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FLAME SPREAD

T. Hirano

National Research Institute of Fire and Disaster

JAPAN

ABSTRACT

This paper presents a brief survey of the key aspects of flames spreading across various condensed combustibles, and a discussion on flame spread mechanisms. Flames can be divided into two types, diffusion flames and premixed flames. A diffusion flame spreads across the combustible surface by heating the combustible material, ahead of the leading flame edge, to the gasification temperature. The flammable gas ejected from the surface sustains the flame. Behaviour of the flame in this case is closely related to the gas movement near the leading flame edge. In contrast, a premixed flame propagates through a flammable mixture layer established over the combustibles. The flame propagation in this case depends on the characteristics of the flammable layer such as its thickness and the concentration profile across it. It is also shown that propagating flame behaviour is closely related to the gas movement near the leading flame edge. The reason is that the gas velocity field greatly influences the heat and mass transfer needed for flame spread or flame propagation. Therefore, data on the gas movement near the leading flame edge is desirable in studies aimed at understanding the mechanisms of flame spread or propagation.

Keywords: Fire research, flame spread, flame spread mechanisms, flow field, review.

INTRODUCTION

Characteristics of flames spreading across various condensed combustibles have been studied, not only for understanding the phenomena at the early stages of fires, but also for accumulating fundamental knowledge in fire science. Flame spread across a number of combustibles under various conditions has been examined and a large amount of data has been accumulated. Based on the accumulated data, elucidation of the mechanisms of flame spread has been attempted, and appropriate models have been proposed. The results of previous studies on flame spread across condensed combustibles have been summarised in several review papers[1-11]. In most of these papers, discussion has been performed on the mechanisms of flame spread.

Spread of combustion zones in some special fires such as smoldering and iron block combustion is also important in fire research and reviewed in a several previous papers[12-15]. In this paper, however, the spread of the combustion zone without a flame in the gas phase is excluded to prevent the discussion from diverging.

When the temperature of a condensed combustible is below its flash temperature, the layer of a flammable mixture is not established ahead of the flame. In this case, the condensed combustible gasifies by the heat from the flame. The gasified combustible gas is ejected into the ambient oxidiser gas (air), a combustion reaction occurs to form a diffusion flame, and the heat released at the flame reaction zone transfers to the condensed combustible. Most previous studies on flame spread over solid combustible surfaces have been performed on the basis of this process, with a number of recent papers published on this subject[16-20]. However, when the temperature of a condensed combustible is above its flash temperature, a layer of a flammable mixture of vaporised gas and ambient oxidiser gas (air) is established over the combustible surface before ignition[5,8,10]. In this case, a premixed flame propagates through the layer. Thus, the flames spreading (or propagating) across condensed combustibles can be subdivided into two types, diffusion flames and premixed flames.

In previous papers, various models of flame-spread mechanisms have been proposed. These models are obviously based on the results of flame-spread experiments under various conditions. In each individual model, the processes of heat and mass transfer in the gas phase are assumed, which are closely related to the gas flow field[1-11, 16-20]. However, the gas flow field near a spreading or propagating flame has not been measured in the flame spread experiments except for those performed by the current authors[6,8,10,11].

The objective of this paper was to show several examples of the measured gas movement near spreading or propagating flames and to indicate the importance of knowledge on gas phase aerodynamics for understanding the flame spread. Although the flow in the liquid phase is important for understanding the flame-spread mechanisms across a liquid combustible at sub-flash temperature, discussion on the liquid flow is not presented in this paper because it has been presented in a number of previous review papers[5,8,10].

Diffusion flame spread

A flame spreading over a sheet of polymeric material such as filter paper or polymethylmethacrylate (PMMA) is a diffusion flame. For understanding the flame-spread mechanisms, knowledge on the characteristics of the leading flame edge is indispensable. Since the leading flame edge is blue and a narrow dark zone is observed beneath it, researchers can be misled about the characteristics of that part of the flame and may believe that it is a premixed flame. However, the blue leading flame edge is not one of the characteristics of a premixed flame. Under certain conditions, a diffusion flame is blue[21] and the color does not necessarily indicate premixed combustion.

Proofs can be found in previous papers indicating the characteristics of the leading flame edge spreading over a solid combustible. The papers of Frey and T'ien[22] and Yashima and Hirano[23] are examples of such papers. The former is an earlier paper of numerical simulation about the concentration and temperature distributions near the leading flame edge[22]. The result of their simulation shows that the fuel concentration ahead of and underneath the leading flame edge is far below the lower flammability limit. This fact implies that the combustion at the leading flame edge is controlled by diffusion under quenching. The number of oxygen molecules approaching the leading edge near the combustible surface decreases mainly by diffusion to the leading edge and only a negligibly small fraction of the oxygen molecules in the free stream would be able to pass through the dark zone. Consequently, the oxygen molecules passing the dark zone scarcely influence the fuel concentration behind the leading flame edge. The latter is a paper presenting experimental verification of the characteristics of a flame spreading over a solid combustible. Yashima and Hirano[23] provided a special experimental apparatus. They changed the movement of the gasifying region of the solid combustible using a velocity controllable apparatus on which a PMMA piece was installed. It was shown that the leading flame edge was kept stable when the velocity of the apparatus, i.e., the velocity of the leading flame edge, was below a limiting velocity between 30 and 40 cm/s. This result indicates that a diffusion flame can move with the gasified region if its velocity is below the limiting velocity.

The first paper to present the results of velocity measurements near the leading flame edge spreading over a solid combustible appeared in Combustion and Flame in 1974[24]. Hirano et al. measured the velocity profiles near the leading flame edge spreading over a paper sheet at three different angles by using particle tracer techniques. In the case of a downward flame spread over a vertical paper sheet, the velocity field was rather stable, while the velocity fields in the cases of downward flame spread over inclined paper of angle 30° from the horizontal surface and horizontal flame spread were not so stable, and the velocity profiles changed greatly with time. In each case, the gas velocity in the vicinity of the spreading flame was much higher than the flame spread rate except very close to the paper surface. In the case of downward flame spread over inclined paper, a small vortex was occasionally observed ahead of the leading flame edge at the bottom side. For horizontal flame spread, gas in the vicinity of the leading flame edge at the bottom side flowed in the same direction as the flame spread. These observed flow fields near the leading flame edge were useful to interpret the mass and heat transfer controlling the flame spread. The small vortex or forward flow was inferred to enhance the heat transfer to the unburned material and increase the spread rate.

Hirano and Sato[25] performed an experimental study of downward flame spread over a paper sheet using a vertical wind tunnel. They measured the effects of external radiation and ambient air velocity on the flame spread and found a range of ambient air velocities for stable flame spread (Figure 1). In this air velocity range, the flame spread rate decreased very slightly with the increase of the air velocity. The gas velocity profiles near the leading flame edge were measured and it was found that the air stream approaching the leading flame edge decelerated to form the lower velocity region near the paper surface ahead of the leading flame edge. In the range of ambient air velocities for stable flame spread, the velocity profiles of this region change only slightly. This is the reason why stable flame spread could be observed in a certain range of ambient air stream velocities.

Flow field measurements have provided extremely comprehensible and reasonable information on the mechanisms of unstable flame spread[26]. When the upward free-stream velocity is above that of the stable downward flame spread limit over a paper sheet, a series of local blow offs were found during the spread. In this case, most leading flame edges were inclined or bended, and blow offs occurred mainly at the locations where both the inclined angle of the leading flame edge from the horizontal surface and the curvature of the leading flame edge were small.

The flame spread phenomena, including blow offs at the burning zone with a straight leading flame edge, can be considered to depend mainly on the velocity component of the free stream normal to the leading flame edge and only slightly on the velocity profile in the boundary layer of the approach flow.

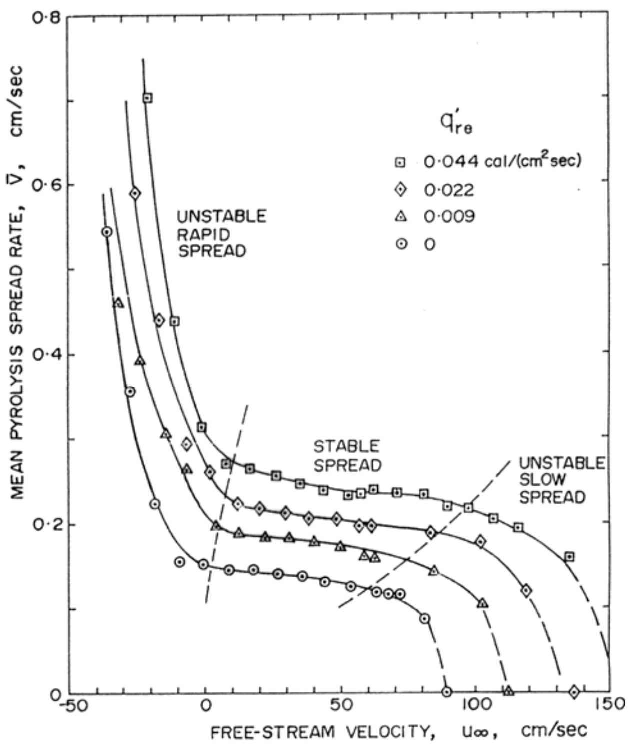

Figure 1: Variation of mean pyrolysis spread rate with free-stream velocity.

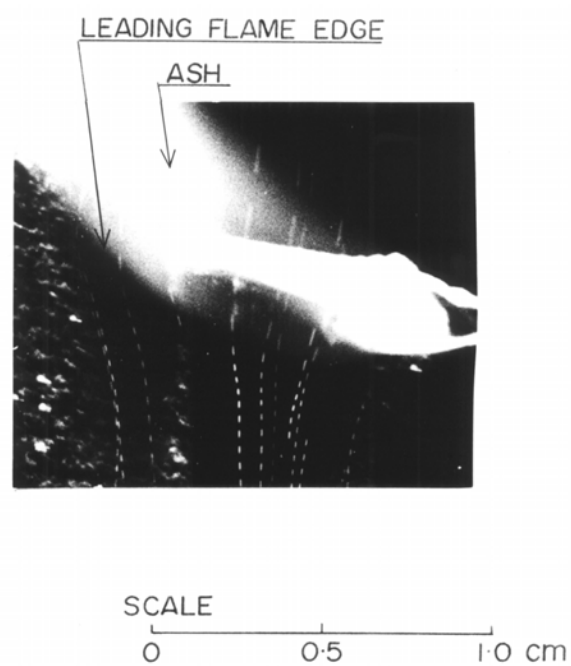

Figure 2: Typical photograph of particle tracks which indicate the flow field near a burning zone. Free-stream velocity: 80 cm/s; particle track: 360 interruptions/s.

At a given velocity of the free-stream, the deceleration of the gas stream near the burning zone with a curved leading flame edge decreases as its curvature decreases. The deceleration of the gas stream near the burning zone was found to be necessary for locally stable flame spread. Near the burning zone with a curved leading flame edge, the gas stream was found to decelerate as it approached the leading flame edge and the stream-tube expansion in the direction parallel to the paper surface could be observed (Figure 2). A local blow off was inferred to occur when the gas velocity across the flame edge becomes larger than a critical value. When the gas velocity across the leading flame edge in any configuration cannot be kept smaller than the critical value, a complete blow off would occur.

Even when a flame spreads upward, its spreading could be restricted by increasing the downward air stream velocity[27]. The experiments were performed in a vertical duct, which was placed underneath a converging nozzle of a wind tunnel and the combustible solid was a sheet of filter paper. Following detailed observation of the behaviour of flame spread, the effects of air stream on gas-temperature profiles near the preheat zone and streams passing through the preheat zone were examined using particle tracer techniques, fine-wire thermocouples, and schlieren photography.

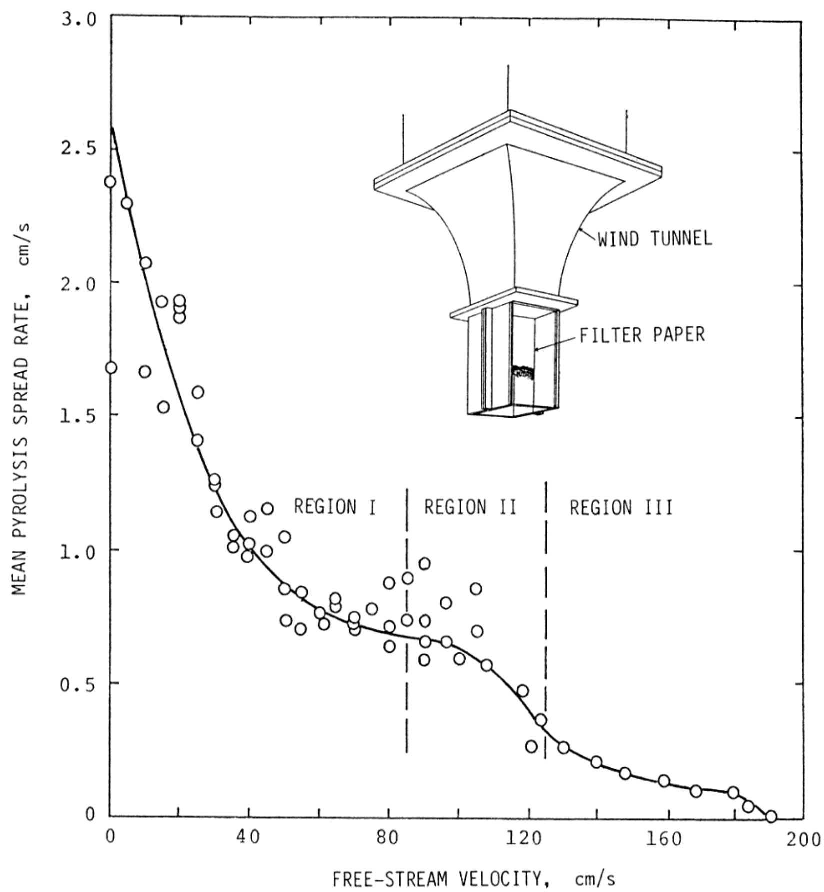

Figure 3: Variation of mean pyrolysis spread rate with downward free-stream velocity.

Based on the observations, the types of flame spread were divided into three regions characterised by ranges of the air stream velocities (Figure 3). In Region I, representing the range of air-stream velocities from 0 to 85 cm/s, flame spread was accelerative, although the acceleration decreased with the increase of the air-stream velocity. In Region II, representing the range of air-stream velocities from 85 to 125 cm/s, local flame spread rate fluctuated greatly, and flame spread was of intermediate characteristics between those of accelerative flame spread and steady flame spread. In Region III, representing the range of air-stream velocities from 125 cm/s to 190 cm/s, flame spread was almost steady and resembled that of downward flame spread.

In Region I, a hot gas stream preheated the unburned material far ahead of the pyrolysis front. In Region II, the unburned material preceding the pyrolysis front was preheated periodically. In this case, the heat transfer from one side of the paper was different from the other side. In Region III, the preheating of the unburned material was confined in a narrow region ahead of the pyrolysis front.

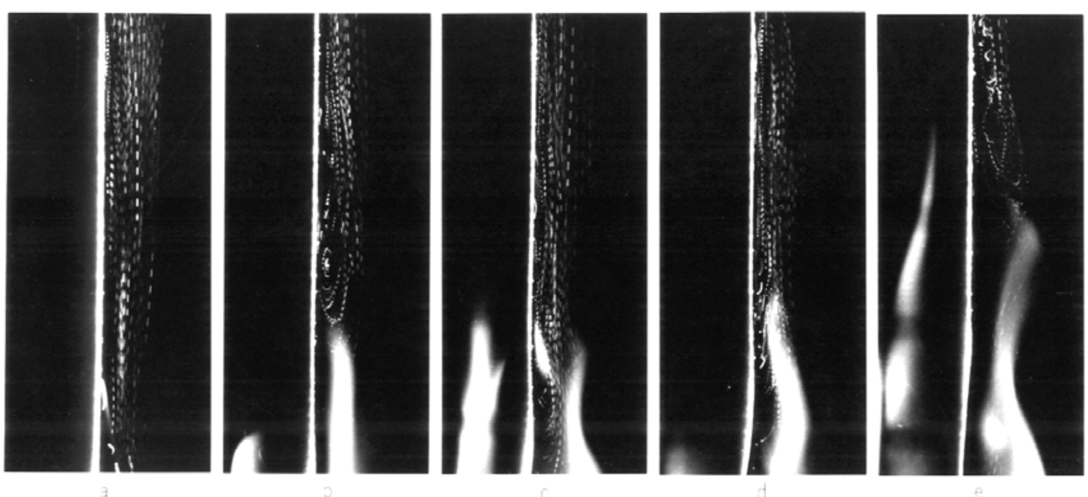

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Figure 4: Flow field change near the leading flame edge under conditions of Region II. Free-stream velocity: 120 cm/s; Particle track: 360 interruptions/s; frame speed: 1 frame/s.

The difference of flame behaviour in Region I and that in Region III is attributable to the difference of gas stream directions. In Region I, the gas near the leading flame edge flowed upward, while in Region III it flowed downward. In Region II, it flowed upward and downward alternatively. Figure 4 shows a series of particle tracer photographs representing the variation of the flow field. It is seen that acceleration, deceleration, and vortexes appear and flame spread depends on the flow field. When the gas stream velocity ahead of the leading flame edge decreases (Figure 4a) a vortex appears and the leading flame edge moves upward due to the upward stream near the surface (Figure 4b). Just after the flame stops to move upward and stagnates, the vortex disappears and the gas stream ahead of the leading flame edge changes its direction to downward (Figure 4c). This process occurs repeatedly (Figure 4d and Figure 4e).

It was inferred that the flame spread phenomena in different directions resembled each other if the external air stream cancelled the difference of the boundary effects caused by the density difference between the gas near the flame front and ambient air and induced similar flow fields near the leading flame edges. The momentum difference of external air streams for the cases, when similar stable flames spread vertically upward and downward, was estimated to be about 0.2 $kg/(m^2s)$.

Knowledge on flow fields near the leading flame edges can make the discussion on the flame-spread mechanisms reasonable. An experimental study has been conducted to elucidate the mechanism by which the spread rate of a stable, downward-spreading flame over paper increases with the increase of the radiation flux from an external heat source[28]. The gas velocity and temperature profiles near the leading flame edges under various external radiation fluxes were examined by using particle tracer techniques and fine wire thermocouples.

Velocity profiles ahead of the leading flame edge were greatly influenced by the external thermal radiation. As the external radiation flux was increased, the gas-stream velocity upstream of the leading flame edge increased and the deceleration of the gas stream approaching the leading flame edge became intense.

The temperature profiles near the leading flame edge were also greatly influenced by the external thermal radiation. At the station 0.2 cm ahead of the pyrolysis front the temperature gradient at the paper surface in the direction normal to it decreased as the external radiation flux was increased, while at the station just ahead of the pyrolysis front the temperature gradient increased with the external radiation flux. Although the preheat-zone width decreased with the increase of external radiation flux, the net heat flow to the unburned material increased with it.

The increase of the flame spread rate with the increase of external radiation flux could be attributed not only to the increase of the unburned material temperature but also to the increase of the rate of heat transfer from the flame zone to the unburned material through the gas phase.

Premixed flame propagation

When the concentration of the gasified combustible ahead of the leading flame edge is large enough to form a flammable mixture layer with ambient oxidiser gas (air) over the condensed-phase combustible, a premixed flame propagates through the layer[29]. In this case also, knowledge on the gas movement near the flame is useful to understand the flame behaviour.

The flame propagation velocity in this case is larger than the burning velocity. This fact has been known and theoretically predicted[30]. In the theory, aerodynamic aspects near the flame were analysed. Because of the difficulty in velocity measurement, however, confirmation of the analysis was not performed. No experimental data on the flow field ahead of a flame propagating through a layered flammable mixture was available prior to the efforts of a group including the current author[29]. It is usual to take a long period of time to recognise the reliability of a new method. The results obtained in the present study were fairly accurate, indicating the reliability of the method.

The method was simple and applied to the measurement of the velocity profiles near the propagating flames across methanol in a tray. In the experiments, a hot gas generator (Nichrome wire of 0.5 mm in diameter) was installed horizontally over the fuel surface. The temperature of the hot gas track was controlled to be only slightly higher than the ambient gas so that its velocity was a few cm/s which is much smaller than the flame propagation velocity. After a hot gas track was generated and it was directed vertically upward, methanol in the tray was ignited at one end. The time from the start of

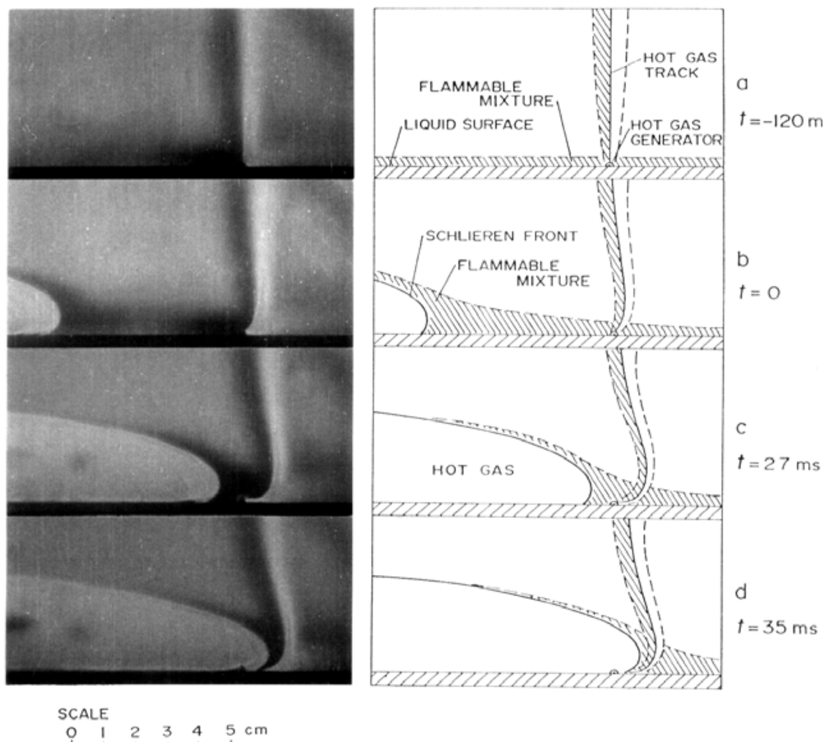

Figure 5: Typical schlieren photographs representing the movements of flame front and hot gas track. Methanol temperature: 29°C; *t*: the time after the photograph b was taken.

heating the Nichrome wire to ignition was less than 10 s, during which the temperature rise of the methanol surface underneath the wire was less than 1°C. The gas movement was measured using high-speed schlieren photography.

Typical schlieren photographs representing the gas movement ahead of a propagating flame are shown in Figure 5. It is seen that the gas ahead of the leading flame edge moves forward. This gas movement was inferred to be due to the expansion of the gas at the flame. Figure 6 shows the variation of the maximum velocity u_{m0} just ahead of the leading flame edge and flame propagation velocity V_f with methanol temperature. The difference of V_f and u_{m0} at a temperature above 22°C was about 50 cm/s, corresponding to the burning velocity of a stoichiometric methanol-air mixture.

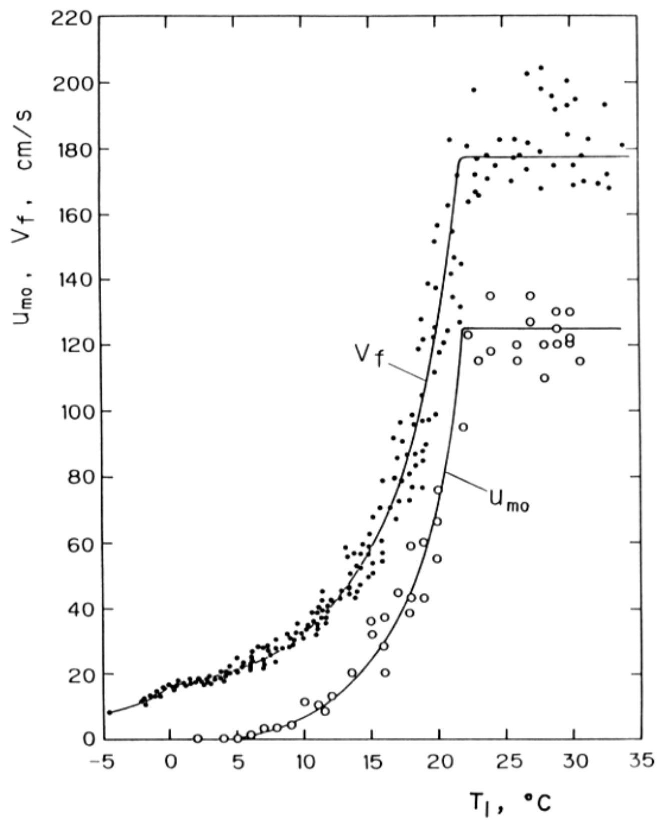

Figure 6: Variation of the maximum gas velocity ahead of the leading flame edge with initial methanol temperature. V_f: flame propagation velocity; u_{m0}: maximum velocity just ahead of the leading flame edge; T_l: methanol temperature.

It should be noted, however, that the velocity difference at a temperature near the flash point and below does not correspond to the burning velocity. The results of previous studies indicated that the gas stream passes a diffusion flame at a finite velocity[21,23]. Flames at methanol temperatures near the flash point would be of an intermediate type.

Detailed gas movements ahead of propagating flames through layered flammable mixtures were theoretically simulated on the basis of convenient models[32]. In the analyses, two-dimensional inviscid flow fields and constant flame velocities during propagation were assumed. Thermal expansion of gas due to combustion at the flame front was replaced by an imaginary source behind the flame front. Two cases were analysed. In one case, a flat flammable mixture layer, through which a flame propagates, was assumed to be established in an open space, and in the other case, it was assumed to be established in contact with a liquid or solid surface parallel to the layer. Equations representing the flow fields, fuel concentration distributions, gas particle paths, and flame front shapes were derived. The phenomena discussed in this section are those in the latter case. The results agreed fairly well with the experimental results[32].

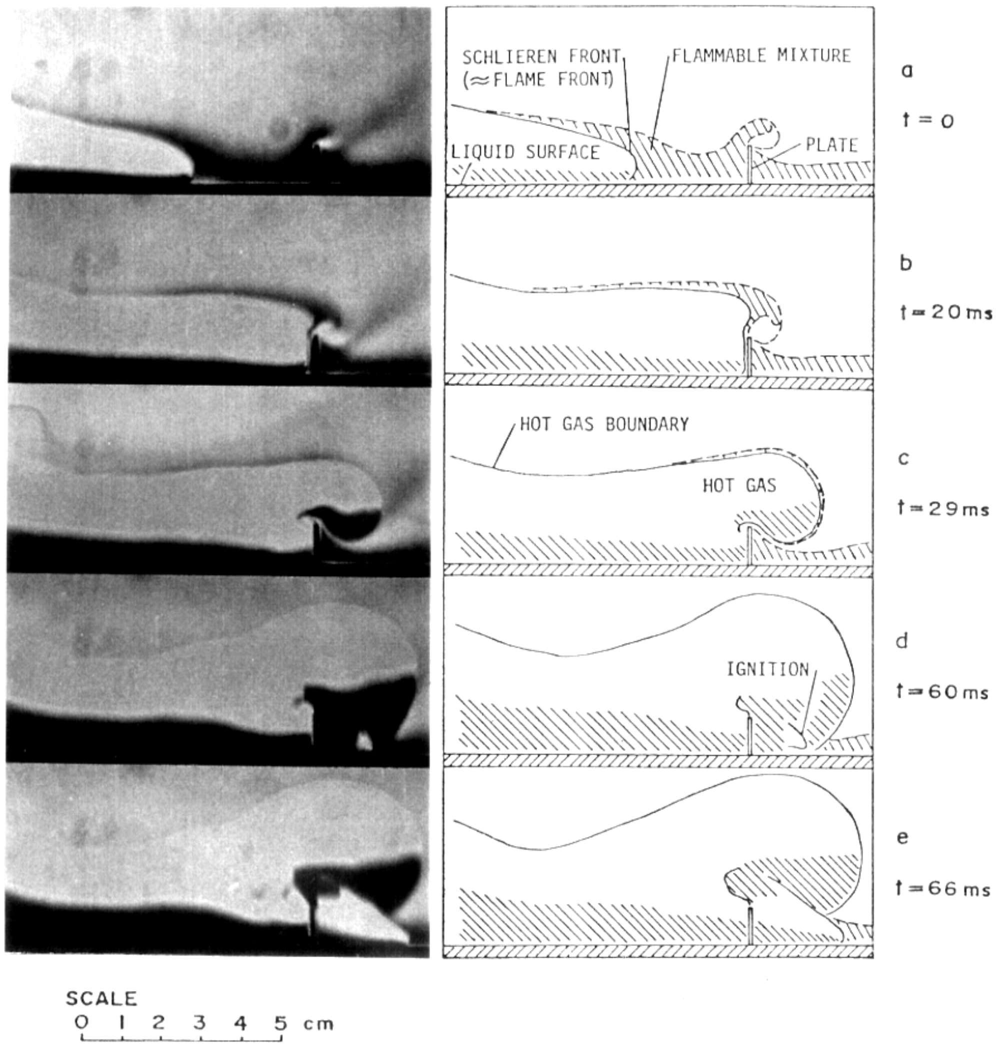

Figure 7: Schlieren photographs of a flame jumping over the top edge of a plate. *t*: elapsed time after the state shown in a was recorded; Methanol temperature: 25°C; plate height: 1.0 cm.

Behaviour of a flame propagating across an obstacle on a combustible at a super-flash temperature is closely related to the gas movement ahead of the leading flame front. Figure 7 shows a series of schlieren photographs representing the process of a flame jumping over a plate on a flammable liquid surface at a super-flash temperature[33]. It was found that a flame jumps over a plate, whose height is 2 to 4 times the thickness of the flammable layer of the methanol vapour/air mixture above the methanol surface. Movement of the flame front and the gas ahead of the front near a plate is simulated by a similar manner adopted in[32].

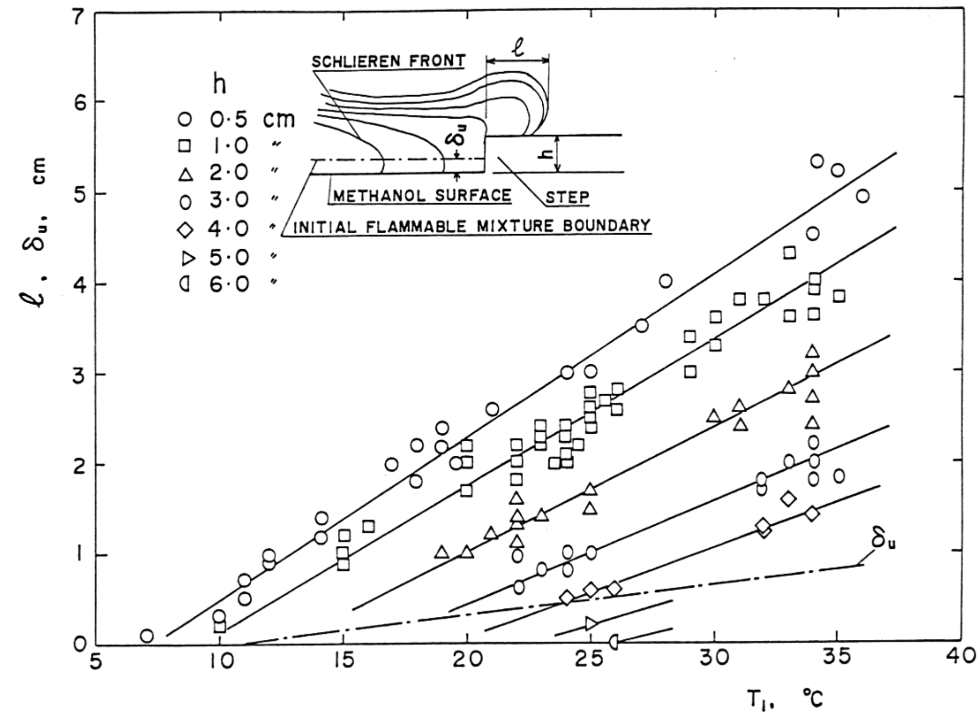

Figure 8: Range of flame propagation on the top surface of the step. *L*: distance of flame propagation along the top surface; δ_u: thickness of the flammable mixture before ignition.

The predictions of flame movement near a plate agree fairly well with experimental observations. As a consequence, the flame spilling over the top edge of a plate whose height is much larger than the thickness of the corresponding flammable mixture layer appears to result from the gas movement preceding the leading flame front.

A study was also made of flame behaviour near steps bounding layered flammable mixtures established over liquid or solid surfaces[34]. When the step height is less than a few times the thickness of the flammable mixture layer before ignition, a flame is shown to climb on the step and to propagate along its top surface (Figure 8). The distance of flame propagation along the top surface is found to increase as the height decreases or as the layer thickness increases. The flame movements near steps can be fairly well simulated by a similar theory. Both the experimental and theoretical results indicate that the distance of flame propagation depends on the ratio of the effective initial thickness of the flammable mixture layer to the step height.

A flame can propagate through a flammable layer even when the air stream velocity is larger than the flame propagation velocity in quiescent air (Figure 9)[35]. Discussion has been performed on the aerodynamic aspects of the leading flame edge in the air stream of a limiting velocity when flame stops propagating. If the flame is premixed, the gas flow velocity at the leading flame edge should be equal to the burning velocity. It was pointed out that if the methanol temperature is higher than 20°C the gas flow velocity at the leading flame edge was equal to the burning velocity. For a methanol temperature below 15°C, however, the gas-flow velocity is higher than the burning velocity. This result implies that the characteristics of the leading flame edge are not of a premixed flame.

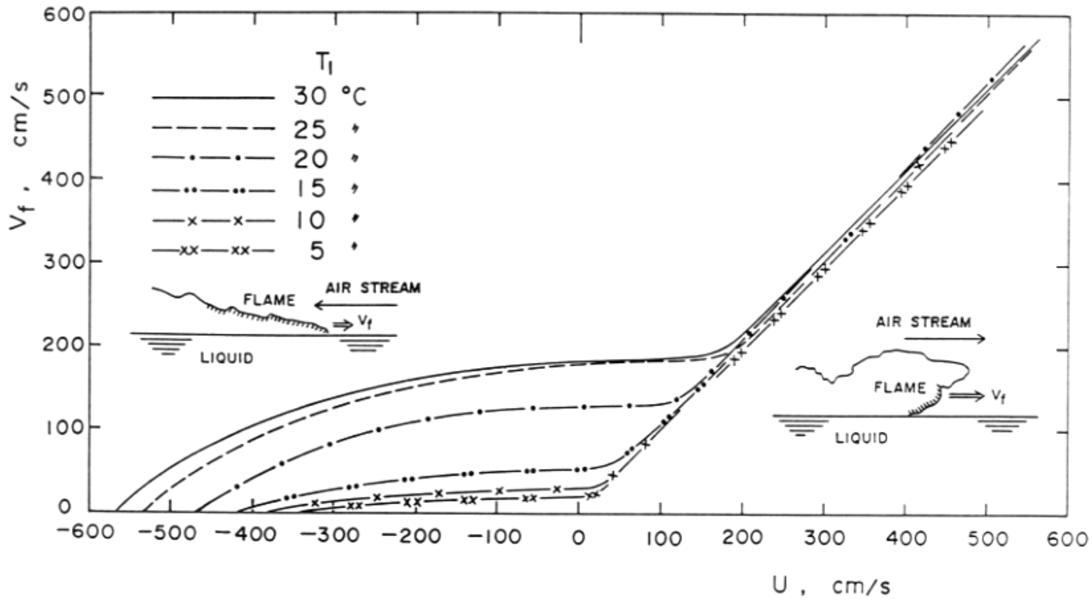

Figure 9: Variation of flame propagation velocity with free stream velocity for various values of initial methanol temperature.

CONCLUSIONS

Throughout this paper, it has been shown that the aerodynamic measurements and their consideration are extremely important in understanding the flame spread or propagation mechanisms. When accurate measurements are impossible, only flow visualisation has provided information on the mechanisms.

Very little data is available on the gas velocity fields at flame spread or propagation. This would not imply that knowledge on gas velocity fields is not important for understanding the flame spread or propagation mechanisms. In most theories or explanations on flame spread or propagation, flow fields have been assumed[1-11,16-20]. To verify the appropriateness of the assumption or explanation, data on the flow fields would be the most useful. The only reason why available data is scarce is the difficulty of making flow field measurements.

The examples of flow field measurements and consequently revealed facts presented in this paper are mainly cited from previous papers by the current authors.

In some recent studies, the mechanisms of flame spread under specific conditions have been sought. In the studies on flame spread in microgravity, the flame-spread mechanisms have been discussed without experimental data of flow fields near the flame leading edge, which would be different from those in normal gravity[17,20,36-40]. Nevertheless, the explanation has been frequently based on heat and mass transfer under the influence of the gas flow, so that the appropriateness of the explanation of flame behaviour has not yet been verified. Also, in the studies on flame spread over napped fabrics, the variation of flame-spread velocity has been explained without experimental data of flow fields near the leading flame edge[41-43]. If researchers succeed to measure the velocity profiles across the leading flame edge, the explanation about the spread rate jump would be more rational. It is important to make clear whether the gas ahead of the leading flame edge at surface flash spread moves or not. A new model of flame spread in this case is anticipated. Most parts of uncertainty on flame spread would be clear if the flow fields were measured. Flow fields should be measured if the flame spread mechanisms are to be studied in further detail.

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