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Australian-American Match Tests

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Abstract—What is the variability in American and Australian matches as radiation sources? Measurements and calculations of heat requirements for ignition, radiation outputs, heat contents, flame and ignition temperatures, and burning times for two species of wooden match, show there is large variability in the radiant heat output. Also, there is substantial variation in the temperature needed to light a match. These factors mean that the ignitibility of two closely spaced matches, once one is lit, will vary markedly, especially since most ignition is a result of the initial flare of the adjacent match head rather than the gradual accumulation of radiant heat. Tabulated values for the variables listed are included.

Keywords: fire, percolation, matches, radiation heating

Recent interest in the study of wildfire spread as a percolation process through a random network on a two-dimensional lattice, has included Stauffer (1985), who considered the situation in which a given fraction of sites on a square lattice is randomly occupied by burnable sites (their probability of ignition is unity); the remainder of the lattice is occupied by nonburnable sites (their probability of ignition is zero). The ability of such a numerical model to propagate its fire depends on the percentage of burnable sites on the lattice, the characteristics of the sites, the intensity and range of the interaction between sites, and the physical size of the lattice used in the simulation.

Beer (1990a) tested the simple percolation model of Albinet and others (1986) and Stauffer (1985) in which a burning site can ignite only its nearest neighbors. This was done with physical experiments using matches vertically inserted into random sites on a wire mesh; the match locations were the burnable sites. These experiments reveal that a burning match can fail to ignite a nearest neighbor match, but at the same time ignite a match several lattice sites away.

The laboratory results and the results predicted by simple percolation theory differ (Beer 1990a). Part of the reason for the discrepancy seems to be that ignition of vertical matches (whose ignitible heads are left intact to ensure a high probability of ignition) can arise from at least two causes. When a match is enveloped in the flare of an igniting neighbor it may ignite, but if it does not, accumulated radiation from surrounding burning elements may ignite it.

Interpretation of laboratory studies of percolation thus requires fundamental quantitative information on the ignition characteristics of the matches used. Questions to be answered include: What are the criteria for radiation to ignite a match? What is the variability in matches considered as radiative ignition sources? Which of the two readily available match species, Australian or American, might be more suitable for laboratory studies of percolation?

Fortunately, we had a number of tools at our disposal to help answer these questions. We applied these tools to Australian Redhead wooden safety matches manufactured in Melbourne, Victoria, by Bryant and May, and American Ohio Blue Tip Strike-Anywhere wooden matches manufactured by Ohio Match Co. in Wadsworth, OH.

This report is in two parts. The first deals with the properties of matches once they are aflame; the second deals with the conditions necessary for ignition.

Flaming

Experiment

A batch of 10 of each match species was selected at random. Each match was weighed and its physical dimensions measured. These same 10 matches were

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used in the radiation experiment described later. Additional batches of 10 matches were sacrificed to thermogravimetric, bomb calorimetric, and combustible gas analysis to determine heat content. Three more of each species were burned in a vertical position on an electronic balance to determine mass loss rate. One of each species of match was burned in front of a video camera. Image analysis of the resulting videotape provided the area of the visible flame normal to the match axis.

The radiated energy from the previously weighed and measured matches was measured using a thermopile detector (Northwood Technologies model C-1) at a distance of 20 cm from the vertically burning match in a direction normal to the axis of the match. The output of the thermopile was amplified by a factor of 1,000 and the result recorded as a function of time using a Nicolet sampling oscilloscope (fig. 1).

Results

Experimental results are presented in table 1 and figure 1. Reduction of the data was straightforward. The length, width, weight, burning time, and energy content (supplied by standard laboratory techniques) were all directly measured and the mean and standard deviation calculated. Flame velocity was calculated as an average from the length of the match and the burning time, with the match vertical and the flame propagating downward. Total heat output was taken from the average weight and the energy content for two different 10-match batches. Mass loss rate was determined from plots of the weight experiments and proved to be substantially constant for each of the species. However, the determination of radiated heat required some assumptions.

We obtained the total radiant output, the average radiant output, and the radiant conversion efficiency from the radiometric data by assuming the flame to be an isotropically radiating point source at a distance *d* cm from the detector. The detector calibration, *R*, was obtained from the manufacturer's specifications as 10 V/W. The integrated output in Volt-seconds was measured by weighing cut-outs from the radiometer traces, samples of which are shown in figure 1. The total radiant output, *E*, for each match was then calculated from:

$$E = 4\pi d^2 Vt/(RA_d). \tag{1}$$

where *V* is the measured voltage and *t* the measured burn duration. A_d (1.117 cm^2) is the area of the radiation detector. Since we had the measured burn time for each match, the radiant output rate was readily calculated for each single match experiment. The radiant conversion efficiency uses the results of measuring two different batches of matches, and was found by dividing the average heat content by the total radiant output.

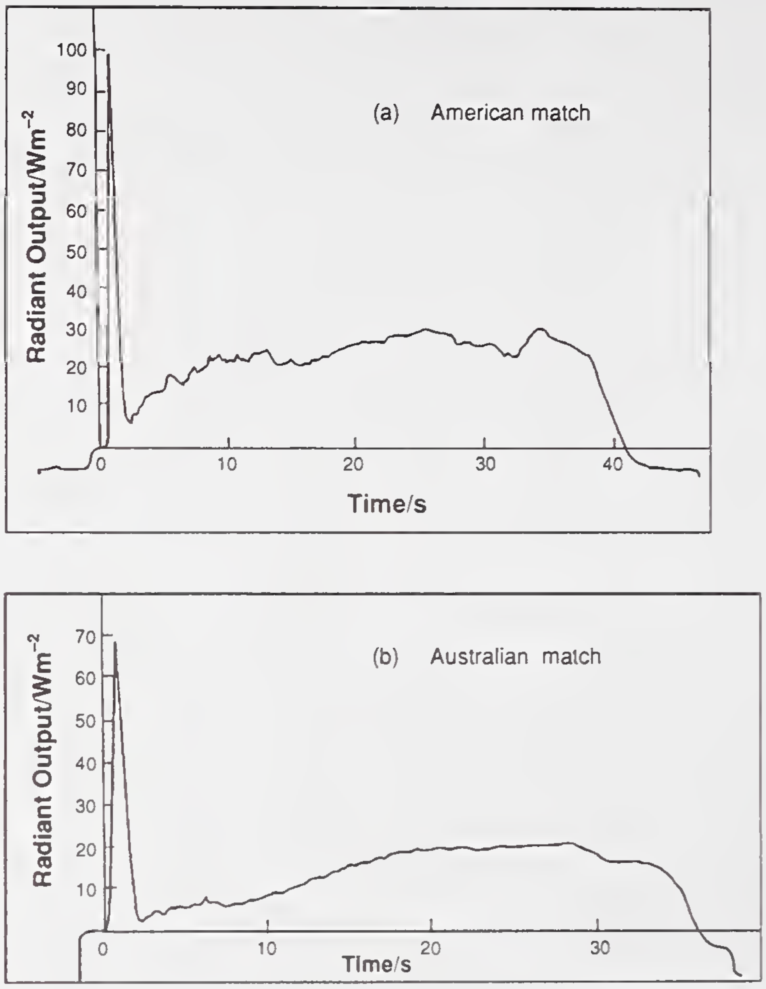

Figure 1—Radiant output of a typical Australian match (1a) and a typical American match (1b) as measured by a thermopile detector. The matches were vertical and burned downwards.

Flame temperature was calculated by assuming a different model. The flame was treated as a surface of area A_f and surface emissivity *e*, facing a detector surface A_d, each surface normal to the line connecting them. In that case, if T_d is the detector temperature, the flame temperature, T_f, is given by Eckert and Drake (1959), Eqs. 14-5:

$$T_f^4 = \frac{\pi d^2 V}{RA_f A_d se} + T_d^4 \tag{2}$$

where *s* is the Stefan-Boltzmann constant. The emissivity, *e*, was taken as 0.28 (Anderson 1969). These flame temperatures are summarized in table 1 for reference use, although they are not used in the subsequent discussion.

As a simple check for similarity of burning mechanism between match species, we calculated the product of the average flame velocity and the match diameter. According to the theory and experimental results of Parker (1973), this number should be invariant for similar cross-section columns burning vertically. We found this product to be 0.032 cm^2/s for Australian matches and 0.029 cm^2/s for American matches, a good correspondence considering the crudity of the experiments.

Table 1—Comparison of match species characteristics.

Characteristic	Australian	American	Units
Length[1]	4.175 ± 0.056	5.521 ± 0.050	*cm*
Width[2]	0.212 ± 0.023	0.303 ± 0.009	*cm*
Weight[1,3]	0.113	0.235	g
Burning time	27.5 ± 6.8	52.2 ± 8.9	*s*
Heat content[4]	23149 ± 16	20628 ± 75	$J\,g^{-1}$
Flame velocity[5]	0.152 ± 0.008	0.097 ± 0.016	$cm\,s^{-1}$
Average heat content	2616	4848	*J*
Mass loss rate	0.0029	0.0018	$g\,s^{-1}$
Total radiant output	205 ± 94	742 ± 117	*J*
Average radiant output	7.45 ± 2.01	14.2 ± 1.7	*W*
Radiant conversion efficiency	0.078	0.153	
Flame temperature	999 ± 67	1078 ± 58	*K*
Ignition temperature	490 ± 20	488 ± 51	*K*

[1] Includes match head.
[2] Approximately square cross-section; both dimensions measured.
[3] Averaged by weighing batch of 10 matches, no standard deviation.
[4] Does not include match head.
[5] 0.5 cm of match used for holder.

Similarity in burning characteristics is seen also in figure 1. Here, an American species example with a burning time shorter than the mean has been chosen for easier comparison. The peak due to ignition of the head material is clear. The small precursor is due to the presence of the hand and arm of the experimenter in the field of view of the radiometer. Following the peak, there is a period of a few seconds as the flame burns to the point at which it is in equilibrium. It then burns at a reasonably constant rate for the duration of the burn and expires as the flame reaches the holder at the bottom of the match. We set the zero level of figure 1 as the radiant heat output at which the flame starts. Thus the radiometer signal is negative after the flame has gone out, while the match cools to the ambient temperature. The mass loss experiments do not show significant differences corresponding to the flame establishment, that is, the starting transient. The loss rate samples are, however, taken at 5-second intervals beginning after the flare subsides and the transient is minimized.

Ignition

Experiment

The energy needed to ignite an Australian match was found by blowing hot air using a Raychem Minigun CV5302 and measuring the temperature at the match head with a Fluke 52 K/J Thermometer using a chromel-alumel thermocouple. The ability of radiation to yield such temperatures was tested on both Australian and American matches by using a magnifying glass to focus the sun on the match head, (ensuring that the size of the focal spot was less than the match head) and noting the time to ignition. The radiation experiments were conducted in Melbourne, Australia (38 °S) on the sunny days of October 15, 1989, at 9:20 a.m. and October 16, 1989 at 10:20 a.m., and at Missoula, MT (46 °N) on November 15, 1989, at 2:15 p.m. We used the Applied Environmetrics Meteorological Tables (Beer 1990b) to estimate the solar radiation at the ground normal to the magnifying glass (table 2).

Results

Ignition Temperature—The temperature at which an Australian match head ignites by convective heating displayed an unexpectedly large variation, ranging (over 12 trials) from 103 °C (466.2 K) up to 266 °C (539.2 K). The mean ignition temperature was 216.4 °C (489.6 K) with a standard deviation of 20 °C. The large variation also manifested itself visually. The match that failed to ignite until 266 °C had a wooden portion that was significantly charred before the match ignited; most match heads ignited well before any charring took place.

Table 2—Results of solar ignition experiments.

Solar radiation	W	T	<t>	S.D.	Match type
W/m^2	*(Watts)*	*(°Kelvin)*	*(Seconds)*		
850	2.403	291	1.72	0.71	Aus
950	2.686	291	0.76	0.19	Aus
513	2.15	280	1.4	0.78	US

Solar Ignition—The solar ignition results in table 2 give the radiation incident on the match head (W), the ambient temperature (T_o), and the mean measured time to ignition (τ) for Australian and American matches. From these values, we can calculate the critical radiation power necessary to ignite a match from the following argument.

If radiation of power W watts strikes a match head, then its ability to heat the head to an ignition temperature, T_{ig}, depends on whether the heating rate exceeds the cooling rate. If we assume Newtonian cooling, which is linear in temperature, and neglect heat diffusion, then energy continuity requires

$$\frac{dT}{dt} + \beta T = \alpha W \qquad (3)$$

where T is the temperature at time t, β is the heat loss constant, and α is inversely proportional to the product of the mass and specific heat capacity of ignitible material. Equation (3) is subject to the initial conditions that $T = T_o$ at $t = 0$ and $T = T_{ig}$ at $t = \tau$, where τ is the measured time to ignition. Solving and rearranging, we find

$$\tau = (1/\beta) ln \left(\frac{T_o - (\alpha W/\beta)}{T_{ig} - (\alpha W/\beta)} \right) \qquad (4)$$

If we take $T_{ig} = 490$ K (table 2), we find $\alpha/\beta = 208\ KW^{-1}$ and $\beta = 1.8\ s^{-1}$. The critical incident radiation power on a match head is found from (3) when $dT/dt = 0$. For the values of α, β, and T_{ig} above, this power is 2.4 Watts.

Discussion

Equation (3) indicates that, for ignition to take place, the radiation incident on a match head must exceed a certain minimum value, W_{min}, which we find, based on our measurements, as approximately 2.4 W. For the radiation from a burning match to ignite a nearby unignited match, the two must be closer than a distance, d_{min}, where

$$d^2_{min} = (A_m/4\pi)(W/W_{min}) \qquad (5)$$

with A_m = cross-sectional area of match head and W the average radiated power. For Australian matches $W = 7.17\ W$, $W_{min} = 2$ and $A_m = 6 \times 10^{-6}\ \mathrm{m}^2$, which implies $d_{min} = 1.3$ mm.

In fact, we found that adjacent matches were lit up to a spacing of about 8 mm for Australian matches and 9 mm for American matches. This suggests that the initial flaring of the adjacent match head plays a more important role in ignition of adjacent or randomly placed matches than the heat due to radiation from the flames of an adjacent match.

As crude as the experiments were, the results definitely pointed to variation in burning characteristics as a major contributor to the differences among trials in percolation experiments. Regardless of the model used in calculation of the radiant output, the results showed clearly that from the point of view of a neighboring match, there can easily be differences in excess of a factor 2 in the total radiation energy received by the Australian matches.

The variability in radiant output was less in the American matches. This was due in part to the increased size of the match, causing the char, or blackened part of the match, to vary less in shape and participate in maintaining the flame. We observed in several informal trials that the smaller Australian matches were harder to keep lit (at the same moisture content) when vertical than the American ones. This occurred despite the fact that the combustible gas analysis showed that combustible gases were generated at a lower temperature in the Australian matches and that the specific heat content of these matches was higher than that of the American species.

We could not measure the variability in performance due to moisture content of the matches. Informal experiments did verify that the performance of the matches when burning vertically was affected by this variable. In fact, neither species of match would burn vertically if the moisture content was much in excess of 10 percent of ovendry weight. The burning performance when held at slight downward angle, however, as those with experience know, was less dependent on moisture content (Weber 1990).

Conclusions

The idea of using a theory from statistical physics to describe the spread of fire has superficial attraction. However, our results cast doubt on the ability of simple percolation theory to describe the behavior of real matches because a lattice of matches will have two modes of ignition: first, piloted ignition from the initial flare of a match head that ignites an adjacent match, and second, radiant ignition from lots of neighboring burning matches. Existing models of fire spread as a percolation process appear to deal only with the first mode of ignition. In addition, our results confirm that an array of matches, which one would suppose to be a uniform fuel, exhibits considerable statistical variability due to match-to-match variation.

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