Effects of Humidity and Temperature on Downward Flame Spread over Filter Paper

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ABSTRACT

Effects of humidity and temperature on downward flame spread over combustible solids have been studied experimentally. The flame spread tests were carried out in a vertical duct mounted on a nozzle of a wind tunnel. The humidity and temperature of the air flowing in the duct were controlled with a humidifier and heater installed in the wind tunnel. The velocity and temperature were adjusted to the values of 10 cm/s, and 20 °C or 30 °C, respectively, and the humidity was widely varied. The test pieces used were of filter paper as a typical hygroscopic material. It was found that the ratio w / w_0 of the weight of water absorbed in the paper, to the weight of the paper sheet does not depend on the thickness of the paper sheet, and is closely related not to the absolute humidity but to the relative humidity. The humidity is supposed to affect the flame spread rate both in the gas and condensed phases. From the comparison of these effects in two phases, the effect in the condensed phase, namely, the effect of the higroscopicity of the paper sheet, is inferred to be the desicive factor. The effect in the gas phase is also examined by estimating the heat transfer from the spreading flame into the preheating region of the sheet. The results show that the heat supply from the flame is closely related to the absolute humidity.

KEYWORDS: flame spread, fire physics, humidity, moisture

NOMENCLATURE

C_s : Specific heat of cellulose
C_{wl} : Specific heat of water (liquid)
h : Width of the paper sheet
M_w : Molecular weight of water

Q : heat transfer per unit time from spreading flame to unburnt material in the preheat zone
T_p : Pyrolysis temperature of cellulose
T_b : Boiling point of water
T_i : Initial temperature
V : Flame spread rate
w_0 : Weight of the paper sheet dried in the conditioned desiccator
w : Weight of the paper sheet at the state of equilibrium of moisture content
δ : Thickness of the paper sheet
ΔH_{wl} : Latent heat of water
ρ_s : Density of the paper sheet dried in the conditioned desiccator
ρ_{wl} : Mass of absorbed water per unit volume of the paper sheet

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. It has been found that the flame spread over combustible solids depends strongly on mass and heat transfer phenomena near the leading flame edge [1-5].

It is commonly known that the flame over combustible materials is easy to spread at low humidity and difficult at high humidity. The 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 fame spread phenomena, it is important to explore the effects of humidity on flame spread. Therefore, the authors have been studied the effect of humidity on downward flame spread over combustible materials [6]. In our previous study, the effect of humidity at room temperature was examined for test pieces of filter paper and PMMA, typical hygroscopic and non-hygroscopic materials.

In real fires, it will be very important to know the effect of temperature on the flame spread phenomena, since the combustible material to be burnt in the fire will probably be placed close to the burning point and be heated before it will burn. Although it is known that the temperature will affect humidity in the air and moisture content in combustible materials, the effect on the mechanism of flame spread is not well understood. Thus, in this study, the effect of humidity and temperature on flame spread phenomena has been explored.

EXPERIMENTAL

Figure 1 shows the experimental apparatus used in this study. The flame spread tests were carried out in a vertical duct of 10 cm × 10 cm cross section and 21 cm long, which was mounted on a converging nozzle of a wind tunnel. The flame spread phenomena were observed through an optical Pyrex plate serving as duct walls parallel to the paper surface. The air was introduced to the system by a blower and humidified with water vapor from a heated water tank. Since the humidity of the air in the room was not sufficiently low, dry air was

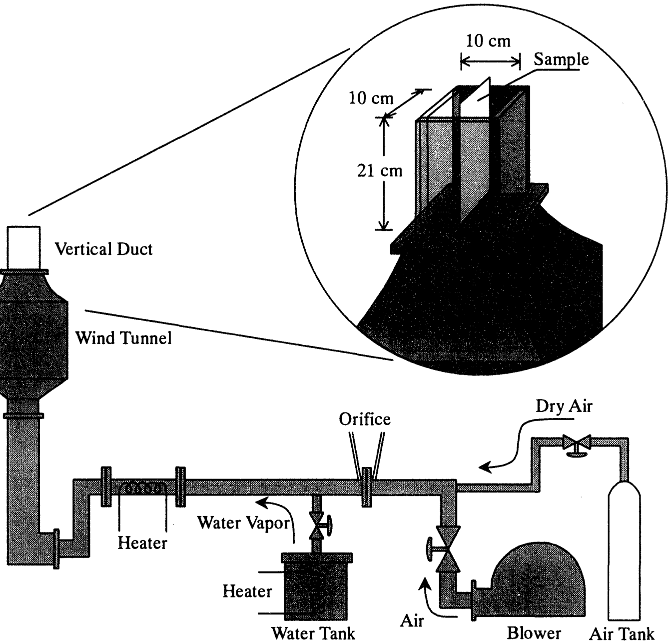


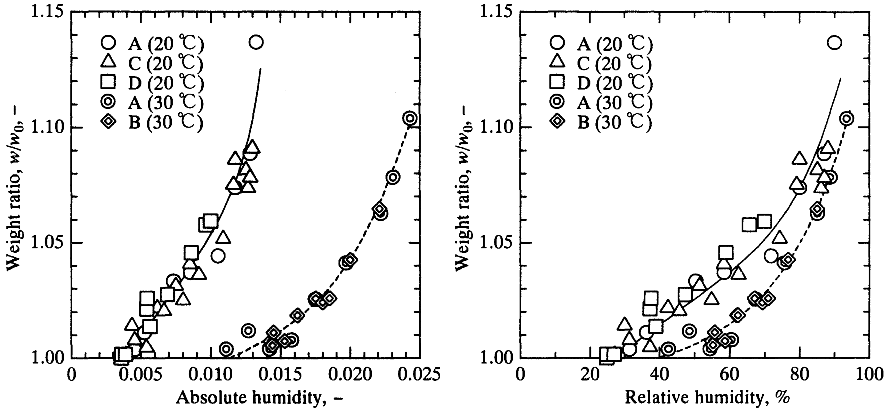
FIGURE 1. Experimental Apparatus

supplied from an air tank for the condition of lower humidity. The temperature and humidity in the duct were regulated using two heaters; one is installed in the wind tunnel, and the other in the water tank. The temperature was controlled to 20 °C or 30 °C, and the value of relative humidity was varied from 25 % to 95 %. The velocity was regulated to 10 cm/s throughout the experiments.

In the experiments, four kinds of filter paper were used. Their thickness δ and density ρ_s are shown in table 1. The thickness of paper A, 0.026 cm, was notably smaller than those of the others were. Although papers B, C, and D differed in thickness, their difference in weight $\delta\rho_s$ per unit area was negligible. The paper sheets were of a surface area of 10 cm × 20 cm. It is known that the amount of absorbed water in paper depends on the history of its surrounding

TABLE 1. Filter paper used for the experiments

Filter Paper	Thickness, δ, cm	Density, ρ_s, g/cm^3	$\delta\rho_s$, g/cm^2
A	0.026	0.51	0.013
B	0.057	0.54	0.031
C	0.068	0.46	0.031
D	0.075	0.43	0.032



(a) Dependence on the absolute humidity (b) Dependence on the relative humidity

FIGURE 2. Dependence of the weight ratio of w to w_0 on the humidity
w_0 : weight of the dried test piece
w : weight of the test piece at the state of equilibrium of the moisture content

condition [7]. In order to prevent the fluctuation caused by this hysteresis, the amount of absorbed water was controlled as follows: the paper sheets 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 and temperature till the amount of absorption became unchanged. Generally, higher the humidity or thicker the paper sheets, more time was needed for the saturation. The time was about 50 minutes for thick paper (paper C) under high-humidity condition (20 °C, 87%RH) [6]. The equilibrium condition was confirmed for each test from the measurement of the weight of the paper.

An electrically heated nichrome wire (0.07 cm in diameter) was used as an ignition system to simultaneously ignite the top edge of the paper sheet. The ignition system was removed just after the paper sheet was ignited in order to minimize disturbance of the ambient atmosphere during the test. The behavior of the flame spread was videotaped.

RESULTS

Hygroscopicity

Figure 2(a) shows the variation of ratio of w to w_0, with absolute humidity, where w and w_0 are the weight of the filter paper at the state of equilibrium of moisture content, and the weight of the filter paper dried in a desiccator, respectively. 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) /

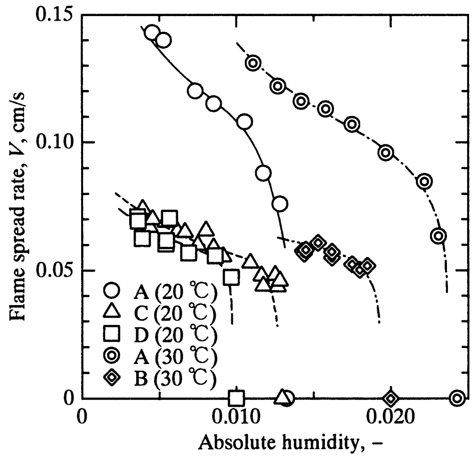


FIGURE 3. Dependence of the flame spread rate on the absolute humidity

(mass of dry air). It is seen that the ratio (w/w_0) increases as the absolute humidity increases. Moreover, the ratio is found not to depend on the thickness of the paper in this study since the variations of the ratio for tested paper sheets are on the same curve for each temperature.

On the other hand, it strongly depends on the temperature of the air. When the temperature increases from 20 to 30 °C, the ratio (w/w_0) at 0.01 in absolute humidity decreases from 1.05 to 1.00. However, if we compare the ratio for relative humidity, the difference is quite small, as shown in Fig. 2(b), compared to the difference shown in Fig. 2(a). It is noted from these results that the amount of water absorbed in the paper is closely related not to the absolute humidity but to the relative humidity.

Flame Spread Rate

The variation of mean flame spread rate *V* with absolute humidity is shown in Fig. 3. *V* was obtained by measuring the time to for spreading from 4 to 16 cm from the ignition line. The data of $V = 0$ represent that the flame spread becomes unstable after the ignition and have stopped before the leading flame edge touches the line on 16 cm from the ignition line.

The flame spread rate over each paper sheet decreases as the absolute humidity increases, and becomes zero when the absolute humidity is higher than a critical value for the paper. From the comparison of the results for same paper (paper A) at the air temperature of 20 and 30 °C, it is seen that the flame spread rate increases when the air temperature increases. The critical value of the absolute humidity also increases from 0.013 to 0.024 as the temperature increases from 20 to 30 °C. On the other hand, comparison of the data for papers at the same air temperature, it is seen that *V* is higher for the thinner paper (A) than that for the thicker one (B, C, or D). The critical value of the absolute humidity also seems to be higher for the thinner

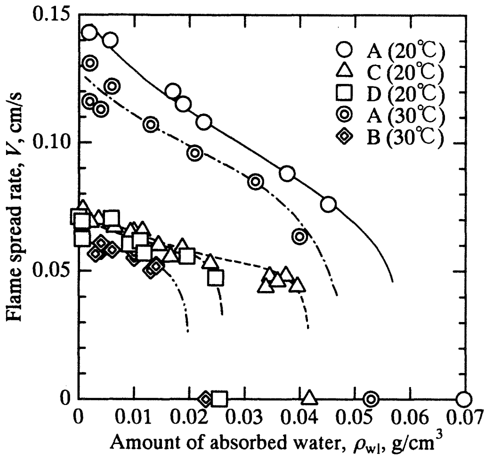


FIGURE 4. Dependence of the flame spread rate on the amount of absorbed water

paper than that for the thicker one. However, it should be noted here that the critical value 0.013 for paper C is significantly larger than the value 0.010 for paper D, and almost same to the value for paper A, although the papers C and D have negligible difference in thickness and density. This infers that the critical value would be affected by some factors other than thickness and density.

DISCUSSION

Heat transfer to the preheat region of burning material has strong influence on flame spread. Flame spread rate V is predicted on the basis of the balance between the heat Q transferred from a spreading flame to the unburnt material in the preheat zone, and the energy needed for preheating the material from the initial temperature to the pyrolysis temperature. In the preheating process, the paper material, cellulose, should be heated from its initial temperature T_i to the pyrolysis temperature T_p prior to its pyrolysis reactions. The water absorbed in the paper also needs preheating from the initial temperature to the vaporizing temperature, and latent heat for the evaporation. Since the time for the heating process is short, the vaporizing temperature is regarded as the boiling point of water. Considering the balance of the energy in the preheat region, V is predicted with the following equation:

$$V = \frac{Q}{h\delta\left[\rho_s C_s (T_p - T_i) + \rho_{wl}\left\{C_{wl}(T_b - T_i) + \Delta H_{wl}/M_w\right\}\right]} \,. \tag{1}$$

The first and second terms in the denominator of the right-hand side represent the heat needed per unit time to raise the paper temperature from its initial temperature T_i to the pyrolysis temperature T_p, and water temperature to the boiling point T_b, respectively. The third term

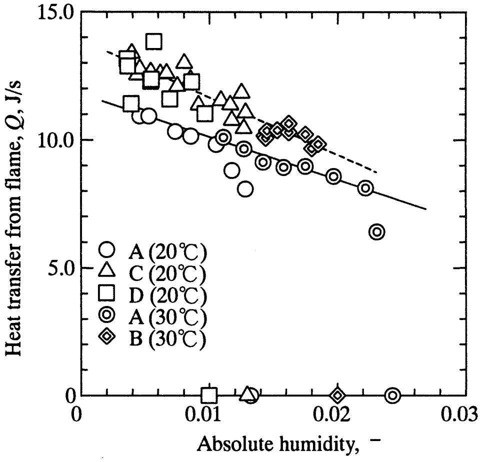


FIGURE 5. Dependence of the estimated heat transfer from the flame on the absolute humidity

represents the latent heat needed to evaporate absorbed water.

The effect of humidity on the flame spread rate will appear both in the gas and condensed phases. In the gas phase, the moisture in the air will affect the flame temperature by changing the thermal properties and chemical reactions. These will cause the change of Q in the nominator of the equation. This effect would be characterized by absolute humidity, which represents the moisture content in the air, rather than relative humidity. On the other hand, in the condensed phase, humidity will affect the amount ρ_{wl} of the absorbed water and changes the denominator of the equation. From this point, the relative humidity seems to be important rather than the absolute humidity since ρ_{wl} is strongly related to the relative humidity as it has been explained with Fig. 2.

Figure 4 shows the dependence of V on ρ_{wl}, which is a replot of data in Fig. 3. It is seen that the differences between the curves for the temperatures of 20 and 30 °C seem to be small compared to those in Fig. 3. It is inferred from this result that the higroscopicity of the paper sheets is the desicive factor of the effect of humidity in the experiments.

If the temperature T_i of the air increases, $(T_p - T_i)$ and $(T_b - T_i)$ in the deliminator of the equation decreases. However, this effect on V is estimated to be of neglegible because the temperatures T_p and T_b, which are about 450 and 100 °C, respectively, is large enough compared to T_i of the experiments. On the contrary, V decreases as it is seen in Fig. 4. This change should be caused by the decrease of Q.

Q can be estimated with the equation by using experimental results. The result is shown in Fig. 5. Values of h, C_s, C_{wl}, M_w, T_p, T_b, and ΔH_{wl} used for calculations are 10 cm, 1.32 J/g K, 4.18 J/g K, 18 g/mol, 723 K, 373 K, and 4.07 x 10^4 J/mol, respectively. For each paper sheets,

Q decreases as the absolute humidity increases. Moreover, the data for paper A at the temperature of 20 °C and those at the temperature of 30 °C seem to make a single line if the plots near the critical values are ignored. The data for papers B, C, and D also seem to be in a single line. The difference between these two lines are convincing, since the value of Q for thicker paper sheet is expected to be larger than thinner one as it has been figured out in our previous study [8]. The results show that the heat supply from the flame is closely related to the absolute humidity.

It is pointed out that the flame spread rate can be predicted from the consideration of the heat transfer as it is shown in the equation 1. However, further investigation is required for explaining the condition of the extinction. Since the flame spread rate V does not approach linearly to zero as shown in Figs. 3 and 4, there should be a discrete transition from the quasi-steady flame spread to the extinction. This transition would hardly be explained just from the discussion of heat balance equations. As the humidity increases, the heat transfer from the flame to the solid decreases. This reduces the supply of combustible volatile to the leading flame. If the supply of the gas becomes less than a critical value, the extinction would occur.

CONCLUSIONS

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

Hygroscopicity of the filter paper used in this study has been examined. It is found that the amount of water absorbed in the filter paper does not depend on the thickness of the paper sheets, and is closely related not to the absolute humidity but to the relative humidity.

From the results of flame spread experiments, the dependence of flame spread rate on the humidity has been examined. The effect of humidity on the flame spread rate is considered to appear both in the gas and condensed phases. From the comparison of these effects in two phases, the effect in the condensed phase, namely, the effect of the higroscopicity of the paper sheet, is inferred to be the desicive factor.

Heat transfer from a spreading flame into the preheat region of the material has been estimated by using experimental results with a proposed equation. The heat transfer is found to decrease as the absolute humidity increases. The data for each paper at the temperature of 20 and 30 °C seem to be in a single line. The results show that the heat supply from the flame is closely related to the absolute humidity.

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