Heat and mass transfer of flame spread along a combustible slope

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1 Introduction

Flame spread along an inclined surface is often observed in wild and residential fires. During flame spread, upward and downward spreading of flames is seen. Under wild fire conditions, the thin combustible is close to the ground. The presence of the ground may affect the flow and temperature fields, which govern the heat and mass transfers in the spreading flame.

Flame spread along the combustible close to the ground was examined by Professor Torahiko Terada more than 80 years ago [1]. He reported that the downward-spreading flame is only observed along a combustible that is inclined approximately 35° close to the ground.This phenomenon is called the "Terada phenomenon." However, his report has not been widely referenced by recent studies.

In a previous study [2], the Terada phenomenon, as depicted in Figure 1, was seen at an inclined angle θ = 25 °–55 ° when the separation dL between the combustible bottom and the base was 3 mm. The range of inclined angle θ where the Terada phenomenon occurs decreased as the gap height dL increased. The Terada phenomenon was not observed when d_L = 6 mm. It is considered that the Terada phenomenon occurs because flow in between the combustible bottom and the base changes with the gap height d_L and inclined angle θ.

In this study, the flame spread in the vicinity of the thin combustible surface was observed using the Schlieren equipment to investigate the influence of the flow between the combustible bottom and the base.

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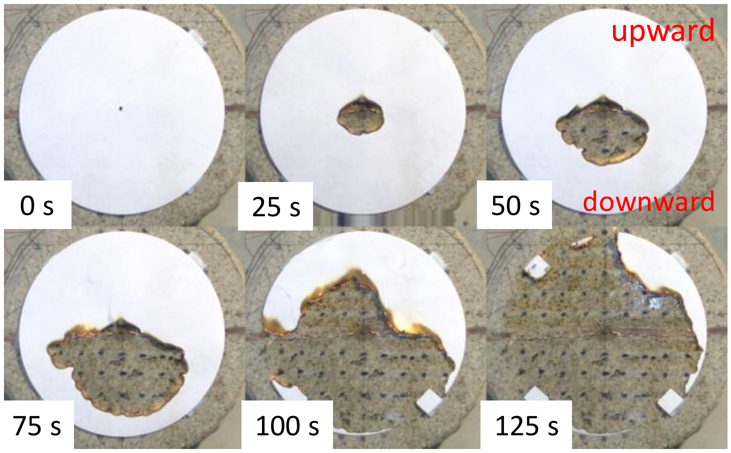

Figure 1. Flame spread when the Terada phenomenon occurs (d_L = 3 mm, θ = 35 °)

2 Experimental equipment

Figure 2 illustrates the experimental equipment. A round granitite disk of diameter 380 mm was used as the base. Circular filter paper 300 mm in diameter was used as the thin combustible. Aluminum blocks with thicknesses of 3 mm each were installed for the criterion of the gap height d_L..The circular filter paper was supported by spacers 3 mm in diameter. The spacers were located at 3 mm grid points. The absence of spacers made the sample surface convex downward and resulted in local extinction of the spreading flame.

The circular filter paper was ignited at the center by an electric heater of chromel wire. Two copper plates of 100 μm were laid along the base to supply the power to the heater. The inclined angles θ of the circular filter paper were 0 °, 15 °, and 35 °. Figure 3 illustrates the Schlieren equipment. The vicinity of the filter paper surface at points 15 mm from the ignition point in the downward and upward directions was observed using the Schlieren equipment.

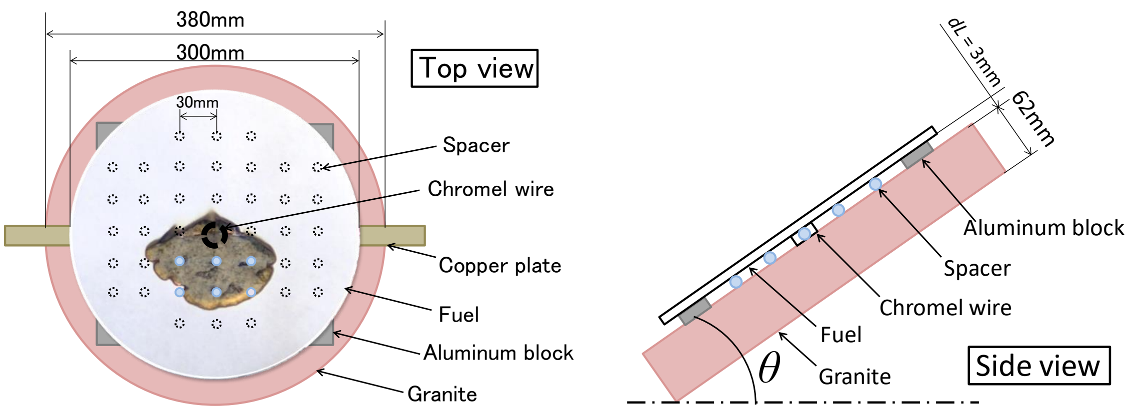

Figure 2. Outline of experimental equipment

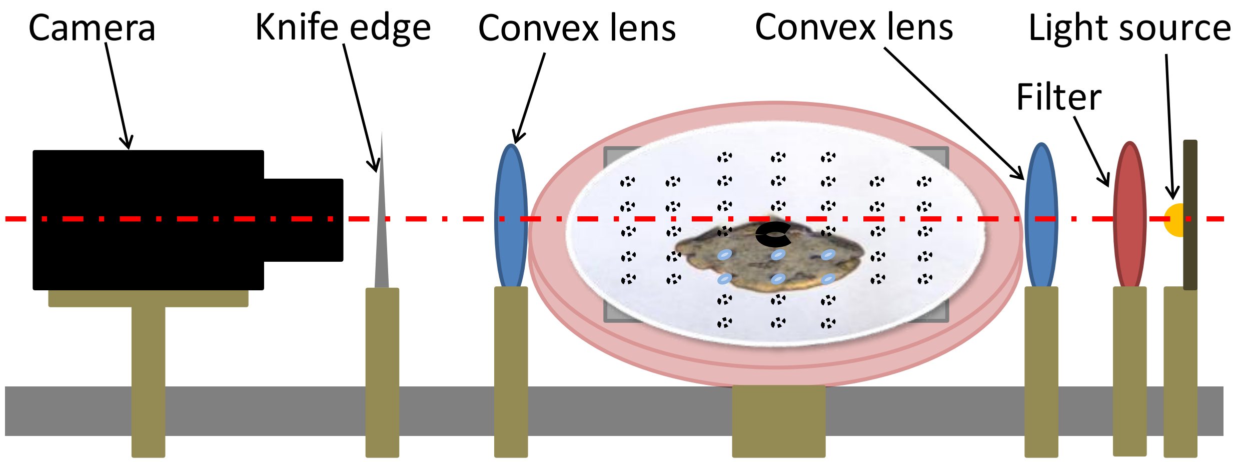

Figure 3. Outline of Schlieren equipment

3 Experimental results

Figure 4 illustrates the vicinity of the filter paper surface at θ = 0 °. Figure 5 illustrates the x-t diagram at the point 1 mm below the filter paper surface. After ignition, the pyrolysis gas was generated. This gas vibrated in in the gap when the flame spread.

In the upward flame spread at θ = 15 °, after ignition, the pyrolysis gas was generated at more than θ = 0 ° and remained in the gap. Then, the flame spread upward when the pyrolysis gas flowed downward. The pyrolysis gas vibrated in the gap when the flame spread.

In the downward flame spread at θ = 15 °, after ignition, the pyrolysis gas generated was much lesser than that in the upward spread and did not stay. The pyrolysis gas vibrated in the gap along with the flame spread. After a short time, the gas did not vibrate, but the flame continued to spread.

Figure 6 depicts the vicinity of the filter paper surface at the upward flame spread at θ = 35 °. After ignition, a large amount of pyrolysis gas was generated as with upward flame spread at θ = 15 °, and stays in the gap. Then, the pyrolysis gas did not flow downward, and there was an upward flame spread while the gas continued to remain in the gap. The gas vibrated in the gap while the flame spread. When the pyrolysis gas did not vibrate and the gas concentration decreased, the flame did not spread.

In the downward flame spread at θ = 35 °, after ignition, the pyrolysis gas was generated, and it vibrated in the gap while the flame spread. After a short time, as with the downward flame spread at θ = 15 °, the pyrolysis gas did not vibrate, but the flame continued to spread.

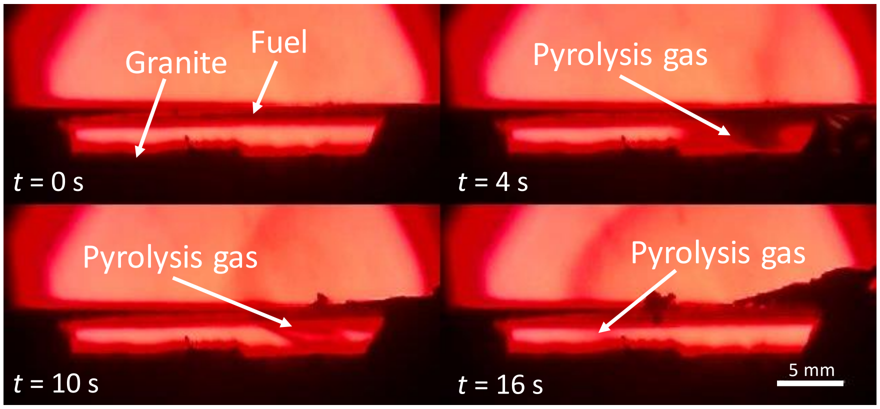

Figure 4. Vicinity of the filter paper surface (d_L = 3 mm, θ = 0 °)

Figure 5. *x*-*t* diagram (d_L = 3 mm, θ = 0 °)

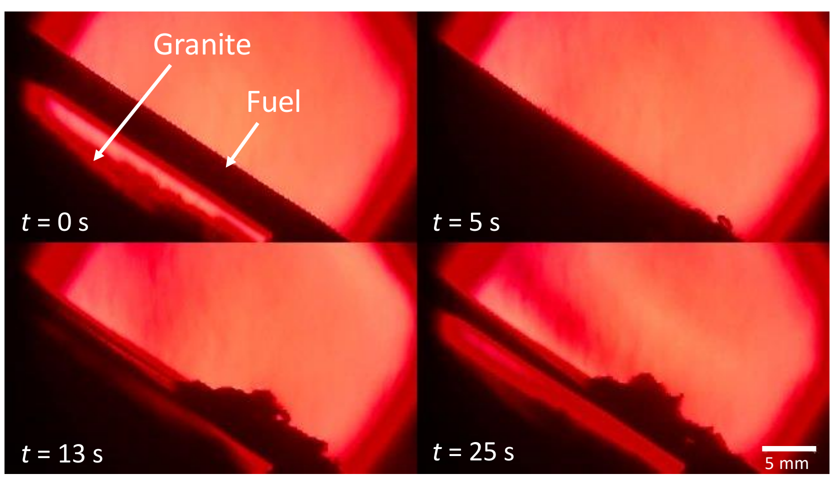

Figure 6. Vicinity of the filter paper surface in the upward slope direction from the ignition point (d_L = 3 mm, θ = 35 °)

4 Discussion

Equation 1 shows the consumption rate ω_i of species *i* per flame unit area.

$$\omega_i = A\, C_i\, \left(\frac{V\, D_i}{L}\right)^{\frac{1}{2}} \tag{1}$$

A is proportionality constant, C_i is the concentration of species i, V is the flow velocity, D_i is the diffusion coefficient of species i, and L is the representative length.

Figure 7 illustrates the relationship between the consumption rate ω_i and representative length L. If representative length L is constant at L_1, the consumption rate ω depends on the flow velocity V.When the consumption rate ω_i becomes larger than the critical consumption rate ω_c, the flame under the filter paper cannot consume all the pyrolysis gas, and it continues to stay in the gap. As the amount of pyrolysis gas increases, the heat loss also increases, so the flame under the filter paper extinguishes. Thereafter, the gas that stays as a result of the flame heat over the filter paper is consumed, and a flame is again generated under the filter paper. However, because many pyrolysis gases are generated and the above phenomenon is repeated, the vibration shown in Figure 5 is observed.

Figure 8 depicts the temporal change of vibration amplitude. Immediately after ignition, the heat loss to the base is large, and thus, the flame is not steady. Therefore, the amplitude is large at θ = 0 ° and at the downward flame spread at θ = 15 ° and θ = 35 °. After a short time, the amplitude becomes small and does not vibrate at the downward flame spread at θ = 15 ° and θ = 35 °. Because the consumption rate ω_i is smaller than the critical consumption rate ω_c, the flame can consume pyrolysis gas. The pyrolysis gas continues to vibrate at θ = 0 °, because the consumption rate ω_i is larger than the downward flame spread at θ = 15 ° and θ = 35 °.

The amplitude gradually increases with the upward flame spread at θ = 15 ° and θ = 35 °. Because the flow velocity V in the upward direction is larger than rate V in the downward direction owing to the influence of buoyancy, the consumption rate ω_i becomes larger than the critical consumption rate ω_c.Because θ = 35 ° is significantly affected by buoyancy, the consumption rate ω_i is larger than at θ = 15 °.

Therefore, as illustrated in Figure 6, a considerable amount of pyrolysis gas continues to stay in the gap. Not only the flame under the filter paper, but also the flame over the filter paper is extinguished by the heat loss to the pyrolysis gas.

5 Conclusions

The pyrolysis gas vibrated in the gap along with the flame spread.

In the downward flame spread, the pyrolysis gas did not vibrate, and the flame was stabilized.

In the upward flame spread at θ = 35 °, the flame was extinguished by the heat loss to the pyrolysis gas.

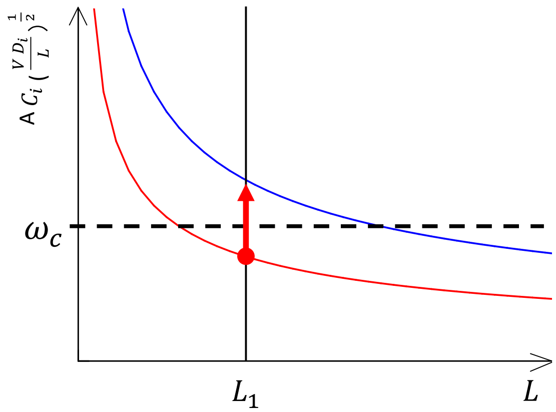

Figure 7. Relationship between consumption rate ω_i and representative length L.

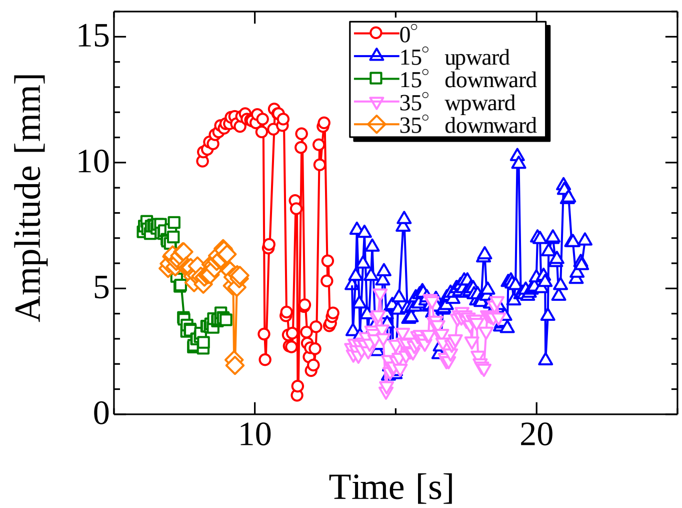

Figure 8. Temporal change of amplitude of vibration

References

[1] Torahiko Terada (1930) Preliminary Study on Flame Spread along combustible surface, Research Report of Riken 9-7:551-560.

[2] Keiichiro Hiyama, Takashi Tsuruda, Tadafumi Daitoku (2018) Flame spread limit along combustible slope, Japan association for fire science and engineering, Proceedings of JAFSE Annual Symposium 2018, 126-127.