A REVISIT TO THE FIRE HAZARD ASSESSMENT OF LINING MATERIALS BASED ON THE ASYMPTOTIC BEHAVIOR OF CONCURRENT FLAME SPREAD——AN INTERIM NOTE

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INTRODUCTION

From the 1980's to the early 1990's, numbers of studies were conducted on the prediction of the occurrence of flashover by one-dimensional analytical/numerical flame spread models. It is believed that these studies have helped development of rational evaluation method of the fir safety of lining materials. However, although many of the studies along this approach have derived simple models, diagrams or formulae, they have been seldom validated by practitioners nor succeeded by studies on larger compartments while most of these studies dealt with the ISO9705 Room Corner Test. Also, it is believed that models and conclusions of these studies have inevitable limitations due to its simplicity and rich variety of the combustion behavior of practical lining materials. It also seems that there are several overlooks in this approach, especially in the interpretation of the theoretical concepts and the phenomena that actually happen in the fires. This approach is being revisited for the subjugation of the gap between the theory and real/practical world.

SELF-EXTINGUISHMENT OF FLAMING FIRE ON A COMBUSTIBLE SOLID

The analytical approaches to flashover generally try to connect asymptotic behavior of flame spread with the occurrence of flashover. Divergence of flame spread velocity is generally interpreted as a condition for the occurrence of flashover, while its convergence is considered as the sign for a room fire terminating in a local burning. In this section, discussion will be made on how the divergence/ convergence criteria should be formulated and connected to the interpretation of real fires using the generalized SQW equation.

Generalized SQW Equation

In the paper by Saito, Quintiere and Williams delivered at the First International Symposium on Fire Safety Science, a simple expression, equation 1, was proposed for the concurrent turbulent flame spread over a solid. For the symbols, please consult the papers in the reference.

$$V_p(t) = (x_f - x_p)/\tau = [K\left\{\dot{Q}_o(t) + x_{po}\dot{q}''(t) + \int_0^t V_p(\xi)\dot{q}''(t-\xi)d\xi\right\} - \left\{x_{po} + \int_0^t V_p(\xi)d\xi\right\}]/\tau \qquad (1)$$

Equation 1, normally called as "SQW Equation", has been generalized to evaluate more correctly the effect of burnout as follows. In this paper, equation 2 will be referred to as the "generalized SQW Equation".

$$V_p(t) = [K\left\{\dot{Q}_o(t) + x_{po}\dot{q}''(t) + \int_0^t V_p(\xi)\dot{q}''(t-\xi)d\xi\right\} + U(t-t_b)\left\{\int_0^{t-t_b} V_p(\xi)d\xi + x_{po}\right\} - \left\{x_{po} + \int_0^t V_p(\xi)d\xi\right\}]/\tau \qquad (2)$$

Condition for Autonomous Extinction of Flaming Fire without Flame Spread

When a *noncombustible* lining material such as gypsum board with thin wall paper is ignited by a pilot flame, it is often observed that the flame dies out once either the pilot flame is removed or the burning of the part of the surface directly ignited by the pilot flame is terminated. These conditions are believed to correspond to those not permitting the solution of equation 2 for V_p.

(1) Self-extinguishment after the removal of the pilot flame

Equation 2 cannot be solved for V_p under the following condition, which is believed to mean that flame spread does not occur under this condition. More physically, the following condition means that the flame above the surface ignited by the pilot flame does not cover the unburnt surface beyond the pyrolysis front unless the pilot flame itself assist the growth of the flame.

$$K\dot{q}''_{\max} \le 1 \tag{3}$$

(2) Self-extinguishment after the burnout of the part directly exposed to the pilot flame

Equation 2 cannot be solved for V_p for $t>t_b$ also under the following condition. This condition can be interpreted as the termination of flame spread once the part directly ignited by the pilot flame is burnt out. If the local heat release rate, q''(t), is constant in $0<t<t_b$, this condition coincides with equation 3.

$$\overline{K\dot{q}''} \equiv \int_0^{t_b} K\dot{q}''(\xi)d\xi / t_b \le 1 \tag{4}$$

Condition for Weak Flame Spread Yielding Autonomous Extinction

Even if neither equation 3 or 4 is satisfied, flame spread is decelerated and will finally die out if $dV_p(t)/dt<0$. Since equation 2 can be written for $t>t_b$ as

$$V_p(t) = \int_{t-t_b}^{t} V_p(\xi)\{K\dot{q}''(t-\xi)d\xi - 1\}/\tau \tag{5}$$

the critical condition for $d V_p/dt<0$, namely $V_p = constant$, is given by

$$\int_{t-t_b}^{t} \{K\dot{q}''(t-\xi)d\xi - 1\}/\tau = \{K\int_{t-t_b}^{t} \dot{q}''(t-\xi)d\xi - t_b\}/\tau = 1 \quad \text{or} \quad \overline{K\dot{q}''} \equiv \int_0^{t_b} K\dot{q}''(\xi)d\xi/t_b < 1 + \tau/t_b \tag{6}$$

For any material with which burn-out may not occur, equation 1 leads to the similar criterion;

$$K\dot{q}''_{\max} < 1 + \tau/t_c \tag{6'}$$

where t_c is a characteristic time scale of heat release rate, e.g. t_c in $q''(t)= q''_{max}\exp(-t/t_c)$. It should be noted that these conditions are to guarantee only that flame spread should be decelerated all the time and then terminate. Notable flame spread and subsequent fire hazard may still occur especially if the pilot flame, or the fire source, is not sufficiently large. In this sense, this condition could be referred to as the "weak" condition for autonomous extinction while the other can be the "strong" condition.

Comparison with Analytical Solutions

Equation 1 and 2 have been solved for a few simple functional forms of q''(t). Equation 6 has been certainly proven to give the criterion for the divergence/convergence and acceleration/ deceleration of flame spreading velocity for q''(t) represented as a rectangular function of *t*. However, solution of equation 1 for q''(t) represented as an exponential function of *t*, e.g. $q''(t)= q''_{max}\exp(-t/t_c)$, demonstrates a violation against the criterion; even if equation 6' is not satisfied, flame spread starts to be decelerated after an acceleration at the beginning and finally die out if $\tau/t_b > \{1- Kq''_{max})^{1/2}\}^2$. This interesting feature of the SQW equation has been long considered to actually occur; however, this conflict is rather believed to represent the limitation of the disregard of burnout by the original SQW equation; termination of flame spread is not believed to occur for $Kq''_{max}-1>\tilde{\tau}\,t_c$.

Although burning behavior of charring material and thin combustible layer above an inert slab is generally represented by an exponential function of time, it is common that flaming combustion is terminated when the mass pyrolysis rate becomes weak enough. Many analytical work using heat release rate often ignore the burnout in such a way; however, that is believed to make a significant influence on the evaluation of the preheating of the unburnt surface. Flame length on a wall, the key for the preheating of unburnt surface, is controlled solely by the heat release rate from the whole burning surface, and has to be measured upward from the location of the burn out front. The location of the flame front, x_f in equation 1, is thus defined as the sum of the flame length and the location of the burnout front. Disregard of burnout will naturally result in the disregard of the "burnout" part of the x_f which can be significant for $t>>t_b$. On the other hand, disregard of burnout should not cause any notable difference in the evaluation of heat release rate from the whole burning surface since the contribution of fuel from the area beneath the burnout front should be anyway extremely weak. With these effects, disregard of burnout is believed to lead to significant underestimate of flame spreading velocity as the location of burnout front develops. From this analysis, it is natural to assume that equations 6 and 6' give critical condition for divergence/convergence and acceleration/deceleration of flame spread for any form of the time history of local heat release rate.

FLASHOVER CRITERIA IN ROOM CORNER TEST AND MATERIAL PROPERTIES

It is important that equations 3, 4, 6 and 6' use only simple material properties obtained from heat release measurements under simulated heating condition in fire. In this section, predictability of the occurrence of flashover from such material data is examined using the data from the ISO 9705 Room Corner Test and the ISO5660 Cone Calorimter obtained during the MOC R&D Program on Fire Tests(1992 - 1998). In this project, Room Corner Tests and Cone Calorimeter tests were conducted on numbers of lining materials using specimens produced from same lots of the products. The Room Corner Test uses a nominal 100kW fire source, and if the fire does not reach flashover in 10 minutes then the fire source intensity is increased to 300kW for another 10 minutes. From the discussion in the previous section, it is believed that fire will grow rapidly from the beginning and reach flashover during the first 10 minutes if the properties of the tested material satisfy the divergence-acceleration mode of flame spread. Even if the material properties satisfy the convergence-deceleration mode of flame spread, the fire may lead to flashover if the fire source intensity is increased to 300kW. 300kW is large enough for the source flame to cover a part of the ceiling, and the ceiling has been already preheated by the smoke layer during the first 10 minutes. The preheating is believed to shorten the time to ignition, τ, of the ceiling, which may further let such materials having escaped narrowly from flashover during the first 10 minutes go across the critical line. Focus of this section is to examine if the criteria derived in the previous section can explain the occurrence of flashover in the first 10 minutes and study what mechanism can lead to flashover in the following 10 minutes. Cone Calorimeter data for $50kW/m^2$ heat flux level are used as some of the tested materials did not ignite at $30\ kW/m^2$. However, there is not yet clear evidence that $50kW/m^2$ heat flux correctly represent the fire exposure during a Room Corner Test.

Equations 1 and 2 needs empirical determination of K, flame length per unit heat release rate per unit area. From experiments on wall and ceiling fires, K is believed to be between 1/50 and 1/100. The analysis assuming K=1/65 in equation 2 resulted in all the materials causing flashover in 10 minutes satisfying $K\overline{\dot{q}}'' > 1 + \tau / t_b$, and all the materials not causing flashover until the end of the test falling in $K\overline{\dot{q}}'' < 1 + \tau / t_b$. However, data for the materials causing flashover at 10 - 20 min are scattered around the critical $K\overline{\dot{q}}'' = 1 + \tau / t_b$ straight line, especially near its intercept to the Kq" axis. It is also noteworthy that although there are numbers of materials falling near the critical line, those materials far from the Kq" axis intercept did not cause flashover until the end of the test. This may suggest that occurrence of flashover at 10 – 20 min is typical for lining materials of low heat release but relatively easy to ignite, say $\tau < 10$ s at 50kW/m^2 heat flux level. The ambiguous scattering of those data suggest s the fire exposure during a Room Corner Test slightly weaker than 50kW/m^2. All of the specimens that caused flashover before 10 min were such materials having relatively thick combustible layer, while all of those that caused flashover in 10 – 20 min were gypsum board with wall paper. Some other gypsum board based specimens with longer time to ignition did not cause flashover. Since temperature field of the specimen before ignition is believed to be controlled by the gypsum layer in these materials, it is believed that the shorter time to ignition with such material should mean lower temperature of piloted ignition. It is natural that preheating cause more significant influence on the time to ignition of such materials with low ignition temperature. It is probably the reason why only the gypsum board based materials caused flashover in 10 – 20 min in our project. This further suggests importance of the evaluation of ignition temperature or ambient-temperature dependence of τ and the consideration of the smoke layer temperature in the fire hazard assessment of lining materials especially in a large enclosure where flame development beneath the ceiling can be the key for the occurrence of flashover.

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