EFFECT OF TOP END CONDITION OF FUEL BED CONTAINER ON DOWNWARD SMOLDER SPREAD

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ABSTRACT

An experimental study was performed of natural-convection downward smolder spread across a sawdust bed peripherally enclosed with an insulating container, to examine the effect of the opening condition at the top end on downward smolder spread. Experiments were conducted by using relatively coarse sawdust and 25-cm-long cylindrical container. The variations of temperature profiles along the bed axis with time were determined for different opening conditions and were compared with those in smolder spread from open top to open bottom. It was shown that the smolder zone initiated from open top toward closed bottom penetrates the bed with keeping high peak temperature like the case of open top to open bottom spread, although mean spread rate is smaller. This indicates that the downward smolder zone can be sustained stably if sufficient air or oxygen is supplied from the back of it by natural convection even if upward draft entering from the bottom of the bed is absent. When the top end was partially closed by mounting a cover after stable smolder spread had begun from open top toward open bottom, the temperature at the peak decreased more than 200 K and the smolder zone became to spread with thickening residue. In this case, the shape of temperature profiles continuously changed or decayed until end-effect at the open bottom end enhanced the reaction. The temperature at the shrunk peak, free from the end-effect, was almost identical with the temperature at the exothermic oxidative-degradation zone in smolder spread from open top to open bottom. From these results, it can be inferred for natural-convection downward smolder spread that the oxidation reaction of the char is very sensitive to the oxygen supply by natural convection in the space above the smolder zone, and that the top end opening condition strongly alters the completeness of reactions, structure, and behavior of the smolder zone.

INTRODUCTION

Smoldering is a combustion mode of solid combustibles in which pyrolysis reaction and succeeding surface reaction of produced char occur. Although smoldering has slow reaction rate, the product of it is highly toxic and it often leads to initiation of fire. Therefore, many researches have been conducted to understand the characteristics of smolder zone and consider the method of reducing the hazard due to it [1- 3].

Nearly one-dimensional downward smolder spread across a bed of permeable combustibles or fuels with opposed flow is a typical and basic phenomenon. From earlier experimental studies on this type of smolder spread, the role of oxygen supply due to upward interior airflow has been focused and examined by adopting fuel containers having permeable ends [3, 4]. Recent studies of Torero et al. [5, 6] pointed out that the oxygen supply from recirculating flow over the smolder zone due to natural convection also plays an important role in controlling the spread rate. They expected that this recirculating flow is primarily induced by the boundary layer flow at cold wall of the container, and that this flow enhances the smolder reaction while it also has cool down effect. Their studies suggest that the condition of top opening affects smolder spread characteristics. In actual cases, the top of the smolder zone is exposed to surrounding air through various opening conditions. Thus, systematic studies of the effect of top end are necessary.

In the present study, to explore the effect of the top end opening condition, or of the natural convection in the space above the smolder zone on downward spread phenomena in detail, downward smolder spread experiments under natural convection were conducted. The variations of the axial temperature profile with time were determined and compared.

EXPERIMENTAL

Figure 1 shows a cross-sectional view of the smolder apparatus and the data-acquisition system. The sawdust bed of 11.6-cm-diam. and 25-cm-deep is peripherally enclosed with a cylindrical container made of thermal insulating brick. The inside of the container is coated with aluminum cement. The examined sawdust was chosen from primary wood sawdust by using screens, and its particle dimension was distributed between 30-mesh and 10-mesh. Before packing, the sawdust was kept in air-conditioned room for more than 48 hours. The packing density is about 0.156 g/cm^3, and care was taken to attain uniform packing. To hold the sawdust bed, the bottom was supported by a 50-mesh screen or non-porous aluminum plate. Since the drag force to the flow by the 50-mesh screen must be negligible compared with that by the contacting sawdust bed, the bottom end with the screen can be regarded as open end. The top of the container is basically open and exposed to ambient atmosphere. To produce partially closed top end condition, a cover made of insulating brick and lapped with aluminum foil was mounted with placing a space between it and the container. Permeable top covers were not adopted since it was intended to keep the same opening condition during a run by eliminating the influence of tar accumulation at the cover.

To examine the temperature profiles along the centerline, 24 chromel/alumel (K type) thermocouples of 0.1-mm-wire diam. were installed with one-cm space. The thermocouples were connected to a data-logger and the outputs were scanned every two minutes and recorded by a microcomputer. Approximate temperature profiles were monitored during a run. The smolder apparatus was placed in a draft chamber to minimize the disturbance of environment, and the flow in the chamber was controlled just enough to maintain minimum amount of flow to avoid the stay of smoke.

Smolder was initiated by heating the opened top surface uniformly with a small torch. The heating period was about ten minutes. In the case of examining the smolder spread with partially closed top end, the top cover was mounted when the temperature peak reached the position 5 cm from the top end since at earlier period after ignition the influence of heat flow to cold wall is large and also strong transient phenomena take place.

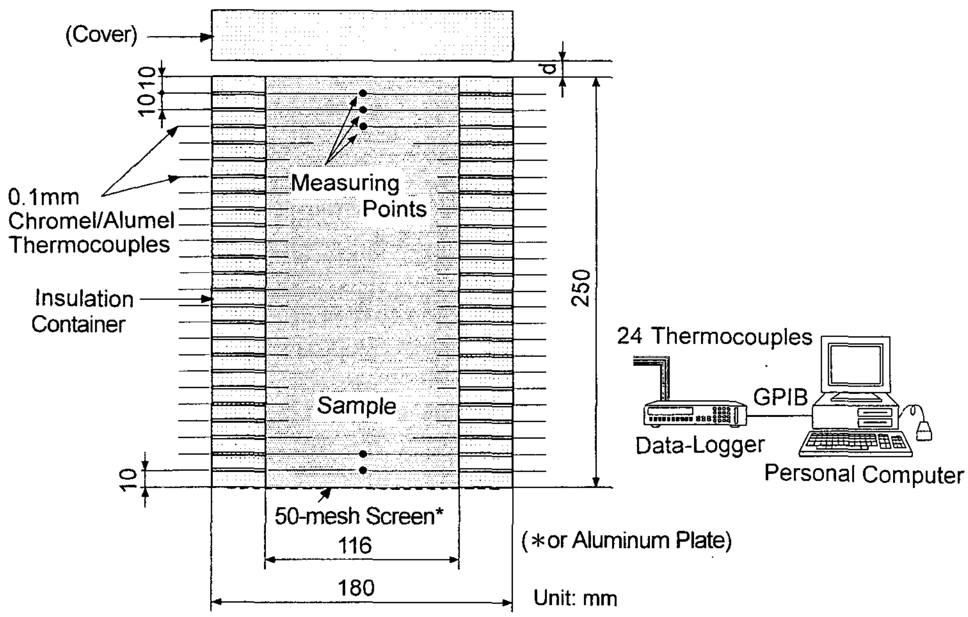

Fig. 1 Cross-sectional view of smolder apparatus and data-acquisition system.

RESULTS AND DISCUSSION

Variation of Temperature Profile

Figures 2 to 5 show the variation of the temperature profile with time for different end conditions. Temperature profiles of every 90 minutes are represented. In all experimental runs, transition to flaming was not observed. x indicates the distance from the top end of the container. To reduce the influence of the difference in ignition procedure on the comparison of temperature profiles, the time t is taken as the time measured from the moment when the temperature peak has reached $x = 1$ cm. To produce precise temperature profiles including steep tip at temperature peak, fixed-position temperature histories and interpolated peak temperature distribution along x were referred.

Figure 2 shows the variation in smolder spread from the open top end to the open bottom end. It took about ten hours from the smolder initiation to the end of elevated-temperature decay. Until $t =$ 270 min, the peak temperature gradually increased with keeping sharp tip. During this phase, the distance between the foot of preheat zone and the temperature peak increased, or the smolder zone became broader. In unburned side of the peak, a hump emerged, and then it was progressively augmented. From the viewpoint of heat balance, it is reasonable to consider that around the hump heat release occurred. In the back of the hump the temperature increased steeply once more toward the peak, and then the temperature rapidly dropped. This indicates that concentrated exothermic reaction took place in a narrow region including the peak. Above the top of the smolder zone, a hollow space extended except near the container wall where incompletely burned or quenched sawdust was left. The temperature at the region behind the rapid drop was observed to fluctuate with time. As the preheat zone reached the open bottom, according to the end-effect [7, 8], the temperature at the hump began to increase and then the hump changed to a new or secondary peak. With the growth of the new peak, the temperature at the primary peak decreased continuously, and the peak disappeared at last.

Figure 3 shows the variation in smolder spread from open top to closed bottom. In contrast to the previous case, the temperature profile held essentially same contour except near the bottom end. The peak had a sharp tip, and its temperature increased gradually at first and then kept virtually constant value except near the bottom end where large cooling occurs. The peak temperatures in the upper half took approximately correspond to these in the previous case. In the unburned side of the peak, a slightly concave part was observed. The smolder spread rate gradually lowered, and the rate near the bottom was about 1.2 - 1.4 cm/h.

Figure 4 shows an example for the case of partially closed top end and open bottom end. The distance d between the top of the container and the base of the cover is 10 mm, and the ratio of the opening area to the bed cross section area is 0.34. As was mentioned, the cover was mounted when

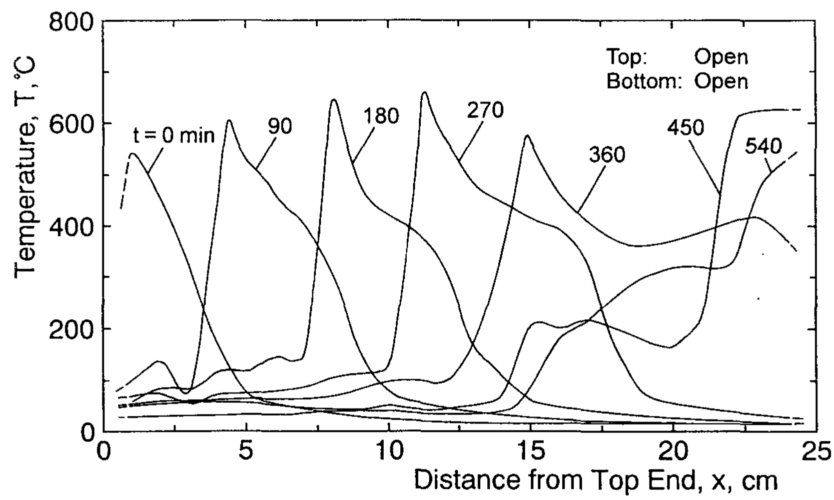

Fig. 2 Variation of temperature profile. Both of top end and bottom end are open. t is the time taken from the moment when the temperature peak has just reached $x = 1$ cm.

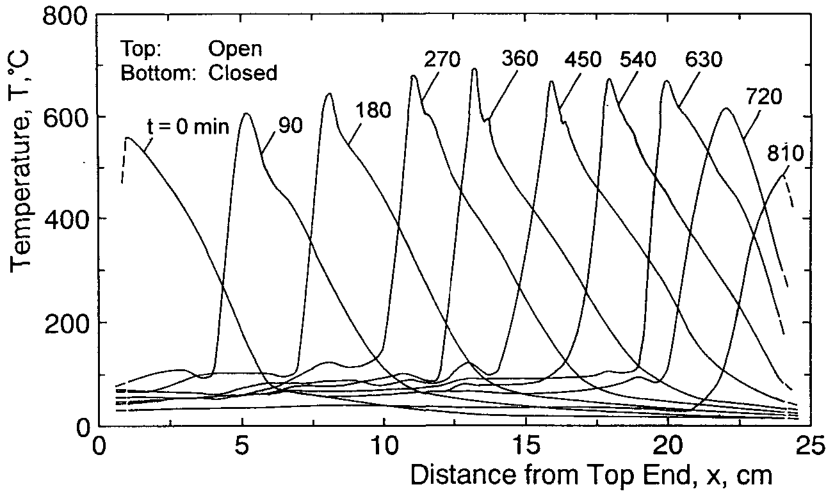

Fig. 3 Variation of temperature profile. Top end: open. Bottom end: closed.

the temperature peak reached the point x = 5 cm. After setting the top cover, the shape of temperature profile continuously changed. The temperature at the peak lowered with losing sharpness of the tip, while the shape of temperature profiles up to approximately 400 ℃ in the unburned side of the peak changed little. Consequently, a hump similar to that shown in Fig. 2 appeared. The hump proceeded with keeping nearly constant temperature. Following the decay of the primary peak, the hump became a new and unique temperature peak. Behind the new peak, the thickness of high temperature region decreased and also the tail of temperature dropping region stopped moving, resulting in the decrease of the temperature gradient with time. The length of the time before the smolder zone reached the bottom was much larger than that in open- to open-end spread. It is difficult to determine the local spread rate, since the relative location of the main peak in the smolder zone changes continuously. When the smolder zone front reached close to the bottom, end-effect took place.

Figure 5 shows another example for the case of partially closed top and open bottom. d is 5 mm. As the opening area was reduced, influence of confinement at the top was augmented. The decline of the primary temperature peak was enhanced further although the difference was not apparent during early period. After the shape of the new temperature peak changed from a rounded tip to a stiff tip, the peak temperature suddenly dropped down to approximately 200 ℃, which is extremely

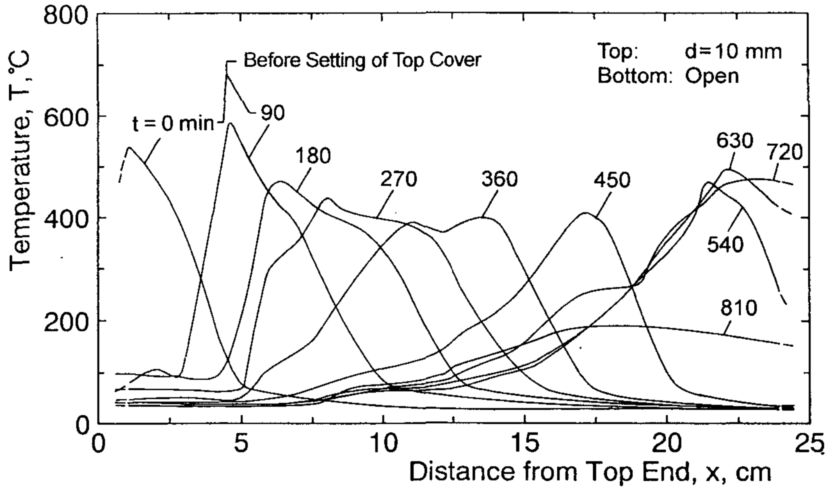

Fig. 4 Variation of temperature profile. Top end: partially closed, d = 10 mm. Bottom end: open. Top cover is set when temperature peak has reached x = 5 cm.

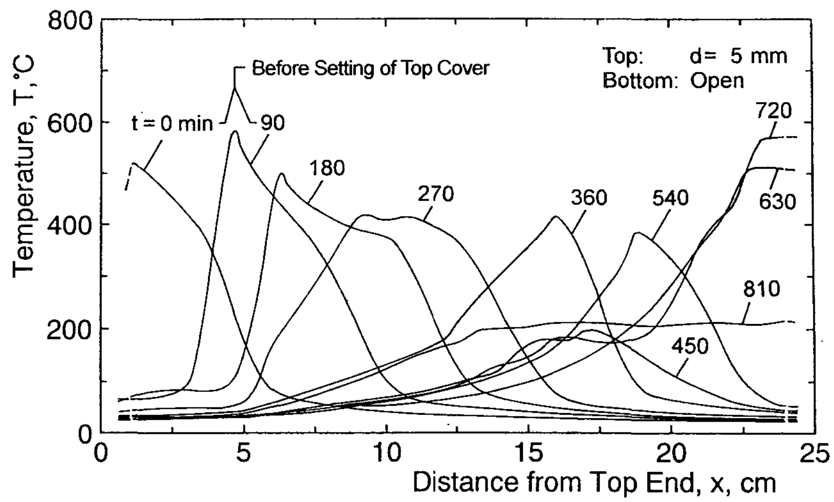

Fig. 5 Variation of temperature profile. Top end: partially closed, d = 5 mm. Bottom end: open. Top cover is set when temperature peak has reached x = 5 cm.

low temperature for normal self-sustaining smolder. After keeping this low value with no spread for around two hours, the smolder zone temperature turned to increase, and smolder spread resumed. After this restart, the end-effect appeared and high temperature was attained.

It may be worthwhile to compare directly the typical temperature profiles, free from the end-effect, in smolder spread toward open bottom end, although the aspect of temperature profiles changed continuously with time. Figure 6 shows a comparison of the temperature profiles in these cases. In the figure, temperature profiles having roughly same location of the preheat zone are compared. When d is 20 mm, both of the decaying primary temperature peak and the new peak exist, and the distance between these two peaks reaches about 7 cm. This distance is larger than that between the peak and hump in open- to open-end spread. In the cases of d = 5 and 10 mm, the primary peak has completely decayed and the new peak only goes on. It is interesting that the temperature gradients in front of the hump or peak coincide well each other.

Distribution of Peak Temperature

Figure 7 shows the distribution of the temperature at the temperature peak, or the peak tempera-

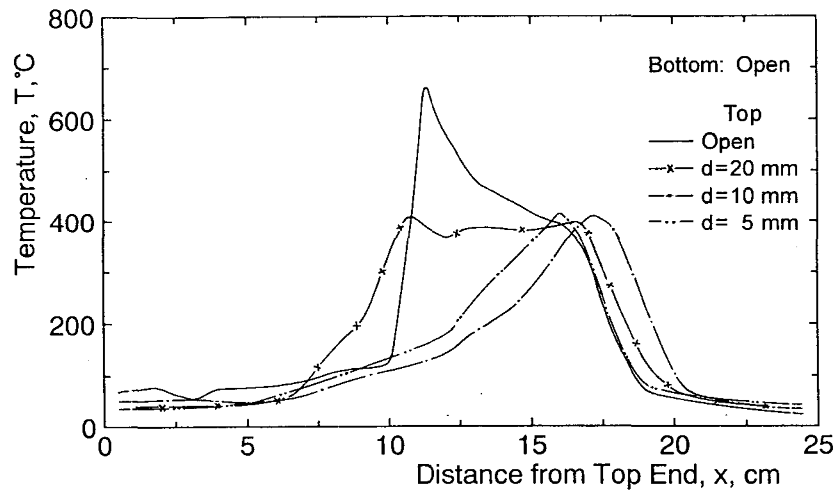

Fig. 6 Comparison of temperature profiles in smolder spread toward open bottom end.

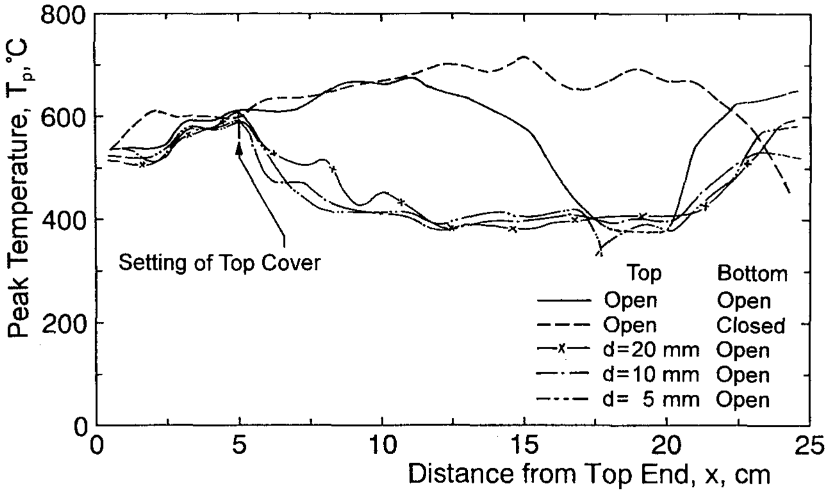

Fig. 7 Distribution of the peak temperature T_p along x. T_p: the temperature at the temperature peak measured at each position. When peak passes a position twice or more, the greatest value is indicated.

ture, T_p along x. For particular cases, in which temperature peak passes at least twice, the greatest value of them are indicated. For the region where temperature peak skipped because of the rapid development of a new peak, the maximum temperature is indicated by dotted line locally for convenience. In the case of open- to open-end spread, moderate increase of the peak temperature continued in the former half of the bed, then following early emergence of the end-effect the peak temperature turned to decrease. With remarkable shift of temperature profile induced by the end-effect, the location of temperature peak skipped several centimeters and it left a region of relatively low maximum temperature. On the contrary, in the case of open- to closed-end spread, high peak temperature (600 – 700 ℃) continued except the location close to the bottom end. In the cases of the spread with partially closed top and open bottom, from the setting of the top cover, the peak temperature started to decrease, and after reaching about 400 ℃, it hold essentially constant value until the end-effect took place. It can be seen that the rate of temperature decrease after the setting of the cover for $d = 5$ or 10 mm is larger than that for $d = 20$ mm. The distribution of T_p for $d = 5$ is close to that for $d = 10$ mm. However, it should be noted that for $d = 5$ mm extremely low peak-temperature period continued for a while as was shown in Fig. 5.

Relation between Top End Condition and Smolder Zone Characteristics

It has been well recognized that there are two kinds of reaction when cellulosic materials are pyrolized thermally [3,4]. In inert atmosphere without oxygen, the reaction is endothermic pyrolysis reaction. With oxygen, the reaction becomes exothermic reaction so-called oxidative-degradation. In spite of these differences, both reactions produce char as well as volatile components. If the temperature is high enough, the char is oxidized and heat is released with leaving only ash component. Considering these processes, relation of the top end condition and smolder zone characteristics is interpreted here through the temperature profiles.

Figure 8 shows schematic illustration of inferred aspects of the smolder zone. The sawdust bed stores oxygen a priori. Although this oxygen can be used for reactions, most of the oxygen to sustain smoldering combustion may be provided from surrounding air by convection and/or diffusion. In the case of open- to open-end spread with natural convection, two types of natural convection take place concurrently. One is upward interior flow entering from the bottom and slowly moving through the bed with large drag force. The other is up-and-down or circulating flow in the hollow space above the smolder zone, where gases can flow freely with negligible drag. Torelo et al. [5, 6] already suggested for the results of their experiments, where downward smolder in polyurethane foam bed initiated from the middle of the container were performed with posing char layer above it.

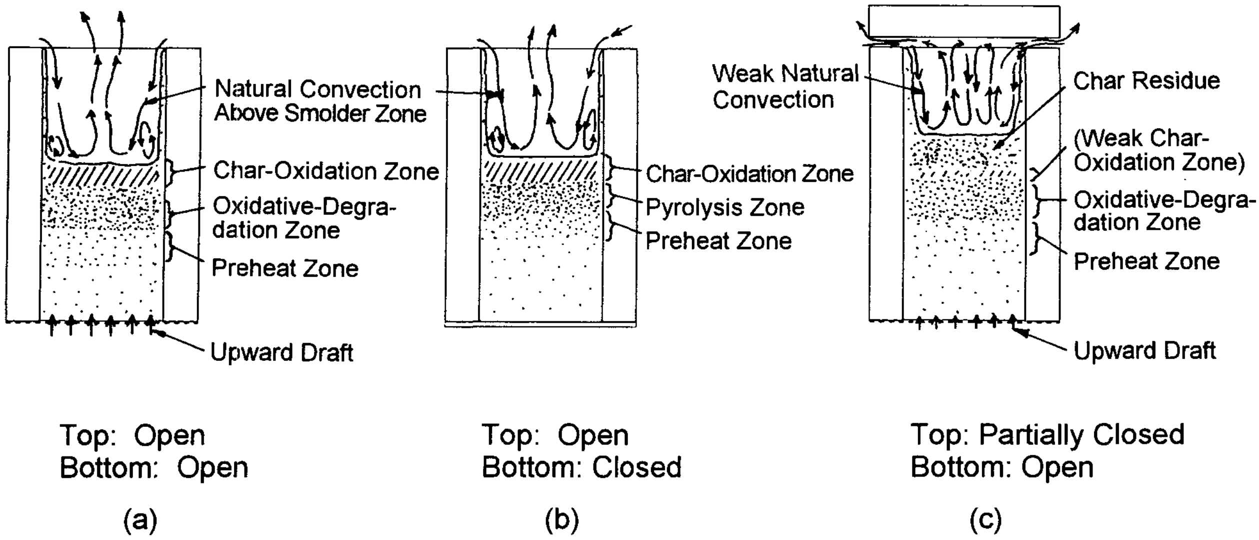

Fig. 8 Schematic illustration of inferred aspects of smolder zone.

that circulating flow above the smolder zone is induced by cooling of burned gas by the cooler wall. However, in open- to open-end spread in this study, the flow above the smolder zone must be primarily produced from inherently unstable density fields where the light burned gas lies under heavy cold gas. Thus, the flow is considered strong and rather fluctuated.

From the difference between the temperature profiles in open- to open-end spread and that in open- to closed-end spread, it can be said that the hump observed in the former spread mode corresponds to the zone of exothermic oxidative-degradation due to upward draft through the bed. It can be said also that the sharp temperature peak in both cases corresponds to the zone of char-oxidation, except the region with the end-effect. Two-stage temperature rise in the former spread mode must also imply that the oxidative-degradation reaction consumes most of the oxygen in the upward draft. Thus, it is expected that the char oxidation reaction in these cases is essentially sustained by the natural convection above the smolder zone. In the latter spread mode, the slightly convex part in the unburned side may suggest that oxidative degradation occur a little by using a priori oxygen or diffused oxygen along with major endothermic pyrolysis reactions.

The variation of temperature profiles of partially closed- to open-end spread must indicate that by the setting of the top cover the circulating flow above the smolder zone and the oxygen supply by it are diminished, and this reduces char oxidation reaction drastically. The rounding and shrinkage of the sharp tip of the temperature peak are considered to be closely related to the decay of the concentrated reaction and hence to the generation of dense char residue. Since the temperature at the new peak has almost same value as that at the hump, the peak is supposed to be tightly sustained only by exothermic oxidative-degradation consuming the oxygen from the bottom. The development of the char residue region must increase the drag to upward draft and the radial direction heat loss. If the bed is thicker, the smolder spread under these conditions may become more difficult.

Although the detail of the increase of the peak temperature after dropping to 200 ℃ (Fig. 5) are not clear, two major possible mechanisms are supposed. One is that small hot spot survived and it led to intense reaction as a core, and another is that after the reduction of oxygen consumption the oxygen concentration in the bed was raised and it resulted in thermal ignition of porous fuel [9].

From above discussion, it can be inferred that for natural-convection downward smolder spread the oxidation reaction of the char is very sensitive to the oxygen supply by natural convection induced in the space above the smolder zone, and that the top end opening condition strongly alters the completeness of reactions, structure, and behavior of the smolder zone. For further understanding of the general features of the effect of top end opening condition on downward smolder spread, it will be also necessary to study the effect on forced-convection downward smolder spread.

CONCLUSIONS

An experimental study was performed of natural-convection downward smolder spread across a sawdust bed, to examine the effect of the opening condition at the top end on downward smolder spread. Brief conclusions are as follows:

1. The smolder zone initiated from open top toward closed bottom penetrates the fuel bed with keeping high peak temperature like the spread from open top to open bottom. This indicates that the downward smolder zone can be sustained stably if sufficient oxygen is supplied from the top even by natural convection.
2. In natural-convection downward smolder spread, the exothermic reaction of char is very sensitive to the oxygen supply by natural convection occurring in the space above the smolder zone.
3. When the smolder zone spreads from partially closed top to open bottom with insufficient oxygen supply through the top end opening, smolder zone spreads with thickening residue and low peak temperature, and the shape of temperature profile continuously decays. In this case, the smolder zone may be sustained primarily by the heat released by exothermic oxidative-degradation consuming oxygen in upward draft through the bed.

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NOMENCLATURE

d space between the top of the container and the base of top cover
T temperature
T_p temperature at the tip of temperature peak, or peak temperature, measured at each position (If temperature peak passes the same position twice or more, it indicates the greatest value.)
t time from the temperature peak arrival at $x = 1$ cm
x vertical distance from the top end of the container

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