up the fuel to its smolder temperature. Thus, if the flux of oxidizer is not large enough to ensure a strong reaction (low flow velocities), or the convective cooling losses are too large (high flow velocities, end of the sample), then it is expected that the model would not predict correctly the experimental measurements. This is further verified from the correlation of the smolder velocity data of Fig. 6, at a forced flow velocity of 2.8 mm/s and at different initial temperatures, which is presented in Fig. 14. It is seen that the model does not correlate the data well at low initial temperatures, when the smolder velocity decreases along the fuel sample tending toward extinction. However, as the

TABLE I

Properties

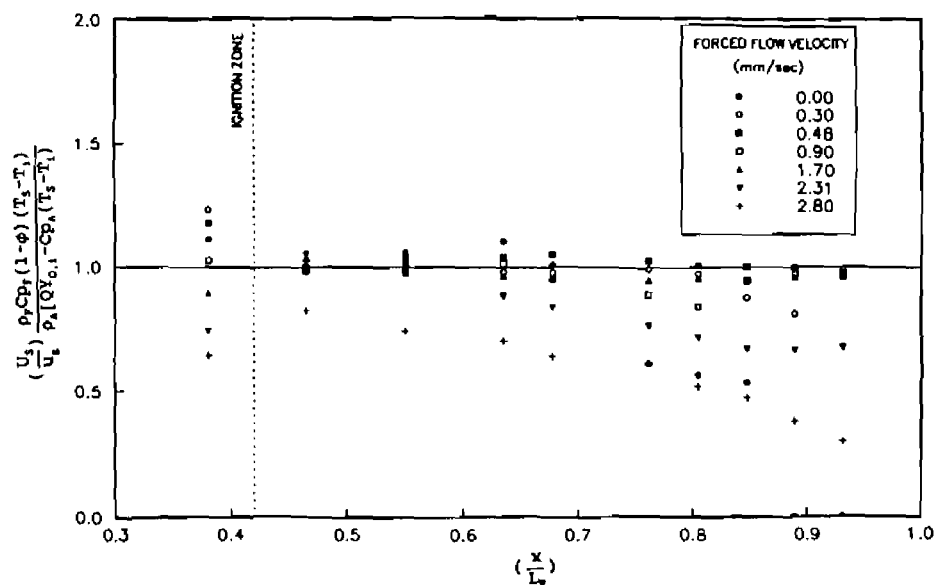|	
Cp_A	= 1.088 KJ/KgK
Cp_F	= 1.700 KJ/KgK
D	= 4.53 x $10^{-5} m^2/s$
d_P	= 0.05 mm
K_F	= 2.76 x $10^{-9} m^2$
g	= 9.81 m/s^2
L_C	= 150 mm
W	= 150mm
Q	= $3,900KJ/Kg$
T_w	= 483 K
$Y_{O,i}$	= 0.235
α	= 1.122 x 10^{-4} m^2/s
β	= 1.684 x $10^{-3} K^{-1}$
λ_{eff}	= 0.047 W/mK
μ	= 1.50 x 10^{-5} Kg/ms
ϕ	= 0.9750
ρ_A	= 1.225 Kg/m^3
ρ_F	= 1,034.0 Kg/m^3
σ	= 5.67 W/m^{2}K^4

FIGURE 13   Correlation with model of measured smoldering propagation velocities for different forced flow velocities. The experiments were conducted in downward burning configuration and all samples were 150 mm long.

initial foam temperature is increased and the smolder process becomes more vigorous, the model predicts increasingly better the experimental measurements.
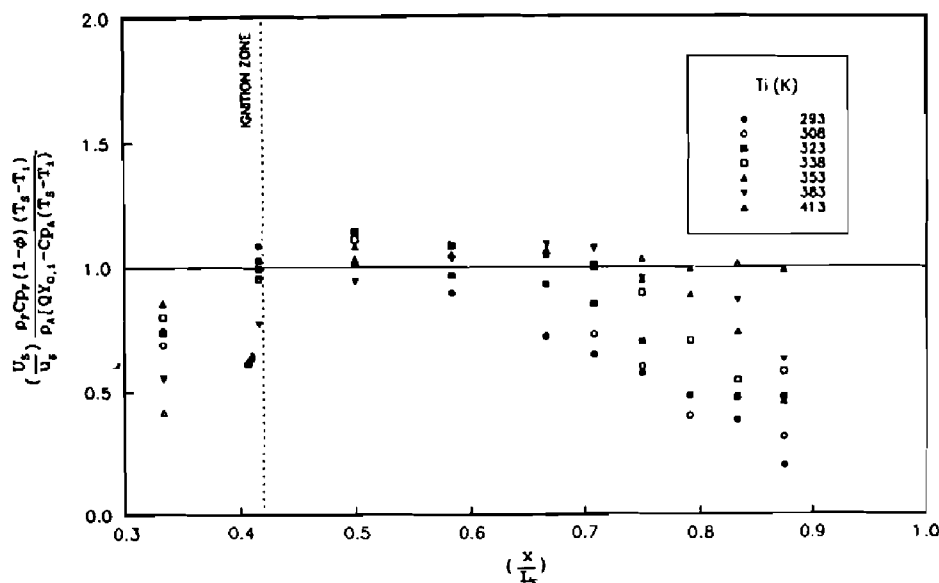
FIGURE 14   Correlation with model of measured smoldering propagation velocities for different initial temperatures of foam and air. The experiments were conducted in downward burning configuration and all samples were 150 mm long.

For this reason, when correlating with the model all of the different data obtained in the present experiments we have excluded those conditions of flow velocity and sample location where the smolder process was clearly not self-sustained and moving toward extinction. The resulting correlation of the data is presented in Fig. 15, where data from downward and upward smoldering, and for different sample lengths and initial temperatures are correlated in terms of Eq. (7). It is seen that the model predicts very well all the different data, verifying that when the smolder process is vigorous and self-sustained it is controlled primarily by the transport of oxidizer to the reaction zone and the transfer of energy from the reaction zone to the virgin fuel ahead. However, when the smolder process is weak and approaching extinction, the model fails to predict the experiments, indicating that it will be necessary to include in the model the chemical kinetics of the smolder reaction in order for it to describe adequately the actual smolder process.

DISCUSSION OF THE RESULTS

The above results point out to a smolder process that is controlled by the competition between the supply of oxidizer to the reaction zone and the loss of heat from the reaction zone. The presence of two competing controlling mechanisms, chemical kinetics and heat losses, has been suggested before by Ohlemiller and co-workers (Ohlemiller (1986)) from their observations of the effect of oxygen concentration and pressure on the smolder of polyurethane foam. To understand how these two controlling mechanisms affect the characteristics of the smolder process it is convenient to analyze the raw smolder data and the model correlations presented above.
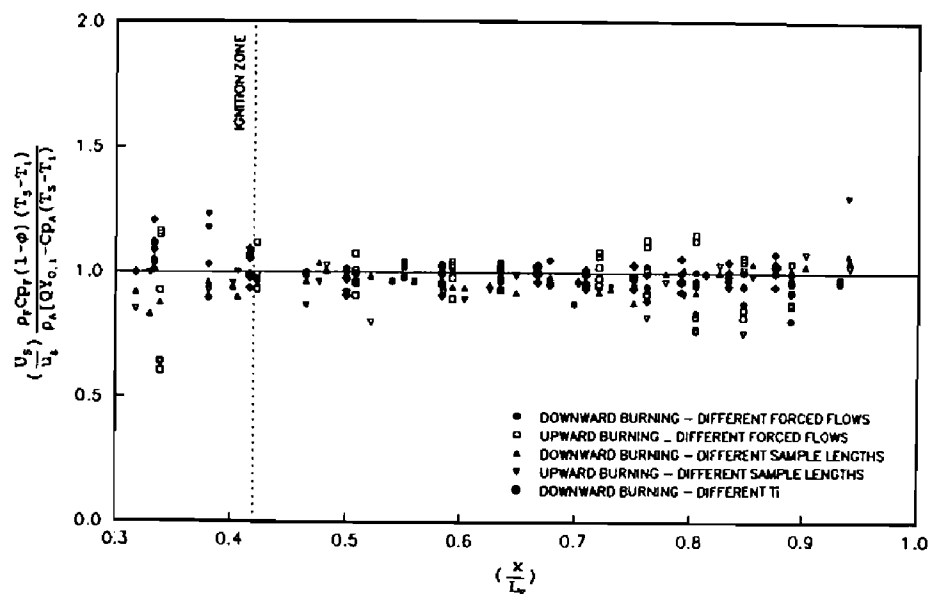
FIGURE 15   Correlation with model of measured smoldering propagation velocities for different velocities (upward and downward burning), different lengths (forced air velocity of 1.70 mm/s, upward and downward burning, sample length 150, 175, 200 and 300 mm), different initial temperatures (forced air velocity of 0.48 mm/s, initial temperatures, 293, 308, 323, 338, 353, 383, 413 K).

Downward Smoldering

Analyzing first zone 11, which as indicated above, is the most representative of self smolder. The temperature data of Fig. 3 shows that for zero and low air flow velocities (¡ 0.5 mm/s) the reaction zone temperature is low, indicating the presence of a weak smolder reaction. This is most likely due to the low supply of oxidizer to the reaction zone. The weak reaction also results in a small smolder propagation velocity, and in a poor prediction of the data by the model. It is interesting to note that the smolder reaction propagates even at zero flow rate, which indicates that the oxygen contained in the foam pores and transported by recirculation is enough to sustain the smolder reaction, although weakly. As the air flow velocity is increased, the smolder reaction temperature and velocity first increase, reach a maximum (at approx 2.5 mm/s), and then starts to decrease. The initial increase in the smolder temperature and velocity is due to the increased supply of oxidizer to the reaction zone which enhances the chemical reaction and consequently the heat production. This regime is the one predicted better by Eq. (7). The larger amount of heat generated by the smolder reaction compensates for the larger convective heat losses caused by the increased air flow rate. As the air velocity is increased further, the heat generated at the reaction and the convective heat losses eventually balance each other and the smolder reaction reaches a maximum in temperature and velocity. If the air flow rate is increased even further the heat losses overcome the heat generation and the smolder temperature and velocity start to decrease. For air flow rates larger than 2.8 mm/s, the heat losses dominate and cause the weakening and final extinction of the smolder reaction. Here again the model starts to fail since the energy generation cannot overcome the heat losses, and the chemistry of the smolder reaction starts to have increased importance.

The above discussed controlling mechanisms also apply to the other two zones, although the external effects modify somewhat the balance between them. In zone I the fuel is preheated by the igniter which helps the establishment of the reaction, and results in elevated fuel temperatures as it is seen in Fig. 3. However, since the forced air is not initially on, as explained above, the amount of air available to the reaction is small and consequently the reaction is weak and propagates slowly initially (Fig. 2). Once the air flow is turned on, and sufficient oxygen is made available to the reaction, the smolder becomes vigorous with high propagation velocities. The temperatures are however, reduced from the cooling effect of the flowing air. As the smolder reaction moves further away from the zone of igniter influence, the convective cooling of the air flow becomes dominant over the increased oxygen supply and the reaction temperature and velocity start to decrease until the reaction stabilizes itself in zone II, or extinguishes.

In zone III, the unburnt fuel length and its drag resistance are small enough to permit the generation of buoyant flows through the virgin foam and remaining char as explained above. Furthermore, the air velocities generated by the buoyant flow can be similar or even larger than those of the forced flow, and consequently can play an important role in the smolder process. As it is seen in Fig. 2, the onset of buoyant currents affects the characteristics of the ongoing smolder reaction by either enhancing the reaction or by weakening it, depending on whether the added supply of air is dominant over the convective cooling. This in turn depends on whether the ongoing reaction is already strong or not. For example, at low flow velocities the reaction is already weak, and as the heat losses to the environment increase toward the end of the sample, the reaction weakens even further reducing the smolder temperature (Fig. 3), and the propagation velocity (Fig. 2). Under these conditions the model is not capable of predicting the experimental data. At intermediate air flow velocities, the smolder is strong enough to benefit from the increase in air supply caused by the buoyant flows, and the smolder temperature and velocity increases. This regime is well predicted by the model. At large flow velocities the buoyant flows are too small to affect the already decaying smolder reaction.

Upward Burning

The quantitative differences between the smolder in the upward and downward configurations are worth discussing. In upward smoldering the buoyantly generated flow tends to flow upwards against the downward forced flow, and consequently a recirculation flow must be generated at low forced flow velocities. This recirculating flow can have a dual effect. In one hand it can produce a region of low longitudinal velocity, but with a large lateral air supply where the flow turns around, that will favor the propagation of the smolder reaction. This type of effect is more likely to occur in region II, and appears to explain the observation that smolder can propagate at higher air velocities in upward smolder. The upward recirculating air can also flow past the reaction zone, heating up as it flows past the char and preheating the virgin fuel ahead of the smolder zone as it flows down after turning, which would result in larger smolder velocities. However, these upwardly moving gases also contain combustion products that can reduce the supply of oxidizer to the reaction zone and cause the weakening of the smolder reaction. Depending on which effect is dominant, the buoyant flow could deter or enhance the progress of the smolder reaction. The former seems to be what takes place in the zone between regions II and III, and the latter at the end of the sample. The smolder temperature variation along the sample appears to confirm this view of the process.

CONCLUDING REMARKS

The present experiments on the effect of an opposed forced flow of oxidizer on a smolder reaction propagating downward and upward through a high void fraction porous fuel have helped to identify the controlling mechanisms of opposed smoldering, and to determine the potential importance of buoyancy on the process. They have also helped verifying the potential predictive capabilities of the theoretical models presently available of smolder combustion. Particularly interesting is the verification that the competition between oxygen supply and heat losses determines, in conjunction with the state of the reaction, the fate of the smolder reaction. The reaction presents an intensity maximum at relatively low air velocities (2 to 3 mm/s). At lower and larger air velocities the smolder reaction is weak due to either lack of oxidizer or excessive heat losses.

The range of air velocities that produce the stronger smoldering reactions are surprisingly small in comparison to those in other combustion phenomena, which confirms that the smolder reaction is weak and very sensitive to the balance between heat losses and oxygen supply. Also surprising is the observation that the air contained in the foam pores seems to be capable of sustaining the propagation of the smolder reaction, although weakly, through the foam sample. These observations also indicate that buoyancy can have a significant role in the smolder process since buoyantly generated air currents, even if they are small, can easily influence weak smolder reactions. Also, in the presence of an interface these currents may have velocities that can be larger than the ones observed to cause the extinction of the smolder reaction in forced flows.

ACKNOWLEDGEMENTS

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