MECHANISMS OF FLAME SPREAD OVER BOUND FLAT COMBUSTIBLES

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ABSTRACT

A study has been conducted to elucidate the mechanisms of flame spread over a filter paper by adhesive permeation. Two adhesives of polyvinyl acetate resin and urea resin were chosen, which are most widely used for manufacturing furniture or finishing walls of residents. Thermogravimetric characteristics of samples were examined. Also, temperature distributions near the leading flame edges were measured. Based on the measured thermogravimatric characteristics and temperature distributions, the mechanisms of flame spread were discussed. Flame spread depends strongly on the pryrolysis reaction of a permeated adhesive. The amount of heat transferred through gas phase to the pure filter paper sheet was indicated to be larger than that to the filter paper sheet permeated with an adhesive. This was inferred to be the main cause to decrease the flame spread rate with polyvinyl acetate resin permeation.

KEYWORDS: Flame spread, Fire, Adhesive, Flame structure

INTRODUCTION

Flame spread over a combustible solid surface is a basic phenomenon in a fire and a number of studies have been performed to characterize the process [1-6]. However, little is known concerning flame spread over a combustible solid which is glued to another solid by an adhesive, although various types of adhesives are widely used in furniture manufacturing and interior decoration of buildings. The development of a building fire may not be reasonably predicted without understanding of flame spread over such furniture or interior decoration.

It is easily imaginable that a solid glued by an adhesive to other solid has a complex structure, and that behavior of a flame spreading over the surface of such a solid may not be easy to explain in terms of the individual characteristics of the solid and the adhesive. This would be the reason why few studies have examined the role of an adhesive on flame spread over a sample of multiple solids glued by an adhesive.

To explore the characteristics of flame spread phenomena along the surface having complex structures combined by adhesives, we have to accumulate data on flame spread over solid surfaces of simple structure. Thus, in our previous study, flame spread over filter paper sheets permeated with adhesives was examined experimentally [7]. To obtain a systematic understanding of the effect, fuel samples including adhesive were prepared. The direction of flame spread was chosen to be downward because downward flame spread is steady and suitable for examining the basic characteristics of materials in fires. Two types of adhesives have been used in the experimental study. One is of the main component of polyvinyl acetate resin, which is a typical thermoplastic resin, and the other is of urea resin, which is a typical thermosetting resin. Both are widely used in furniture manufacturing and interior decoration of buildings.

Throughout the study, it was shown that for both adhesives, the flame spread rate decreases with increasing amount of the permeated adhesive. The reduction of the flame spread rate was found to be much larger in the case when urea resin was permeated into the filter paper sheet compared to that in the case when polyvinyl acetate resin was permeated. Even these results would provide us a method for evaluating fire hazards for combined materials. If we would have knowledge on the retardation mechanisms of flame spread for those cases, however, we could provide a more reliable method useful for fire safety.

Thus, we have performed a study to explore the retardation mechanisms of flame spread over a filter paper permeated with polyvinyl acetate resin or urea resin. For understanding the phenomena concerning flame spread, the thermogravimetric characteristics of samples would be helpful, so that we performed experiments to examine the thermogravimetric characteristics of samples used in flame spread experiments. Also, we have measured the temperature distributions near spreading flames, which are necessary to evaluate the heat-transfer to drive the flame.

EXPERIMENTAL

Three kinds of samples, which are the same with those used in our previous study [7], are used in the present experiments. One is pure filter paper dried in an oven and kept in a desiccator. Its density, thickness, and mass per unit area are 0.26 g/cm^3, 0.53 mm, and 14 mg/cm^2, respectively. Others are of dried filter paper permeated with polyvinyl acetate resin and urea resin. Those samples are of surface area of 10 cm x 20 cm and prepared in the process as follows:

1) Each filter paper sheet was placed in a solution of a certain concentration of an adhesive (Urea resin of 45.7% in water or polyvinyl resin of 41.4 % in water) for three minutes.
2) Then, the sheet was taken out from the solution and placed in an oven. After drying in the oven at 105 ± 2 ^{o}C for three hours, it was kept in a desiccator.

Through this process, we could prepare samples of dry filter paper uniformly permeated with urea resin or polyvinyl acetate resin in the range of 0 to 30 mg/cm^2. The thickness of those samples was 0.53 ± 0.02 mm. The densities of samples were 0.26 g/cm^3 for dried pure filter paper and from 0.26 to 0.83 g/cm^3 for filter paper permeated with polyvinyl acetate resin or urea resin. Sheets of pure resin were also provided for comparison.

The weight of a sample in a platinum cell, whose initial value was 2.0 ~ 5.0 mg, was measured during its heating in the air from room temperature to 800 ^{o}C at a fixed temperature increasing rate. The rates of 10, 20, 30, 40, and 50 ^{o}C/min were adopted in the present experiments to examine the thermogravimetric characteristics of samples. The curve indicating the change of mass as a function of temperature or time is a TG (Thermal gravimetry) curve, and the first derivative of the TG curve is a DTG (Derivative of thermal gravimetry) curve. Both were recorded and analyzed.

The temperature variation of the gas phase and test piece was measured using a set of 4 thermocouples of 1 cm interval in the direction perpendicular to the sample surface. The wire diameter of the thermocouple was 50 μm and the signals from the thermocouples were recorded electrically. Just before each spread test a sample was taken from the desiccator and set in a flame spread test facility, which is similar to that used in our previous studies [7,8]. Since both sides of the sample were held by the frames, the exposed area for burning was reduced to 5 x 20 cm. A slit burner was used to ignite the sheet on its top edge, and behavior of the downward spreading flame was recorded using a video camera. The temperature distributions were determined on the basis of the recorded temperature variation and the flame behavior.

RESULTS AND DISCUSSION

Thermogravimetric Characteristics of Samples

The temperature-increasing rate should affect pyrolysis reactions. In order to investigate the characteristics of pyrolysis of various samples, in the present study, a pure dried filter paper is firstly used as a reference. The pyrolysis temperature can be inferred as a peak on a DTG curve. Figure 1 shows the variation of the pyrolysis temperature with temperature increasing rate. It is seen that as the temperature-increasing rate increases, the pyrolysis temperature increases and the increasing rate of pyrolysisis temperature decreases to zero for higher temperature increasing rate. Thus, the pyrolysis temperature at flame spreading, when the rate of temperature increase would be much higher, was assumed to be much the same as that at 50 ^{o}C/min.
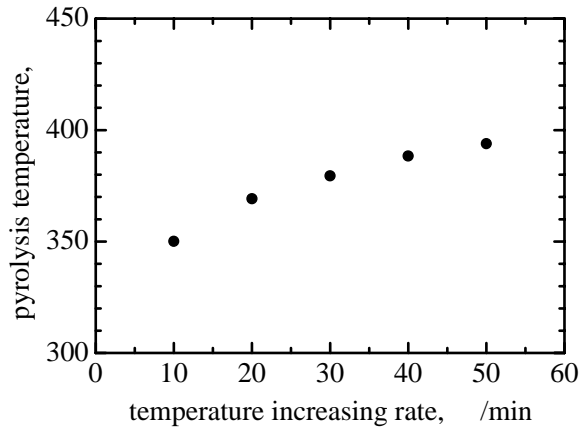
FIGURE 1   Variation of the pyrolysis temperature with temperature increasing rate

The DTG curve of pure filter paper represents that about 90 % of mass is lost in the temperature range from 317 to 440 $^\circ$C. At 440 $^\circ$C, char remains. Then the mass is lost further at a range of temperatures higher than 440 $^\circ$C and finally the sample becomes ash. It was inferred from the DTG curve of a pure polyvinyl acetate resin sheet that about 75 % of mass is lost in the temperature range from 310 to 431 $^\circ$C. This means that the amount of remaining carbon of the polyvinyl acetate resin sheet by pyrolisis reactions is larger than that of the pure filter paper. For the case of a pure urea resin sheet, the mass starts to decrease at 200 $^\circ$C, and about 10 % mass is lost until 240 $^\circ$C. Then the rate of mass loss increases, and about 70 % mass is lost in the main process of pyrolysis reactions. In this case, the product gas at the pyrolysis reactions which start at a lower temperature should be carbon dioxide.
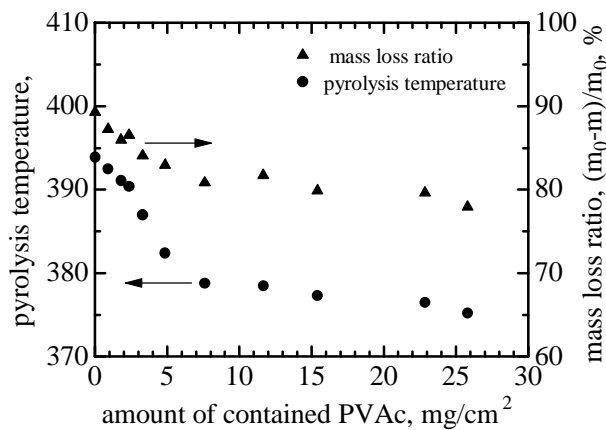

FIGURE 2   Variation of the pyrolysis temperature and the mass loss ratio for the filter paper permeated with the amount of polyvinyl acetate resin.

Figure 2 shows variations of the pyrolysis temperature and the mass loss ratio for the filter paper permeated with the amount of polyvinyl acetate resin. It is seen that in the range of the amounts of permeated polyvinyl acetate resin smaller than 7.6 mg/cm^2, both the pyrolysis temperature and the mass loss ratio decrease with the increase of the amount of permeated resin. On the DTG curve of a paper sheet permeated with urea resin, two peaks were observed. One is small at a lower temperature region, and the other is large at a higher temperature region. The small peak on the DTG curve represents the mass loss before main pyrolysis reaction starts and is a distinct characteristic of the

pyrolysis reaction of a filter paper permeated with urea resin. Figure 3 shows variations of the pyrolysis temperature and the mass loss ratio at lower temperatures. It is seen that the pyrolysis temperature decreases with the increase of the amount of permeated urea resin. This result is similar to that of the filter paper permeated with various amounts of polyvimyl acetate resin. It should be noted that the mass loss ratio at a lower temperature region, representing carbon dioxide ejection, increases with the amount of permeated urea resin.

It can be realized through the experiments on thermogravimetric characteristics that flame spread depends strongly on the pyrolysis reaction of the permeated adhesive.
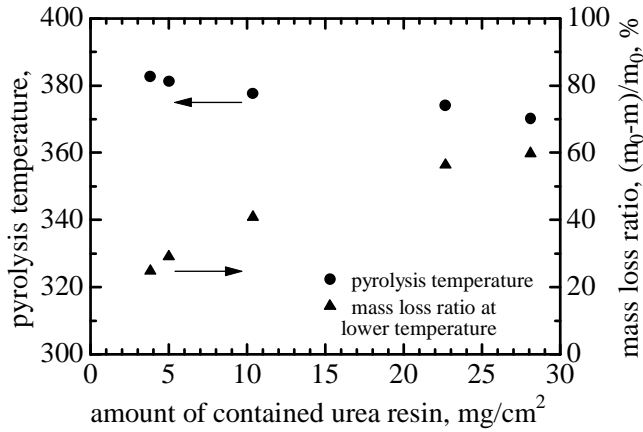

FIGURE 3   Variation of the pyrolysis temperature and the mass loss ratio at lower temperatures with the amount of urea resin.

Temperature Distributions near Leading Flame Edges

Figure 4 shows temperature distributions near the leading flame edges spreading over a pure filter paper, polyvinyl acetate resin permeated filter paper, and urea resin permeated filter paper. It is seen that the distance from a higher temperature zone to the surface is largest for the pure filter paper and shortest for urea resin permeated. The temperature at the surface is lowest for the pure filter paper and highest for the urea resin permeated filter paper. These results are not inconsistent with those of flame spread experiments by Hirano et al. [9]. Near the limit of flame spread the surface temperature is higher than that at stable flame spread. In this study, the flame spread over a pure filter paper sample is more stable than those of other two and that over urea resin permeated sample is more unstable.

Heat Transfer and Retardation Mechanisms of Flame Spread

In discussion on the retardation mechanisms of flame spread, it is would be important to explore the process of heat transfer to the not-yet burning part of sample. In previous studies on flame spread [1-6], various equations have been derived to predict the flame spread rate on the basis of heat transfer consideration. The following is one of such equations:

$$V\delta\rho = \frac{\delta}{c\int_{-\delta/2}^{\delta/2}(T_{x=0}-T_r)dy}\left\{2\int_{-\infty}^{0}\left(\lambda_g\frac{\partial T}{\partial y}\right)_w dx - 2\int_{-\infty}^{0}\varepsilon\sigma\left(T_w^4-T_r^4\right)dx + \int_{-\delta/2}^{\delta/2}\left(\lambda_s\frac{\partial T}{\partial x}\right)_{x=0}dy\right\} \qquad [1]$$

where ρ and c are the density and specific heat of the sample, respectively. T is the temperature and λ_g and λ_s are thermal conductivities of the gas and solid, respectively. The coordinates are shown in

Figure 5, and suffixes, $x=0$, r, and w for T refer to the leading edge of the pyrolysis zone, room, and sheet surface respectively.
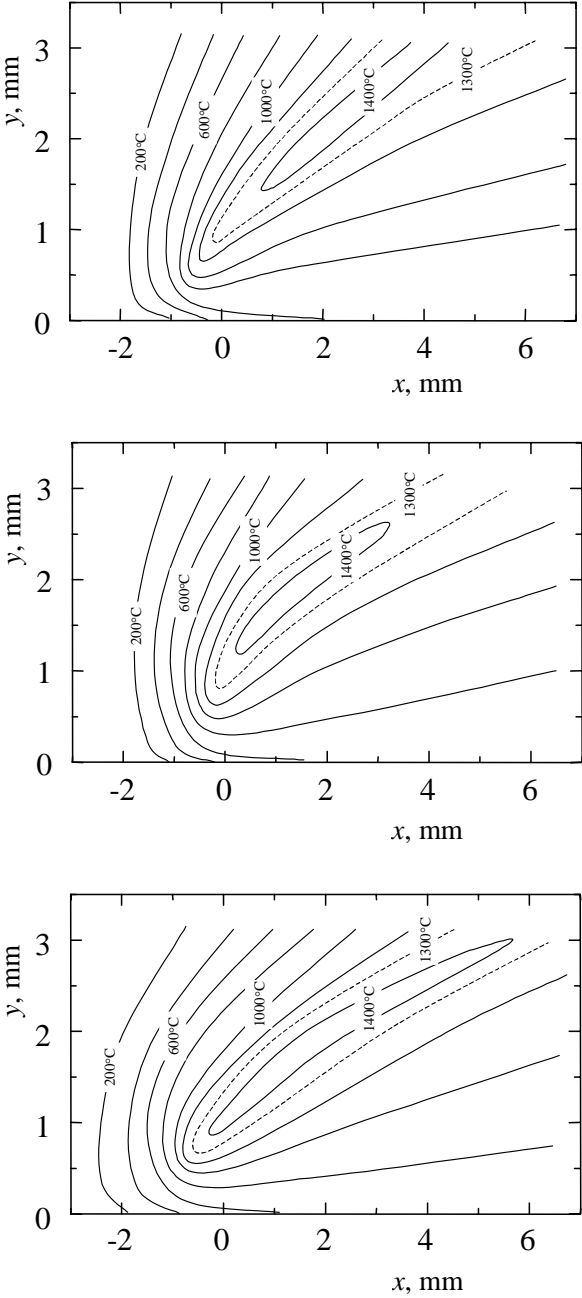

FIGURE 4   Temperature distributions near the leading flame edges spreading over (a) a pure filter paper, (b) polyvinyl acetate resin permeated filter paper, and (c) urea resin permeated filter paper.
x : distance from the leading flame edge
y : distance from the test piece surface

The first, second, and third terms in the braces of the right hand side of Eq. (1) represent the heat flux Q_I from the gas phase to the sheet surfaces of both sides, radiation heat loss Q_{II} from the sheet surfaces to ambient, and heat flux Q_{III} through solid phase in the direction of flame spread. Equation [1] can be rewritten as

$$V\delta\rho = A(Q_I + Q_{II} + Q_{III}) \qquad [2]$$

Where

$$A = \frac{\delta}{c\int_{-\delta/2}^{\delta/2}(T_{x=0} - T_r)dy} \qquad [3]$$

A is the effective factor for temperature increase by heating, and for discussion on flame spread the values of AQ_I, AQ_{II}, and AQ_{III} are more convenient than those of Q_I, Q_{II}, and Q_{III} .
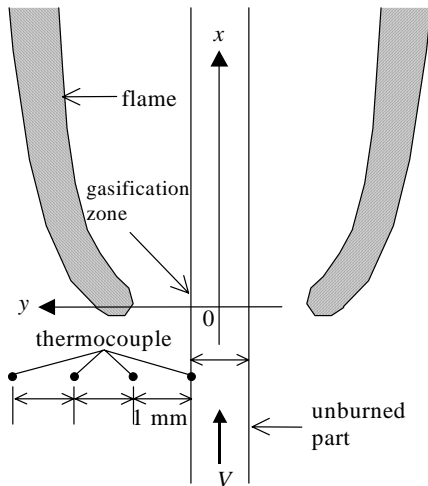

FIGURE 5   Coordinates for discussion on retardation mechanisms of flame spread.

On the basis of the results of temperature measurements, AQ_I, AQ_{II}, and AQ_{III} are evaluated. Figures 6 and 7 show the results of the evaluation. The left hand side $V\delta\rho$ of Equation [1] represents the mass burning rate per unit width of the sheet, and can be estimated on the basis of the results of flame spread experiments. $V\delta\rho$ are also presented in Figures 6 and 7. The values of AQ_{II} and AQ_{III} for polyvinyl acetate resin permeated filter paper are not so different from those for pure filter paper. This fact means that the cause of retardation can be attributed to the reduction of heat flux from the gas phase to the sheet surface. AQ_{III} for urea resin permeated filter paper is almost the same with that for pure filter paper, while AQ_{II} for urea resin permeated filter paper is larger than that for pure filter paper. This fact means that the cause of retardation can be attributed not only to the reduction heat flux from gas phase to the sheet surface but also to the increase of radiation loss.

As mentioned previously, the pyrolysis temperature is shown to decrease with increase of the amount of permeated resin. Since specific heats of paper and resin as well as the thickness of the sample are almost the same, the decrease of pyrolysis temperature should result in the increases of A. If Q_I, is constant, and Q_{II}, and Q_{III} can be neglected as assumed in previous studies [1-6], then $V\delta\rho$ should increase with the decrease of pyrolysis temperature. However, the results of previous flame spread experiments indicate that the mass burning rate decreases with the decrease of pyrolysis temperature caused by the increase of the amount of permeated resin [7]. According to the results, the first term in the braces should decrease with the increase of the amount of permeated resin. This coincides with the results of temperature measurements (Figure 4).

The results of the present thermogravimetric experiments indicate that residue, the main component of which would be carbon, increases with the amount of permeated resin. This means that the thickness of a layer composed of residue established over the sample surface increases with the increase of the amount of permeated resin. The residue layer would be effective to reduce the heat flux from the gas phase. The reduction of combustible gas to the gas phase would be the cause to approach the leading

flame edge to the surface. These are the reasons why the flame spread rate decreases and the higher temperature region approaches to the sample surface with the increase of the permeated resin.

In the case of the sample permeated with urea resin, the amount of residue is larger than that of pure filter paper or that of filter paper permeated with polyvinyl acetate resin. Also, the results of thermogravimetric experiments indicate that carbon dioxide would be ejected to the gas phase by pyrolysis reaction at a lower temperature. This carbon dioxide ejection near the leading flame edge is also inferred to be effective to enhance the retardation of the flame spread.
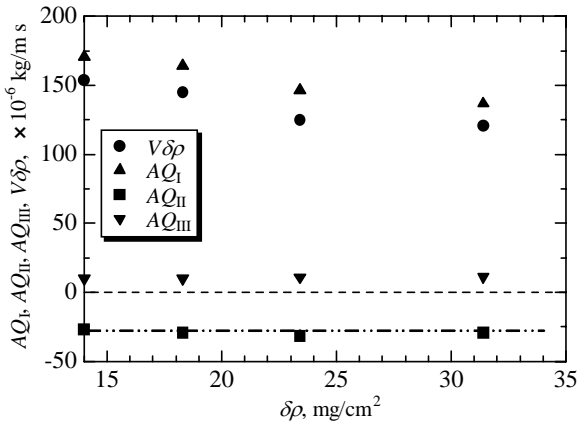
FIGURE 6   Heat transferred to the solid in various modes and mass burning rate in the cases of flame spread over filter paper sheets permeated with various amounts of polyvinyl acetate resin.
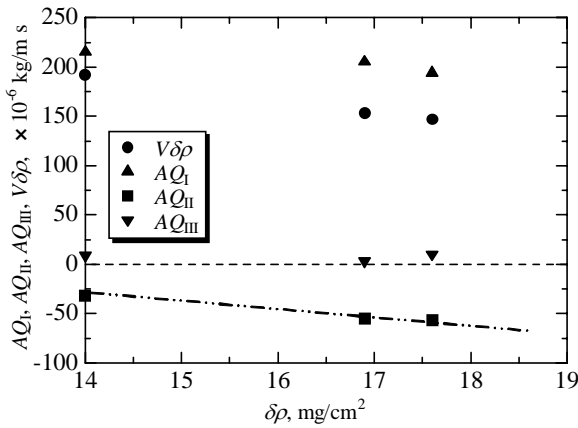
FIGURE 7   Heat transferred to the solid in various modes and mass burning rate in the cases of flame spread over filter paper sheets permeated with various amounts of urea resin.

CONCLUSIONS

A study has been performed to elucidate the retardation mechanisms of flame spread over filter papers permeated with an adhesive by thernogravimetric analyses and temperature measurements, an the following conclusions are derived :

1. Flame spread depends strongly on the pyrolysis reaction of a permeated adhesive. The highest pyrolysis temperature is of the pure filter paper, and the pyrolysis temperature decreases with the

increase of the amount of permeated resin. However, the flame spread rate decreases with the increase of the amount of permeated resin. This means that the heat flux from the gas phase to the sample surface decreases with the increase of the amount of permeated resin.

2. The decrease of the heat flux to the sample surface with the increase of the permeated resin is inferred to be the main cause to decrease the flame spread rate over a filter paper permeated with polyvinyl acetate resin permeation. For polyvinyl acetate resin, the residue after pyrolysis reaction forms a layer to reduce the heat flux to the sample surface.

3. For urea resin, also the residue forms a layer over the sample surface. Also, the results of thermogravimetric experiments indicate that carbon dioxide would ejected to the gas phase beneath the leading flame edge. Thus, the reduction of flame spread over a filter paper permeated with urea resin is inferred to be not only due to residue layer formed on the surface but also due to carbon dioxide ejected to the gas phase.

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