Effects of Humidity on Downward Flame Spread over Combustible Solids

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ABSTRACTS

Effects of humidity on downward flame spread over combustible solids have been studied experimentally. The experiments were performed using a wind tunnel with heater and humidifier. The temperature and velocity of the air flowing in the tunnel were controlled to be 20℃ and 10 cm/s, respectively, and the moisture content was varied. The test pieces used were of filter paper and PMMA, typical hygroscopic and non-hygroscopic materials, respectively.

Although both the flame spread rates over these materials decreases as the moisture content increases, the decreasing rate for filter paper is much larger than that for PMMA. It is shown that filter paper is influenced by moisture more strongly than PMMA. This result indicates that flame spread in an air stream with moisture depends strongly on the hygroscopicity of the combustible material. When the moisture content in the air is high, local blow offs are observed repeatedly at various parts on the leading flame edge spreading over a test piece of filter paper, while the flame spread over PMMA seems stable. Amount of heat transferred from the spreading flame to unburned material at preheat zone is calculated on the basis of experimental results. When the moisture content increases, the heat input for both materials decreases though the decreasing rate for filter paper is larger than that for PMMA. This result shows that the moisture in the air stream influences not only the phenomena in the solid phase but also in the gas phase. The effects of the moisture in the air stream on the flame spread is inferred to be attributable to the reduction of chemical reaction rate in the gas phase caused by water vapor ejected from the solid surface.

NOMENCLATURE

C_p	Specific heat of test piece material
C_w	Specific heat of water

h	Width of the test piece
M_w	Molecular weight of water
Q	Amount of heat transferred from spreading flame to unburnt material at preheat zone
T_p	Pyrolysis temperature of test piece material
T_w	Boiling point of water
T_0	Initial temperature
V	Flame spread rate
w_0	Weight of dried test piece
w	Weight of test piece (at the state of equilibrium of moisture content)
δ	Test piece thickness
ΔH_w	Latent heat of water
ρ_p	Density of the test piece
ρ_w	Mass of absorbed water per unit volume of the filter paper

INTRODUCTION

Flame spread over combustible solids is a fundamental phenomenon in fires. For understanding fires and improving fire technologies, knowledge on the mechanisms of flame spread is essential. Flame spread is found to depend on three major processes: heat transfer from flame to burning material, generation of volatile, and oxidation reaction between fuel and air. These processes are closely related to one another, so that the change of one of them will result in the changes of others. Various groups interested in fire research have been concerned with this subject[1-5]. As a result of efforts of these groups, flame spread over combustible solids was found to depend strongly on mass and heat transfer phenomena near the leading flame edge.

It is commonly known that the flame over combustible materials is easy to spread at low humidity and difficult at high humidity. Flame spread rate may decrease by slowing down any of those processes as the humidity increases. Taking this into consideration, the amount of moisture content in the air and absorbed water in the combustible solids also affect heat transfer phenomena near the leading flame edge. In previous studies, therefore, flame spread experiments were conducted considering the effects of humidity [1-5]. However, the effects have never been clearly explored quantitatively. In order to elucidate the flame-spread phenomena, it is important to explore the effects of humidity on flame spread. In the present study, flame spread rates at various moisture concentrations over filter paper and PMMA, typical hygroscopic and non-hygroscopic materials, were measured, and the amount of heat transferred from the spreading flame to unburnt materials are calculated on the basis o experimental results.

EXPERIMENTAL

The experiments were conducted in a vertical duct of 10 cm × 10 cm cross section and 2 cm long, which was mounted on a converging nozzle of a wind tunnel (Fig. 1) with heater and

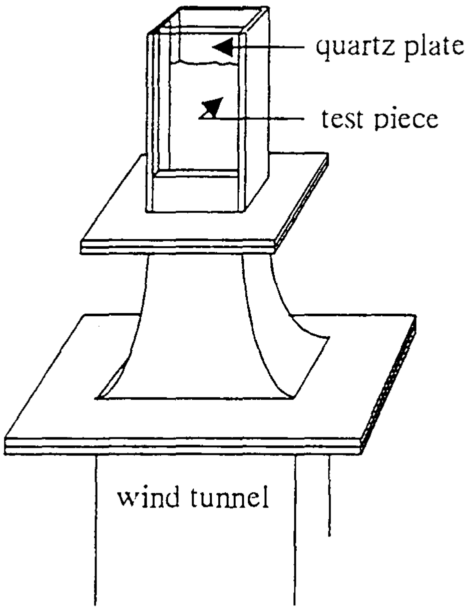
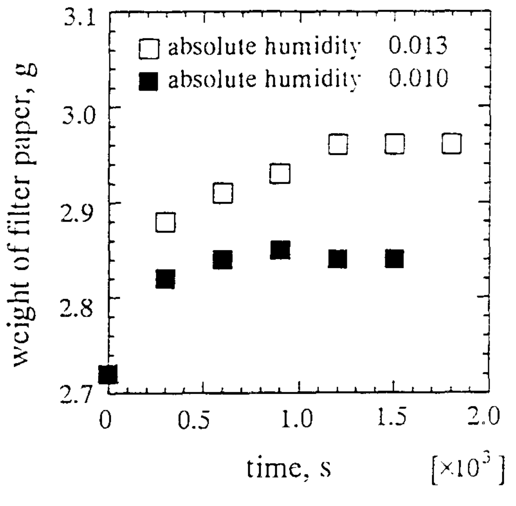
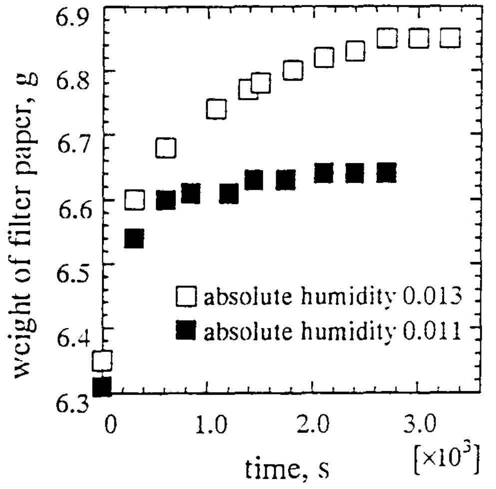


Figure 1 Experimental apparatus



(a) 0.026 cm-thick filter paper



(b) 0.068cm-thick filter paper

Figure 2 Weight variation of filter paper with time

humidifier. The flame spread phenomena were observed through an optical Pyrex plate serving as duct walls parallel to the test piece surface. The temperature and velocity of the air flowing in the tunnel were controlled to be 20 °C and 10 cm/s, respectively, and the value of absolute humidity was varied from 0.005 (31%RH(relative humidity)) to 0.015 (90%RH). The absolute humidity, which is a quantity suitable to represent the moisture content in the air, is defined as (mass of vapor in the air)/(mass of dry air).

The test pieces used for the experiments were sheets of filter paper and PMMA, typical hygroscopic and non-hygroscopic materials, respectively. The test pieces of filter paper and PMMA were of a surface area of 10 cm x 20 cm. The thicknesses of the test pieces of filter paper were 0.026 cm and 0.068 cm, and that of PMMA was 0.10 cm.

The amount of absorbed water was controlled as follows: test pieces were dried for more than 48 hours in a desiccator (20 °C, 10%RH). Then, they were placed at the center of the duct in which the air was flowing at objective humidity till the amount of absorption became unchanged.

An electrically heated nichrome wire (0.07 cm in diameter) was used as an ignition system to simultaneously ignite the top edge of the test pieces. The ignition system was removed just after the test pieces were ignited in order to minimize disturbance of the ambient atmosphere during the test. The flame spread phenomena were recorded by using a video camera.

RESULTS AND DISCUSSION

Hygroscopicity

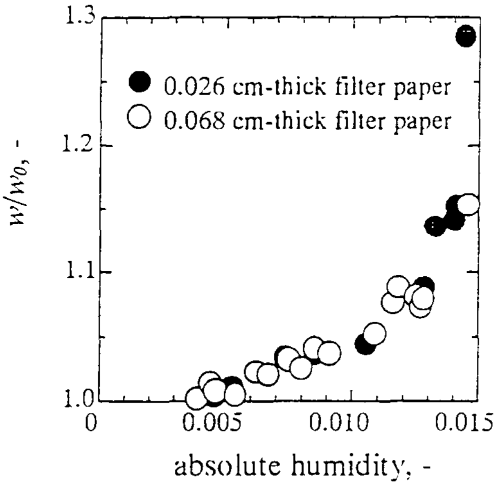


Figure 3 Variation of the ratio of w to w_0 with absolute humidity

w_0: Weight of the dried test piece
w : Weight of the test piece (at the state of equilibrium of moisture content)

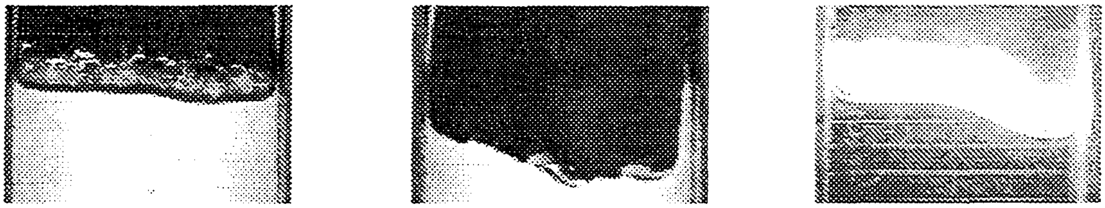
Cellulose, of which paper is mainly composed, has a very strong affinity for water [6]. Cellulose fibers absorb or desorb water vapor until they reach a state of equilibrium with the surrounding atmosphere and the moisture content depends on the humidity of the atmosphere, the condition of the cellulose, and the history of the cellulose. If a given sample of cellulose approaches the state of equilibrium from a high humidity condition, it will be of a higher moisture content than that when it approaches the state of equilibrium from a low humidity condition. This phenomenon, which is inherent in all cellulose, is known as hysteresis. Figures 2(a) and (b) show weight variation of 0.026 cm-thick and 0.068 cm-thick test pieces of filter paper with time, respectively. It is seen that more time is needed to approach the equilibrium as the absolute humidity increases or filter paper becomes thick. Figure 3 shows the variation of the ratio of w to w_0, with the absolute humidity. It is seen that in the range of the absolute humidity from 0.005 to 0.010, the ratio (w/w_0) is changed slightly with humidity. It rapidly increases in the range from 0.010 to 0.015. Moreover, the ratio is found not to depend on the thickness of the test piece in this study since the variation of the ratio for 0.026 and that for 0.068 cm-thick filter paper are on the same curve.

The hygroscopicity of PMMA was also examined. A sheet of PMMA was dried for more than 48 hours in a desiccator and then placed in water for 48 hours. The variation of moisture content in PMMA under this condition was found to be 0.9% of the PMMA dry weight. From this result, PMMA is considered to be non-hygroscopic, compared with the filter paper.

Behavior of Spreading Flames

Typical photographs of burning test pieces are shown in Figs. 4(a)-4(c), and typical records of their configurations are shown in Figs. 5(a)-5(b). Solid lines indicate the configurations of leading flame edges, which were recorded every 10 seconds.

Figures 4(a) and 5(a) show behavior of a spreading flame over a test piece of 0.026 cm-thick filter paper when the absolute humidity is 0.005 (31%RH). Under this condition, stable, straight burning zone is established by igniting simultaneously the top end of the paper and begin to spread downward. Burning behavior of a spreading flame over a test piece of 0.026 cm thick filter paper at the absolute humidity 0.013 (90%RH) is shown in Figures 4(b) and 5(b). It is seen that the leading flame edge cannot be kept a straight line. Local blow offs are observed repeatedly at various parts on the leading flame edge spreading over the filter paper. When the absolute humidity is 0.015 (99% RH), only small parts of the ignition line



(a) absolute humidity
0.005
0.026 cm-thick filter paper

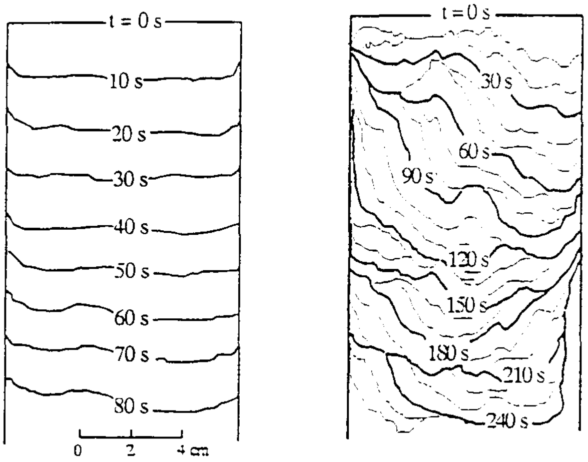
(b) absolute humidity
0.013
0.026 cm-thick filter paper

(c) absolute humidity
0.014
0.10 cm-thick PMMA

Figure 4 Typical photographs of burning test pieces

are found to remain burning just after ignition, but do not spread downward at all.

Figure 4(c) shows burning behavior of a spreading flame over a test piece of 0.010 cm thick PMMA when the absolute humidity is 0.014 (94%RH). Even at such high humidity, the flame spread over PMMA seems stable.



(a) absolute humidity
0.005

(b) absolute humidity
0.013

Figure 5 Typical records of burning filter paper configurations

Spread Rate

The variation of mean flame spread rate V with absolute humidity is shown in Fig. 6. V was obtained by measuring the time to spread from 4 to 16 cm from the ignition line. Although the flame spread rate over both materials decreases as the absolute humidity increases, the decreasing rate in spreading rate over the test piece of filter paper is much larger than that of PMMA. When the absolute humidity increases from 0.005 to 0.010, a 23% decrease in the spread rate is observed for filter paper and a 5% decrease for PMMA. It is seen that the flame spread rate over the test piece of filter paper is influenced by moisture more strongly than that of PMMA. This result indicates that flame spread in an air stream with moisture depends strongly on the hygroscopicity of the combustible material.

Heat Transfer to Unburnt Materials

Amount of heat transferred from a spreading flame to the unburnt material in the preheat zone is calculated on the basis of experimental results using the following equation:

$$Q = h\rho_p \delta V C_p (T_p - T_0) + h\rho_w \delta V C_w (T_w - T_0) + h\rho_w \delta V \Delta H_w / M_w \ .$$

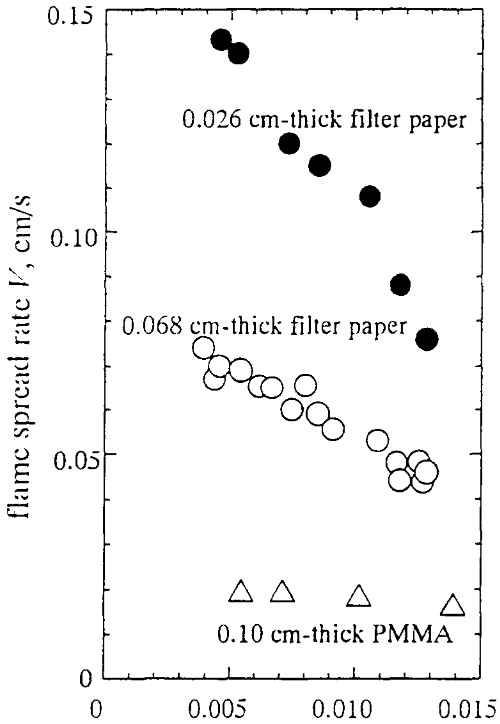


Figure 6 Variation of mean flame spread rate V with absolute humidity

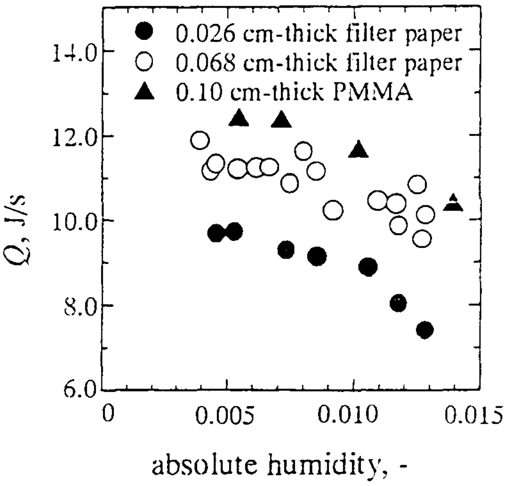


Figure 7 Variation of Q with absolute humidity

The first and second terms on the right-hand side represent the heat needed per unit time to raise the test piece temperature from its initial temperature T_0 to the pyrolysis temperature T_p, and water temperature to the boiling point T_w, respectively. The third term represents the heat needed to evaporate absorbed water. When the test piece is of PMMA, the second and third terms are considered to be 0 because PMMA is non-hygroscopic material.

Q can be estimated by using experimental results. The result is shown in Fig. 7. For each test piece, Q decreases as the absolute humidity increases. When the absolute humidity increases from 0.005 to 0.010, an 8% decrease in the heat input is obtained for filter paper and a 5% decrease for PMMA. This result shows that the moisture content in the air stream influences not only the phenomena in the solid phase but also in the gas phase. The decreasing Q for filter paper is larger than that for PMMA, so the effects of the moisture in the air stream on the flame spread over filter paper are inferred to be attributable to the reduction of chemical reaction rate in the gas phase caused by water vapor ejected from the solid surface.

CONCLUSIONS

Effects of humidity on downward flame spread over combustible solids have been studied experimentally.

Although both the flame spread rates over test pieces of filter paper and PMMA decreases as the absolute humidity increases, the decreasing rate in the spread rate over the test pieces of filter paper is much larger than that of PMMA. When the absolute humidity increases from 0.005 to 0.010, a 23% decrease in the spread rate is observed for filter paper and a 5% decrease for PMMA. It is shown that the flame spread rate over a test piece of filter paper is influenced by moisture more strongly than that of PMMA. This result indicates that flame spread in an air stream with moisture depends strongly on the hygroscopicity of the combustible material.

When the absolute humidity is 0.013 (90%RH), local blow offs are observed repeatedly at various parts on the leading flame edge spreading over a test piece of filter paper, while the flame spread over PMMA seems stable.

The amount of heat transferred from the spreading flame to unburned material at preheat zone is calculated on the basis of experimental results. When the absolute humidity increases from 0.005 to 0.010, an 8% decrease of the heat input is resulted for filter paper and a 5% decrease for PMMA. This result shows that the moisture in the air stream influences not only the phenomena in the solid phase but also in the gas phase. The effects of the moisture in the air stream on the flame spread are inferred to be attributable to the reduction of chemical reaction rate in the gas phase caused by water vapor ejected from the solid surface.

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