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Diffusion Flame Modeling as a Basis for the Rational Fire Safety Design of Built Environments

Yuji Hasemi
School of Science and Engineering, Waseda University
Okubo, Shinjuju-ku, Tokyo, 169- 8555, Japan

ABSTRACT

Turbulent diffusion flame is one of the most important driving force for the growth of a fire. Progress in the computer application to the fire safety science and innovation in fire measurement since around 1980 has enabled a precise prediction of the effect of flames to fire growth and its application to the wide range of realistic fire problems. After a short review on the progress of the modeling of turbulent diffusion flames since the beginning of the modern fire safety science, recent examples of the application of diffusion flame modeling to the assessment of structural fire safety, classification of lining materials and full scale tests on wooden large building are introduced.

Key Words: diffusion flame, localized fire, structural fire safety, flame spread, wooden construction

INTRODUCTION

Turbulent diffusion flame is a key element in the growth of a fire. In the early stage of a room fire, a diffusion flame has the substantial role in preheating adjacent combustible surfaces and interior linings, and in the formation of the hot gas layer beneath the ceiling. If the flame is tall enough, it may ignite directly a combustible ceiling or damage the structure supporting the ceiling. Concurrent flame spread along a combustible wall, ceiling or inclined surface is a typical process magnifying a local fire to the full involvement of the room by fire. Flame projected from a window of the fire compartment may spread the fire to upper floors or to adjacent buildings.

Importance of these processes were noticed by the pioneers in the fire safety science early in the 1950s to 1960s[e.g. 1 - 5], while there had been a few still earlier noteworthy works before the end of the World War II which however were not well known to the fire community for long time[e.g. 6, 7]. Early achievements in fire research such as the derivation of the dimensional relationships on the flame length, dimensional and analytical modeling of fire plumes, dimensional modeling of fully developed room fires, and the framework for the thermal modeling of flame spread, laid the foundation of the current stream of the fire safety science through demonstrating the effectiveness of the application of the first principles to the understanding of fire, and offering inspirations for modern fire safety assessment.

Assessment on the fire spread by flame projection in the late 1950s[3] is probably the first practical and quantitative application of the early flame modeling. With such few exceptions, application of the early flame modeling was limited to the prediction of the temperature and velocity in the far field[e.g. 8] or of rather qualitative nature until the 1970s. It is perhaps since the 1980s that quantitative prediction and control of turbulent flames has been applied to a wide range of fire safety design and technology. Innovation in the fire measurements and popularization of computer application during the last two decades are believed to be the main background for this advancement in the fire safety assessment. Development of the oxygen consumption calorimetry enabled direct measurement of heat release rate in open atmosphere, and opened a door for the quantitative assessment and control of the burning behavior of combustibles[9]. Diffusion flame studies using porous gas burners since the late 1970s[10] have derived many quantitative and precise correlations for flame height, temperature, velocity, and mass flow rate against heat release rate and source geometry for different fire configurations. Popularization of robust heat flux gages in the fire research community in the 1980s have resulted in the flame heat flux correlations for different configurations[e.g. 11 - 16], which has significantly helped quantification of the fire exposure and flame spread in fires. Many flame heat transfer measurements suggest a practically unique dependence of flame heat flux to the relative location to the flame length, which is controlled substantially only by the heat release rate[17], e.g. as shown in Figure 1. It is noteworthy that the evaluation of the two important properties representing the flame heating, flame length and heat flux, does not directly need any information on the chemical composition of the fuel. The oxygen consumption calorimetry and heat flux measurement makes a closed framework for evaluating the fire exposure due to the burning of any combustible in a built environment. Heat release measurement and heat flux gages have also become a standard tool in standard reaction-to-fire tests on lining materials and furnitures during the last two decades; these are believed to make it possible to reproduce fire exposure in laboratory tests and to give an input for the prediction of fires from bench-scale tests. Such significant improvement of fire measurements, along with the progress in the computer modeling, has led to highly quantitative understanding and control of fires. As there are already some pioneering examples, these quantitative techniques seem to become a substantial tool for the advanced fire safety design of buildings. Progress in the diffusion flame modeling has been reviewed from different points of view by the scientists who made an essential contribution in this area[e.g. 18 - 20].

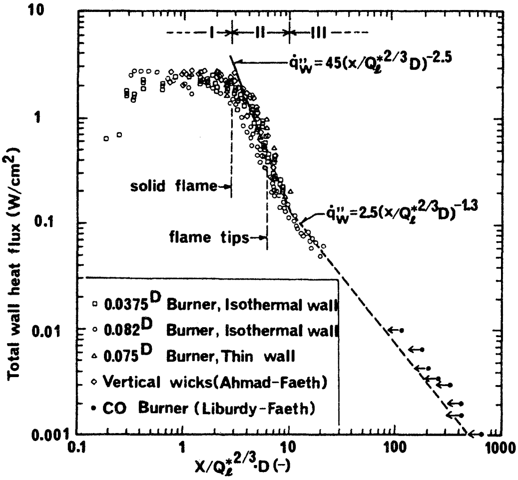


Figure 1 Total heat flux to wall surface correlation for vertical wicks and line burners against an inert wall(from Ref.12)

Albeit such significant progress in fire modeling in the last two decades, there have been numbers of significant fire disasters that have revealed the need of further research into the behavior of flames in fire; the Bradford City Football Stadium fire(UK, 1985), the Kings Cross Underground fire disaster(UK, 1987), the Daxing-anling forest fire(P.R.China, 1987), Oakland Hills conflagration(USA, 1991), Hanshin-Earthquake fire(Japan, 1995) and the Hiroshima high-rise apartment complex fire(Japan, 1996) may be among such important fires. Although these fires took place in relatively old buildings and wildland which the fire safety engineering did not have dealt with, such fires seem to indicate existence of fire phenomena not yet sufficiently understood by the fire safety science. The fast fire spread along an escalator in the Kings Cross Underground Station caused large numbers of victims, and caused strong international interest in the significance of the effect of inclined trench on the flame spread[21]. The Daxing-anling forest fire burned over 11,400km^2 with fire spread velocity between 8.9km/h and 45.0km/h[22]. The Oakland Hills conflagration was an urban/wildland interface fire which finally burned 7.2km^2 and over 2,800 suburban dwellings, and caused the third largest fire loss of properties in the whole history of the USA[23]. The Hanshin Earthquake caused over 200 postearthquake fires which finally burned 0.6km^2 of the Kobe urban district. This was the largest fire damage caused by a single disaster in Japan after the World War II. Such large number of building fires after a strong quake caused considerable confusion to the rescue and other post earthquake managements in the damaged area[24 - 26]. The apartment fire in Hiroshima caused an extremely fast fire spread from the 9th floor to the uppermost 20th floor along the balcony. The apartment balconies were blocked with acrylic fences and were generally loaded with combustibles. The investigation of this fire revealed an interesting mechanism of fire spread along a vertical but discrete combustible surface associated by combustion of the combustibles behind the combustible surface, which had been seldom noticed in the fire safety science[27].

Also it is felt that there is still considerable prejudice against and underestimate of the fire safety science in the public and possibly in fire practitioners. It is probably because of the complicatedness of the fire safety science and the lack of demonstration of fire safety achieved by the fire safety science. The author has been involved and has led several projects to utilize the diffusion flame modeling for fire investigation, fire safety design, development of design method and code development since the mid 1980s. From this experience, the author believes that interaction between the basic fire science and the challenge to the solution of realistic problems is becoming an important source for further development of the fire safety science. In this report, the author would like to introduce some of these projects as examples of diffusion flame modeling applied to realistic problems, along with their background.

FLAME HEATING BY LOCALIZED FIRES AND STRUCTURAL FIRE SAFETY DESIGN

While the conventional fire safety regulations generally require steel and wooden structures thermal insulation against uniform heating by fully developed room fires, there is a strong interest in using unprotected or weakly protected structures for the use of new materials, for economy, for improvement of construction processes, and for the reduction of the weight of structure especially of long-span buildings and off-shore buildings[28]. Previous modeling works on post-flashover compartment fires and results of large scale fire tests have demonstrated that fires may remain localized in a fire room if the openings are too large or the fire load is not large enough. Such conditions would apply to atria, open car parks, museums, some traffic facilities and other buildings with relatively small fire load. Also, further popularization and improvement of the fire calorimetry may someday make it possible to control total heat release rate in fire for considerable building occupancies.

If only a limited part of a structural member is exposed to fire, its fire resistance can be much different from that based on conventional fire regulations. Since the mechanical behavior of a structural member in fire is essentially controlled by its temperature field and mechanical

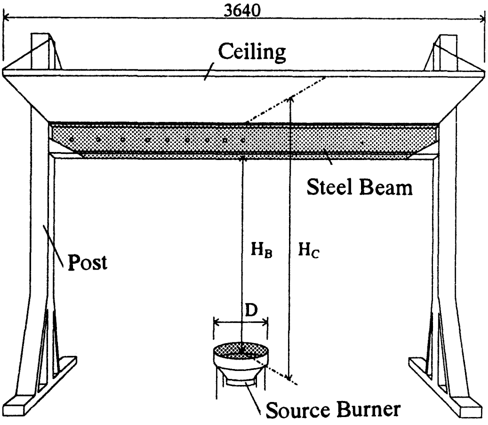


Figure 2 Experimental set up for a H-beam supporting an inert ceiling above a fire source

constraint conditions, prediction of the temperature field is the key for the fire safety design of such structures. Early flame heat transfer measurements had already demonstrated a significant decay of flame heat flux in the upper half of a diffusion flame[29]. It implies if a building element is exposed to an intermittent flame, the thermal exposure should be much weaker than in a fully developed fire. Especially when a metal structure is heated locally in fire, the temperature rise of the exposed part should be rapidly suppressed by the accelerated heat conduction. The temperature field for such simple materials as metal and plastics could be predicted by heat transfer calculations if the heat flux to its surfaces is given as the boundary conditions. The structural fire safety design method for localized fires can be thus divided into the following three elements;
(a) modeling of the heating conditions of a structural member as a function of the fire source intensity and its geometrical relation with the structure
(b) prediction of its temperature field with the heat flux as the boundary conditions, and
(c) evaluation of its mechanical behaviors using the temperature-dependence of the mechanical properties of the material and the constraint conditions.
Nature of the problem is essentially interdisciplinary; the three elements may need expertise in fire physics, numerical heat transfer, and structural engineering respectively.

Until the early 1990s, there had been almost no modeling work on the thermal and mechanical behavior of structural members exposed to localized fires. A research project was initiated in 1994 at BRI under the cooperation with Kumagai Gumi Construction Co. and the Kozai(Steel) Club to quantify heating conditions of a structural member exposed to a localized fire and examine the effectiveness of the numerical prediction of the temperature field of the structure using the measured heating conditions.

Among various structural configurations, a beam supporting a ceiling above an isolated fire source was chosen for this study. It is because there had been already considerable knowledge on the temperature and heat flux distribution due to a weaker fire plume along an unconfined ceiling in the similar configuration to predict the activation of detectors and sprinklers[e.g.8,11,13]. Figure 2 shows the experimental set up. A 1.83 x 3.60 x 0.024m mineral fiber board ceiling was supported above a porous propane burner by a 75mm wide, 150mm tall and 5mm thick steel H-beam. The tests can be regarded as a 1/2 - 1/3 model scale experiment relative to a typical steel beam. Heat flux distribution was measured with Schmidt-Boelter and Gardon heat flux gauges, and temperature field was measured with K-type thermocouples for the validation of its numerical simulation. The heat flux was measured on the downward and upward surfaces of the lower flange, on the web and on the lower surface of the upper flange of the beam at different horizontal distances from the stagnation point above the burner center.

A series of flame heat flux and temperature measurements had been carried out on a flat inert ceiling above a burner without a beam prior to these tests to obtain guiding information for the flame heat transfer modeling. The heat flux at the stagnation point, q_s'', just above the center of the burner for the flat ceiling can be summarized as a function of the height of an unconfined flame for the same heat input, $L_f = 3.5Q^{*n}D$, normalized by the height between the ceiling and the burner surface corrected with the depth of the virtual point source(Figure 3).

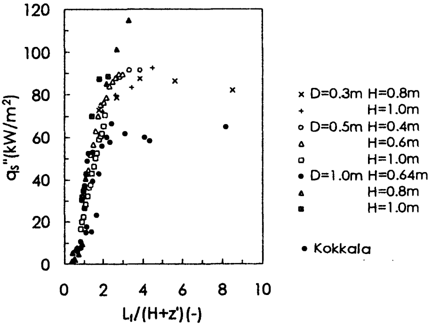


Figure 3 Total heat flux to the ceiling straight above the center of fire source

q_s'' increases significantly with $L_f/(H+z')$ between $1<L_f/(H+z')<2.5$, but it appears to approach to almost a constant for $L_f/(H+z')>2.5$. This change of the flame heat flux is probably because the range $1<L_f/(H+z')<2.5$ corresponds roughly to the intermittent flame. This suggests the particular importance of the "localized fire" concept for the fire exposure in $1<L_f/(H+z')<2.5$, the intermittent flaming region. The conditions for the beam tests were decided to meet $1<L_f/(H+z')<2.5$ with fire sources of different diameters. The heat flux distribution on each surface of the beam, q'', can be summarized as a function of the horizontal distance relative to the flame length, L_B and L_C as seen in Figure 4. L_B and L_C are the horizontal flame lengths at the upper flange and beneath the lower flange respectively, both measured from the stagnation point above the center of the fire source (Figure 5), and are expressed experimentally as

$$L_B = H_B(1.82Q^*_{DHB}{}^{0.30} - 1),\ \text{and}\ L_C = H_C(2.04Q^*_{DHC}{}^{0.33} - 1) \tag{1}$$

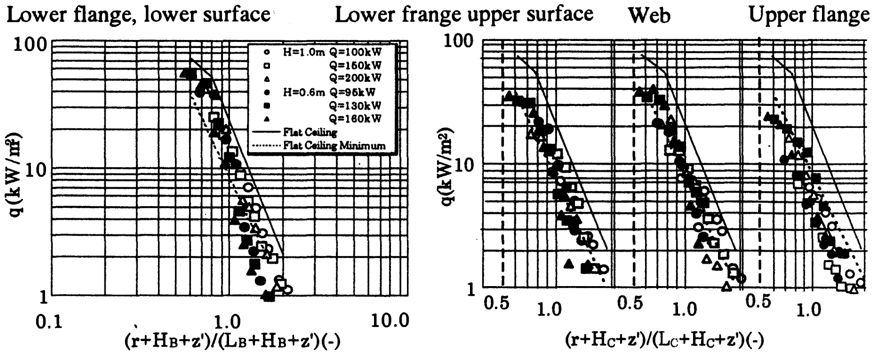
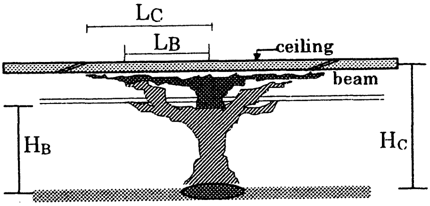


Figure 4 Total heat flux to the surfaces of a H-beam exposed to a localized fire source



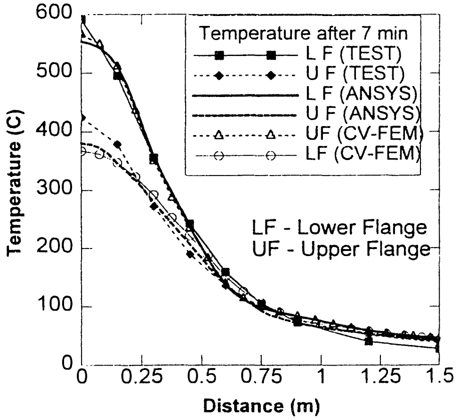


Figure 5 Flame development in a ceiling-beam configuration

Figure 6 Experimental and calculated beam temperatures(upper and lower flanges)

Temperature distribution on the beam surface was then calculated by Finite Element Method(FEM) and its combination with Finite Difference Method(CV-FEM) with the measured heat flux as the boundary conditions and the surface convective heat transfer coefficient tuned as $a_c = 0.01 kW/m^2K$ from the flat ceiling test[29]. Figure 6 describes a comparison between thus simulated temperature profile and the measurement. In Figure 6, it is shown that the difference in the temperatures at an arbitrary distance from the stagnation point is much weaker than the decay of the temperature to the axial direction; this implies that even a much simpler modeling of the thermal conduction assuming a uniform temperature at each horizontal distance may still reproduce the temperature profile within some acceptable error. A comparative study on this configuration has shown considerable matching between the result of a Finite Difference Method(FDM) and the FEM[30].

While the study was initiated with the primary interest in the application to steel structures, there are different potential applications of this methodology; consideration of other structural components such as column, and application to other materials such as plastics, aluminum and other metals. Since a column is more important for the whole building structure than a beam, application of this approach to columns could be more stimulating than the present study. Also, use of such incorrosive but expensive materials, compared to steel, as plastics and aluminum to building structures could be promoted only when a fire safety design method for unprotected structures is thoroughly established. Since the flame heat flux correlation is virtually independent to the material to be used, the correlation obtained for steel could be used for different materials. An exploratory analysis on the applicability of this methodology to different metals has been carried out recently by Wakamatsu et al[30].

Another interesting subject in this area is the numerical prediction of the flame heat flux. Among the three elements of the fire safety design for locally heated structures, determination of the heating condition is the only that needs experimental correlations. Even if future experiments generate heat flux correlations for different structural configurations, there might still be considerable limitation in their application to realistic design problems as heat flux distribution is believed to be dependent on the shape of the section of a structural member, heating by smoke layer and other conditions which experimental approach may not deal with smoothly. If the heat flux can be reproduced numerically e.g. by the Computer Fluid Dynamics, needs of experiments would become less critical in the development of the design method. Generation of experimental data and correlations for basic structural configurations, preferably in a realistic scale, is critical for the development and validation of such numerical prediction tools. A first numerical result on a steel beam in the present configuration shows some agreement with the previous experiments while it still needs further improvement for engineering application[31].

MODELING OF CONCURRENT FLAME SPREAD AND FIRE SAFETY ASSESSMENT OF LINING MATERIALS

Upward flame spread along a wall lining and horizontal flame development beneath a combustible ceiling is very often a direct trigger for the occurrence of flashover. Although the fear of concurrent flame spread was recognized from the beginning of the civilization, development of Fire Safety Engineering(FSE) concepts and tools for lining materials is far behind that in the smoke control and the structural fire safety. This is probably because of the complexity of the phenomena relevant to the fire safety of interior linings. Because of such difficulty in the engineering approach, most of the conventional regulations and tests on lining materials do not seem to have clear relevance with real fires. Moreover, comparative studies on standard reaction-to-fire tests in European countries during the 1960's revealed notable inconsistency among the test methods[32]. Such inconsistency raised a doubt if the conventional classification properly represent the hazard of lining materials in real fires.

On the other hand, modeling of concurrent flame spread is probably one of the research topics on which the progress of scientific understanding have been the most pronounced during the last two decades. Concurrent flame spread attracted combustion scientists relatively early, and the theoretical paradigm for its mathematical formulation was established before the 1980s[e.g.5, 33, 34, 35]. Most of the early works on flame spread, conducted within the combustion science, dealt with simple materials, laminar flow conditions and idealized configurations. Modeling of flame spread in the fire safety engineering since around the 1980s focused the treatment of turbulence, development of simulation method, reformulation using material properties measurable with practical testing apparatus as input, and the derivation of evaluation concepts for fire safety. These efforts have enabled prediction of concurrent flame spread for limited types of lining materials and the evaluation of the asymptotic behavior of fire development. These research efforts have been reflected in the development of performance-oriented reaction-to-fire tests by the ISO/TC92/SC1(reaction-to-fire). However, the complexity of the lining fires still seems to prevent practitioners such as building regulators, architects and material producers to introduce these research results into practice.

Most of the flame spread models in fire are based on a concept of ignition and flame spread as a result of inert heating of the solid to an ignition temperature(Figure 7). These models could be divided into two types; analytical and numerical models. Analytical models[e.g.12, 36, 37, 38] generally introduce simplifications and assumptions whereas the numerical ones[e.g.39,40] generally try to divide the combustible surface into finite difference grids and calculate the surface temperature of each grid. Numerical approach can deal with the precise distribution of the flame heat transfer and does not have to use any simplification. The benefit of analytical approach is the ease to predict asymptotic and global behavior of the flame spread, e.g. autonomous flame extinction and the divergence of the solution.

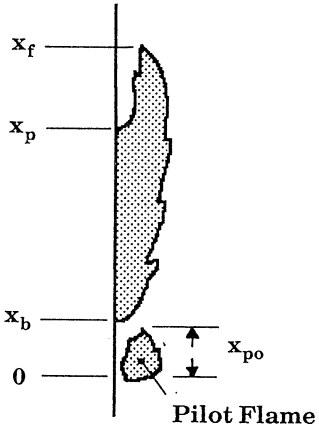


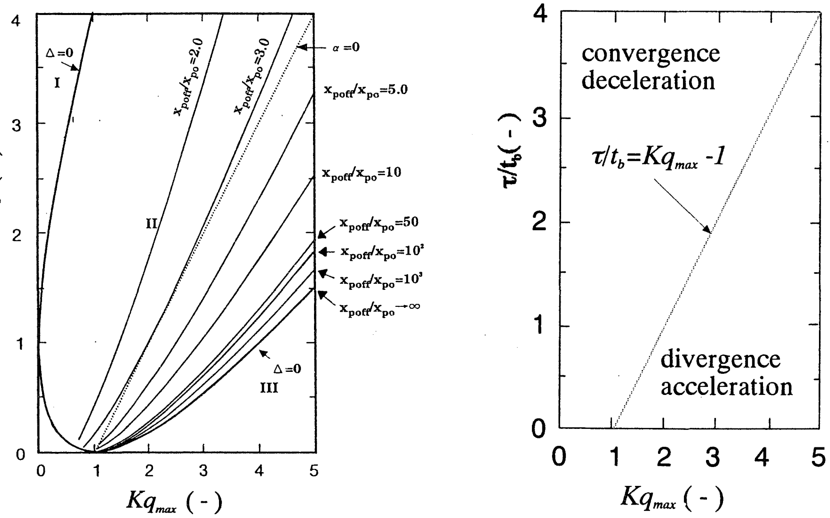
Figure 7 Wall flame spread, schematic diagram

Large scale and intermediate scale experiments on wall fires were conducted for the fire safety design of the wooden lining of the main theater of Japan's recently completed New National Theater. Since the design chosen by an international competition in 1986 proposed wooden lining and was against the then effective Building Standard Law, Japan's Ministry of Construction(MoC) organized a project for the fire safety design of the wooden lining specifically in large enclosures[41]. Thickness, surface finish and other design features of the wooden wall lining was finally determined to localize the wall burning to less than three times the height of the pilot flame above the first ignited package. Although this project was useful to promote research on the combustible lining and flame spread in Japan, it is obvious that such investigations were possible only because it was a very large construction project.

In the application of engineering fire prediction to the practical fire safety design of interior linings, there are however at least two types of difficulties. First difficulty relates to the considerable sensitivity of the growth of a compartment fire to the fire source and other initial and boundary conditions. In spite of the importance of such conditions for the prediction of fire growth, it is generally difficult to predict these conditions since they may change almost everyday or according to occupants. Such difficulty should be more pronounced as the room becomes smaller, because the smoke layer temperature and the interactions of heat transfer tend to be augmented in small enclosures although these conditions are the dominating elements for the growth of a room fire. The another difficulty relates to the limitation in the man power and funds available for the design of interior linings in "common buildings". Despite such complexity in the prediction of lining fires, time, man power and funding allowance for the interior design of a common building is generally not enough to run mathematical models on different fire scenarios.

For the fire safety design of "common buildings", classification is believed to be still a most functional way for lining materials; the central problem for establishing a classification of materials within performance-based code system will be the harmonization between the FSE concepts and the grading system. Originally some of the currently available analytical flame spread models intended to use data from heat release tests such as the ISO5660 Cone Calorimeter as the input[42,43], and have potential capability for the application to the classification. Several works in the 1990s have tried to explain the results of the ISO 9705 Room Corner Test, a full scale test on lining fires, from the asymptotic flame spread behavior predicted by the analytical models with the data the ISO 5660 and other bench-scale tests[44,48].

Figure 8(a) is a graphical representation[38,45] of the asymptotic behaviors of the flame spread predicted from a simple analytical equation for concurrent flame spread first derived by Saito, Quintiere and Williams(the SQW equation, see equation(3))[36] and solved analytically by Thomas and Karlsson[37]. The SQW equation and its variations essentially represent flame spread velocity by the distance between the flame front and the pyrolysis front divided by the characteristic time to ignition, i.e. $V_p = (x_f - x_p)/\tau$. This formulation assumes a uniform flame heating between the flame front and the pyrolysis front and the simultaneous ignition over this area after the characteristic ignition time τ. τ is constant in a stationary flame spread and can be represented by the time to ignition under the flame heat flux level. The SQW equation also employs a linearized flame length approximation, i.e. $x_f = KQ$ where Q is the total heat release rate per unit width of the pyrolysis zone, whilst experiments suggest a weaker power dependence, e.g. $x_f \propto Q^{2/3}$, for upward flame spread[12]. From experimental flame length correlations, K is believed to be around 0.01 - 0.02 for a $[10^{-1}]$ - $[10^{1}]$ m tall flame. The SQW equation has been generalized to incorporate the burnout effect[45], and the power dependence of the flame length[46,47]. While some of such improvements need numerical treatment of the basic equations, the present paper tries to discuss only on the analytical basis. The solution in Figure 8(a) assumes further a charring material, whose time history of heat release rate is represented by an exponential decay function, $q(t) = q_{max} \exp(-t/t_b)$. The solution can be divided into the following three categories according to its asymptotic behavior. Flame spread is decelerated from the beginning and will die out for $\tau/t_b > Kq_{max} - 1$, identified as the region I by the region above the straight dotted line. Flame spreading velocity diverges in the region III, is accelerated at the beginning but is gradually decelerated and finally becomes zero in the region II. Lining materials falling into the region III is believed to cause flashover, and those falling into the region II may cause flashover in an enclosure relatively small compared to the fire source. A room fire should not reach flashover with any lining material in the region I, unless the fire source is large enough. For a heat release rate represented by a rectangular function of time, $q(t) = q_{max}\{1 - U(t - t_b)\}$, it has been found that the qualitative behavior of the solution can be divided into only two categories as seen in Figure 8(b)[45]. In this figure, the acceleration/deceleration criterion, $\tau/t_b = Kq_{max} - 1$, also stands for the divergence/convergence criterion. Through a different analysis, Quintiere derived a acceleration/deceleration criterion for the local heat release rate represented by a rectangular function[48]. This criterion is essentially equivalent with the acceleration/ deceleration boundary in Figure 8(b). He further demonstrated that his criterion can explain if the flashover occur in the first ten minutes in the ISO 9705 Room Corner test.



(a) Charring materials, sustained pilot flame
$q(t) = q_{max}\exp(-t/t_b)$

(b) Non-charring materials
$q(t) = q_{max}\{1 - U(t - t_b)\}$

Figure 8 Asymptotic behaviors of concurrent flame spread

There are some criticisms against this approach from practitioners; possible influence of subjective judgment in the approximation of the heat release rate by a simple function and the use of a small specimen to obtain the input data have been pointed out. A safer side approximation of the test data may resolve the first criticism, but it may spoil the benefit of the prediction-based classification. The second criticism is rather directed to the use of bench scale tests for the evaluation of a large building product. Certainly complicated surface treatment, ribs, cavities and other construction details may not be represented in a 10 cm square specimen to be used for the Cone Calorimeter. Probably those lining materials featuring such complicated construction details need essentially an intermediate or large scale test. Also the basic assumption for the SQW equation has been found to be valid for only limited conditions[45,49], and there is some theoretical doubt in the validity of the analytical solution if it is far from the steady state. However, as long as the analytical approach is applied only for the evaluation of asymptotic flame spread behaviors, this approach should still be effective as there is no direct need to use its solution in such a qualitative evaluation.

An attempt was made to resolve such difficulty of the analytical approach in the recently finished MoC project on the fire safety testing and evaluation. In order to derive an analytical classification using row test data, analysis has been made on the generalized SQW equation:

$$\begin{aligned} V_p(t) = (x_f - x_p) / \tau = {} & [K[Q_o(t)\{1 - U(t - t_b)\} + x_{po} q(t) + \int_0^t q(t - \xi) V_p(\xi) d\xi] + \\ & \{\int_0^{t - t_b} V_p(\xi) d\xi + x_{po}\} U(t - t_b) - \{x_{po} + \int_0^t V_p(\xi) d\xi\}] / \tau \end{aligned} \tag{2}$$

The generalized SQW equation is a generalization of the SQW equation to incorporate the burnout effect[45]. For $t<t_b$, equation(2) can be simplified into the original SQW equation as

$$\begin{aligned} V_p(t) & = [K[Q_o(t) + x_{po} q(t) + \int_0^t q(t - \xi) V_p(\xi) d\xi] - \{x_{po} + \int_0^t V_p(\xi) d\xi\}] / \tau \\ & = [K\, Q_o(t) + x_{po}\{K q(t) - 1\} + \int_0^t \{K\, q(t - \xi) - 1\} V_p(\xi) d\xi] / \tau \end{aligned} \tag{3}$$

If the fire source is removed or extinguished, the fire source term $Q_o(t)$ disappears and equation(3) further becomes

$$V_p(t) = [\, x_{po}\{K\, q(t) - 1\} + \int_0^t \{K q(t - \xi) - 1\} V_p(\xi) d\xi] / \tau \tag{4}$$

Flame spread is sustained only when $V_p(t)>0$; equation(4) suggests that if $Kq(t) \geqq 1$ the flame spread can be sustained and if $Kq_{max} < 1$ the flame spread should be terminated after the removal of the fire source. A "lining material that may ignite in fire but cannot sustain flame spread without the fire source" has a clear implication for fire safety, and this condition can be identified by checking if its heat release rate data satisfies $Kq_{max} < 1$. This condition gives a strong limitation for the flame spread, and materials satisfying this condition may be referred to as "strongly self-extinguishable" materials.

Another characterization can be introduced for those materials that may sustain flame spread but cannot cause any accelerated flame spread. After the completion of the surface burning directly exposed to the pilot flame, namely $t>t_b$, equation(2) yields

$$V_p(t) = \int_{t - t_b}^t \{Kq(t - \xi) - 1\}\, V_p(\xi) d\xi / \tau \tag{5}$$

Even if the flame spread velocity is positive, flame spread will be gradually decelerated and finally die out if $dV_p(t)/dt<0$. The condition for $dV_p(t)/dt<0$ can be obtained by taking the limit for a stationary flame spread. Assuming $V_p(t)=constant$, equation(4) yields

$$\int_0^{t_b} Kq(\xi) d\xi / t_b - 1 = \tau / t_b \tag{6}$$

Equation(6) can be interpreted as a critical condition for the acceleration and the deceleration of flame spread, and if the left hand side is smaller than τ / t_b, the flame spread velocity will be always decelerated. This condition allows some larger fire development than the previous criteria, and those materials satisfying equation(6) may be referred to as "weakly self-extinguishable" materials.

The strongly and weakly self-extinguishable materials can be illustrated graphically as seen in Figure 9. The first term of the left hand side of equation(6) is equivalent to Kq_{max} for those materials whose dynamic heat release rate is represented either by an exponential or a rectangular function, and the equation(6) is equivalent to the criticality, $\tau / t_b = Kq_{\max} - 1$, in Figure 8 for simple analytical solutions. In that sense, Figure 9 is a generalization of the Figures 8(a) and (b). Also, for heat release rate represented as a rectangular function, equation(6) becomes equivalent with the criteria that Quintiere[48] has derived for the classification of lining materials in terms of the time to flashover. It is important that all material properties included in the critical conditions for both the strongly and weakly extinguishable materials, namely $Kq_{max}<1$ and equation(6), can be obtained directly with a material test to measure dynamic heat release rate such as the Cone Calorimeter,maximum and total heat release rates, time to ignition and the burnout time.

Various lining materials were tested against the Cone Calorimeter and the ISO 9705 Room Corner Test within the MoC fire project. Figure 10 shows a relation between the results of the ISO 9705 Room Corner Test and the Cone Calorimeter, summarized on the τ / t_b and $\int_0^{t_b} Kq(\xi)d\xi / t_b$ diagram. Although the materials tested are limited, Figure 10 seems to show a promising prospect for the prediction of the growth of a room fire from bench scale test data in relatively simple way. The Cone Calorimeter data on the heat flux level 50 kW/m^2 were used for this correlation. Cone Calorimeter data on other radiation levels did not seem to explain the results of the ISO 9705 Room Corner Test.

The 2.4m x 3.6m room of the ISO9705 Room Corner Test represents a minimum room size in buildings, and the development of a lining fire should be faster than in a larger and commoner room. As long as the ISO 9705 Room Corner Test is used as the reference for the fire safety assessment of lining materials, the analytical approach has a promising prospect to serve as a practical tool to classify the lining materials. The practically sole domination of the results of the Room Corner Test by the concurrent flame spread may be partly because of the use of a very small enclosure in the Room Corner Test. Role of the downward flame spread along the enclosure boundaries can become more important in a larger compartment. Development of mathematical room fire models[e.g.44,50] is believed to be important for the better understanding of fire behavior in larger compartments.

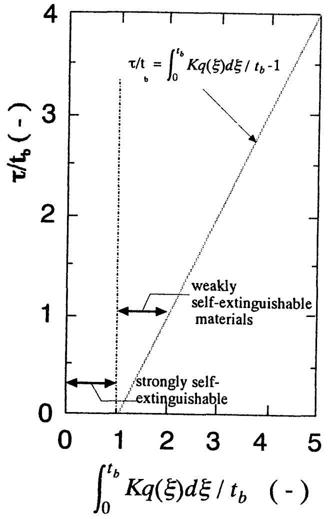


Figure 9 Classification of asymptotic flame spread behaviors by row heat release data

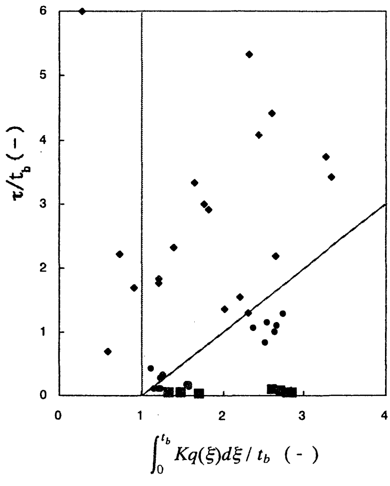


Figure 10 Correlation between the time to flashover in the ISO9705 Room Corner Test and heat release characteristics at heat flux level 50kW/m^2 in the Cone Calorimeter
(time to flashover at ISO 9705: ■ <10min, ● <20min, ◆ no flashover)

FULL SCALE TEST OF A WOOD-BASED BUILDING EXPOSED TO A SIMULATED CITY FIRE

The Hanshin Earthquake fires revealed the weakness of inner cities built densely with old wooden low rise buildings at an earthquake. The investigation of this earthquake suggested a fire exposure of external walls and windows of low rise buildings considerably severer than at normal building fires[24,25]. These fires raised a considerable doubt against the deregulation on the fire safety of wood-based buildings in Japan which had started in the late 1980s.

During the postwar reconstruction of the urban areas in Japan, construction of large wood based buildings were heavily restricted. When the Building Standard Law was introduced in 1950 as the Japan's first building regulation applied to all over the country, it allowed only two-storey wood-based buildings in urban areas. This regulation had not been deregulated until three story individual wood houses were allowed in urban areas in 1987. Subsequent deregulations on wood-based buildings include wood-based three story quasi-fire resistant buildings with the limited total area in urban area and wooden three story apartment buildings outside urban areas in 1992. Most of such newly introduced wood-based buildings employ fire protection of wooden load bearing panels with inert thermal insulation boards. Many fire resistance tests have been carried out on wall assemblies to validate the fire resistance of the protected wooden construction, a few of which were carried out on predamaged specimens to evaluate the seismic effects. Some full scale burn tests had also been conducted, however, all such tests were terminated and extinguished for safety reasons before the collapse or the full involvement of the whole structure by fire. Originally, wooden construction tended to be considered by the public as an origin of conflagrations through the experience of the Kanto Earthquake fire(1923), numbers of city fires common until the 1960s, and the bombing during the World War II. These tests did not provide ideas for what would happen if the fire is left unextinguished for hours. While data from such tests were still enough persuasive as long as the fire fighting is available, it is difficult to ensure fire fighting after an earthquake. When the government was considering a new deregulation on wooden buildings in urban areas before the Hanshin Earthquake, evaluation of the postearthquake fire safety performance of wood based buildings was almost always a sort of endless dispute for this background. For further productive assessment of the fire safety of large wooden buildings in urban areas, it was felt necessary to have clear experimental evidence for the fire exposure due to a large flame in city fires and the behavior of a wood-based fire protective building in fire until its collapse.

Plan of a full-scale burn test was proposed to the Diet by MoC around half year after the Hanshin Earthquake to verify the effectiveness of fire safety measures on wood-based buildings in a city fire scenario. The approved test program consisted of a full scale burn test of a 335m^2 large three-storey wooden apartment building, and a series of loaded fire resistance tests on wood-based wall assemblies with and without damage by horizontal loading simulating a strong earthquake[51]. The full scale burn test was carried out in March 1996.

The arrangement for the full scale test was designed anticipating the wind from north and is summarized in Figure 11. The test house, designed and built solely for the test, had two apartment units on each floor and had "artificial" cracks on the walls to simulate seismic damages. The fire protection of the test house was determined essentially according to the regulation then applied to wooden three-storey apartment buildings outside city areas, except for the ceiling of one unit on the third floor. The live fire load was approximately 28 kg/m^2, approximately one third the average weight density of timber used for the construction. The basic idea for weakening the threat of fire spread from a large wood based construction to adjacent buildings was to separate the burning of the combustible packages and that of the construction. The one-hour fire resistance of the separation walls was believed to be enough to prevent the simultaneous burning of the timber and the combustible packages. Two wooden small buildings, designed to satisfy the minimum fire protection requirements and damaged artificially in similar way as the test house, were built leeward to the test house. The main focus of the test was the observation of the process of fire penetration from the simulated city fire to the test house, fire spread within the test house and fire spread from the test house to the leeward wooden buildings. No fire spread to the leeward wooden buildings had been anticipated with these conditions as long as the combustible packages and the timber do not burn simultaneously. Measurements were conducted on temperature, concentration of O_2, CO_2 and CO in the apartments, heat flux at the wall surfaces and the windows, smoke density and static pressure at main openings. The test became the most comprehensive and the largest full scale burn test on wooden structure ever since the Japan's first full scale fire test was carried out in 1933.

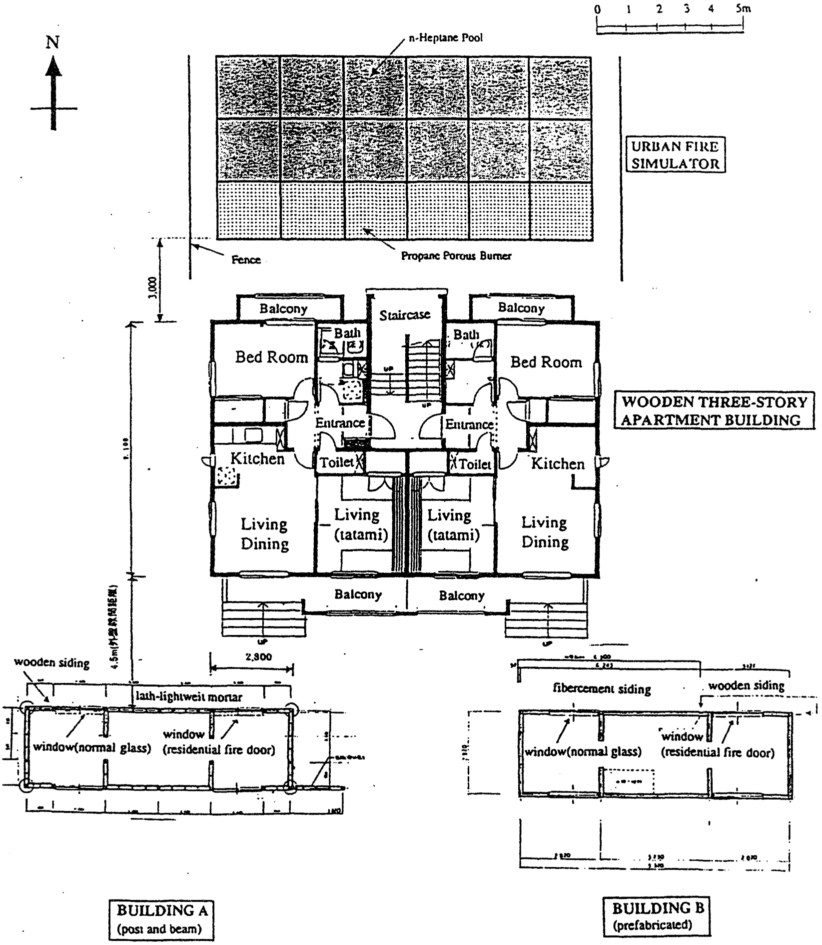


Figure 11 Full-scale wooden three-storey apartment building fire test in city fire scenario, Experimental arrangement

Among the numbers of unprecedented ideas in the test program, reproduction of the large flame recorded at the Hanshin earthquake was felt the most difficult to achieve. From full scale burn tests on traditional wooden buildings and experience of city fires until the 1960s, local flaming of a city fire has been believed to have a sharp peak due to the flaming of individual buildings continuing for 10 to 20 minutes and to continue to burn weakly for hours after the collapse of individual buildings. According to the video record of the Hanshin Earthquake, the maximum flame height reached around 15 m, 20% taller than the height of the test house. From the flame height correlation, e.g. $L_f=3.5Q^{*2/5}D$, it was concluded that over 50 MW fire source is necessary to achieve this flame height and n-heptane pools are the most realistic choice for the fire source under various limitations including the short term available for the project. The post-collapse weak fires of around 500 kW/m^2 were simulated with propane porous burners to ensure a long operation until the end of the experiment. The total area of the n-heptane pools was $48m^2$, which was decided to produce a 50MW fire with reference to the anticipated range of flame heat flux to the fuel surface and the B-number. After some preparatory tests, it was decided to put ice blocks into the pools to restrict the surface area and to maintain the fuel temperature enough below the boiling temperature.

Figure 12 is a picture taken during the burning of the n-heptane pools. The weather was stable with the maximum wind velocity, 6 m/s from north. Maximum heat flux measured at the windows and the external walls of the test house facing the n-heptane pools and the propane burners exceeded 100 kW/m^2, which is considerably higher than those reported in laboratory measurements on porous burners. Fire penetration to the test house occurred only through a window on the first floor and at the eaves of the roof although during the operation of the n-heptane pools the flame covered whole surface of its north external wall and some windows were left open. Air entrainment from the test house to the large flame may be the reason for this unexpectedly weak fire penetration. The penetration through the eaves was attributed to the weaker fire resistance and the complexity of its construction. The test house survived for around 165 minutes until the collapse of its whole west part. There was virtually no fire spread to the leeward wooden buildings.

Figure 12 Test house exposed to the flame from the urban fire simulator

The test has resulted in further deregulation on the wooden large apartment buildings in urban areas in 1997 and 1999. More importantly, this experiment has given a strong impact against the extreme prejudice against the wooden construction through validating the effectiveness of the engineering concept in the fire protection of wood-based building and demonstrating the capability of wooden construction to resist a city fire. This experiment and the facilities built for this experiment founded the technical aspects of the BRI's new R & D program on the fire and seismic safety in urban area and the recent construction of the Fire Research Wind Tunnel at BRI for further study of wind effects in fires[52]. Certainly there are relatively few experimental studies on wind blown fires in buildings and urban areas probably for the lack of appropriate research facility, although some of the recent significant fires demonstrate importance of the wind effects.

CONCLUDING REMARKS

Though the subjects discussed in this paper may appear to spread wide disciplines in fire safety science, the central issue of each topic is the modeling of diffusion flames in different fire scenarios and the evaluation of its impact to its surroundings. All these topics were approached by a common strategy, to try to introduce realistic thermal exposures in the fire safety assessment. Heat transfer in a locally heated building structure, classification oriented analysis of flame spread, and the reaction of wooden construction to a city fire are new research subjects generated from this common methodology.

Results of diffusion flame modeling are a valuable source of inspirations for practical fire problems. However, there is still considerable prejudice in the public and fire practitioners such as building regulators against the applicability of the fire safety science to the real world. On the other hand, the "real world" is a gold mine of stimulants for fire modeling, although there is some tendency that scientists avoid making close contact with the "real world". Promotion of the communication in proper way between fire safety science and such people in the "real world" as fire practitioners, architects, engineers, consumers and manufacturers through demonstration of the significance of fire safety science etc is believed to activate research in the interdisciplinary areas in fire safety science.

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TERMINOLOGY

C_p : specific heat of air
D : characteristic fuel size
H : height
H_B : height of the upper flange of a beam
H_C : height of the lower flange of a beam
K : constant(L_f/Q_ℓ)
L_B : horizontal flame length beneath the upper flange
L_C : horizontal flame length beneath the lower flange
L_f : flame length
Q : heat release rate
Q^* : dimensionless heat release rate$(Q/\rho_o C_p T_\infty g^{1/2} D^{5/2})$
Q^*_{DHB} : dimensionless heat release rate$(Q/\rho_o C_p T_\infty g^{1/2} H_B^{5/2})$
Q^*_{DHC} : dimensionless heat release rate$(Q/\rho_o C_p T_\infty g^{1/2} H_C^{5/2})$
Q_ℓ : heat release rate per unit width
Q_ℓ^* : dimensionless heat release rate per unit width$(Q_\ell /\rho_o C_p T_\infty g^{1/2} D^{3/2})$

$U(t)$: Heaviside's unit function
V_p : flame spread velocity
a_c : surface heat transfer coeff.
g : gravitational acceleration
q :heat release rate per unit area
q_{max}:maximum of q
q'' :heat flux
t : time
t_b : time to burnout or to decay
x_f : location of flame front
x_p : location of pyrolysis front
x_{po} : pilot flame height
x_{poff}: maximum pyrolysis length
z' :virtual point source depth

Q_o : heat release rate of the ignition source
T_o : ambient temperature(K)
ρ_o : density of ambient air
τ :characteristic time to ignition

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