BURNING PROCESS OF CELLULOSIC FIBERS COMPOSING FILTER PAPER DURING FLAME SPREAD

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ABSTRACT

The burning process of fibers composing filter paper was examined during downward flame spread over a filter paper sheet, using microscopic photography, and progress of pyrolysis was visualized. During the period of flame passing, the color of fibers were observed to turn first into yellow, then into black. In an earlier stage, a few fibers at irregular intervals started to blacken and the numbers of blackening fibers increased. After all fibers blackened, the diameters and lengths of fibers started to decrease. The decreasing of lengths resulted in shrinkage of the paper sheet. This shrinkage was measured, and it was found that the length of fibers decreased gradually. The ratio of the volume of char to that of fibers before charring was measured and it was shown that this ratio for thick paper sheet is larger than that for thin one. In this study, it was revealed that the pyrolysis proceeds in a heterogeneous way, and pyrolysis process of such fibrous materials is different from that of homogeneous ones. Consequently the heterogeneous structure of the materials must be taken into consideration for explaining detailed frame spread mechanisms.

Keywords: flame spread, cellulosic material combustion, microscopic measurements, fire development, fire physics

INTRODUCTION

Flame spread over polymeric materials has been experimentally investigated by a number of researchers who are interested in basic fire phenomena.[1] In most of the studies on flame spread, combustible materials have been assumed homogeneous, and flame spread phenomena have been interpreted, analyzed, and predicted on this assumption, although many materials to be burned in real fires are of a heterogeneous fibrous structure. Thus, the results of these studies may be insufficient for explaining detailed flame spread mechanisms.

A fibrous material is of porous structure containing solid fibers and vacant spaces. At burning, heat or gas must pass through or across these fibers and spaces, so that the heat and mass transfer must be complicated in such a situation. The heat flux to a fiber and the gas components surrounding it, which have an strong influence on the pyrolysis process,[2] may be different from those of other fibers composing the material. This implies that the pyrolysis process of heterogeneous materials is different from that of homogeneous ones. The composition and amount of gasified fuel, to which the configuration and behavior of the leading flame edge are closely related, depend on the pyrolysis process. For further understanding of flame spread mechanisms over a fibrous material, therefore, it seems important to elucidate the pyrolysis process of individual fibers composing the material. In this study, behavior of fibers during flame spread over a sheet of filter paper

which is a typical fibrous material, has been examined using microscopic photography and analyzed.

EXPERIMENTAL

Figure 1 shows a schematic of the experimental apparatus used in the present study. It consists of a vertical duct, lighting device, and microscopic camera.

The duct is rectangular (55 mm × 14 mm × 110 mm) without top and bottom, and on both of the narrow sides, slits (1 mm width) are provided along the center line to hold the paper sheet vertically in the duct. On the front wall, a glass plate (thickness 0.17 mm) is installed in a circular window (diameter 10 mm). A sheet of paper is held at an appropriate location in the vertical duct. The distance between the paper surface and the front wall of the duct must be not only short enough compared to the working distance of the microscope lens, but also long enough to reduce the serious influence of the wall. The distance of 7 mm (14 mm × $\frac{1}{2}$) well satisfies these requirements.

In the experiments, a strong ray from a mercury lamp was transmitted by an optical fiber and thrown on the paper surface for illumination through the window. The object lens (working distance 20 mm) of the microscope was movable between the window and the camera.

The filter paper sheets used were of almost pure cellulose. Each paper sheet was held in the duct and ignited at its top end. The fibers at the burning paper sheet surface were observed and recorded by a video camera (30 pictures per second) or a still camera.

To obtain the information on the charring process of fibers, the ratio of the volume of char to that of fiber before charring was measured. A piled filter paper sheet was also used to measure the pyrolysis progress inside the sheet. These measurements were performed after the paper sheet was extinguished suddenly by blowing N_2 gas.

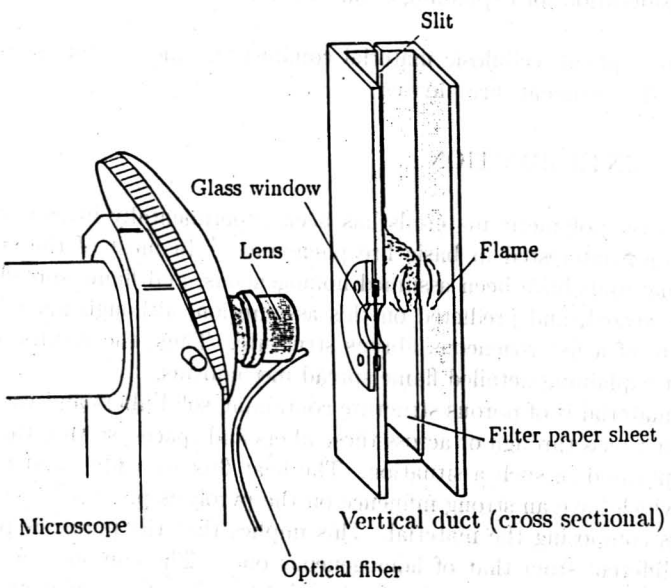
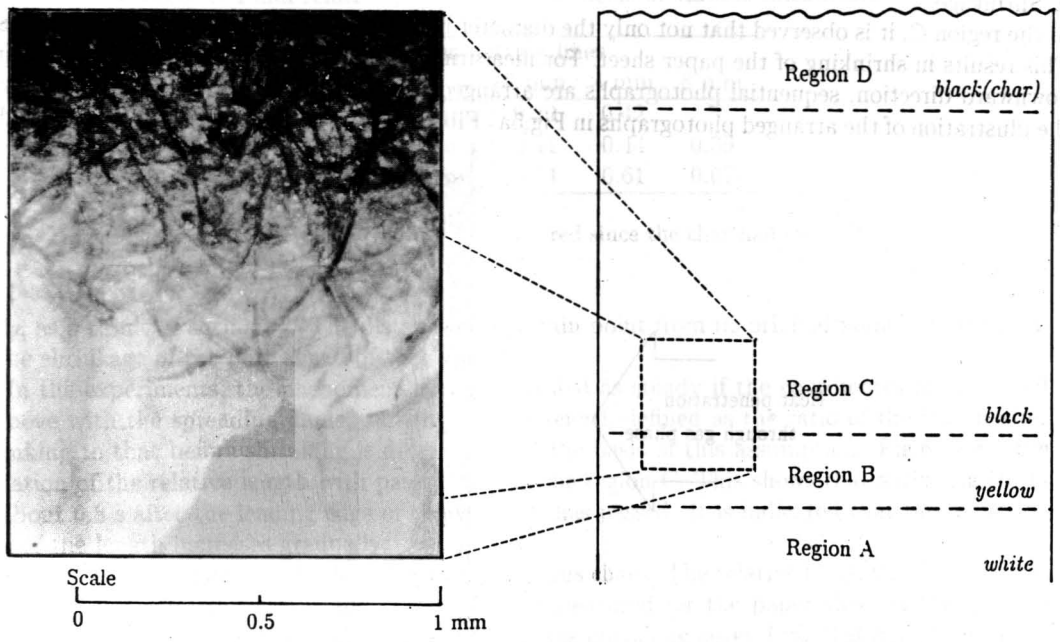


Fig.1 Schematic of the experimental apparatus



a. Pyrolyzing paper surface (thickness 0.68 mm)

b. Illustration of the pyrolysis progress on the surface

Fig.2 Pyrolysis progress on a paper sheet surface

RESULTS AND DISCUSSION

1. Progress of pyrolysis

A typical microscopic photograph of pyrolyzing paper surface (thickness 0.68 mm) is shown in Fig.2-a, and its schematic illustration is shown in Fig.2-b. In this photograph, the pyrolysis of fibers at the top is found to precede that at the bottom because the flame spreads from the top to the bottom. Before burning, the fibers on the surface are white (region A). The color is seem to gradually turn into yellow (region B), then into black (region C) accompanying with shrinking. After pyrolysis is finished, char is formed (region D). Since the turn of color into yellow is intrinsically gradual, the boundary between the region A and region B is arbitrary, and also the boundary between the region B and region C is indistinct because a few fibers start to blacken at irregular intervals. Figure 3 shows a schematic model of the pyrolysis of fibers when burning. This model represents that the black fibers appear at random on the surface when the pyrolysis proceeds from surface to inside in the fibrous structure.

In the present study, the leading edge of the region C is defined as an imaginary line where a black fiber firstly appears. The number of black fibers increases with the distance from the leading edge of the region C. All of the fibers seen on the surface finish to change their color to black at about 0.8 mm behind of the leading edge of the region C for a paper sheet of thickness 0.68 mm.

The observation of each surface of separated sheets having composed a piled paper sheet is made after sudden extinction by N_2. Figure 4 shows the inner pyrolysis profile of a piled paper sheet. It seems that the pyrolysis of the region B occurs continuously in depth. On the other hand, pyrolysis of the region C progresses from the surface to inside. The region B is narrow at the surface, and wide at the inside. This suggests that the pyrolysis process varies with the distance from the surface.

2. Shrinkage

In the region C, it is observed that not only the diameter but also the length of each fiber decreases. This results in shrinking of the paper sheet. For measuring shrinking of the paper sheet surface in downward direction, sequential photographs are arranged in order of time (Fig.5a). Fig.5b shows the illustration of the arranged photographs in Fig.5a. Fibers in the region C moves downward grad-

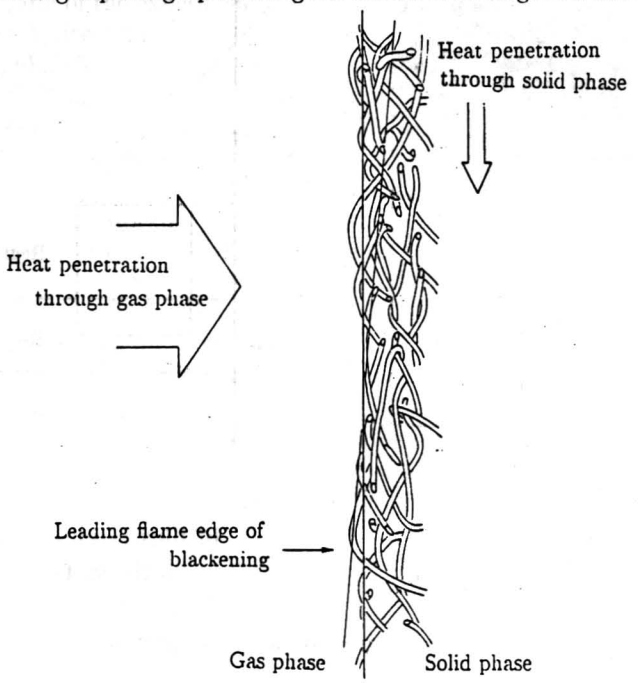


Fig.3 Sectional schematic of a burning paper sheet

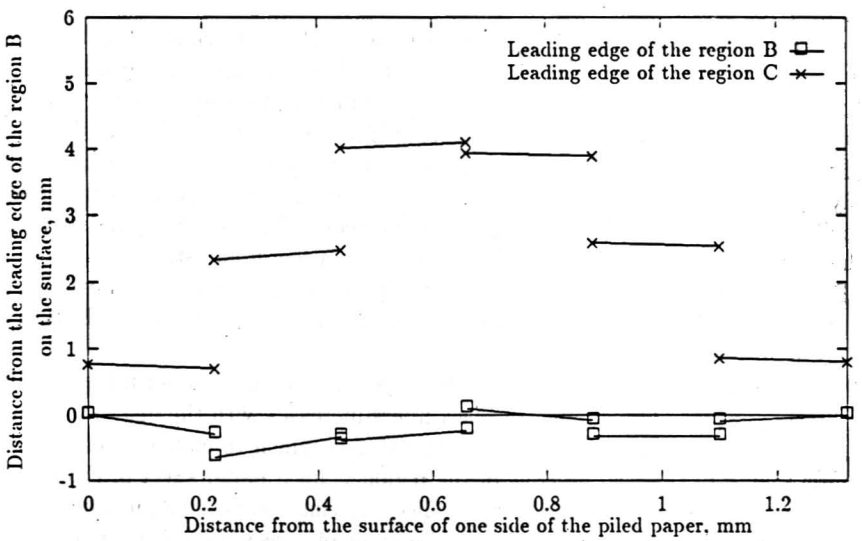


Fig.4 Inner pyrolysis profile
(piled paper; thickness: 1.32 mm = 0.22 mm × 6)

The pair of the points on each sides of the individual sheet is linked by a line.

Table 1: Final relative width for paper sheets of various thicknesses

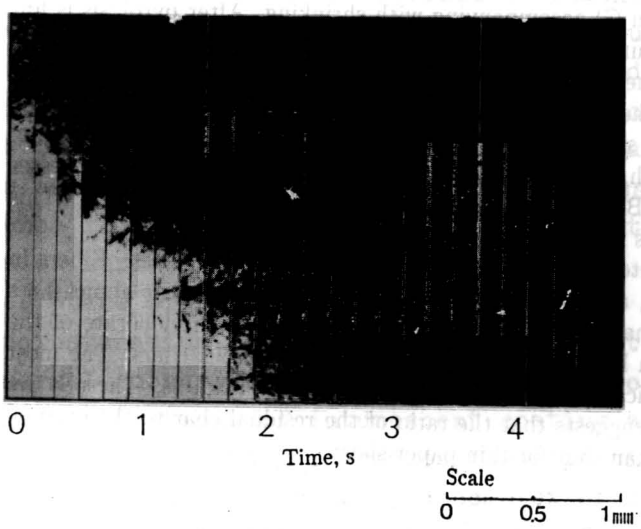
distance between cutting lines	2 mm	4 mm	8 mm
thickness 0.22 mm	0.39	0.42	*
0.28 mm	0.41	0.44	0.39
0.71 mm	0.54	0.61	0.67

* Width couldn't be measured since the char had cleaved

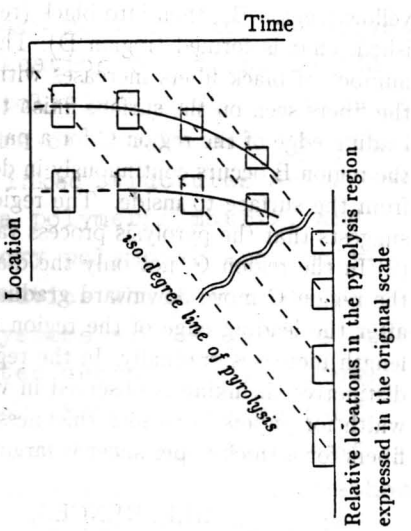
ually, as a result of shrinking. The distance of a certain point from its original point is integration of the shrinkage of the part ahead of that point.

In the experiments, the phenomena can be regarded as steady if the coordinates are assumed to move with the spreading flame, and the ralative length defined as the ratio of the length after shrinking to that before shrinking is determined on the basis of this assumption. Fig.6 shows the variation of the relative length with passed time in the region C. This shows that shrinking starts at about 0.8 s after the leading edge of the region C has passed. It is indicated that the reduction rate of the length increases gradually.

In the region D, fibers pyrolyze and turn into fibrous chars. The relative lengths in 3 directions, i.e., the vertical length, width, and thickness were measured for the paper sheet of 0.71 mm in thickness (Fig.7). Before burning, the paper sheet was cut along several vertical lines to measure the relative widths (the relative lengths in horizontal direction). Sections of several widths between cutting lines are chosen for estimation of the effect of cutting. The measurement is made after sudden extinction by N_2. Figure 7 shows that the most distinctive shrinking is observed in vertical direction and the least one in thickness, and that every relative length becomes small as the distance between the cutting lines becomes small. Table 1 shows the relative width for papers of various thicknesses. This suggests that fibers of the thin paper sheet shrink more than that of thick one, in other words, the ratio of the residual char to the original fibers for a thick paper sheet



a. Arranged sequential photographs in order of time



b. Illustration of shrinking

Fig.5 Aspect of shrinking

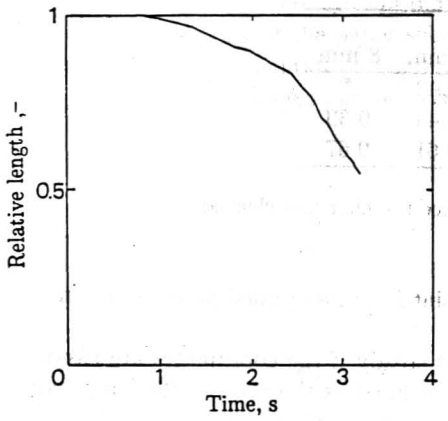


Fig.6 Variation of the relative length with passed time in region C

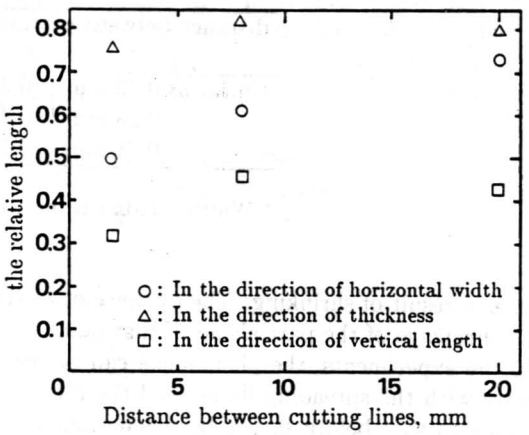


Fig.7 Variation of the relative length in 3 directions

is larger than that for a thin paper sheet.

CONCLUSIONS

The burning process of fibers composing filter paper was examined microscopically during downward flame spread, and following conclusions were derived:

(1) Before burning, the fibers on the surface are white (region A). The color gradually turns into yellow (region B), then into black (region C) accompanying with shrinking. After pyrolysis is finished, char is formed (region D). The turn of color into black starts at irregular intervals. The number of black fibers increases with the distance from the leading edge of the region C. All of the fibers seen on the surface finish to change their color to black at about 0.8 mm behind of the leading edge of the region C for a paper sheet of thickness 0.68mm. It seems that the pyrolysis of the region B occurs continuously in depth. On the other hand, pyrolysis of the region C progresses from the surface to inside. The region B is narrow at the surface, and wide at the inside. This suggests that the pyrolysis process varies with the distance from the surface.

(2) In the region C, not only the diameter but also the length of each fiber decreases. Fibers in the region C move downward gradually, as a result of shrinking. Shrinking starts at about 0.8 s after the leading edge of the region C has passed. It is indicated that the reduction rate of the length increases gradually. In the region D, fibers pyrolyze and turn into fibrous chars. The most distinctive shrinking is observed in vertical direction and the least one in thickness. The relative width for papers of various thicknesses suggests that the ratio of the residual char to the original fibers for a thick paper sheet is larger than that for thin paper sheet.

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