

Experimental Investigation of Flame-Spread Velocity on Solid Fuel Surfaces

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Abstract

Flame spread over combustible solid materials is a fundamental fire-safety phenomenon that influences fire growth, the time available for evacuation, and the performance requirements of fire-protection systems. This study experimentally investigated flame-spread behaviour across four solid wood specimens under normal consistent laboratory conditions. The investigation considered specimen geometry, mass, density, surface temperature, ignition temperature, ignition time, flame-spread distance, mass loss and temperature profile measured using four thermocouples. Flame-spread velocity was evaluated using both a direct distance-to-time relationship and a heat-transfer-based relationship. The measured flame-spread distances ranged from 0.195 to 0.250 m, while total test durations ranged from 135 to 219 s. The direct velocity estimates were approximately 4.77×10^{-4} to 1.14×10^{-3} m/s, whereas the alternative model-based estimates ranged from approximately 2.84×10^{-3} to 4.76×10^{-3} m/s. The results also indicate that flame spread is strongly influenced by orientation and environmental conditions: upward spread can be accelerated by buoyancy, whereas horizontal spread is generally less strongly assisted by buoyant flow. The study demonstrates the value of combining direct flame-front measurements with temperature measurements when characterizing combustible materials, while also highlighting the need for careful control of specimen properties and test conditions in comparative flame-spread experiments.

Keywords: flame spread; flame-spread velocity; solid fuels; temperature gradient; fire safety

1. Introduction

1.1 Background

Flame spread over combustible solids is a key process in the development of compartment and building fires. The rate at which a flame front advances determines how rapidly previously unignited material is exposed to heating and potential ignition. In combustion research, the terms flame speed and flame-spread velocity may be used in different reference frames, and their precise definitions depend on the coordinate system and physical configuration under consideration. In the context of a solid fuel surface, flame-spread velocity is most usefully considered as the rate at which the leading edge of the burning region advances across an initially unburned surface. This quantity is affected by heat transfer from the flame, the thermal properties and geometry of the fuel, the direction of spread, and the surrounding flow field. (Buchanan et. al., 2017)

The behaviour of a spreading flame is governed by coupled heat-transfer and pyrolysis processes. Heat supplied to the unburned material raises its temperature and may initiate thermal decomposition, producing combustible gases that can subsequently ignite. The balance between external heating, heat losses, material properties and gas-phase combustion therefore determines whether the flame front advances rapidly, remains relatively stable or is extinguished (Quintiere 2017). The orientation of the fuel surface is particularly important because buoyancy-driven flow can transport hot gases and flame-generated heat toward unburned fuel. Upward flame spread is consequently often faster than downward or horizontal spread, although the magnitude of the effect depends on the fuel and flow conditions (Zhu N. et. al., 2023).

Material characteristics also exert a major influence on flame spread. Density, thickness, thermal conductivity, specific heat, moisture content, surface condition and permeability affect the rate at which heat is absorbed and the rate at which combustible volatiles are generated. Porous materials may exhibit complex behaviour because internal structure can influence heat penetration and the movement of pyrolysis products (Wu C. et. al., 2022). External airflow may either promote or oppose flame spread depending on its direction relative to the flame front. Research on opposed-flow and wind-driven flames has demonstrated that orientation, external heating and flow conditions can substantially alter flame-spread behaviour (Morrisset et.al., 2023).

Understanding flame-spread velocity is important for fire-safety engineering because the spread rate affects the time available for occupants to respond and evacuate and contributes to the development of fire-protection strategies. Characterizing the behaviour of different combustible materials can assist in evaluating their relative fire performance and in identifying materials or configurations that may delay fire growth. Experimental flame-spread measurements also provide information that can support the assessment of fire dynamics, the selection of fire-resistant materials and the design of appropriate detection, suppression and evacuation measures (Varghese S. et. al., 2022)

The present study focuses on four wood specimens tested under laboratory conditions. By measuring temperature histories alongside flame-spread distance and ignition time, the experiment seeks to relate the observed flame-front movement to the thermal response of the specimens. The approach provides a basis for comparing materials and illustrates the importance of controlling experimental variables when determining flame-spread characteristics.

2. Materials and Methods

2.1 Experimental Design

The experiment examined four solid wood specimens, designated Samples A–D. The specimens had similar overall dimensions but different masses and, consequently, different calculated densities. A constant ignition source was used with the intention of providing a comparable heat input to each specimen. Four thermocouples were employed to monitor temperature at different locations along the fuel surface, allowing the temporal development of the thermal field to be examined as the flame front advanced.

Before testing, each specimen was characterized by measuring its mass, length, width and thickness. The specimen surface was visually inspected for features that might influence flame spread, such as holes or other discontinuities. Moisture content was identified in the original experimental plan as a potentially important variable.

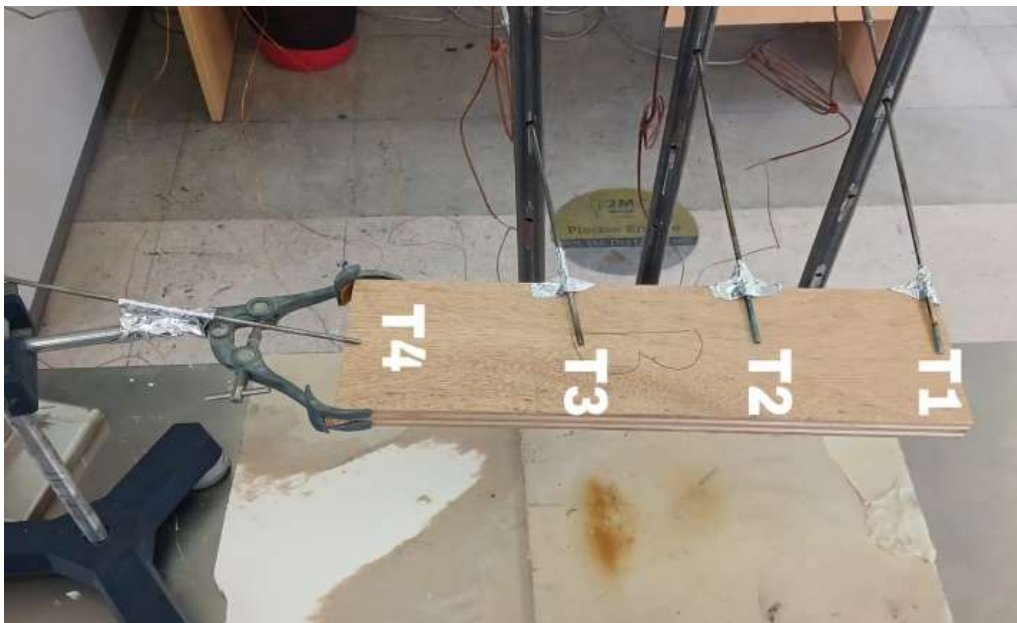


Figure 1. Schematic experimental arrangement for measuring flame-spread velocity on solid fuel specimens.



Figure 2. Solid wood specimens used in the experimental investigation.

2.2 Specimen Geometry and Density

Specimen volume was calculated from length, width and thickness. Density was then obtained by dividing specimen mass by the calculated volume. Cross-sectional area was calculated from specimen width and thickness. These quantities were used to describe the physical characteristics of the specimens and, where applicable, to support the heat-transfer-based flame-spread calculation.

2.3 Flame Spread Test Procedure

Each specimen was exposed to the ignition source and observed throughout the test. The ignition time, total test duration and distance travelled by the flame front were recorded. Temperature data were collected using four thermocouples. The same general procedure was applied to all specimens to facilitate comparison. Following testing, the specimens were weighed again to determine the change in mass associated with combustion.

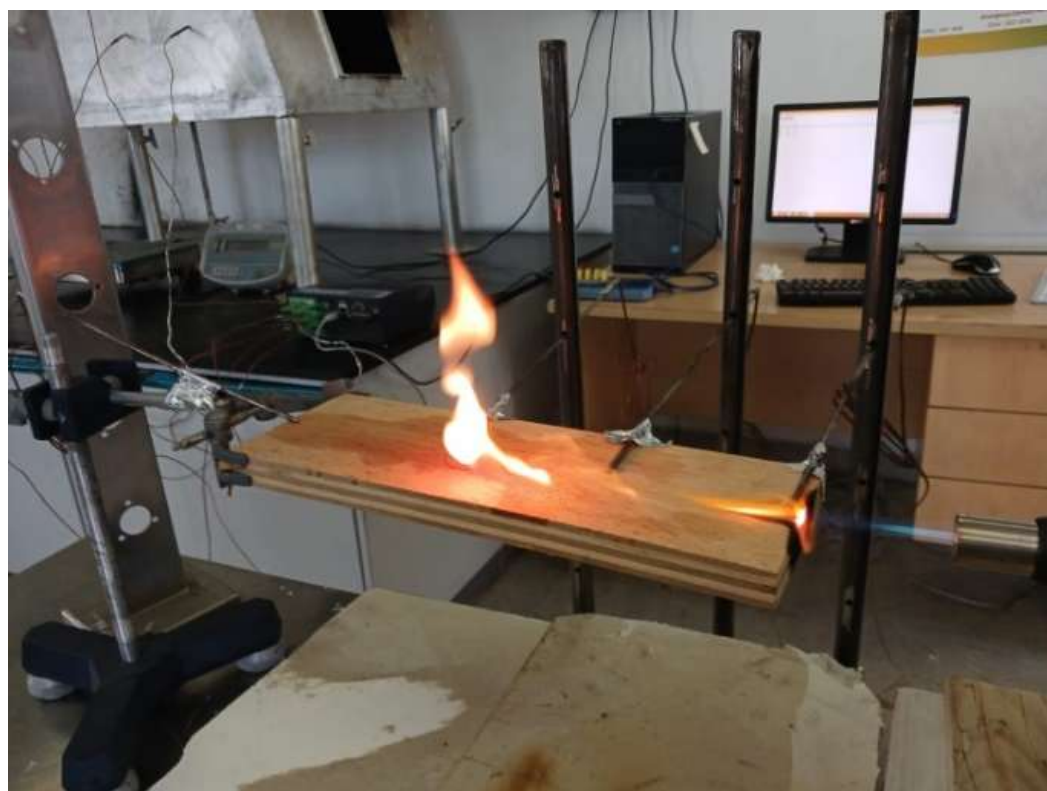


Figure 3. Flame spread test procedure applied on wooden sample along with thermocouples

2.4 Flame Spread Velocity Calculation

A direct experimental estimate of flame-spread velocity was obtained from the measured flame-spread distance divided by the corresponding total time. In addition, a heat-transfer-based relationship attributed to Quintiere (2017) was applied to estimate the flame-spread velocity. As the precise published form of the equation and its dimensional consistency could not be independently verified from the available literature, the present study reports the numerical results obtained using the original calculation.

3 Results

3.1 Physical and Thermal Characteristics

The four specimens differed in mass, dimensions and calculated density. Sample D had the highest initial mass (0.380 kg) and highest calculated density (821.98 kg/m³), whereas Sample A had the lowest density (493.68 kg/m³). The measured surface temperatures before ignition were closely grouped, ranging from 25.86 to 26.35 °C. In contrast, the reported ignition temperatures varied substantially, from 723.5 °C for Sample B to 912.86 °C for Sample D.

Table 1. Summary of specimen properties and principal experimental measurements.

Sample	Mass (kg)	Length (m)	Width (m)	Thickness (m)	Surface temp. (°C)	Ignition temp. (°C)	Total time (s)	Spread distance (m)
A	0.262	0.304	0.097	0.018	26.35	841.63*	135	0.195
B	0.302	0.302	0.100	0.017	25.86	723.50	219	0.220
C	0.271	0.301	0.096	0.016	26.33	824.67	169	0.250

D	0.380	0.301	0.096	0.016	26.32	912.86	176	0.200
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3.2 Change in Mass

The difference between initial and final mass was relatively small for all four specimens. The recorded mass losses were approximately 3.5 g for Sample A, 2.2 g for Sample B, 3.6 g for Sample C and 2.3 g for Sample D. These results indicate that the specimens retained most of their initial mass over the reported test periods. The magnitude of mass loss should, however, be interpreted cautiously because the experiment has not captured complete combustion of each specimen.

Table 2. Initial and final specimen masses and calculated mass loss.

Sample	Initial mass (kg)	Final mass (kg)	Mass loss (g)
A	0.2620	0.2585	3.5
B	0.3020	0.2998	2.2
C	0.2710	0.2674	3.6
D	0.3800	0.3777	2.3

3.3 Flame Spread Distance and Velocity

The measured flame-spread distance varied from 0.195 m for Sample A to 0.250 m for Sample C. Sample C therefore exhibited the largest measured spread distance, while Sample A exhibited the smallest. The total test duration ranged from 135 s for Sample A to 219 s for Sample B.

Using the direct relationship $v = d/t$ and the distances and total times reported in the consolidated results table, the calculated velocities are approximately 1.44×10^{-3} m/s (Sample A), 1.00×10^{-3} m/s (Sample B), 1.48×10^{-3} m/s (Sample C) and 1.14×10^{-3} m/s (Sample D).

Table 3. Flame-spread velocity calculated directly from measured distance and total test time.

Sample	Distance (m)	Time (s)	Direct velocity d/t (m/s)
A	0.195	135	1.444×10^{-3}
B	0.220	219	1.005×10^{-3}
C	0.250	169	1.479×10^{-3}
D	0.200	176	1.136×10^{-3}

The heat-transfer-based calculation as per Quintiere produced values of approximately 4.615×10^{-3} m/s for Sample A, 4.761×10^{-3} m/s for Sample B, 4.421×10^{-3} m/s for Sample C and 2.839×10^{-3} m/s for Sample D. The model-based estimates are higher than the direct distance-to-time estimates. This difference may reflect differences in the physical quantities represented by the two methods, assumptions embedded in the heat-transfer model, uncertainty in the input parameters, or inconsistencies in the equation transcription. The two approaches should therefore not be treated as interchangeable measures without validating the model and ensuring dimensional consistency.

3.4 Thermal Analysis

The thermocouple records showed distinct temporal temperature responses for the four specimens. In Sample A, the first thermocouple showed a gradual increase during the initial approximately 30 s followed by a more rapid rise, while later

thermocouples responded after measurable delays. Thermocouple 3 remained below approximately 130 °C in the reported observations, and no clear response was recorded at Thermocouple 4. This pattern is consistent with a thermal front progressing along the specimen rather than simultaneous heating of the entire surface.

Sample B showed a rapid temperature rise at Thermocouple 1, reaching a maximum after approximately 75–85 s, followed by a decline. Thermocouples 2 and 3 exhibited delayed heating, while Thermocouple 4 showed little apparent change. Sample C displayed relatively rapid heating at Thermocouples 1 and 2, followed by a delayed response at Thermocouple 3. Sample D showed an early rapid response at Thermocouple 1, whereas Thermocouple 2 initially increased more slowly before showing a faster rise. As in the other specimens, Thermocouple 4 showed little measurable change.

Taken together, these temperature histories suggest that the thermal response was spatially non-uniform and that the flame front and associated heat flux did not reach all measurement locations simultaneously. The timing and magnitude of the thermocouple responses provide qualitative evidence of progressive heating and flame movement, although the absence of the original numerical temperature datasets prevents a quantitative analysis of temperature gradients or regression modelling.

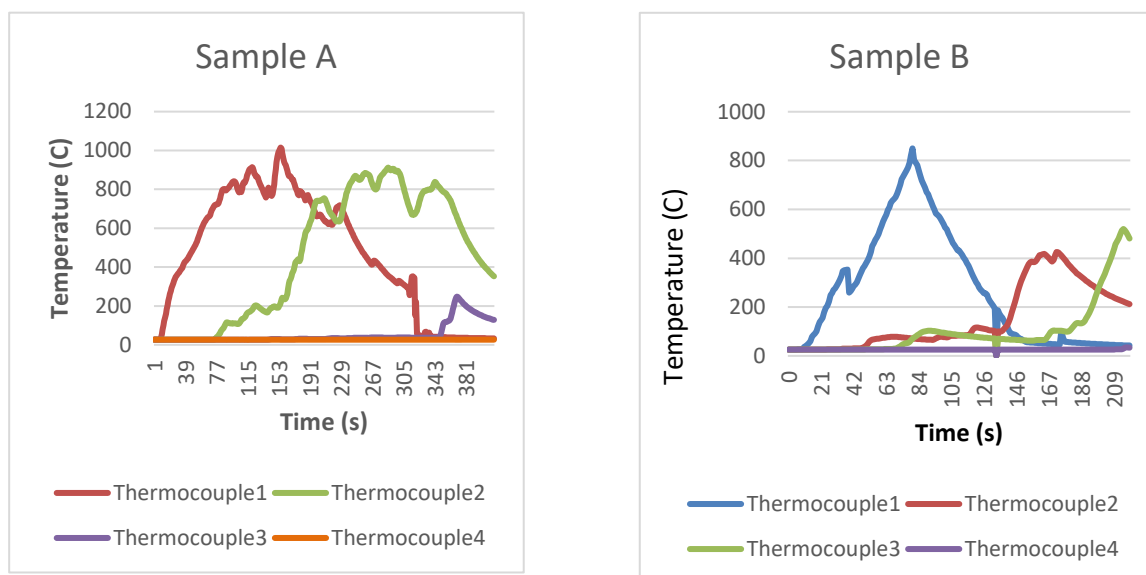


Figure 4. Temperature profiles recorded by four thermocouples for Sample A and B

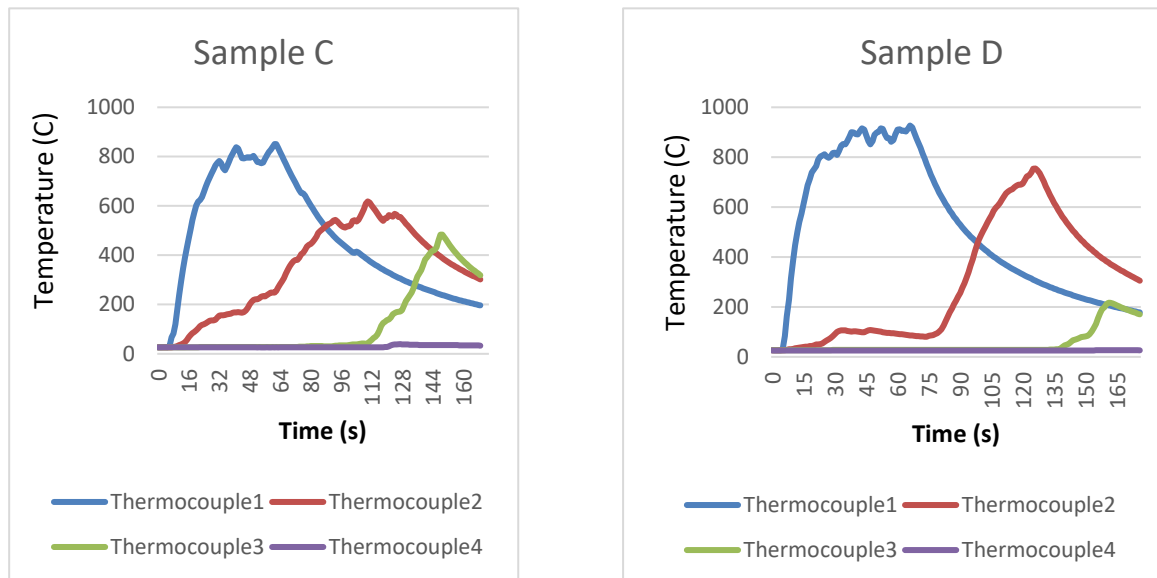


Figure 5. Temperature profiles recorded by four thermocouples for Sample C and D

4. Discussion

4.1 Influence of Material Properties

The results demonstrate that nominally similar wood specimens can exhibit different flame-spread responses. Sample C produced the largest measured spread distance, whereas Sample A produced the smallest. However, distance alone does not define flame-spread velocity; the time associated with that spread must also be considered. The direct velocity calculations suggest that Samples A and C had the highest rates among the four specimens, while Sample B had the lowest. This indicates that the longest test duration for Sample B was not accompanied by a proportionally greater flame-spread distance.

Differences in density may partly explain the observed behaviour. Sample D had the highest calculated density and the lowest heat-transfer-based velocity estimate. A denser material may require greater energy input to raise a given volume to its ignition condition, although density alone is insufficient to predict flame spread because thermal conductivity, specific heat, moisture content, thickness and surface characteristics also contribute. The present experiment did not independently measure all these properties, so causal conclusions should be treated as tentative.

4.2 Ignition and Thermal Response

The large differences between measured surface temperature and reported ignition temperature indicate that ignition was preceded by substantial heating. The ignition temperature varied markedly among specimens, which may reflect differences in material composition, moisture content, density or experimental uncertainty. Because the samples were all described as wood, but their species and moisture contents were not documented, it is not possible to attribute these differences to a single material property.

4.3 Influence of Wind and Atmospheric Conditions

Air movement can either accelerate or retard flame spread. When airflow is aligned with the direction of flame propagation, it may increase the supply of oxygen and promote the transport of heat and combustible gases toward unburned fuel. In opposed-flow conditions, the flow may increase convective heat losses or alter the flame structure, potentially reducing the spread rate. Moisture and ambient temperature can also affect ignition and burning behaviour. The original experiment did not report controlled measurements of wind velocity, relative humidity or oxygen concentration; consequently, these variables should be considered potential sources of experimental variability rather than quantified explanatory factors.

4.4 Experimental Uncertainty and Limitations

The study would be strengthened by repeating each test to obtain replicate measurements and uncertainty estimates; recording specimen moisture content; identifying wood species and grain orientation; controlling and reporting ambient temperature, humidity and airflow; documenting thermocouple positions; and using image or video analysis to track the flame-front position as a function of time. These improvements would allow statistically defensible comparisons and a more rigorous assessment of the mechanisms controlling flame spread.

5. Conclusion

This experimental investigation examined flame-spread behaviour across four solid wood specimens using measurements of specimen properties, ignition behaviour, temperature histories, flame-spread distance and mass change. The results demonstrate measurable differences in the response of the specimens despite broadly similar geometries. Flame-spread distance ranged from 0.195 to 0.250 m, while direct velocity estimates based on the consolidated distance and time data ranged from approximately 1.00×10^{-3} to 1.48×10^{-3} m/s.

The results indicate that flame spread is influenced by the interaction of material properties and thermal behaviour. Density, ignition temperature, heat transfer and the spatial development of the temperature field may all contribute to the observed differences. The thermocouple histories suggest progressive heating of the specimens and demonstrate that the thermal response varies with position and time.

The study also reinforces the importance of flame orientation and environmental conditions. Buoyancy can enhance upward flame spread, while airflow direction may either promote or oppose propagation. Moisture, material structure and other atmospheric conditions can further modify ignition and flame-spread behaviour. These factors are relevant to fire-safety engineering because faster flame spread can reduce the time available for occupant evacuation and increase the rate of fire growth.

Overall, the findings support the use of controlled experimental testing to characterize combustible materials. However, the numerical results should be considered preliminary until the inconsistencies identified in the original dataset are resolved and the heat-transfer model is verified. Future studies should incorporate replicate tests, better characterization of material properties and environmental conditions, and high-resolution flame-front tracking to improve the reliability and generalizability of flame-spread measurements.

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