PHYSICALLY-BASED MODELING OF FIRE SPREAD IN URBAN AREAS

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ABSTRACT

The physically-based urban fire spread model formerly proposed by the authors (Himoto & Tanaka, 2002) is refined by incorporating new sub-models: (1) a transient burning model for charring combustible; and (2) a burn-through model for partition doors/walls forming a path of fire spread to the adjacent compartment. Some fire spread simulations were carried out in fictitious urban areas where buildings were arrayed: (A) in a regular configuration; and (B) in an irregular configuration assuming an actual urban area.

1. INTRODUCTION

To explore the effective measures for reducing the loss caused by urban fires, it is indispensable to develop a rational model for predicting urban fire spread. There are already several empirical models available for identical purpose (Horiuchi, 1973; Itoigawa et al., 1989), represented by the model proposed by Hamada (1951). However, these existing models focus mainly on simulating the overall behaviors of urban fire (e.g., spreading speed of fire, area of burned out district, etc.), and the physical aspects of the urban fire causing the building-to-building fire spread are black-boxed. As a consequence, there were inevitable difficulties in deducing valuable and specific conclusions from the results of numerical simulation. Hence, It is considered that the development of a physically-based model will contribute greatly to solving the above issue.

In such a circumstance, a new fire model is being developed by the authors (Himoto & Tanaka, 2002). In the model, spread of fire in urban area is described by simulating the behavior of individual building fires under the thermal influence of nearby building fires, as urban fire is nothing but an ensemble of multiple building fires. The numerical approach is based on solving the governing equations for mass, energy and chemical species of component compartments of buildings, computing the representative physical quantities such as gas temperature T or concentration of chemical species Y. However, the governing equations are not closed in themselves and additional modeling of some elemental phenomena is necessary.

One of such phenomena is the pyrolysis (gasification) of solid combustible releasing pyrolyzed gas (flammable gas) into the gas phase.

The flammable gas is then used for exothermic reaction with oxygen, which constitutes the major part of heat generation in a fire. In the past version (Himoto & Tanaka, 2002), the mass release rate $\dot{m}_B$ of the flammable gas is calculated in proportion to the net incident heat flux $\dot{q}''_{net}$ to the laid combustible, i.e., steady state reaction is assumed. While this method is computationally simple, it lacks the necessary physics to describe the behavior of urban fire, in which the fire condition transit by time series from ignition to decaying.

Another important aspect, which is not considered in the past version, is the burn-through of partition door/wall separating compartments. When exposed to a severe fire environment for a long while, numbers of building materials lose their functions and make fractures on them. This brings the critical increase in mass and heat exchange between the compartments of both sides, which is almost synonymous with the occurrence of fire spread.

In this work, above two sub-models have been built into the urban fire spread model and some numerical simulations in fictitious urban areas have been carried out.

2. MODELING

Schematic diagram of the model is illustrated in Figure 1. Fire originated in a compartment produces an increase in the internal gas temperature and transfers mass/heat to the adjacent compartment through partition doors/walls. The combustible sited near the opening receives heat and ignites when the surface temperature reaches as high as its pyrolysis temperature T_P, and thus occurs the fire spread. If the compartments are in

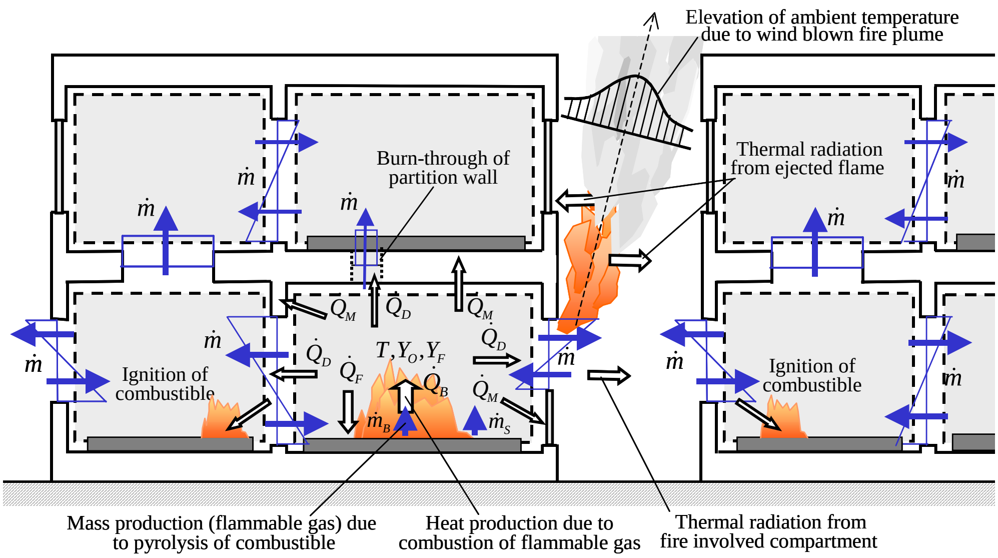


Figure 1: Schematic diagram of the urban fire spread model. Solid and outline arrows represent the transfer of mass and heat respectively.

different buildings, then the heat is also transferred by thermal radiation from ejected flame and thermal convection of wind blown fire plume.

Referring to Figure 1, the conservation equations of mass, energy and chemical species (oxygen=O; fuel=F) for an arbitrary compartment-*i* are described as follows, respectively:

<mass>
$$\frac{d}{dt}(\rho_i V_i) = \sum_j (\dot{m}_{ji} - \dot{m}_{ij}) + \dot{m}_{B,i} \tag{1}$$

<energy>
$$\begin{aligned}\frac{d}{dt}(c_P \rho_i V_i T_i) &= \dot{Q}_{C,i} - \dot{Q}_{F,i} - \sum_j (\dot{Q}_{D,ij} + \dot{Q}_{M,ij}) \\ &\quad + \sum_j (c_P \dot{m}_{ji} T_j - c_P \dot{m}_{ij} T_i) + c_P \dot{m}_{B,i} T_P\end{aligned} \tag{2}$$

<species>
$$\frac{d}{dt}(\rho_i V_i Y_{X,i}) = \sum_j (\dot{m}_{ji} Y_{X,j} - \dot{m}_{ij} Y_{X,i}) + \dot{\Gamma}_{X,i} \quad \text{(X=O,Y)} \tag{3}$$

where ρ is the density, V is the volume, $\dot{m}$ is the mass flow rate through opening, $\dot{m}_B$ is the mass release rate, c_P is the specific heat, T is the temperature, $\dot{Q}_C$ is the heat release rate, $\dot{Q}_F$ is the heat loss to fuel, $\dot{Q}_D$ is the heat loss to door, $\dot{Q}_M$ is the heat loss to wall, T_P is the pyrolysis temperature of combustible, Y_X is the concentration and $\dot{\Gamma}_X$ is the production rate of chemical species. $\sum$ denotes to take the summation of the relevant values with respect to all the boundary elements. The subscript *j* refers to the adjacent compartment of the concerned compartment-*i*, or outdoor space, and *ij* indicate the origin and the destination of mass/heat transfer.

2.1 Transient Burning of Combustible

In order to describe the transient burning of solid combustible, it is essential to take account of the effect of char formation upon unpyrolyzed (virgin) material, as it is such combustible that is most common in general dwellings. In the model, the behavior of the material receiving external heat is divided into following sequential phases (see Figure 2): (I) the heat-up phase; (II) the flaming combustion phase; and (III) the non-flaming combustion phase.

In the phase (I), the material raises its temperature due to external heat and consequently ignites when its surface temperature T_S reaches as high as its pyrolysis temperature T_P.

In the phase (II), flammable gas and residual char is produced by the pyrolysis of virgin material. The flammable gas reacts with oxygen forming flame in the gas phase, whereas the residual char is accumulated upon the virgin layer and relaxes the incoming heat flux. Yet, in the meanwhile, the char oxidates at the surface (surface combustion) at the rate of $\dot{m}_S$ and generates heat, though it is much moderate compared to that of the flammable gas combustion. The boundary temperature of these two layers is held constant at the pyrolysis temperature T_P. The rate of pyrolysis, i.e., the release rate of flammable gas $\dot{m}_B$, is assumed proportional to the net heat flux absorbed by the boundary:

$$\dot{m}_B = \frac{-k_C\left(\dfrac{\partial T_C}{\partial x}\right)_b - \left[-k_F\left(\dfrac{\partial T_F}{\partial x}\right)_b\right]}{L_P} \cdot A_B \tag{4}$$

where k is the thermal conductivity, x is the coordinate orienting to the depth-ward, L_P is the latent heat of pyrolysis, and A_B is the area of burning. The subscript b stands for the boundary, C for the char layer and F for the virgin layer. The temperatures of inside the char layer and the virgin layer are calculated from the simple ordinary differential equations, which are derived from the heat conduction equations by means of integral method (Himoto & Tanaka, 2003(A)).

When whole of the virgin layer is consumed, the phase moves to (III). In this phase, the char surface stays on combustion and generates heat moderately, while the flame is put out. This reaction continues till whole of the residual char is consumed.

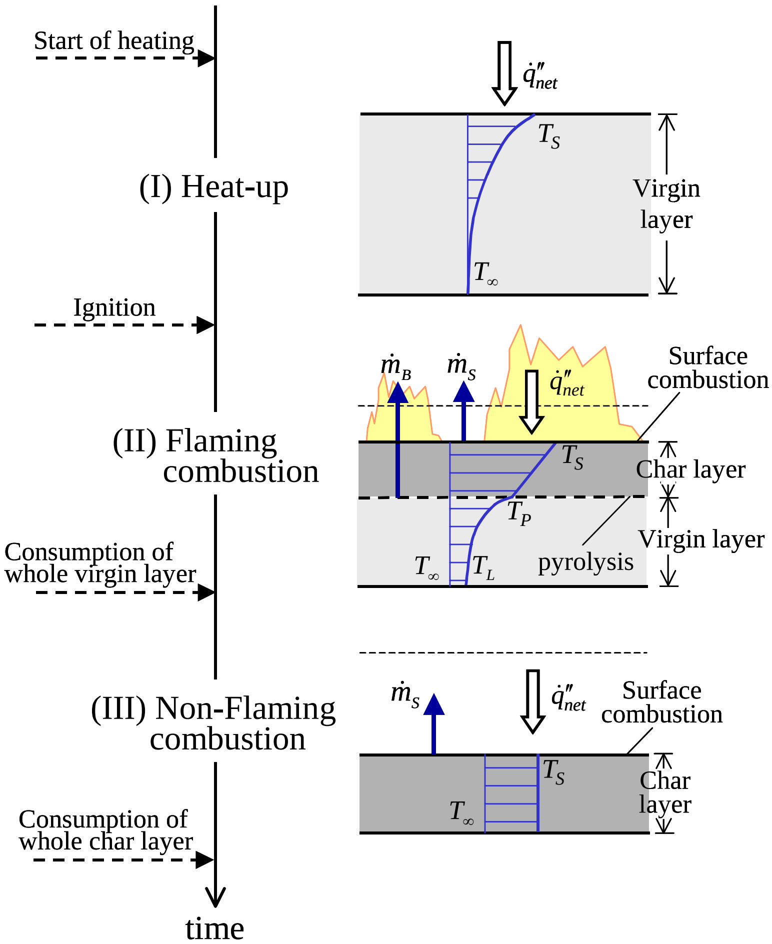


Figure 2: Transient burning model for charring material.

2.2 Burn-Through of Partition Door/Wall

In general, numbers of building materials make fractures on them in a sever fire environment, forming a path of fire spread. Although the mechanism of burn-through is not uniform for different building materials, and this process is accompanied with complex physical/chemical reactions, we assume that the approximate temperature, at which such notable feature change occurs, is conceivable for each material. Hence, it is modeled that the burn-through starts when the material temperature exceeds the critical value T_{BT} , and thereafter, the rate of burn-through is proportional to the incident heat per unit volume of the material $\dot{q}'''_M$. The density reduction per unit time is then expressed as (Himoto & Tanaka, 2003(B)):

$$\frac{d\rho_M}{dt} = \chi_{BT} \cdot \dot{q}'''_M \tag{5}$$

where ρ_M is the density of partition and χ_{BT} is the coefficient. The temperature inside the concerning partition is computed by solving the heat conduction equation discretised by the finite volume method.

3. RESULTS

3.1 Buildings in a Regular Configuration

Fire spread simulations were carried out at the wind velocity *U* of 0.0[m/s] and 5.0[m/s] in an area where 49 identical ALC (autoclaved-light-weight concrete) buildings composed of 10 rooms were arrayed in a uniform distance of 4[m]. In this case, burn-through of partition was neglected except for that of window glasses. The fire was initiated in the building at the central location by imposing a model heat generation.

Figure 3 demonstrates the evolution of fire spread in the urban area, where Figure 3(a) and 3(b) are the results of *U*=0.0[m/s] and *U*=5.0[m/s], respectively. Dark color indicates that the compartment is at the vigorous stage of fire, and it turns back to the light color when the fire stage moves to the decaying phase after the consumption of combustibles.

For both of the cases, the fire spread readily after the ignition and developed to be an urban fire involving multiple building fires. For *U*=0.0[m/s], the fire spread symmetry due to the regular configuration of the buildings. On the other hand, for *U*=5.0[m/s], the fire spread faster to the downwind than that to the upwind as the fire-induced plumes were blown down and raised the ambient temperature of the downwind buildings. However, duration of the vigorous combustion for *U*=5.0[m/s] lasted shorter than that of *U*=0.0[m/s]. The intense combustion induced by abundant oxygen supply by the wind is considered to be the principal cause of the increase in the accelerated consumption of combustibles.

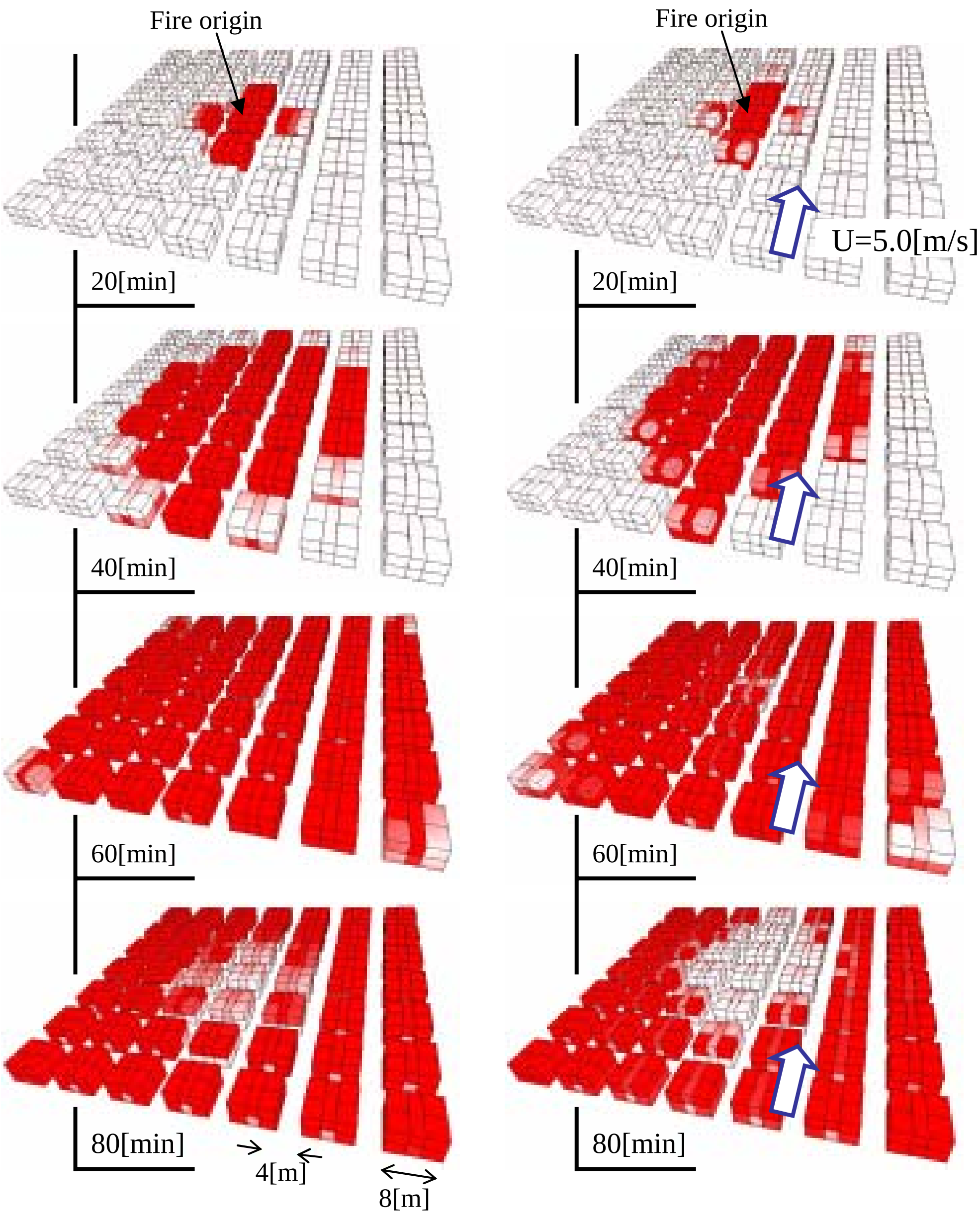
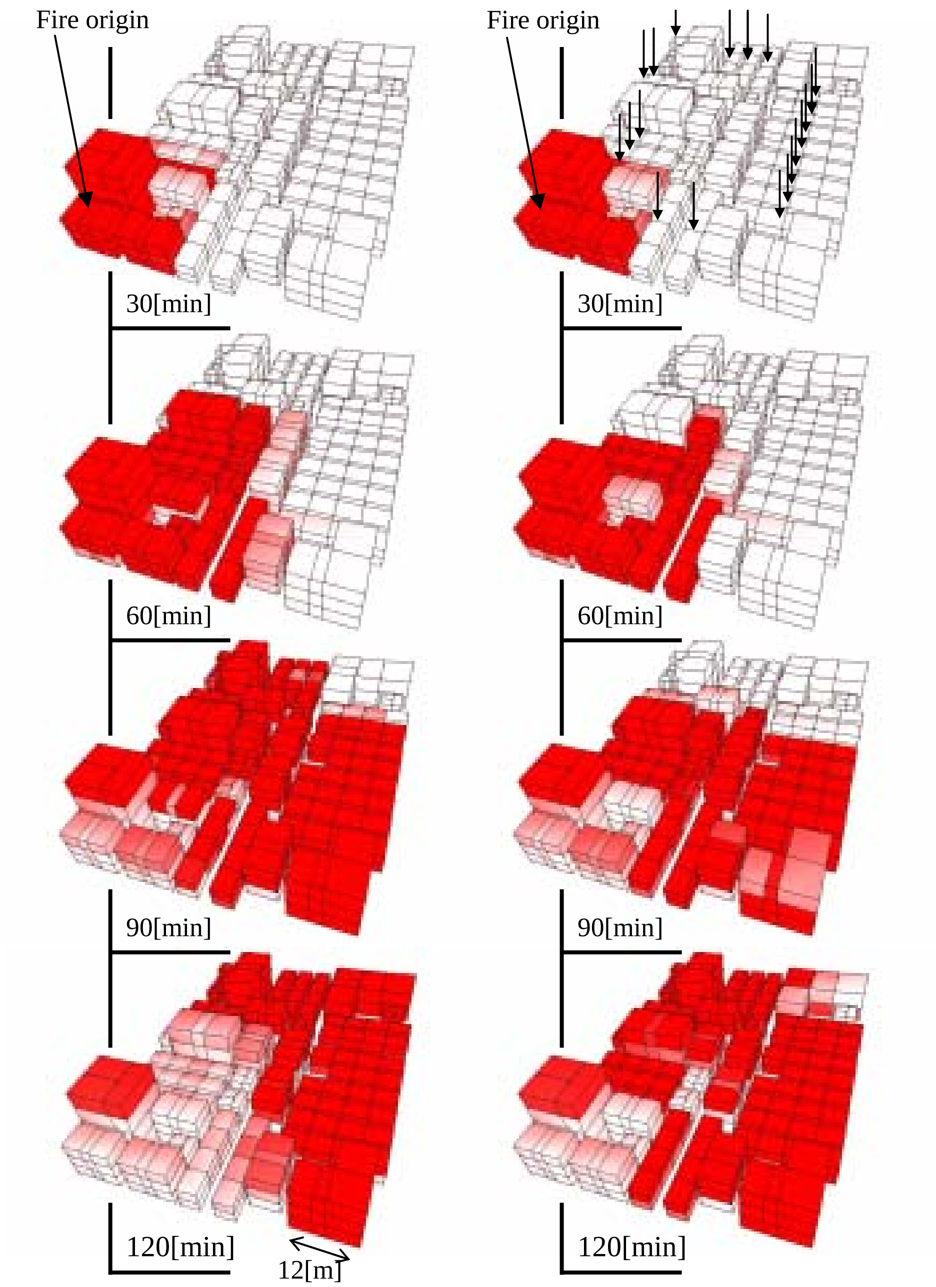


Figure 3: Sample Simulation in an area of irregular building configuration.

3.2 Buildings in an Irregular Configuration

Next, two sample simulations were carried out in an area where 40 buildings were arrayed irregularly varying the types of building structure. For the first case, the structure type of all the building was assumed as ALC. For the second case, 21 out of 40 were assumed ALC buildings, and 19 out of 40 were assumed wooden buildings. The burn-through of ALC walls were not considered as with the previous section, whereas that of the wooden walls were assumed. At this time, no wind effect is considered.



(a) ALC buildings (b) ALC buildings + wooden buildings (arrowed)

Figure 4: Sample Simulation in an area of irregular building configuration.

The results are shown in Figure 4(a) and 4(b), respectively, in which the wooden buildings are pointed out by the arrows. Contrary to the original anticipation, the spreading speed of fire was slower for the case in which the wooden buildings were involved. The possible cause is that the intensity of fire in the wooden buildings was moderate compared to that of the ALC buildings, as large quantity of mass and heat passed through the burn-through openings. In other words, the fire inside the wooden buildings was, so to speak, fuel-controlled condition and thus gas temperature was kept relatively low. Though this result illustrates one of the aspects that the fire behavior in wooden buildings has, it does not describes another commonly perceived aspects, i.e., the fire spreads fast in wooden urban area. It is presumed that the model underestimated the spreading speed as the brand spotting, which is the prevalent means of fire spread especially for wooden buildings, was not considered in the current simulation.

4. CONCLUDING REMARKS

The urban fire spread model formerly proposed by the authors (Himoto & Tanaka, 2002) is refined by incorporating new sub-models: (1) a transient burning model for charring combustible; and (2) a burn-through model for partition doors/walls. Some numerical simulations were carried out by the model in fictitious urban areas. Judging from the results, these new models yield improvements in predictive capabilities of the model, though they are necessary to be verified with reliable experiments. Further work is also needed to resolve the brand spotting issue, which is revealed to be an indispensable phenomena in order to simulate the fire spread involving wooden buildings.

REFERENCES

Hamada, M., 1951, On The Rate of Fire Spread, *Study of Disasters*, Vol.1, Non-Life Insurance Rating Organization of Japan.

Himoto, K., and Tanaka, T., 2002, A Physically-Based Model for Urban Fire Spread, *Proc. 7th Int'l Symp. on Fire Safety Science*.

Himoto, K., and Tanaka, T., 2003(A), A Transient Burning Model for Charring Material and Its Application to Compartment Fire, *J. Environ. Eng.*, No.568, AIJ.

Himoto, K., and Tanaka, T., 2003(B), A Burning Model for The Fire Involved Building with regard to The Room-to-Room Fire Spread, *J. Environ. Eng.*, No.573, AIJ.

Horiuchi, 1973, *Fire Protection of Buildings*, Asakura Shoten.

Itoigawa, E., Iwami, T., Kaji, T., Kawanaka, T., Kumagai, Y., Tsukagoshi, I., and Masuyama, T., 1989, Study of Real Time System for Information Processing of Post Earthquake Fire –Fire Spread Prediction and Evacuation Control-, *Report of the BRI*, No.120.