HEAT TRANSFER MECHANISMS IN MATERIALS ON FIRE RETARDATION

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ABSTRACT

A concept for the flame retardation was discussed from the viewpoint of heat transfer in a material. Recent experiences on the burning properties of wood in China and Japan[1,2] revealed that a composite material of two or more different elements shows the different characteristics compared with a homogeneous one. The differences were considered to be caused by differences in the physical properties of the elements rather than the chemical properties. Especially, thermal properties of the material were inferred to play an important role on the burning characteristics of the material. This suggests that appropriate selection and combination of the thermal properties contribute largely on fire retardation. Based on a simple analysis of heat transfer in composite materials, possible use of the composite materials was discussed.

1. INTRODUCTION

The growth ring is made of spring woods and summer woods. Therefore, a 'wood' is considered to be a type of composite material. A large difference in cell sizes of a spring wood and a summer wood suggests that thermal properties of a spring wood and a summer wood must be different. Such differences between a spring wood and a summer wood should cause differences in thermal properties with the heat flux direction against the growth ring direction, even if there was no directional difference in a spring wood or a summer wood. In this study, a 'wood' was considered as a composite material composed of two elements having different thermal properties. Numerical analyses were done on the temperature profiles in several types of composite materials exposed to external radiation.

2. ANALYTICAL MODEL OF 'WOOD'

As previously mentioned, a 'wood' was modeled as a composite material composed of two thermally different elements, namely a 'spring wood' and a 'summer wood'(Fig. 1). These 'summer wood' and 'spring wood' are rigid materials unlike a real wood. Therefore, heat transfer in the composite was considered to occur only through conduction. Convective heat transfer by transport of vapor, which plays an important role in heat transfer in the case of a real wood, was ignored. Four types of composite materials were considered as listed in Table 1.

Properties of the 'spring wood' and the 'summer wood' were determined from

Table 1 Structural types of composite materials

Types	Structure	Direction of layers to the surface	Material of surface layer
A	Layered	Parallel	Spring wood
B	Layered	Parallel	Summer wood
C	Layered	Normal	-
D	Overlay[a)]	Parallel	Summer wood

a) Overlay means the material has only one layer overlaid on the other element.

those of an actual wood(fir)[3)]. In the literature, properties of fir are as follows; density ρ is 0.54g/cm^3, thermal conductivity transverse to the grain λ_t is 1.38x10^{-3}J/cm/s/K, longitudinal to the grain λ_l is 3.39x10^{-3}J/cm/s/K, thermal diffusivity transverse to the grain α_t is 1.869x10^{-3}cm^2/s, longitudinal to the grain α_l is 4.587x10^{-3}cm^2/s.

In this model, the 'spring wood' was assumed to be 0.3 cm wide and the 'summer wood' was 0.1 cm wide, though propriety of these widths remains uncertain. Concerning density and heat capacity, any information on directional differences is not available. In this calculation, therefore, the 'spring wood' and the 'summer wood' were assumed to have identical density and heat capacity. They were assumed to have difference only in thermal conductivity. Values used in this study were as follows; density and heat capacity c_p of both elements were 0.54g/cm^3 and 1.37J/g/K, respectively. Thermal conductivities of the 'spring wood' and the 'summer wood' were 1.07x10^{-3} J/cm/s/K and 1.04x10^{-2}J/cm/s/K, respectively.

Temperature profile in a composite material was calculated from the following equation.

$$\rho c_p(\partial T/\partial t) = \lambda(\partial^2 T/\partial x^2+\partial^2 T/\partial y^2).$$

where T, t, x, and y are the temperature, time, distances from the origin normal and parallel to the surface, respectively. The origin of coordinates was located at the center of the 'summer wood' surface. Thermal conductivity varies according to the material at the location. For composite A, B and D, there was no difference along layers, so calculation was reduced to one-dimensional one. For composite C, two-dimensional calculation was done for one set of a half of a 'summer wood' layer and a neighboring half of a 'spring wood' layer. This set was considered to represent the whole body.

A composite material was assumed to be semi-infinitely thick, and initially there were no temperature difference in the material, i.e. $T=T_0$ at t=0, where T_0 is room temperature. The boundary condition after exposure to the thermal radiation(t>0) is given as

$$\lambda(dT/dt)_s + \rho c_p(\Delta T/\Delta t)(\Delta x/2) = \varepsilon\sigma(T_f^4-T_s^4)$$

at the surface. The first and the second terms of the left hand side are the heat conducted into the material and heat consumed at the surface. The right

hand side represents the net heat flux from the external heat source. Temperature of the external heat source T_f was assumed to be constant while the material was exposed to radiation.

3. RESULTS AND DISCUSSIONS

3.1 Effects of Layered Structure

Typical surface temperature histories of composite A and B and fir, of which the surface is along the layer, are shown in Fig. 2. In this case, the initial external heat flux and the surface emissivity were assumed to be $0.5W/cm^2$ and 0.8, respectively. Surface temperature of all materials approached gradually to a certain value. This phenomenon was attributed to development of thermal boundary layers in the materials. Thermal boundary layers extended to more than four layers until t = 1 min for composite A and B, so the effective thermal diffusivities in the boundary layers approached to the same value, i.e., the thermal diffusivity of fir. Therefore, effective thermal properties of them became closer as time passed. However, there is a significant difference between composite A and B in required time to reach at a certain temperature, e.g. 400 K. This difference in transient phenomena may play an important role in flame retardation.

3.2 Effects of Heat Flux Direction on Thermal Behavior of Layered Materials

Surface temperature histories of composites B and C and fir, of which the surface is across the layers, are compared in Fig. 3. In the case of the composite C, there was temperature variation along the surface as shown in Figs. 4a and 4b. The highest and the lowest temperatures are shown in Fig. 3. The temperature difference between the highest and the lowest temperatures was about 35 K throughout the time period shown in this figure. For t<50sec(1st period), the highest temperature was larger than the surface temperature of composite B, and became lower for t>50sec. If the highest temperature of composite C in the first period was larger than the ignition point, ignitability of composite C is larger than composite B, and vice versa. Thus result shown in Fig. 4 should be important to evaluate ignitability of a material. Also, it should be noted that the highest temperature for composite C is always higher than the surface temperature of fir.

3.3 Effects of Overlay Thickness

Surface temperature histories of composite D with various overlay thickness are shown in Fig. 5. It is seen that the use of an overlay having larger thermal conductivity than the main body would decrease the surface temperature drastically. Thickness of the overlay need not to be large for reducing the surface temperature, 1 cm is thick enough in the case shown in this figure. Usage of a material with larger thermal conductivity as an overlay would be more effective in flame retardation.

4. CONCLUSIONS

An effective use of composite materials were investigated by using analytical models. Comparison of surface temperature histories for composite A, B and C showed that the composite B was most effective in the early period(t<50sec),

and the composite C was most effective in the rest period for reducing the surface temperature. In the case of composite C, however, there should be a mechanical weakness in practice. In this study, the surface temperature for the composite D was the lowest. If the proper material was used as an overlay, surface temperature could be reduced much more. The results obtained throughout this study suggests that there is a possibility to accomplish flame retardation without chemical treatment.

REFERENCES

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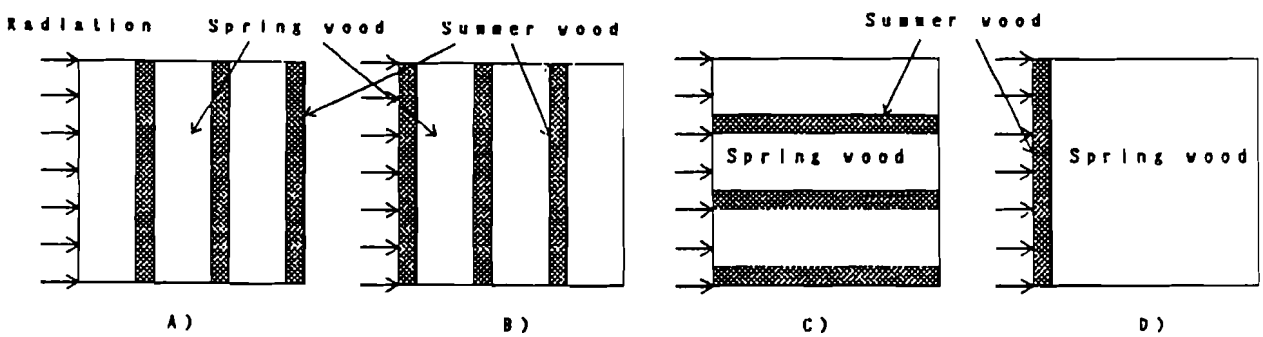


Fig. 1 Schematic illustration of model composites.

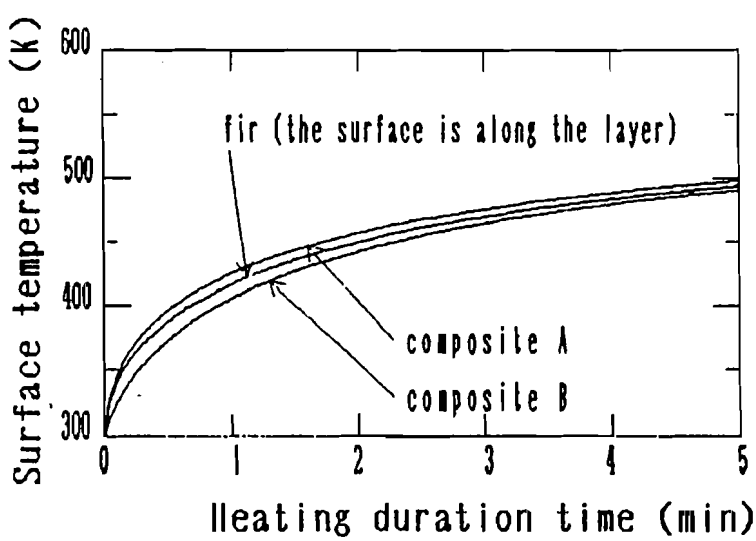


Fig. 2 Surface temperature histories of composites A and B, and fir.

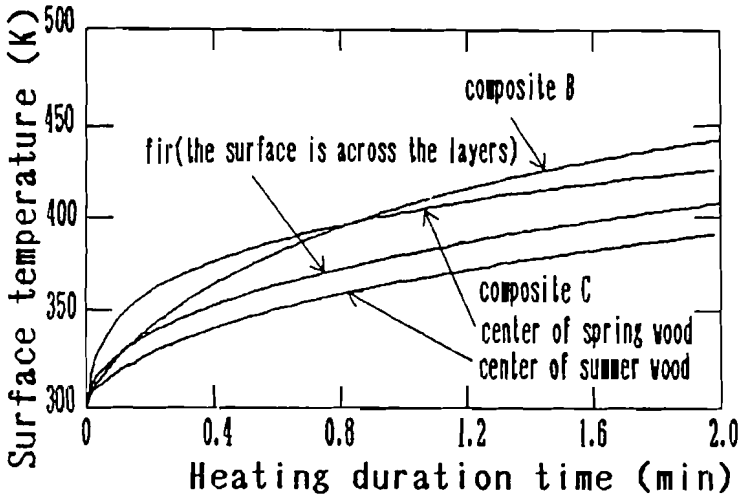
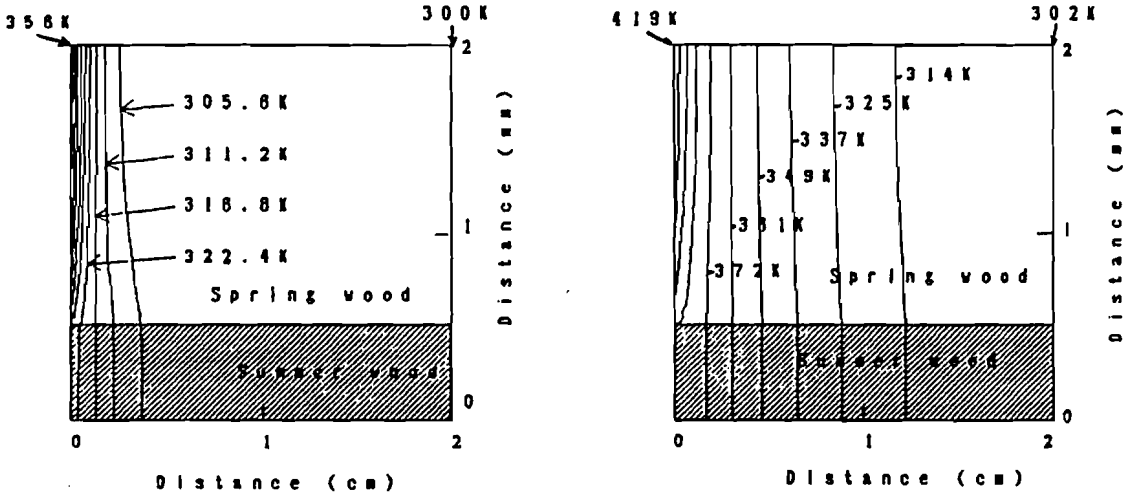


Fig. 3 Surface temperature histories of composites B and C, and fir.



a) 10 sec

b) 110 sec

Fig. 4 Temperature contours in composite C.

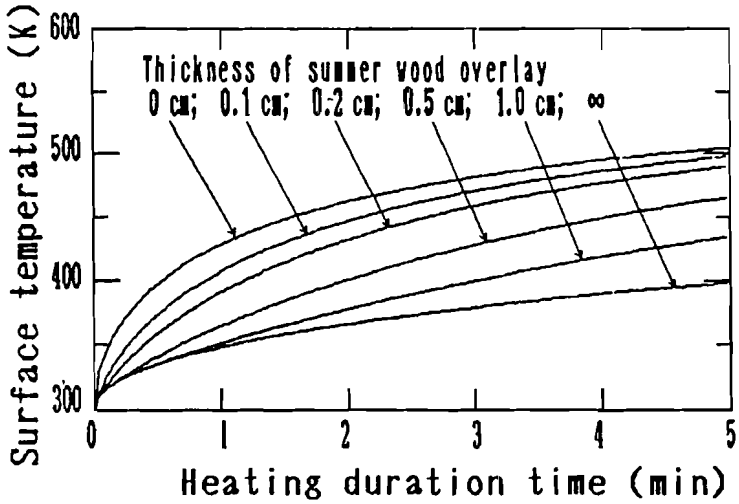


Fig. 5 Surface temperature histories of composite D.