Invited Lecture

Physical Aspects of Combustion in Fires

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ABSTRACT

Present understanding of physical aspects of combustion in fires is summarized in this paper. Following a brief description made on present achievements and remaining problems in fire physics, a comprehensible interpretation is attempted on basic physical phenomena controlling combustion in fires, such as heat and mass transfer, behavior of heat sources, and fire induced flows. Also, a concept of propagation of states is introduced to characterize the fire phenomena. It is emphasized that understanding of fundamental combustion phenomena in fires is essential to enhance the abilities of fire protection engineers.

KEYWORDS: Combustion, Fire, Fire physics, Review

INTRODUCTION

It is clear that reliable prediction of fire processes is indispensable for fire protection engineering[1,2]. For the evaluation of evacuation time, the rate of fire development and the smoke behavior during fire development should be predicted. For recommendation of fireproof materials, the difference of ignitabilities of those materials and other ones under fire conditions should be interpreted. For other types of fire hazard assessments, the prediction of aspects, such as smoldering, mass burning, flame radiation, and flashover would be required.

Reliability of the prediction of fire processes necessarily depends on the quality and amount of knowledge on the processes. The most basic processes in fires are of combustion and/or closely related to it[1-9]. Thus, a number of studies in fire research have been carried out to explore combustion phenomena, such as ignition, flame spread, smoldering, flame retardation, pool burning, flame radiation, fire plume, fire induced gas flow, and fire behavior.

However, it seems rare to utilize appropriately knowledge accumulated throughout the studies on combustion phenomena in fires for protection against fires[2]. Sometimes it can be pointed out that if a person dealing with fire modeling, building design, evacuation planning, detector development, fire suppression system design, or fire fighting tactics

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would have sufficient knowledge of combustion phenomena at fires, he could obtain more reasonable results. On the other hand, in general, the data and models concerning basic combustion phenomena can hardly be involved in the procedure to develop methods for fire protection. Thus, efforts are needed to transfer knowledge obtained throughout basic studies on combustion in fires to practical activities for fire protection, and because circumstances(social and financial conditions as well as scientific and engineering findings) change day by day, such efforts should be continuing.

The topics presented in this article are limited to be of physical aspects of combustion in fires. This does not imply a lesser importance of chemical aspects but should be attributed to the author's past experience and present knowledge.

PRESENT ACHIEVEMENT AND REMAINING PROBLEMS IN FIRE PHYSICS

Ignition

Ignition is the first process at fire occurrence. A large number of studies have been carried out on this subject and the mechanisms of various types of ignition have been revealed[1-12]. Also, quantities representing ignition characteristics, such as ignition temperature, minimum ignition energy, and ignition delay time, have been evaluated or measured. The results of theoretical and experimental studies on this subject were summarized in several review papers[10-12]. A large number of data are available.

However, most of those data are of ignition under idealized conditions, so that in the processes to predict ignition at a practical situation many problems arise[1,2,12]. Certain effects of initial and boundary conditions on ignition are practically impossible to predict. Some examples will be presented in the latter part of this paper.

Flame Spread

The next stage of fire development is flame spread. Flame spread under various conditions has been examined and appropriate models have been proposed. The results of previous studies on this subject have been summarized in several review papers[12-19]. The mechanisms of various types of flame spread have been explored and a large number of data have been accumulated. Studies on this subject seem to be the most advanced of those concerning fire development.

The problems in the next step will be of accurate prediction of the phenomena under complicated conditions observed in real fires. To solve such problems, we have to re-examine the available data obtained through experiments, analyses, and numerical simulations. Careful re-examination of data would lead us to appropriate application to practical cases.

Smoldering

Smoldering and smoldering-flaming transition are important phenomena to understand early stages of fires as pointed out in the previous papers[1,2,20,21]. However, available data concerning this subject are scarce. The smoldering-flaming transition is a subject in need of more attention because the subsequent process of fire development depends upon it. Another important problem is to examine the relation between the product composition and ambient conditions under which smoldering occurs. Very similar to flame spread, almost the same parameters affect smoldering, such as the thickness, convection, radiation orientation, and physical and chemical properties of the material[20,21].

Mass Burning

Knowledge on the rates of combustion and/or resulting product generation must be indispensable for the modeling of fires and prediction of fire hazards[1-9]. A certain amount of data concerning mass burning of liquid and solid combustibles in various configurations and situations have been accumulated. Those data have increased knowledge of mass burning in practical fires and made it possible to predict some fundamental characteristics such as burning rate and radiation intensity for simple cases[1-9, 22-28].

In general, however, prediction of the mass burning rate of real fires is not simple. We have to make efforts to analyze and synthesize previously obtained data and relations and if necessary perform additional experiments for confirming the results. At present, an accurate prediction of burning behavior of a small element, such as a piece of furniture, wall, ceiling, or floor under fire conditions is still not easy.

Smoke Behavior at Fires

The fire plume and gas flow inside a compartment are the subjects suitable for computer simulation, so that many studies have been performed on the prediction of these phenomena by using high-speed computers[1-9]. Consequently, a number of excellent programs for the prediction of the fire plume behavior have been established. However, the programs applicable to the prediction of fire induced gas flows in a large size compartment are still very few. The effect of the mixing inside the high temperature zone should be considered as pointed out in previous papers[1,29]. The gas flow behavior in a long corridor or tunnel is also a problem to be solved because it is very important for the fire prevention and protection activities. This problem seems to be worthy of investigation, although it is not easy to include the heat transfer between the flowing gas and the wall.

BASIC PHYSICAL PHENOMENA CONTROLLING COMBUSTION AT FIRES

Heat and Mass Transfer

Combustion is a type of chemical reaction and necessarily depends on the reactant concentration and temperature, which are closely related to heat and mass transfer processes. Thus, combustion in a fire can be considered to be controlled by the phenomena affecting heat and mass transfer processes in the fire.

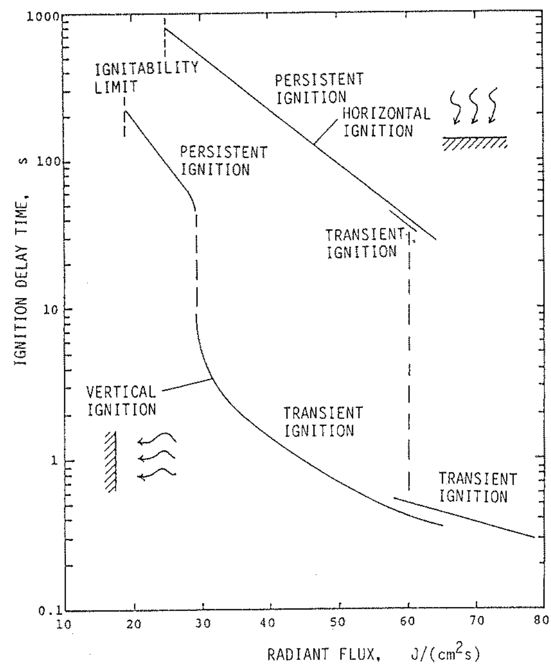

FIGURE 1 Ignition delay time at radiative ignition of a PMMA piece

As mentioned in the previous section, a large number of data on ignition are available. However, if the initial and boundary conditions are actual ones, the ignition characteristics are not always predictable. It can be found difficult to predict the phenomenon that the ignition delay time at radiative ignition depends on the orientation of the irradiated combustible material surface as shown in Fig. 1[12, 30]. Such a difficulty seems to be attributable to lack of data on heat and mass transfer processes near the irradiated surface[30]. This example seems to indicate that more data on heat and mass transfer processes are needed for predicting ignition processes under various initial and boundary conditions.

The results of a large number of previous studies show that the aspects of flame spread under various conditions can be interpreted by exploring heat and mass transfer processes. Based on the variation of dominant heat transfer processes to unburned material from the flame, the variation with the solid thickness of the rate of downward flame spread over solid surface can be interpreted[31-36]. The accelerating upward flame spread along a solid surface under natural convection is also interpretable based on heat transfer processes to unburned material[37-40], which depends on mass transfer supported by convective gas movement.

Typical problems of unsteady flame spread concern the limit of flame

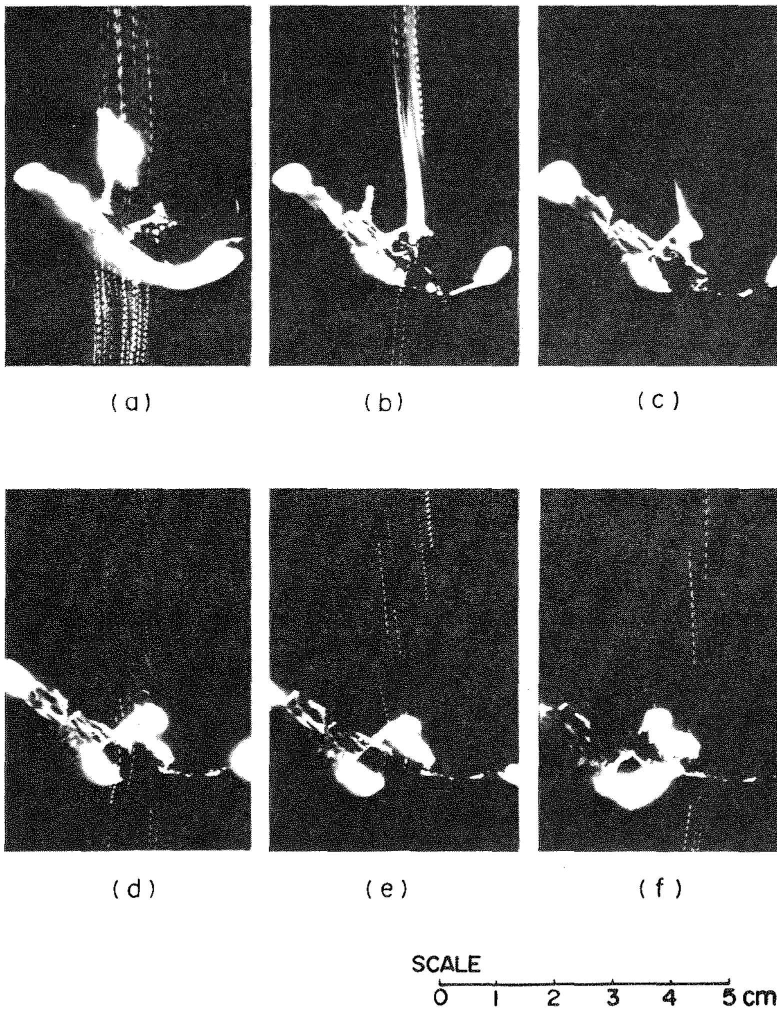

FIGURE 2 Processes of blow off, regeneration, and development of the burning zone with a curved leading flame edge. Photos were taken every 2 s. Sample: 0.026 cm-thick filter paper; Free stream velocity: 80 cm/s; Light: 360 interruptions/s

spread and the transition to extinction[41-44]. Near the limit of flame spread the temperature distribution as well as flow field near the leading

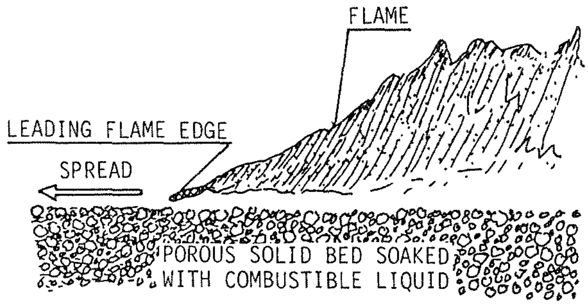

FIGURE 3 Schematic illustration of flame spread over a porous solid bed soaked with a combustible liquid

flame edge changes. Figure 2 shows a series of photographs representing the processes of blow off, regeneration, and development of the burning zone with a curved leading flame edge[41]. It is seen in Fig. 2(a) that the flow near the curved leading flame edge is largely distorted. Also, the pyrolysis temperature was confirmed to increase when a blow off is going to occur.

The mode of transition from stable flame spread to extinction depends on the rate of free stream velocity change which causes changes in mass and heat transfer processes[43]. Indeed, the flame spread phenomena under unsteady conditions are complicated, but have been successfully interpreted on the basis of heat and mass transfer processes[44].

In spite of the accumulation of a large number of data and advanced stages of studies, many ambiguities remain as yet on flame spread. Flame spread under particular conditions is not always predictable. Most of such difficulties in the prediction of flame spread phenomena seem attributable to lack of available data on the heat and mass transfer at the situations under discussion. When a flame is spreading over a porous solid bed soaked with a combustible liquid as shown in Fig.3[45-47], the flame spread rate depends on the heat and mass transfer characteristics of both liquid and porous solid bed. Although the phenomena have been elucidated to some extent, no reasonable model for the prediction of flame spread rate has been proposed. This example implies that the flame spread rate over a material with complicated and/or unknown characteristics concerning heat and mass transfer is hardly predictable.

Various phenomena closely related to combustion are observed at fires. These phenomena are obviously controlled by heat and mass transfer processes. In other words, it is necessary for understanding a fire to collect a sufficient amount of knowledge on heat and mass transfer processes in the fundamental combustion phenomena, of which the fire is composed.

Behavior of Heat Sources

In fires there are various types of heat sources such as flames, hot gases, and heated walls. These heat sources characterize the fire behavior, and for practical purposes, the effects of heat sources on flame behavior have been frequently attempted to examine instead of elucidating the heat and mass transfer processes. Thus, in this section, the effects of the heat sources on fundamental combustion phenomena are briefly reviewed although such effects can be intrinsically interpreted by considering the heat and mass transfer processes caused by the heat sources.

In previous studies, the effects of external heat sources on fundamental combustion phenomena in fires have been examined[1-9]. The delay time of transient radiant ignition of a PMMA plate was found to change discontinuously at a certain radiant flux (see Fig. 1)[12,30]. The ignition delay for just above this critical radiant flux was 50 - 100 times as small as that just below it. The process of ignition was examined by two-wave-length-interferometric measurements of the temperature and fuel concentration distributions in the gas phase during ignition, and it was shown that the ignition process changed discontinuously at the critical radiant flux[12,30].

The effects of externally applied thermal radiation on flame spread rate have been examined in several previous studies[19,48-51]. It has been demonstrated that the flame spread rate primarily depends on the temperature of the solid surface ahead of the leading flame edge. The heat flux from an external heat source is not directly effective in enhancing the spread rate. The temperature of the solid surface is increased by the heat flux and consequently the difference of the temperatures at pyrolysis reaction and on unburned material surface far ahead of the leading flame edge becomes small. If the effect of convection and the variation of pyrolysis temperature can be neglected, the flame spread rates along thin and thick solid surface are respectively expected to be inversely proportional to this temperature difference and its square[19,52]. As a matter of fact, however, the effect of convection is not always neglected[50] and the pyrolysis temperature depends on the spread rate[41].

The flame spread under a situation without the influence of external heat source must be sustained by the heat flux from the flame to unburned material. A stable and sufficient flux of heat transfer is needed to keep a sufficient rate of pyrolysis reaction which sustains a stable flame. Near the limit of flame spread, its rate was observed to be closely related to the size and configuration of a flame even if it was established downstream[41,53](see Fig. 2). This implies that the stability and spread rate of a flame near the limit of spread depends not only on the external conditions but also on the behavior of the flame itself.

It is well known that the mass burning rate is proportional to the net heat flux to unburned material[25]. In real fires, the heat flux to unburned material would change with time. During the early stages of a fire, the heat flux from walls or the smoke layer will be small, and at later stages it is expected to increase. Flame retarded furniture which would not ignite in the early stages of a fire would start to burn at later stages.

In certain cases of gas explosions in enclosures, the transition to fires occurred. At a gas explosion a premixed flame propagates in the enclosure, and it is a main heat source to cause a fire. For the inception of a fire, at least a certain piece of combustible material in the enclosure must ignite during the flame propagation. In our previous study on this subject, it was shown that the probability of fire inception increased with the decrease of the flame propagation velocity[54].

Fire Induced Flows

Heat and mass transfer phenomena are known to depend on the flow field. This implies that combustion phenomena in fires which are controlled by heat and mass transfer processes are necessarily dependent of the flow field. The fluid under the influence of combustion is in general heated partially and its temperature becomes non-uniform. The non-uniform temperature distribution thus generated in combustion processes causes a fluid flow due to buoyancy or surface tension difference. This fluid flow nd combustion processes interact each other, i.e., the physical aspects of combustion in fires depend largely on the induced fluid flow.

In previous basic studies on fires, the mechanisms of a number of phenomena have been interpreted by exploring the fluid flow behavior induced in combustion processes or as a result of combustion, because heat and mass transfer in fires depends on it. Thus, in this section, some examples are presented of the fluid flows observed in fundamental studies of fires and their effects on the phenomena.

In Fig. 1, we can find a large difference in the relations of the radiant flux and ignition delay time for vertical and horizontal surfaces. This difference can be interpreted by considering the induced gas flow[12,30]. At the persistent ignition, the flaming was first observed near the the plume boundary on the surface. For the vertical surface, the air flow approached the bottom side of the plume boundary where the first flaming was observed. The results shown in Fig. 1 imply that the temperature and concentration distributions near the bottom side of the plume boundary on the vertical surface more easily becomes ignitable than that near the plume boundary on the horizontal surface.

Upward flame spread is apparently different from downward flame spread. This difference is attributable to the difference of induced gas flows and resulting difference of heat and mass transfer processes. This can be more clearly understood by examining the variation of flame spread phenomena with the sample orientation[33,34,55-60]. Detailed observations of the variation of the flow field with the sample orientation by using schlieren photography[55] and particle tracer techniques[33] indicated the importance of the convective heat and mass transfer processes for the flame spread.

Figure 4 shows the variation of the upward flame spread rate with downward free stream air velocity[61]. In Region I, flame spread is accelerating and in Region III, it is steady and very similar to the downward flame spread in natural convection. This result also emphasizes the fact that flame spread depends mainly on the flow field near the leading flame edge.

Flame spread under microgravity conditions shows a different behavior from that under normal gravity. In recent studies on this subject, several interesting phenomena have been revealed[62,63]. Most of such phenomena could be explained by considering the gas flow field.

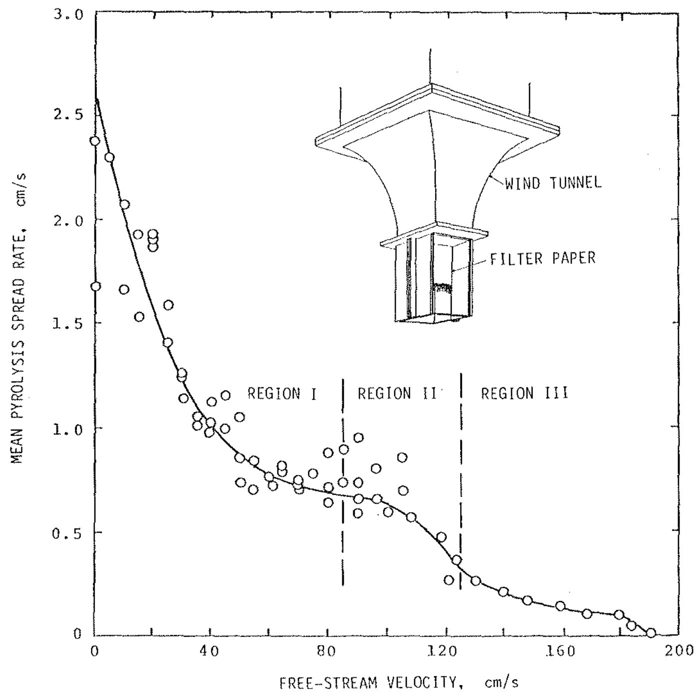

FIGURE 4 Variation of mean pyrolysis spread rate with free stream air velocity. Sample: 0.026 cm-thick filter paper of 10 cm wide and 23 cm long; Spread direction: upward; Free stream direction: downward.

Flame spread over a combustible liquid surface at a sub-flash temperature is known to be assisted by the liquid flow ahead of the leading flame edge in the spread direction. The mechanisms of flame spread in this case have been explored by a number of previous studies[14,16,18,64]. In such studies, discussion has concentrated on the induced liquid flow behavior, i.e., to explore the liquid flow behavior and its generation mechanisms has been considered to be a key to understand the flame spread at a sub-flash temperature.

The gas movements ahead of a propagating flame through a flammable mixture layer over a combustible liquid surface at a super-flash temperature are closely related to the flame behavior[65,66]. Because of this gas movement, the flame propagates at a velocity higher than the burning velocity[65], jumps over a vertical plate higher than the mixture layer on the surface[67], and climbs on a step bounding the layered flammable mixture[68].

To understand the details of heat and mass transfer phenomena during flame spread over a porous solid soaked with a combustible liquid, the

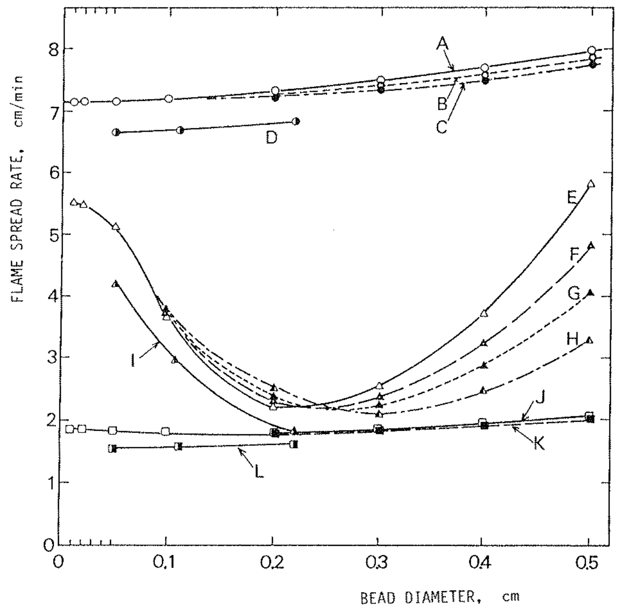

FIGURE 5 Dependence of the rate of flame spread over porous bed soaked with combustible liquid on the bead diameter, bead material, liquid composition, and liquid viscosity.

TABLE 1 Experimental conditions of combustible liquid soaked beds.

	Combustible liquid	Viscosity (cp)	Material of beads	Initial liquid level(cm)*	Symbol
A	90% decane + 10% hexane	0.846**	glass	0.0	○
B	90% decane + 10% hexane	2.617	glass	0.0	**o**
C	90% decane + 10% hexane	4.552	glass	0.0	○
D	90% decane + 10% hexane	0.846	lead	0.0	◑
E	100% decane	0.846	glass	0.0	△
F	100% decane	2.617	glass	0.0	**△**
G	100% decane	4.552	glass	0.0	△
H	100% decane	6.872	glass	0.0	▲
I	100% decane	0.846	lead	0.0	▲
J	100% decane	0.846	glass	- 0.5	□
K	100% decane	4.552	glass	- 0.5	■
L	100% decane	0.846	lead	- 0.5	◨

* The distance from the bead layer surface. 0.0 and - 0.5 mean the levels of liquid equal to and - 0.5 cm below the bead layer surface, respectively.
** The viscosity without thickening agent.

liquid behavior has been shown to be extremely important[46]. Figure 5 shows the dependence of the rate of flame spread on the bead diameter, bead material, liquid composition, and liquid viscosity, and Table 1 shows the experimental conditions under which the results shown in Fig. 5 were obtained[46]. When the liquid movement in the porous bed is not effective for heat transfer because of the included volatile component(A-D) or the lower liquid level(J-L), the flame spread rate scarcely depends on the bead diameter. In the cases of flame spread over a decane filled porous bed(E-H), the flame spread rate markedly depends on the liquid behavior. Two opposing effects on the flame spread were found. One is the effect of liquid surface depression which decreases the spread rate and the other is that of convective heat transfer ahead of the leading flame edge which increases the spread rate. For smaller pores, the former is more effective than the latter and this relation becomes inverse for larger pores. It is seen in Fig. 5 that for beds of smaller beads, the flame spread rate decreases as the bead diameter increases, while for larger bead beds, it increases as the bead diameter increases or the viscosity decreases.

The smoke behavior is known to characterize fires, so that a number of studies have been done on this subjects. The development of a hot smoke layer beneath a ceiling depends on the characteristics of the plume over burning materials[29]. The occurrence of flashover in an enclosure fire can be predicted only when ventilation through openings and plume behavior inside the enclosure are known[1-9]. Knowledge on the fire induced gas flows is also needed for understanding fire spread from a room to its neighbor or through a corridor, and more general smoke movements through a building. The quality of the fire hazard assessments seems to depend largely on the amount of knowledge on gas movements induced during fires.

Propagation of States

In the processes of fire development, there are various types of propagation of states. Some examples are shown in Table 2. The concept to characterize phenomena in fires on the basis of the type of propagation of states seems useful for understanding fire dynamics to a further extent. Thus, in this section a few examples of attempts to describe fundamental phenomena in fires based on the above concept.

Ignition in most fires is a process of transition from the input of heat to stable propagation of a thermal wave supported by heat release from combustion. It does occur only when the initial heat input from an ignition source and succeeding one by combustion reaction are sufficient to establish a thermal wave. Since the material to start burning in most fires is in the solid or liquid phase, ignition in fires is regarded as a process to establish a thermal wave in those phases. In few studies on ignition in fires, however, have such processes been discussed.

Extinction can be defined in the similar manner as a process to decay the thermal wave supported by combustion reaction. Also, in few studies on extinction at fires, the problems have been considered to be related to such a process.

In the analyses of flame spread over combustible solid surfaces, the characteristics of thermal wave propagation through the solid phase have been frequently examined. The most famous and important one of such papers

TABLE 2 Examples of propagation of states in fires.

Phenomenon in fires	Representative states to propagate	Characteristics of propagation
Ignition	Temperature; Density; Species concentration; Reaction intensity	Transient to formation of wave with combustion
Flame spread	Temperature; Density; Species concentration; Reaction intensity; Gasification intensity	Stable wave with gas phase combustion
Smoldering	Temperature; Pyrolyzing intensity; Reaction intensity	Stable wave with surface combustion
Mass burning	Temperature; Gasification intensity	Stable wave propagating in the direction normal to the solid surface
Smoke spread	Smoke density	Assisted by hot gas stream
Evacuees behavior	Population	Depend on design and management
Wildland fire spread	Burning intensity	Discontinuous spread caused by fire brands being possible

would be that by de Ris [52]. He obtained several important results, which have been used for interpreting the experimental results on flame spread[19]. In almost all of the papers concerning analysis or numerical simulation of flame spread over a combustible solid surface, attempts either explicit or implicit have been made to explore thermal wave propagation in the gas or solid phase[12-19, 69]. In such cases, no knowledge of the structure of the leading flame edge is necessary for the prediction of flame spread. Instead, the profile of heat flux from the gas phase to solid phase must be assumed or predicted. It would be of interest to examine earlier papers on this subject from this new viewpoint.

Flame spread over the surfaces of combustible liquids or solids soaked with combustible liquids can be also characterized by analyzing thermal wave propagation. In few studies, however, the flame spread in such cases has been considered to be closely related to the thermal wave. Probably, this has resulted from the fact that the mass and heat transfer which largely influences the thermal wave is generally very complicated in such cases.

Smoldering spread, fire development from a room to another or from a floor to another, fire spread across a city or forest, smoke spread, and even evacuees behavior would be characterizable on the basis of the propagation of states.

CONCLUDING REMARKS

Understanding of combustion phenomena in fires is obviously indispensable for the development of reliable fire protection systems and facilities. However, it is also important to utilize knowledge already accumulated through basic studies on combustion phenomena in fires for protection against fires. Thus, in this review an attempt has been made to indicate some important ideas which are comprehensible for practical engineers and easily applicable for practical purposes.

Because I have been interested mainly in the physics of fires, the topics that this paper has dealt with are restricted only to physical aspects. The most important physical phenomenon controlling combustion in fires is heat and mass transfer. Various problems of fires have been solved by examining heat and mass transfer processes concerning the phenomena under discussion.

For practical purposes, the behavior of heat sources or fire induced flows are more convenient to characterize the fires than the heat and mass transfer processes themselves. Thus, the effects of the heat sources and fire induced flows on combustion phenomena have been presented. I believe that a clear understanding of the characteristics and roles of heat sources and fire induced flow in fires is useful to utilize knowledge obtained in basic studies for practical engineering.

The concept to characterize phenomena in fires on the basis of the type of propagation of states has been presented. This concept has been introduced in order to better understand overall aspects of fires.

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REFERENCES

1. Hirano, T. "Combustion Phenomena at Early Stages of Fires", 8th UJNR, Tsukuba, pp. 214-227, 1985.

2. Hirano, T. "Concepts of Fire Protection Based on Present Understanding of Combustion Phenomena", 8th International Fire Protection Seminar, Karlsruhe, Paper 3.1(Vol. II, pp. 143-158, 1990.

3. Kanury, A. M., Introduction to Combustion Phenomena, Gordon and Breach, London, 1975.

4. Kishitani, K. ed., Shimpan Kasai Benran(JAFSE Fire Hand-book, New Edition), Kyoritsu, Tokyo, 1984(in Japanese).

5. Drysdale, D., An Introduction to Fire Dynamics, John Wiley and Sons, Chichester, 1985.

6. Grant, C. E. and Pagni, P. J. ed., Fire Safety Science,Proc. 1st Int. Symp., Hemisphere, New York, 1986.

7. Hirano, T., "Critical Discussion on Fire Development", 9th UJNR, Norwood, MA, pp. 73-82, 1987.

8. DiNenno, P. J., Beyler, C. L., Custer, R. L., Walton, W. D., and Watts, J. M. ed., SFPE Handbook of Fire Protection Engineering. NFPA, Quincy MA, 1988.

9. Wakamatsu, T. Hasemi, Y., Sekizawa, A., Seeger, P. G., Pagni, P. J., and Grant, C. E. ed., Fire Safety Science, Proc. 2nd Int. Symp., Hemisphere, New York, 1989.

10. Kanury, A. M.,"Ignition of Cellulosic Solids - a review", Fire Research Abs. Rev., 14, 24-52, 1972.

11. N.F.P.A., National Fire Codes, Vol. 13, NFPA, Quincy MA, 1979.

12. Akita, K. and Hirano, T., "Ignition of PMMA and Flame Spread Over its Surface", Saigai-no-Kenkyu, 11, 291-297, 1980(in Japanese).

13. Friedman, R. A.,"A Survey of Knowledge about Idealized Fire Spread over Surfaces", Fire Research Abs. Rev., 10: 1, 1-8, 1968.

14. Glassman, I. and Hanzel, J. G., "Some Thoughts and Experiments on Liquid Fuel Spreading, Steady Burning and Ignitability in Quiescent Atmospheres", Fire Res. Abs. Rev., 10: 3, 217-234, 1968.

15. Magee, R. S. and McAlevy III, R. F., "The Mechanism of Flame Spread", J. Fire Flammabl., 2: 4, 271-297, 1971.

16. Sirignano, W. A., "A Critical Discussion of Theories of Flame Spread Across Solid and Liquid Fuel", Comb. Sci. Technol., 6: 1, 95-105, 1972.

17. Williams, F. A., "Mechanisms of Fire Spread", 16th Symp.(Int.) on Comb., pp. 1281-1294, The Combustion Institute, Pittsburgh, Pa., 1976.

18. Glassman, I. and Dryer, F. L., "Flame Spreading Across Liquid Fuels", Fire Safety J., 3: 1, 123-138, 1980.

19. Fernandez-Pello, A. C. and Hirano, T., "Controlling Mechanisms of Flame Spread", Comb. Sci. Technol, 32: 1, 1-31, 1983.

20. Ohlemiller, T. J., "Modeling of Smoldering Combustion Propagation", Prog. Energy Comb. Sci., 11: 4, 277-310, 1985.

21. Hirano, T. and Sato, K. ed., "Smoldering -Materials and Data-", 2nd Conf. on Smoldering, JAFSE, Tokyo, 1989 (in Japanese).

22. Hottel, H. C., "Review; Certain Laws Governing Diffusive Burning of Liquids, by V. I. Blinov and G. N. Khudiakov", Fire Res. Abs. Rev., 1: 1, 41-44, 1959.

23. Akita, K. and Yumoto, T., "Heat Transfer in Small Pools and Rates of Burning of Liquid Methanol", 10th Symp.(Int.) on Comb., pp. 943-948, The Combustion Institute, Pittsburgh, Pa., 1965.

24. Orloff, L. and de Ris, J., "Modeling of Ceiling Fires", 13th Symp. (Int.) on Comb., pp. 979-992, The Combustion Institute, Pittsburgh, Pa., 1971.

25. Tewarson, A. and Pion, R. F., "Flammability of Plastics - I. Burning Intensity", Comb. Flame, 26: 1, 85-103, 1976.

26. Ohtani, H., Akita, K. and Hirano, T., "An Analysis of Bottom Stagnation Region Combustion of Polymeric Material Pieces Under Natural Convection", Comb. Flame, 53: 1, 33-40, 1983.

27. Emori, R. I. and Saito, K., "A Study of Scaling Laws in Pool and Crib Fires", Comb. Sci. Technol., 31: 5/6, 217-231, 1983.

28. Babrauskas, V., "Free Burning Fires", Fire Safety J., 11: 1, 33-51, 1986.

29. Zukoski, E. E., "Fluid Dynamic Aspects of Room Fires," Fire Safety Science, Proc. 1st Int. Symp., pp. 1-30, Hemisphere, New York, 1986.

30. Mutoh, N. Hirano, T. and Akita, K., "Experimental Study on Radiative Ignition of Polymethylmethacrylate," 17th Symp. (Int.) on Comb., pp. 1183-1190, The Combustion Institute, Pittsburgh, Pa., 1979.

31. Campbell, A. S., "Some Burning Characteristics of Filter Paper", Comb. Sci. Technol., 3: 1, 103-120, 1971.

32. Parker, W. J., "Flame Spread Model for Cellulosic Materials", J. Fire Flammabl., 3,: 3, 254-269, 1972.

33. Hirano, T., Noreikis, S. E. and Waterman, T. E., "Measured Velocity and Temperature Profiles Near Flames Spreading Over a Thin Combustible Solid.", Comb. Flame, 23: 1, 83-96, 1974.

34. Fernandez-Pello, A. C. and Williams, F. A., "Laminar Flame Spread Over PMMA Surfaces, 15th Symp.(Int.) on Comb., pp. 217-231, 1975.

35. Hirano, T. and Tazawa, K., "Effect of Thickness on Downward Flame Spread Over Paper", Bull. JAFSE, 26: 1, 7-13, 1976(in Japanese).

36. Hirano, T., Koshida, T. and Akita, K., "Flame Spread Mechanisms Over PMMA Surfaces", Bull. JAFSE, 27: 2, 23-39, 1977(in Japanese).

37. Markstein, G. H. and de Ris, J, "Upward Fire Spread Over Textiles", 14th Symp.(Int.) on Comb., pp. 1085-1097, The Combustion Institute, Pittsburgh, Pa., 1973.

38. Orloff, L., de Ris, J. and Markstein, G. H., "Upward Turbulent Fire Spread and Burning of Fuel Surface", 15th Symp.(Int.) on Comb., pp. 183-192, The Combustion Institute, Pittsburgh, Pa., 1975.

39. Saito, K., Quintiere, J. and Williams, F. A., "Upward Turbulent Flame Spread", in Fire Safety Science, Proc. 1st Int. Symp., ed. C. E. Grant and P. J. Pagni, pp. 75-86, Hemisphere, New York, 1986.

40. Hasemi, Y., "Thermal Modeling of Upward Wall Flame Spread", in Fire Safety Science, Proc. 1st Int. Symp., ed. C. E. Grant and P. J. Pagni, pp. 87-96, Hemisphere, New York, 1986.

41. Hirano, T., Sato, K. and Tazawa, K., "Instability of Downward Flame Spread over Paper in an Air Stream", Comb. Flame, 26: 2, 191-200, 1976.

42. Frey, A. E., Jr. and T'ien, J. S., "Near-Limit Flame Spread Over Paper Samples", Comb. Flame, 26: 2, 257-267, 1976.

43. Sato, K., Miki, K. and Hirano, T., "Flame Spread Over Paper in an Air Stream with a Velocity Change", J. Heat Transfer, 106: 4, 707-712, 1984.

44. Takeno, K. and Hirano, T., "Delayed Extinction of Flames Spreading Downward over Paper Sheets," in Fire Safety Science, Proc. 2nd Int. Symp., ed. T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. G. Seeger, P. J. Pagni and C. E. Grant, pp. 97-105, Hemisphere, New York, 1989.

45. Takeno, K. and Hirano, T., "Flame Spread Over Porous Solids Soaked with a Combustible Liquid," 21th Symp.(Int.) on Comb., pp. 75-81, The Combustion Institute, Pittsburgh, Pa., 1986.

46. Takeno, K. and Hirano, T., "Behavior of Combustible Liquid Soaked in Porous Beds During Flame Spread", 22nd Symp. (Int.) on Comb., pp. 1223-1230, The Combustion Institute, Pittsburgh, Pa., 1988.

47. Suzuki, T., Kawamata, M. and Hirano, T., "Flame Spread Over Fuel Soaked Sand in an Opposed Air Stream", in Fire Safety Science, Proc. 2nd Int. Symp., ed. T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. G. Seeger, P. J. Pagni and C. E. Grant, pp. 199-208, Hemisphere, New York, 1989.

48. Hirano, T. and Sato, K., "Effects of Radiation and Convection on Gas Velocity and Temperature Profiles of Flames Spreading Over Paper", 15th Symp.(Int.) on Comb., pp. 233-241, The Combustion Institute, Pittsburgh, Pa., 1975.

49. Kashiwagi, T., "A Study of Flame Spread over a Porous Material under External Radiation Fluxes", 15th Symp.(Int.) on Comb., pp. 255-265, The Combustion Institute, Pittsburgh, Pa., 1975.

50. Hirano, T. and Tazawa, K., "A Further Study on Effects of External Thermal Radiation on Flame Spread over Paper", Comb. Flame, 32: 1, 95-105, 1978.

51. Quintiere, J., "A Simplified Theory for Generalizing Results from a Radiant Panel Rate of Flame Spread Apparatus", Fire Materi., 5: 2, 52-60, 1981.

52. de Ris, J. N., "Spread of a Laminar Diffusion Flame", 12th Symp.(Int.) on Comb., pp. 241-252, The Combustion Institute, Pittsburgh, Pa., 1969.

53. Hirano, T., Lin. C. S., Yang, B. R. and Ishizuka, S., "Limit of Downward Flame Spread Over Paper and Extinction", 1990 Annual Meeting of JAFSE, Tokyo, Paper 36(pp. 113-114 in the abstract book), 1990.

54. Hirano, T., Tsuruda, T., Hisano, T., Dobashi, R. and Sato, K., "An Experimental Study of Gas Explosion-Fire Transition Phenomena Using a Small Scale Model", Bull. JAFSE, 36: 1/2, 1-8, 1987.

55. Hirano, T., Noreikis, S. E. and Waterman, T. E., "Postulations of Flame Spread Mechanisms", Comb. Flame, 22: 3, pp. 353-363, 1974.

56. Sibulkin, M., Ketelhut, W., and Feldman, S., "Effect of Orientation and External Flow Velocity on Flame Spreading Over Thermally Thin Paper Strips", Comb. Sci. Technol., 9: 1, 75-77, 1974.

57. Sibulkin, M. and Lee, C. K., "Flame Propagation Measurements and Energy Feedback Analysis for Burning Cylinders", Comb. Sci. Technol., 9: 2, 137-147, 1974.

58. Kashiwagi, T. and Newman, D. L., "Flame Spread Over an Inclined Thin Fuel Surface", Comb. Flame, 26: 2, 163-177, 1976.

59. Wichman, I. S. and Saito, K., "An Experimental Study of the Effects of Gravity on Flame Spread in High Oxygen Concentration Environments", Comb. Flame, 52: 3, 291-297, 1983.

60. Weber, R. O. and de Mestre, N. J., "Flame Spread Mechanisms on Single Ponderosa Pine Needles: Effect of Sample Orientation and Concurrent External Flow", Comb. Sci Technol., 70: 1, 17-32, 1990.

61. Tazawa, K. and Hirano, T., "Upward Flame Spread Over Paper in an Air Stream", Bull. JAFSE, 27: 1, 9-16, 1977(in Japanese).

62. Olson, S. L., Ferkul, P. V. and T'ien, J. S., "Near-Limit Flame Spread over a Thin Solid Fuel in Microgravity", 22nd Symp.(Int.) on Comb., pp. 1213-1222, The Combustion Institute, Pittsburgh, Pa., 1989.

63. Olson, S. L., Mechanisms of Microgravity Flame Spread over a Thin Solid Fuel: Oxygen and Opposed Flow Effects," Comb. Sci. Technol., (in press).

64. Ito, A., Masuda, D. and Saito, K., "A Study of Flame Spread Over Alcohols Using Holographic Interferometry", Comb. Flame, :(in press).

65. Hirano, T., Suzuki, T., Mashiko, I. and Tanabe, N, "Gas Movements in Front of Flames Propagating Across Methanol," Comb. Sci. Technol., 22: 1/2, pp. 83-91, 1980.

66. Hirano, T. and Suzuki, T., "Theoretical Simulation of Gas Movements in Front of Propagating Flames Through Layered Flammable Mixtures, Comb. Sci. Technol., 23: 3/4, pp. 215-224, 1980.

67. Suzuki, T., Mashiko, I., Tanabe, N. and Hirano, T., "Flame Jumping Over

Obstacles on the Surface of a Flammable Liquid at Superflash Temperatures", in Combustion in Reactive Systems, Vol. 76 of Progress in Astronautics and Aeronautics, ed.J. Ray Bowen, N. Manson, A. K. Oppenheim and R. I. Soloukhin, pp. 646-656, AIAA, New York, NY, 1980

68. Hirano, T., Suzuki, T. and Mashiko, I., "Flame Behavior near Steps Bounding Layered Flammable Mixtures," 18th Symp.(Int.) on Comb., pp. 647-655, The Combustion Institute, Pittsburgh, Pa., 1981.

69. Di Blasi, C., Crescitelli, S., Russo, G. and Fernandez-Pello, A. C., "Prediction of the Dependence on the Opposed Flow Characteristics of the Flame Spread Rate Over Thick Solid Fuel", in Fire Safety Science, Proc. 2nd Int. Symp., ed. T. Wakamatsu, Y. Hasemi, A. Sekizawa, P. G. Seeger, P. J. Pagni and C. E. Grant, pp. 119-128, Hemisphere, New York, 1989.