Effect of Sample Orientation on Piloted Ignition and Flame Spread

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ABSTRACT

An experimental investigation is conducted to study the effect of sample orientation on piloted ignition and opposed-wind flame spread. Two types of wood (red oak and mahogany) were used for the purpose and two orientations (horizontal and vertical) were investigated. In the horizontal mode, axisymmetric fire spread over wood samples was studied and the corresponding piloted ignition tests were conducted on smaller samples of the same wood. In the vertical mode, lateral flame spread and piloted ignition tests were conducted in a radiant panel test apparatus.

The experimental data were reduced according to the thermal flame spread theory of deRis using the measured surface temperatures. It was found that as long as the temperatures are defined consistently with the thermal theory, the results are orientation independent within the measurement error. The reasons for this orientation independence are: (i) dominant re-radiative losses, and (ii) insensitivity of the flame spread rate to the induced air velocity at ambient O_2 concentrations.

Key words: Ignition, Flame spread, Sample orientation, Wood, Measurements.

INTRODUCTION

The ultimate goal of fire research is to provide a scientific and technical basis to minimize fire losses. Typically, in building fires, a wide variety of materials oriented at different angles relative to gravity burn under varying levels of externally supplied radiation. Hence, it is important to understand the effect of sample orientation and external radiation on fire initiation (i.e. ignition) and fire growth (i.e. flame spread).

The literature on both flame spread and ignition is abundant. Several reviews have also been published on these subjects. The pioneering work of deRis [1] on flame spread and the review by Fernandez-Pello and Hirano [2], the extensive work of Kashiwagi [3,4] on ignition and the review by Kanury [5] provide excellent sources of information.

Generally, two modes of flame spread (wind-aided and wind-opposed) and two modes of ignition (auto and piloted) have been recognized. A close relationship between piloted ignition and opposed-wind flame spread has also been established by Quintiere and coworkers [6,7]. However, in these previous studies, the effect due to changes in sample orientation on piloted ignition and opposed-wind flame spread has not received much attention. For instance, horizontal and vertical sample orientations provide very different buoyant flow configurations that would be expected to significantly affect both ignition and flame spread. Thus, the objective of this work is to experimentally investigate the effect of sample orientation on piloted ignition and opposed-wind flame spread mechanisms.

Horizontal and vertical sample orientations were examined for two kinds of wood (red oak and mahogany) under different levels of externally supplied radiation. In the horizontal mode, axi-symmetric fire spread over wood samples was studied and the corresponding piloted ignition tests were made on smaller samples of the same wood. In the vertical sample mode, lateral flame spread and piloted ignition tests were conducted in a radiant panel test apparatus. The results for the two types of wood were qualitatively similar, thus data for only mahogany are presented here.

EXPERIMENTAL PROCEDURE

The experimental arrangements used for the horizontal and vertical modes are schematically shown in Figures 1 and 2. Further details of the experimental setup are given in Reference 8 for the horizontal mode and Reference 9 for the vertical mode.

The Horizontal Mode

In the horizontal mode [Figure 1] the flame spread tests were conducted on samples two feet in diameter and 0.75 inches thick. The fire was started at the center of the sample and allowed to grow up to the edge under conditions of prescribed external radiation. Surface temperatures were measured by thermocouples installed perpendicular to the radial spread direction and the spread rate was determined by photographs taken during the tests. At least six tests were conducted on each type of wood. The data for the first six inch diameter and the last one inch were not used to avoid possible variations caused by ignition and edge effects.

The ignition tests in the horizontal mode were conducted on 3" x 3" x 0.75" samples exposed to a known external radiation flux. The sample edges

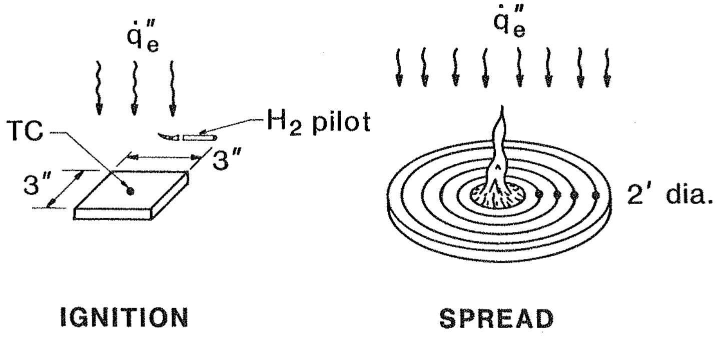


Figure 1 A schematic of the experiments in the horizontal mode. The black dots represent the thermocouples.

were shielded by aluminum foil to avoid any edge effects. To test for piloted ignition, a small hydrogen flame was lowered at regular intervals (one second) close to the pyrolyzing surface at a height no more than two millimeters. The pilot flame was off-center and the sample was very slowly rotated to avoid heating a particular spot. The surface temperature was continuously monitored and no measurable rise in surface temperature was observed because of the pilot flame. The exposure time required for sustained flaming was also recorded.

The Vertical Mode

In the vertical sample mode, lateral flame spread experiments were conducted on 6" x 31" x 0.75" samples [Figure 2] exposed to a known external irradiance. Ignition was instigated by an acetylene-air pilot positioned in the fuel plume above the sample. Flame position as a function of time was recorded by a video camera and the flame spread rate was determined by applying a running 3-point least square fit of the data. Thermocouples positioned at several locations along the sample monitored the surface temperature.

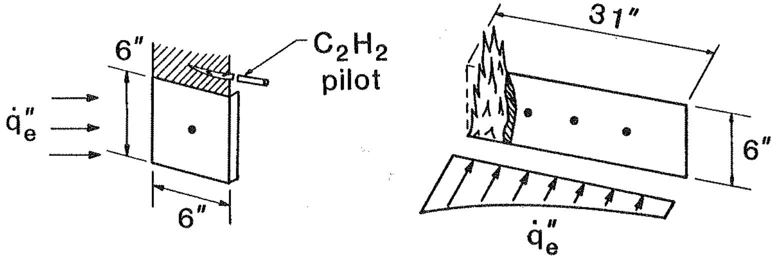
For piloted ignition tests in the vertical mode, 6" x 6" x 0.75" samples were used. These samples were exposed to different external irradiances and the time required for sustained flaming was recorded. As in the horizontal case, the surface temperature was also continuously monitored by thermocouples mounted on the sample surface.

SURFACE TEMPERATURE MEASUREMENTS AND THEIR INTERPRETATIONS

Measurement Method

For both piloted ignition and flame spread, surface temperature is a very important parameter. It is also very difficult to measure accurately. In the past, therefore, it has often been estimated by the use of a linear conduction theory (Simms [10]).

Primarily two methods of measuring surface temperature have been employed: (i) By mounting thermocouples on the sample surface (e.g. Gordon [11]; Kashiwagi [3]), and (ii) by using an infrared pyrometer (e.g. Smith et al [12]). The difficulty with using infrared pyrometers is that a knowledge



IGNITION **SPREAD**

Figure 2 A schematic of the experiments in the vertical mode. The black dots represent the thermocouples.

of surface emissivity, which changes as the thermal decomposition proceeds, is essential. Furthermore, the decomposition products and their exothermic reactions with oxygen interfere with the measurements. The use of surface thermocouples is also plagued with problems. This is because the measured values depend on the mounting method. Martin [13] estimated surface temperatures by extrapolating temperatures measured in depth. Gordon [11], on the other hand, had his thermocouples sprung lightly against the surface.

The method employed here is based on the observation that a thermocouple output is significantly reduced when not in contact with the surface. Thus the heat flows from the wood to the thermocouple junction when in contact. A method that produces the largest response to the same incident heat flux would then be the most correct (Beyler [14]). Due to large temperature gradients on both sides of the sample surface (in the gas and the solid phase), large errors are caused by either poor contact or by embedding the thermocouple in the solid.

Experimentally, the best compromise that was achieved is shown in Figure 3. Here the thermocouples used were made by electrically welding fine Chromel and Alumel wires 0.003" in diameter. The wires and the bead were then flattened to obtain a film thermocouple about 0.001" thick. A very fine incision was then made on the surface of the wood and the thermocouple was slid underneath this "skin" which was approximately 0.001" thick. The rest of the thermocouple was secured with as little wood glue as possible. The entire assembly was then pressed together and allowed to set. In the end, the thermocouple bead was visible through the "skin". This method was the most repeatable and gave the fastest and largest response to the same incident heat flux. The measured surface temperatures were repeatable to within ±5°C.

Piloted Ignition

The preceding technique was used to measure surface temperature for piloted ignition. A typical surface temperature-time curve obtained during the ignition experiments is shown in Figure 4. Also shown plotted on this

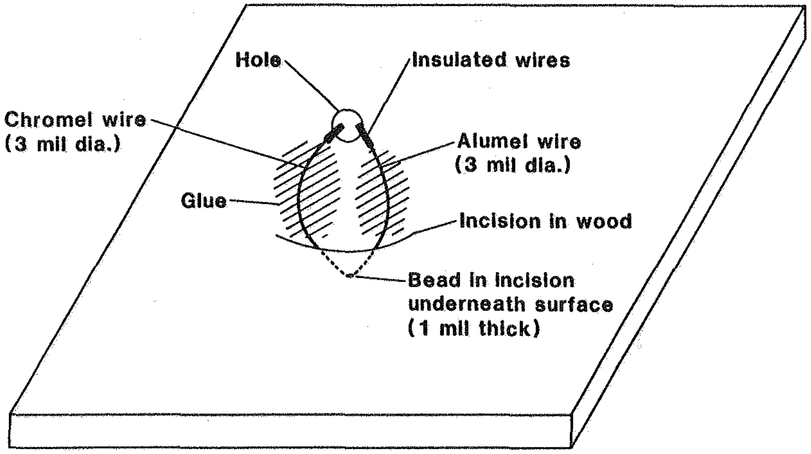


Figure 3 Method of surface temperature measurement.

curve is the time at which sustained flaming ignition was observed. This result is very similar to that obtained by Smith et al [12]. Note the sharp rise in the surface temperature due to flaming combustion and the fact that the time for the observed appearance of the flame plots on this sharp temperature rise. This, too, corroborates with Smith et al's [12] observation: "Sometimes the appearance of flame would produce a sudden large jump in millivolts, and other times the increase in millivolts would proceed the appearance of the flame." Since the time for visual flame observation typically has an error of plus or minus one second, large errors in piloted ignition temperatures are to be expected. Smith et al's measured ignition temperatures for pine blocks range from 343 to 571° C. This is clearly unacceptable for use in a thermal flame spread theory.

A closer look at the ignition process leads to a better understanding. An enlarged view of the temperature history (in Figure 4) during the last few instants before ignition is shown in Figure 5. A similar result was obtained for the horizontal case. This is shown in Figure 6. The flashes (unsustained momentary flaming) are more pronounced for the horizontal case than for the vertical case. This is because for the horizontal case the flashes occur in the middle of the sample, right where the thermocouple is, whereas in the vertical case they often did not cover the entire sample and remained close to the pilot flame far from the thermocouple. From Figure 6 it is also clear that there was enough time between the flashes for the surface to come to thermal equilibrium with the external radiation. Also note that the extrapolated surface temperature, caused by external radiation, at the time of sustained flaming is less than the momentary rise in temperature because of the flashes and yet sustained flaming was not achieved. In other words, for sustained flaming to occur, it is necessary for the surface temperature, caused by external radiation, to rise to some critical value. Any contributions due to gas phase exothermicity must not be included in determining this critical value. This is consistent with the concept of critical mass flux at ignition (Rashbash [15]) and implies that the required critical mass flux at ignition is produced by the solid indepth. The total heat contribution due to the flashes (proportional to the area underneath the peak) is small and limited to a thin surface layer. Also, this heat is quickly lost by reradiation. Furthermore, since the rise in surface temperature is faster for higher

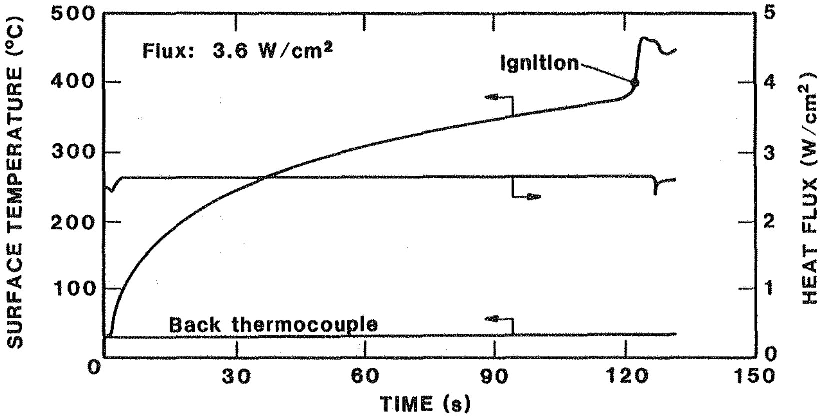


Figure 4 A typical surface temperature-time history for ignition. (Mahogany - Vertical Case)

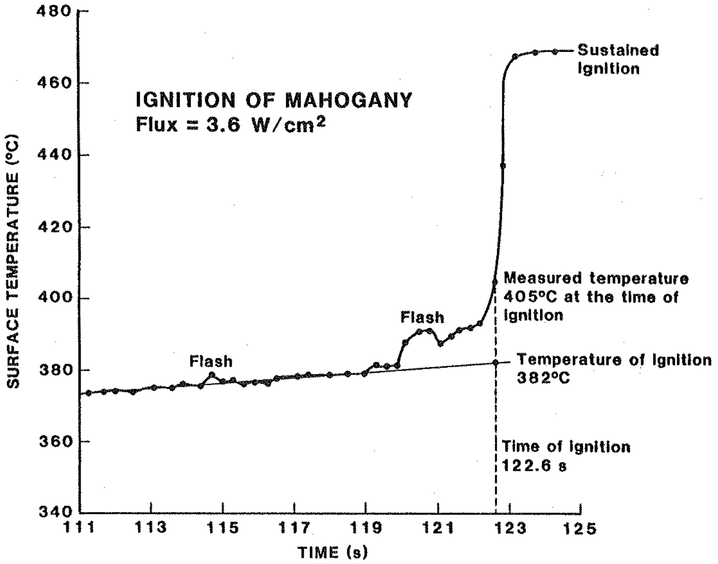


Figure 5 An enlarged view of the surface temperature-time history shown in Figure 4 at the time of sustained ignition.

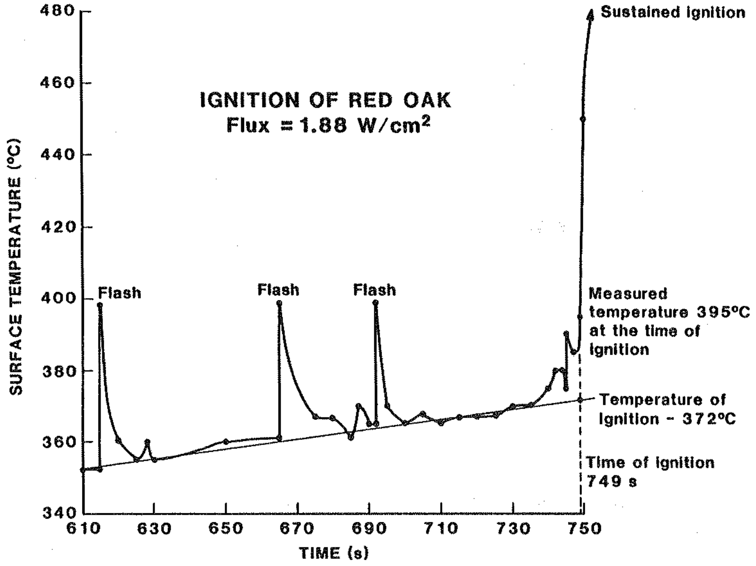


Figure 6 An enlarged view of the surface temperature-time history at the time of sustained ignition for the horizontal case.

heat fluxes, flashes and sustained ignition will be more closely spaced in time as is evidenced by a comparison of Figures 5 and 6. Hence, the surface temperature may not have time to come to equilibrium with the external radiation. This makes the flashes and ignition more difficult to distinguish.

Based on these observations, the critical surface temperature defined in this work is the temperature at the time of ignition achieved by external heating alone. Thus in Figure 6, 372°C rather than 395°C is the ignition temperature. This definition is consistent with the thermal flame spread theory.

Flame Spread

Surface temperatures measured during the flame spread experiments are shown in Figure 7 for the horizontal case and Figure 8 for the vertical case. The results for the two cases are qualitatively similar. Both figures show a sharp rise in surface temperature because of the arrival of the flame front. However, the source of "long-distance" heating is different. For the horizontal case (Figures 1 and 7), the rise in surface temperature prior to the arrival of the flame front takes place due to external radiation from the heaters and due to the radiation from the flame itself. Whereas, for the vertical case (Figures 2 and 8), the "long-distance" heating effects due to flame radiation are negligible because of the poor configuration factor, and the temperature rise is caused primarily by external radiation.

To determine the surface temperature consistent with the definition of ignition temperature and suitable for use in a thermal flame spread theory, consider the enlarged view shown inlaid in Figure 8. In Figure 8, T_{ig} is the ignition temperature as defined in the previous section, $T_s(t_f)$ is the temperature when the flame visually arrives at the thermocouple location and

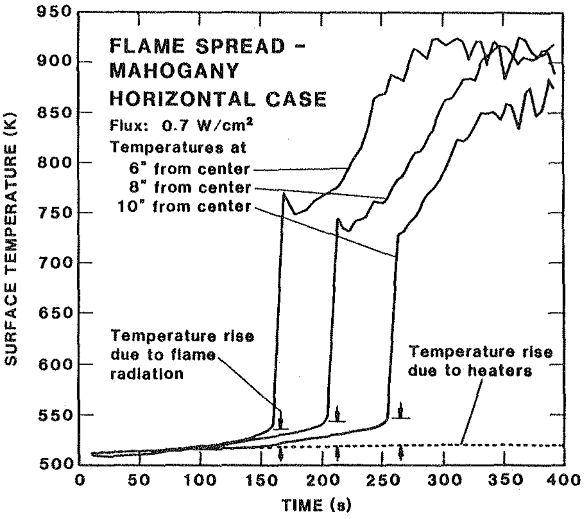


Figure 7 Measured surface temperatures during the flame spread experiments for the horizontal case at three locations.

$T_s(t_1)$ is the temperature rise due to external radiation alone. Thus, a suitable temperature for flame spread calculation is $T_s(t_1)$ extrapolated to time t_f, i.e. before the effect of gas-phase conduction is felt. A similar definition was used for the horizontal case (Figure 7); however, flame radiation was included in the "long-distance" heating effects. The rate of flame propagation will then depend upon how quickly the surface temperature ahead of the flame foot is brought up to the ignition temperature by the flame foot.

RESULTS AND DISCUSSION

Piloted Ignition

Figure 9 shows the measured surface temperatures for mahogany at the time of ignition as a function of external radiation for both the vertical and the horizontal samples. The plain bars represent the measured range (results of at least 6 experiments) of piloted ignition temperatures for the horizontal mode, whereas, the circles with bars are for the vertical mode. For the vertical mode, the error bars represent the net uncertainty in surface temperature for a single experiment caused by: (i) the error in measurement, and (ii) the ±1 sec uncertainty in observation of flaming combustion and the resulting uncertainty in temperature obtained from measured surface temperature profiles. These values are well within the range of surface temperatures reported in the literature (300-540°C). It also seems that the ignition temperature increases somewhat with decrease in external radiation. This is probably due to the depletion of surface reactants caused by charring.

It is important to note that surface temperature is an indirect measure of ignition. The actual ignition process is fairly complex. The solid must first chemically decompose to inject fuel gases into the boundary layer. These fuel gases must then mix with air and the local mixture ratio must be near or within the flammability limits. At this instant, a premixed flame, originating from the pilot flame, flashes across the surface of the solid through the fuel-air mixture formed in the boundary layer. To obtain ignition or

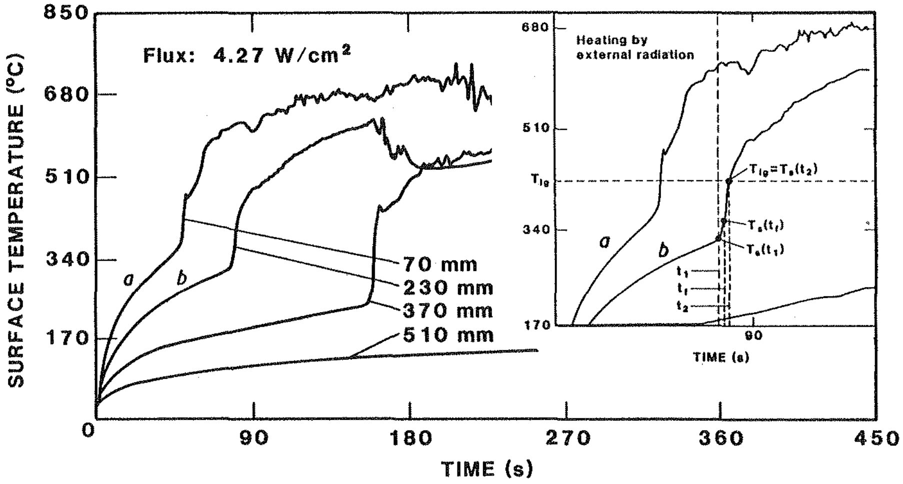


Figure 8 Measured surface temperatures at 4 locations during the flame spread experiments for the vertical case. INLAID: An enlarged view of curves 'a' and 'b'.

sustained flaming, which is marked by the establishment of a diffusion flame in the boundary layer, further heating of the solid is necessary. Evidence of this process can be seen in the measured surface temperature history depicted in Figure 6. Thus at the instant of ignition, pyrolysis gases must issue at a high enough rate to permit the establishment of a diffusion flame at a location far enough from the surface to avoid thermal quenching. Orientation relative to gravity was expected to significantly alter this process because of differences in the heat transfer to the surface and in the flow pattern of decomposition products and their mixing with entrained air. However, the results from both sets of experiments are within the error bars of only ± 30°C. Considering the error in the surface temperature measurements and the variation in the properties of wood from one sample to another, an average ignition temperature of 375°C seems to adequately represent both the horizontal and vertical modes. Experiments with red oak yield essentially the same conclusion, with the average ignition temperature being 365°C.

Since the ignition temperatures (as defined in this work) include only the effect of heating by external radiation, these results imply that at high temperatures (~650°K) necessary for ignition, convective losses (which depend on the sample orientation) are much less important than the re-radiative losses. Thus, the time required for the surface temperature to rise to the piloted ignition temperature is controlled primarily by re-radiation. Such measured times to ignition are shown in Figure 10 as a function of external radiation. Once again, the difference between the horizontal and the vertical modes is small. There is, however, a slight tendency for the ignition times to be shorter for the horizontal samples than for the vertical ones. This trend is consistent with Kashiwagi's [4] work on auto-ignition.

Figure 10 also shows that the time required for the surface temperature to reach the ignition temperature increases asymptotically to infinity as the

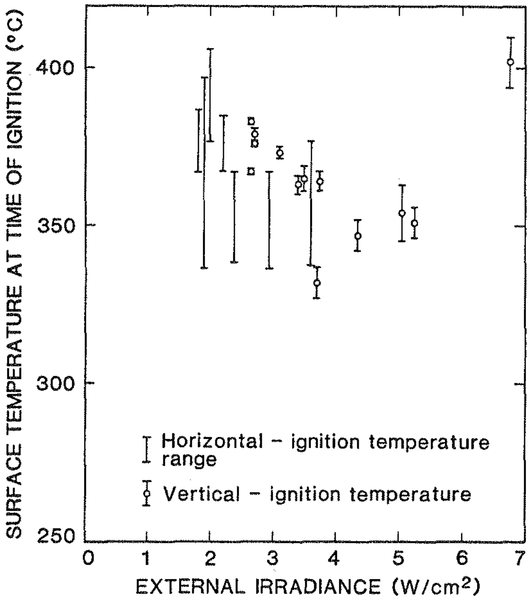


Figure 9 Measured surface temperatures at the time of ignition for different external radiation conditions.

external radiation is reduced. This asymptotic value can be found from the surface energy balance for an inert solid (assuming negligible thermal decomposition occurs prior to ignition) expressed as;

$$(-k \frac{\partial T}{\partial x}) = \dot{q}''_e - h(T_s - T_\infty) - \varepsilon\sigma(T_s^{\,4} - T_\infty^{\,4}). \qquad (1)$$

Here the surface temperature 'T_s' is replaced by the ignition temperature 'T_{ig}' and as the time tends to infinity the left hand side of Equation (1) tends to zero. Hence, the minimum heat flux for piloted ignition is given by;

$$(\dot{q}''_e)_{min} = h(T_{ig} - T_\infty) + \varepsilon\sigma(T_{ig}^{\,4} - T_\infty^{\,4}). \qquad (2)$$

For wood, due to charring of the surface at low heat fluxes, 'ε' is very nearly unity and 'h' calculated from convective heat transfer correlations is about 10 W/m^2K for the horizontal case and 15 W/m^2K (Quintiere [7]) for the vertical case. Using these values along with T_{ig} = 375°C and T_∞ = 20°C, Equation (2) yields; $(\dot{q}''_e)_{min}$ = 1.32 W/cm^2 for the horizontal case and $(q'')_{min}$ = 1.50 W/cm^2 for the vertical case -- a difference of only about 10%. Furthermore, this difference in the asymptotic values vanishes with only a ± 10°C change in the ignition temperatures which is well within the ± 30°C

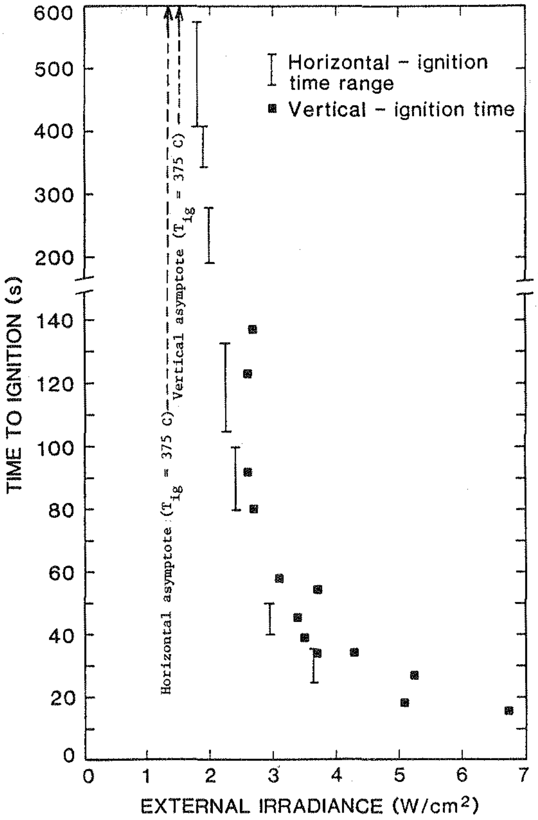


Figure 10 Measured time to ignition as a function of external radiation.

error in measurement. It is, therefore, not surprising that the experimental results do not show any significant difference between the horizontal and vertical modes.

Flame Spread

The thermal theory (deRis [1]) for opposed-flow flame spread over a thermally thick solid gives the flame spread velocity 'V' by the formula:

$$V = \frac{V_a \, (\rho ck)_g \, (T_f - T_{ig})^2}{(\rho ck)_s \, (T_{ig} - T_s)^2} \tag{3}$$

where $(\rho ck)_g$ and $(\rho ck)_s$ respectively are the thermal responsivities of the gas and of the solid phase, 'T_f' is the flame temperature and 'V_a' is the opposed-flow gas velocity. From the previous discussion, it is clear that 'T_{ig}' is essentially the same for both the horizontal and the vertical cases. However, it remains to be seen if the numerator of Equation 3 (represented by 'ϕ'), which explicitly contains the air velocity 'V_a', is also invariant with changes in the sample orientation.

For appropriate definitions of 'T_s' [see Figure 8, $T_s = T_s(t_1)$], Equation (3) can be used to correlate the data for both the horizontal and the vertical cases. If $\phi/(\rho ck)_s$ is indeed a constant, then $V^{-1/2}$ must be linearly related to 'T_s'. Figure 11 shows the experimental results plotted in this manner for both the horizontal and the vertical cases. Once again, within the experimental errors, the two cases are almost indistinguishable, although the flames look very different.

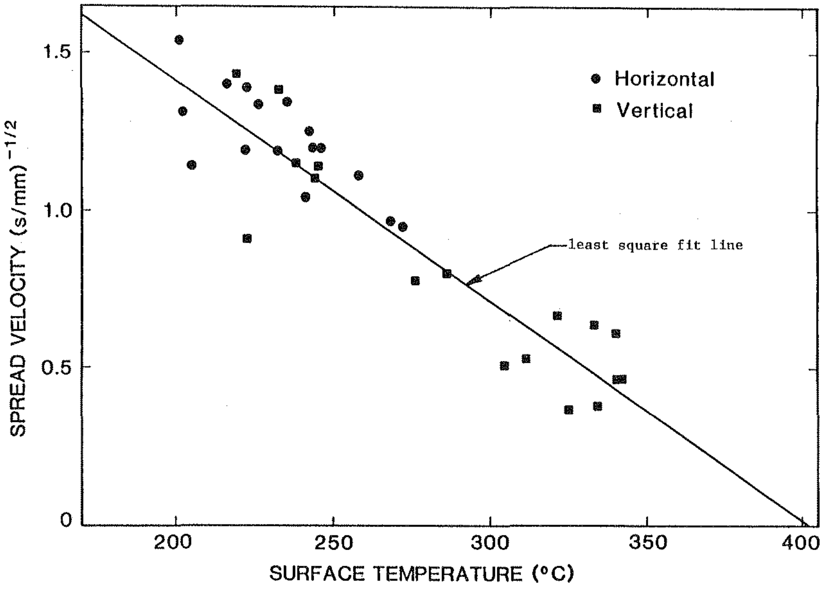


Figure 11 Flame spread rate correlation according to the thermal flame spread theory.

The fact that 'ϕ' for the two cases is the same (within experimental errors) was somewhat surprising because it is directly related to 'V_a' (via Equ. (3)) which is different for the two cases. Similar results were also obtained by Fernandez-Pello et al. [16]. Their data shows that at ambient oxygen concentrations, the flame spread velocity is insensitive to the opposed-flow velocity, except near extinction. The nature of these results cannot be explained by a purely thermal theory used in the derivation of Equ. 3. As suggested by Fernandez-Pello, et al. [16], the increase in the flame spread rate at high opposed-flow velocities caused by the closer proximity of the flame is counteracted by the gas phase chemical kinetic effects. Thus, Equ. 3 and therefore 'ϕ' need to be modified by an appropriate correction factor which accounts for the gas phase chemical kinetic effects. This correction factor was found to be a function of the Damköhler number [16]. [Further improvements in Equ. 3 have also been suggested by Wichman, et al. [17] by incorporating a velocity gradient at the fuel surface and thus eliminating the uniform gas velocity assumption used in the derivation of Equ. 3.] Hence, these results are in agreement with the established mechanisms of opposed-flow flame spread (Ref. [2]). They confirm that for the present experimental conditions, the flame spread rate is controlled entirely by the processes taking place in the leading edge of the flame and that the flame geometry alters only the "long-distance" heating effects. Also, although the processes occurring at the flame foot are the result of a complex interaction between heat transfer and gas phase chemical kinetic effects, they can be lumped into the parameter 'ϕ' which is experimentally found to be approximately constant.

Finally, according to Equation (3), the intercept of the least square fit line with the x-axis [Figure 11], is the ignition temperature. This gives a value of 402°C for piloted ignition temperature. This number is within the range of the measured ignition temperatures, although on the high side of the scatter.

CONCLUSIONS

In this work the effect of sample orientation on piloted ignition and flame spread was experimentally investigated for two woods -- red oak and mahogany. Within the measurement error, the results appear to be orientation independent and seem to indicate that the relationship between ignition and flame spread, as assumed in the thermal flame spread theory, is valid. However, to be consistent with the thermal theory, both the ignition temperature 'T_{ig}' and the surface temperature ahead of the flame foot 'T_s' must not include gas-phase heating effects. For the horizontal case, flame radiation alters only the "long-distance" heating effects and hence must be included in the determination of 'T_s'.

It was found that there are two reasons for orientation independence: (i) At high temperatures in question, heat loss by re-radiation dominates over the convective losses. (ii) At ambient O_2 concentrations, the flame spread rate is insensitive to small changes (~0.1 m/sec) in the induced air velocity that are caused by changes in the sample orientation.

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