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Propagation of Cigarette Static Burn*

by

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SUMMARY

A propagation model of cigarette static burn at the cigarette periphery is proposed. Propagation of cigarette static burn is characterized by intermittent burn of the cigarette paper. The burning rate depends on the period of flash burn of the paper and is independent of the burning width. By measuring the local temperature near the front line of the burning propagation, the rate-determining step was identified as the time required to ignite the paper. A mathematical analysis was performed by calculating the heat transfer at the periphery during the paper heating period, and it was revealed that the thermal properties of the cigarette are the dominant factors of cigarette static burn. Modeling results showed good agreement with measured data. [Beitr. Tabakforsch. Int. 19 (2001) 277–87]

ZUSAMMENFASSUNG

Es wird ein Modell zur Ausdehnung des statischen Abbrennens an der Außenfläche der Cigarette vorgestellt. Die Ausdehnung des statischen Abbrennens einer Cigarette wird durch das diskontinuierliche Abbrennen des Cigarettenpapiers bestimmt. Die Abbrenngeschwindigkeit ist von der Phase des aufflammenden Brennens des Cigarettenpapiers abhängig und von der Ausdehnung des Glimmbereichs unabhängig. Beim Messen der lokalen Temperatur an der Ausdehnungsgrenze des Glimmbereichs wurde der geschwindigkeitsbestimmende Schritt als die Zeitdauer identifiziert, die notwendig ist, um das Papier zu entzünden. Es wurde eine mathematische Analyse durchgeführt, wobei der Wärmetransfer an der Peripherie während der Erhitzung des Papiers berechnet wurde. Dabei wurde festgestellt, dass die thermischen Eigenschaften der Cigarette die bestimmenden Faktoren des statischen Abbrennens der Cigarette sind. Die Ergebnisse der Modellrechnung stimmten mit den gemessenen Werten überein. [Beitr. Tabakforsch. Int. 19 (2001) 277–87]

RESUME

On propose un modèle de propagation de la combustion statique à la périphérie de la cigarette. La propagation de la combustion statique des cigarettes est caractérisée par la combustion intermittente du papier à cigarette. La vitesse de combustion dépend de la phase d'inflammation du papier et est indépendante de la largeur de combustion. En mesurant la température près de la zone de propagation de la combustion, le paramètre déterminant la vitesse de combustion a été identifié comme étant le temps qui est nécessaire pour enflammer le papier. Une analyse mathématique a été effectuée en calculant le transfert de chaleur à la périphérie au cours de la période de chauffe du papier. On a trouvé que les propriétés thermiques de la cigarette constituent les facteurs déterminants de la combustion statique des cigarettes. Les résultats obtenus par modélisation sont en bon accord avec les données mesurées. [Beitr. Tabakforsch. Int. 19 (2001) 277–87]

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INTRODUCTION

The static burn of a cigarette is a typical type of smoldering combustion, and it is a complicated process involving heterogeneous reactions along with heat and mass transfer. A theoretical description of the specific aspects of cigarette static burn would assist in clarification or improvements in the basic understanding of the more usual puff–smolder burn associated with smoke formation. Several mathematical models of cigarette burn have already been published (1–5). These models reportedly can be used to calculate the overall burning characteristics of the cigarette and some of the detailed features within the burning zone. For example, MURAMATSU (5) developed a two-dimensional model which represented the heat and mass transfer characteristics throughout a statically burning cigarette. This model illustrated two-dimensional distributions such as temperature and oxygen concentration, and has been used to predict the static burning rates and the peak temperatures from cigarette design parameters such as the cigarette radius and the packing density. The trends in burning behavior were accurately predicted by this model. However, it was difficult to clarify the role of the cigarette paper and to verify the dominant factors of cigarette static burning because homogeneity of the cigarette structure was assumed in the model.

Herein, we have adopted a different approach to clarify the mechanisms of cigarette static burn. The burn of the cigarette periphery, i.e., the front line of the burning propagation, is focused on as the characteristic phenomenon of cigarette static burning. Static burn of a cigarette propagates relatively steadily, forming a cone-shaped burning zone. It has also been observed that the burning cone length is proportional to the burning rate (6). At the cigarette periphery, where the burning zone reaches the free surface region, the following specific features are evident:

1) burning can spread rapidly over this region, not only in response to local oxygen supply conditions but also due to heat transfer considerations;

2) a tobacco bed consisting of scattered tobacco shreds is wrapped in a sheath of paper or ash and is in contact with a continuum of the cigarette paper or paper ash.

Thus, if we assume that the burn at the periphery controls the burning propagation and that the interaction between tobacco shreds and paper plays an important role in the burning cigarette, then a model of cigarette burning can be developed. Measurement of the local temperature variation with time near the paper char line allows us to describe the rate-determining factors of cigarette static burn. Mathematical analysis based on this model enables us to identify the dominant factors of the static burning rate.

Cigarette paper as well as tobacco shreds play an important role in cigarette burning, and the paper properties can have a large effect on the cigarette static burning rate (7). A model has been proposed in which the rate of oxygen diffusion through the paper has a direct influence on the static burning rate (8). However, it was found in our recent study that the oxygen diffusion coefficient of the paper was not related to the oxygen supply in a statically burning cigarette. (9). It can be considered that the oxygen diffusivity of the paper is not the only paper property to control the cigarette static burning rate. Herein, we propose a model in which the contribution of cigarette paper properties to the cigarette static burning rate is clarified theoretically, and demonstrates that these interpretations can be verified experimentally. The effects of cigarette paper properties on cigarette static burn are discussed.

EXPERIMENTAL

All measurements were done in an ambient atmosphere conditioned at 22 °C and 60% relative humidity. The blended cigarettes used were 59 mm in length, 8 mm in diameter and contained 690 mg of tobacco. The apparent density of the tobacco shreds was found as to be 0.65 g/cm^3 by the mercury displacement method (10). The effective diameter of the tobacco shreds was estimated to be about 0.5 mm from the dependency of draw resistance on the air flow rate of the cigarette column by an extended Ergun equation (11). Static burning rates were measured for vertically set cigarettes. The heat capacity of the cigarette paper was determined with a differential scanning calorimeter (Mac Science Co., DSC3100S) (12). The anisotropic thermal conductivity of cigarette paper was measured by transient plane source method with a Hot Disk sensor (Hot Disk Inc.) (13), and a plane direction value was used as the thermal conductivity of the paper. The porosity of the cigarette paper is expressed in CORESTA units (CU) [cm^3/(cm^2 min kPa), air permeability]. The surface temperature of the burning cigarette was measured with a thermograph system (Nippon Avionics Co., TVS2000).

RESULTS AND DISCUSSION

Burning propagation model of the cigarette periphery

The propagation of the static burning zone of the cigarette can be seen as the movement of the paper char line, where the paper color turns black. The position of the paper char line over time was determined by analysis of black and white images taken with a charge coupled device (CCD) camera (Sony Co., XC-77). The movement of the paper char line has unique characteristics, as shown in Figure 1. The movement of the paper char line of a statically burning cigarette was not continuous but intermittent. The burning of the cigarette paper is immediately extinguished after the ignition. The paper char line stays stationary for a while, and then moves as the paper is ignited again. The differences amongst cigarette static burning rates are presumably caused by

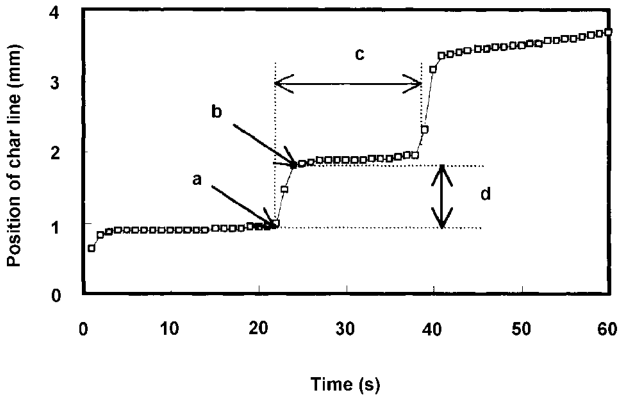

Figure 1.
Movement of the paper char line on the static burning cigarette (cigarette A); a: ignition of the paper (starting of the char line movement); b: extinction of the paper burn (stopping of the char line movement); c: ignition period (time between the stopping and re-starting); d: amplitude of the paper burn (distance between the ignition points)

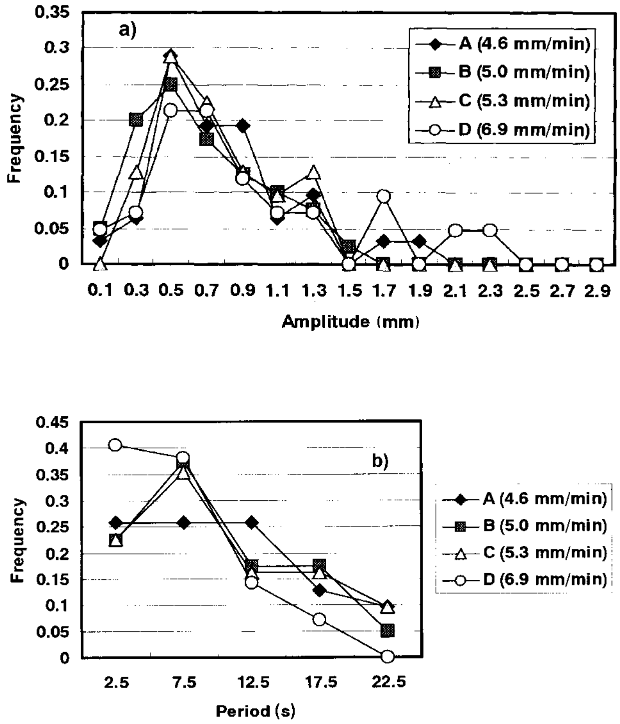

Figure 2.
Frequency distribution of the paper burning amplitude (a) and the paper ignition period (b)

the change of the ignition period (time between the stopping and re-starting of the paper char line movement) and/or the change of the amplitude of the paper burn (the distance between the ignition points).

Frequency distributions of the paper ignition period and the amplitude for various cigarettes are shown in Figure 2. The characteristics of sample cigarettes are shown in Table 1. Because the tobacco bed inside a cigarette is assumed to be granular, the spherical equivalent diameter of a tobacco shred is about 0.5 mm. The mean distance between tobacco shreds is estimated to be about 0.6 mm, because the volume fraction of the tobacco is about 0.35. The amplitude varies widely ranging from 0.1 mm to 1.5 mm. The peak value of the amplitude is about 0.5 mm for cigarettes A, B, C and D, which is almost the same value as the mean distance between the tobacco shreds. The scatter of these data is due to the non-uniformity of the tobacco bed configuration. Although the ignition periods also vary widely, it can be seen that the ignition period decreases as the cigarette burning rate increases as shown in Figure 2b. These results indicate that the cigarette static burning rate is limited by the ignition period of the cigarette paper.

If the cigarette rod contained no tobacco shreds, the cigarette paper would burn continuously and about twenty times faster than the cigarette burning rates shown in Table 1. The burning rate of the cigarette paper during its flash burn in the burning cigarette seemed approximately equal to the free burning rate of the paper. It appears that cigarette paper, once ignited, can burn freely during this interval of no contact with the tobacco shreds, and then it is extinguished at the next contact point. As a result, the cigarette static burning rate is controlled by the time required to ignite the paper.

Figure 3 shows the burning propagation model of the cigarette periphery. We believe that the burning propaga-

Table 1.
Characteristics of sample cigarettes (tobacco density: 0.23 g/cm^3, circumference: 25 mm)

Cig	Cig static burning rate (mm/min)	Porosity (CU)	Basis weight (g/m^2)	Filler content (%)	Potassium citrate (%)	Paper burning rate (mm/min)
A	4.6	29	30	32	0	90
B	5.0	25	31	40	0	95
C	5.3	88	30	36	0	95
D	6.9	31	32	31	4.9	114
E	5.7	60	27	31	0.5	87
F	4.1	26	32	14	0	65

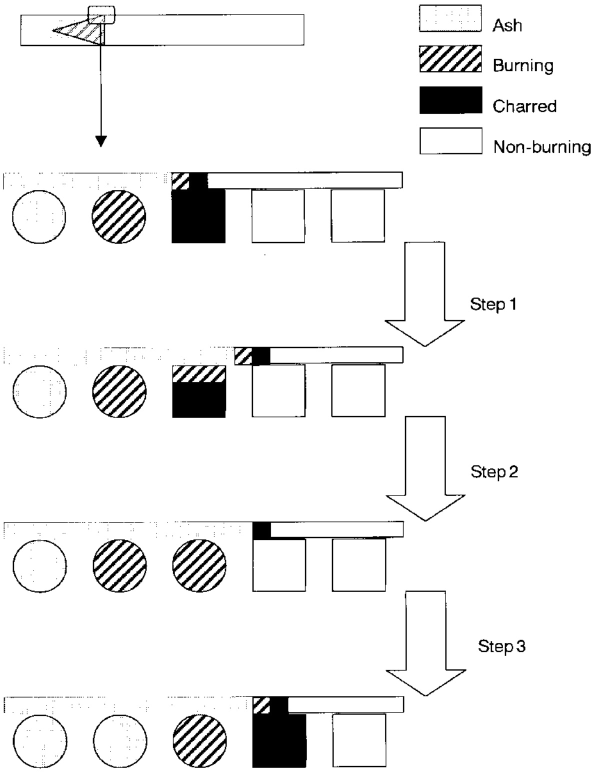

Figure 3.
Burning propagation model of the cigarette periphery

tion of the cigarette periphery has three steps as follows. First, the paper burns continuously until it is extinguished at the point where the paper makes contact with the tobacco shreds, leaving charred paper and tobacco (Step 1). Next, the tobacco shreds below the burnt paper begin a substantially oxidative reaction and become a source of heat (Step 2). Then, the paper is heated by the burning tobacco shreds near the charred point and ignites (Step 3). After step 3, the cigarette periphery returns to Step 1 conditions.

In this model, we believe that the cigarette paper functions as the heat transfer medium. If we assume a tobacco rod without paper, then some of the tobacco combustion heat would be directly radiated from the rod. Cigarette paper reduces the heat emission from the burning tobacco, and heat is transferred to the non-burning region through the paper. In addition to this, the paper burn heats the tobacco shreds resulting in their ignition.

Temperature near the char line

The effects of tobacco temperature on paper burning have been investigated. The experimental setup is shown in Figure 4. Cigarette paper was put on the tobacco bed heated by a silicon rubber heater. The heater output was controlled to set the tobacco bed temperature that was measured with a thermocouple. When the tobacco temperature became stable the edge of the paper was ignited. The paper burn was observed for various tobacco temperatures. It was observed that paper burning propagation stopped at the contact point when the tobacco temperature was less than 150 °C. It was also observed that the paper could burn continuously when the tobacco temperature was more than 200 °C, at which temperature the tobacco shreds ignited. These results indicate that paper burn stops at the contact point with the low tobacco temperatures and that high tobacco temperatures permit ignition of the tobacco shreds by the paper combustion heat.

The paper temperature near the char line was measured by thermography. To identify the accurate position of the char line, visual images were also taken at the same viewing angle with a CCD camera. A schematic diagram of the thermography and the CCD camera system is shown in Figure 5. Thermal and visual images were taken

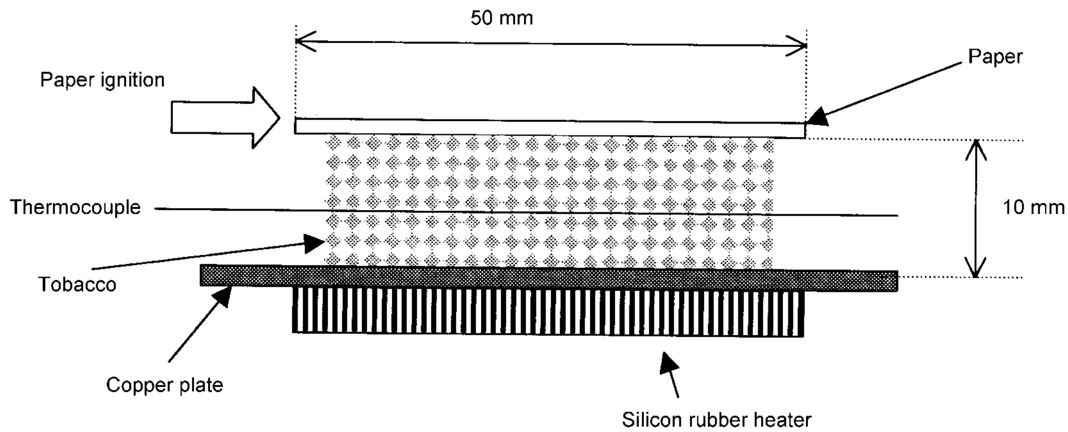

Figure 4.
Burning test of paper on tobacco bed

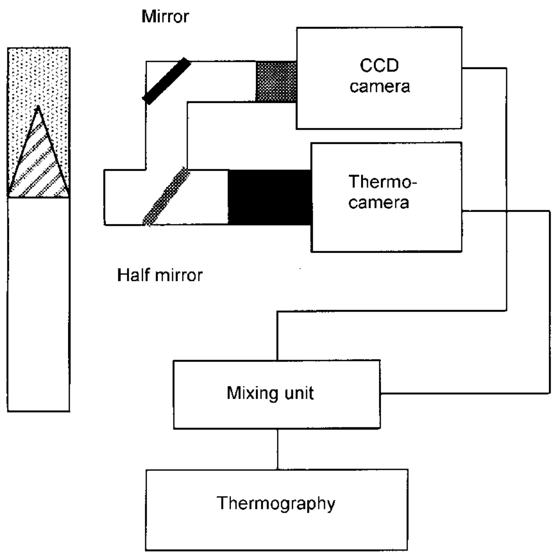

Figure 5.
Schematic diagram of thermography with a CCD camera system

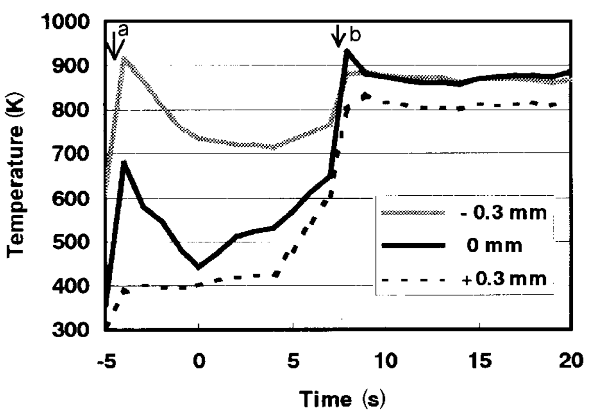

Figure 6.
Paper temperature of the static burning cigarette (cigarette E); a: previous paper burn; b: ignition of the char line

and analyzed every second. The temperatures were calcu lated assuming the emissivity of the paper was unity. The paper temperature plotted against time is shown in Figure 6. At the char line (0 mm), the paper had already been decomposed to char by the previous flash burn of the paper, and several seconds later it was ignited. The temperature of the char line went up and down by the previous flash burning, then gradually increased until the next ignition took place. At 0.3 mm from the char line on the burning side (–0.3 mm), the paper has already turned to ash and then maintained a high temperature. At 0.3 mm from the char line on the non-burning side (+0.3 mm), the paper temperature rose significantly following the ignition of the char line. Thus, the temperature near the char line showed a unique variation at each point. After the previous flash burn of the paper, the char line temperature increased for several seconds even though the char line itself was stationary.

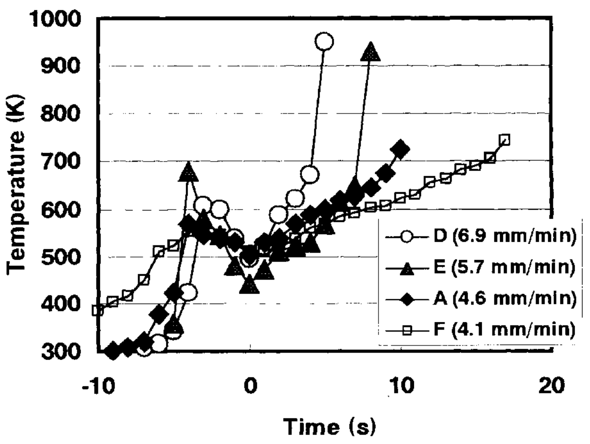

Figure 7.
Paper temperature at the char line of cigarettes with various static burning rates

Figure 7 shows the paper temperature at the char line for various cigarettes. The characteristics of the sample cigarettes are shown in Table 1. The paper was ignited between 350 and 400 °C. The time interval for intermittent burning was larger for lower static burning rate cigarettes and was smaller for higher ones. There were no remarkable differences in the temperature or in the time for cooling after the previous flash burning of the paper. For slower burning cigarettes, it took a longer time to raise the temperature to the ignition point. We conclude that the static burning rate of the cigarette is determined predominantly by the time required to ignite the charred paper, and that cigarettes with a higher static burning rate have a higher rate of increase in the temperature of charred paper. This means that Step 3 of the model is the rate-determining step of the cigarette burning propagation.

Mathematical analysis of the heat transfer at the cigarette periphery near the char line

The results of the char line movement analysis indicate that the cigarette static burning rate is limited by the ignition period of the paper. The measurement of char line temperature shows that a higher burning rate cigarette has a higher increasing rate of char line temperature during the period between the paper ignitions. This means that the paper heating period of the proposed model is the rate-determining step of the cigarette static burn. If the temperature increasing rate of the char line is the rate-determining factor of the burning propagation, the cigarette property which affects the char line temperature should be the dominant factor of the cigarette static burn. Heat transfer at the cigarette periphery near the char line was calculated using the following mathematical model. A configuration of the cigarette periphery near the char line and the assumed heat flow are shown in Figure 8. Burning tobacco shreds and unburnt tobacco shreds are in contact with paper. The paper at the burn-

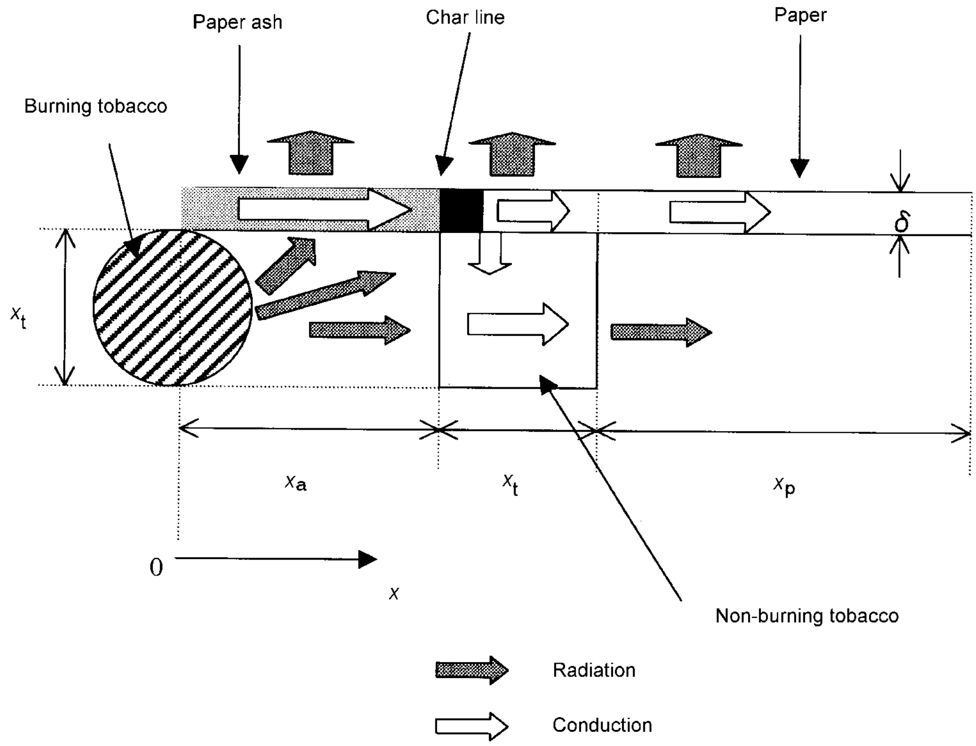

Figure 8.
Schematic diagram of mathematical model at the cigarette periphery near the char line

ing side that is in contact with burning tobacco shreds is paper ash, and at the other side it is unburnt paper. The burning tobacco shreds and the unburnt tobacco shreds are shown by a circle and a square, respectively. The temperatures of the burning tobacco, the atmosphere and the edge of the paper are held constant during the calculation. Heat is transferred by radiation in the void space inside the cigarette and from the surface of the paper to the outside. Heat transfer by convection from the surface of the paper to the outside of the cigarette is neglected for simplification and because calculation with a convection term only gives a slight difference in the results. No heat transfer is assumed to take place at the edges of the paper in the longitudinal direction or at the surface of the unburnt tobacco in the radial direction. The initial temperatures of the paper ash, the normal paper in contact with unburnt tobacco, and the unburnt tobacco are constant. The initial temperature of normal paper not in contact with the tobacco shred decreases linearly to the paper edge temperature. Based on these assumptions, the energy equations for the paper and for the unburnt tobacco are as follows:

$$\frac{\partial T_a}{\partial t} = \frac{\lambda_a}{(C_p\rho)_a}\frac{\partial^2 T_a}{\partial x^2} - \frac{\varepsilon_a\sigma}{(C_p\rho)_a\delta}\left(T_a^4 - T_\infty^4\right) + \frac{\varepsilon_t\varepsilon_a F_{ta}\sigma}{(C_p\rho)_a\delta}\left(\theta^4 - T_a^4\right), \quad [1]$$

$$(0 < x < x_a)$$

$$\frac{\partial T_p}{\partial t} = \frac{\lambda_p}{(C_p\rho)_p}\frac{\partial^2 T_p}{\partial x^2} - \frac{\varepsilon_p\sigma}{(C_p\rho)_p\delta}\left(T_p^4 - T_\infty^4\right) - \frac{2\lambda_t}{(C_p\rho)_p\delta x_t}\left(T_p - T_t\right), \quad [2]$$

$$(x_a \le x < x_a + x_t)$$

$$\frac{\partial T_p}{\partial t} = \frac{\lambda_p}{(C_p\rho)_p}\frac{\partial^2 T_p}{\partial x^2} - \frac{\varepsilon_p\sigma}{(C_p\rho)_p\delta}\left(T_p^4 - T_\infty^4\right), \quad [3]$$

$$(x_a + x_t \le x < x_a + x_t + x_p)$$

$$\frac{\partial T_t}{\partial t} = \frac{\lambda_t}{(C_p\rho)_t}\frac{\partial^2 T_t}{\partial x^2} + \frac{2\lambda_t}{(C_p\rho)_t x_t^2}\left(T_p - T_t\right), \quad [4]$$

$$(x_a < x < x_a + x_t)$$

where,

T: temperature [K], t: time [s], x: longitudinal coordinate [m], λ: thermal conductivity [W/(mK)], $C_p\rho$: heat capacity [J/(m^{3}K)], ε: emissivity [–], σ: Stefan-Boltzmann constant [W/(m^{2}K^4)], δ: thickness [m], F; geometric factor [–], θ: temperature of burning tobacco [K], T_∞,: ambient temperature [K];
subsucripts: a = ash, p = paper, t = tobacco.

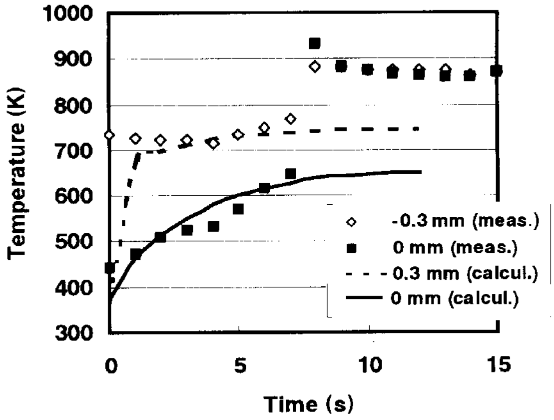

Figure 9.
Temperature variation with time at the paper char line (cigarette E)

The boundary conditions are:

$$\frac{\partial T_a}{\partial x} = 0, \ (x = 0) \qquad [5]$$

$$T_p = T_\infty, \ (x = x_a + x_t + x_p) \qquad [6]$$

$$-\lambda_t \frac{\partial T_t}{\partial x} = \varepsilon_t^2 F_{tt} \sigma \left(\theta^4 - T_t^4\right), \ (x = x_a) \qquad [7]$$

$$-\lambda_t \frac{\partial T_t}{\partial x} = -\varepsilon_t \sigma \left(T_t^4 - T_\infty^4\right), \ (x = x_a + x_t) \qquad [8]$$

The initial conditions are:

$$T_{p,a}\big|_{t=0} = T_0, \ (0 \le x \le x_a + x_t)$$
$$= T_0 - \frac{T_0 - T_\infty}{x_p}\left(x - x_a - x_t\right), \qquad [9]$$
$$(x_a + x_t < x \le x_a + x_t + x_p)$$

$$T_t\big|_{t=0} = T_0, \ (x_a \le x \le x_a + x_p) \qquad [10]$$

The parameters given were based on the measured values except for the followings. The thermal conductivity of the tobacco was considered to be the same as that of the cigarette paper. The emissivity of the cigarette paper was taken to be 0.9 because the emissivity of the general paper is about 0.9 (14). The emissivity of ash and tobacco were taken to be 0.9. The length of paper ash (x_a, the distance between tobacco shreds) was estimated using the volume fraction of the tobacco, and was taken to be 0.6 mm. The length of the paper (x_p) was set at 4.9 mm. The temperature of burning tobacco (θ) and the initial temperature (T_0) were taken to be 800 °C and 100 °C, respectively.

A comparison of the calculated and measured temperatures of the paper char line is shown in Figure 9. The material properties used for the calculation are shown in Table 2. The calculated temperature variation almost agrees with the measured one. The measured temperature at the char line shows a significant increase at a time of 7 to 8 s, when the paper ignited. The calculated temperature of the char line gradually increases after about 5 to 12 s because we did not use an exothermic and endothermic reaction model. The temperature of the tobacco in contact with the paper was found to be slightly lower than the paper temperature at all times. This indicates that the tobacco shreds on the periphery are heated directly by radiation from the burning tobacco and indirectly through the paper. Although this calculation cannot be used for an accurate simulation of cigarette static burn, the results explain the unique characteristics of cigarette static burning propagation, in which the paper is re-ignited several seconds after its extinction. We believe that this model gives a reasonable estimate of the effects of material properties on the time required to ignite the paper.

The effects of cigarette properties on the heating rate of the paper at the periphery were estimated by single parameter variation. The results are shown in Figures 10–12, and the properties of the control cigarette are given in Table 3. The results of the mathematical analysis can be summarized as follows:

(i) increasing the thermal conductivity of the paper ash, decreasing the thermal conductivity of the paper,

Table 2.
Material properties used in the model calculations

Property	Value	Unit	Property	Value	Unit
Thermal conductivity of ash λ_a	0.2	[W/(mK)]	δ	40	µm
Thermal conductivity of paper λ_p	0.4	[W/(mK)]	x_a	0.6	mm
Thermal conductivity of tobacco λ_t	0.4	[W/(mK)]	x_t	0.5	mm
Heat capacity of ash $(C_p\rho)_a$	0.3	[MJ/(m^{3}K)]	x_p	4.9	mm
Heat capacity of paper $(C_p\rho)_p$	0.9	[MJ/(m^{3}K)]	θ	800	°C
Heat capacity of tobacco $(C_p\rho)_t$	0.9	[MJ/(m^{3}K)]	T_0	100	°C
Emissivity of ash ϵ_a	0.9	—	T_∞	22	°C
Emissivity of paper ϵ_p	0.9	—			
Emissivity of tobacco ϵ_t	0.9	—			

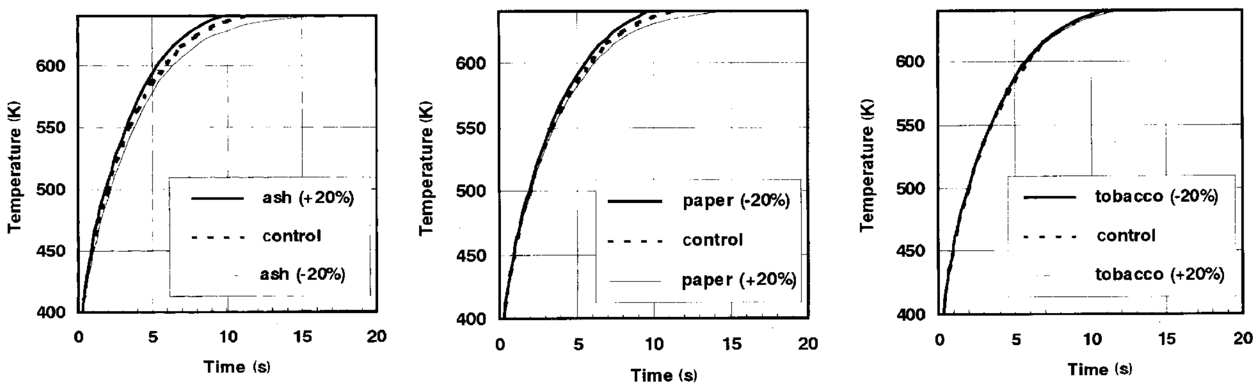

Figure 10.
Effect of thermal conductivity of paper ash (a), paper (b), and tobacco (c)

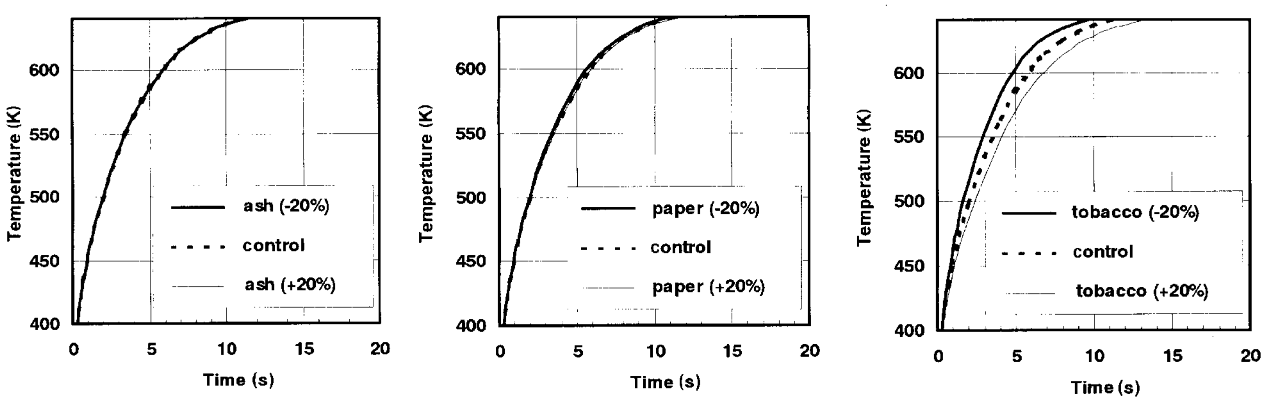

Figure 11.
Effect of heat capacity of paper ash (a), paper (b), and tobacco (c)

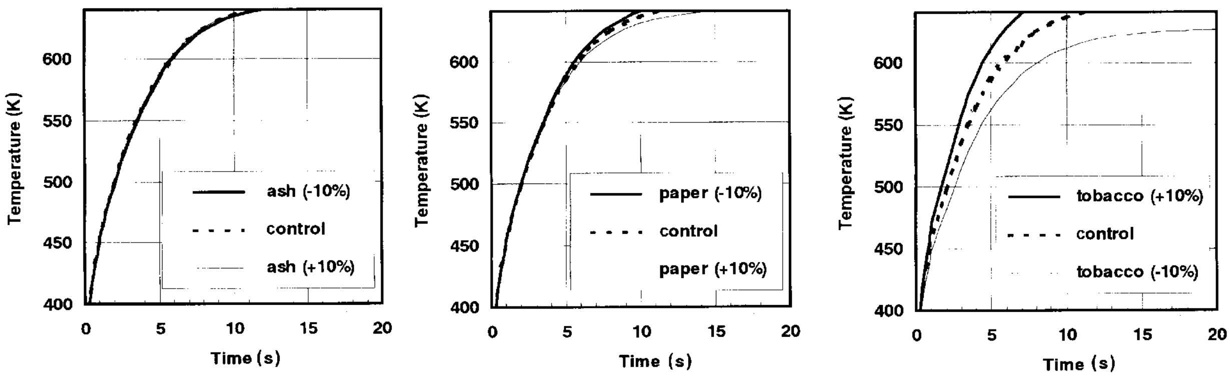

Figure 12.
Effect of emissivity of paper ash (a), paper (b) and tobacco (c)

decreasing the heat capacity of tobacco, decreasing the paper emissivity, or increasing the tobacco emissivity causes a decrease in the time required to ignite the paper;

(ii) thermal conductivity of the tobacco, heat capacity of the paper ash and heat capacity of the paper do not affect the heating rate of the paper for the range of parameters tabulated in Table 3.

We have shown that the dominant factors of cigarette burning propagation are the thermal conductivity of the paper ash, the thermal conductivity of the paper, the heat capacity of the tobacco, the emissivity of the paper, and the emissivity of the tobacco. The effect of the paper properties on the static burning rate, which is predicted by the model, is summarized in Table 4.

Table 3.
Material properties used in the model calculations

Property	Value	Unit
Thermal conductivity of ash λ_a	0.2	[W/(mK)]
Thermal conductivity of paper λ_p	0.4	[W/(mK)]
Thermal conductivity of tobacco λ_t	0.4	[W/(mK)]
Heat capacity of ash $(C_p\rho)_a$	0.3	[MJ/(m^{3}K)]
Heat capacity of paper $(C_p\rho)_p$	0.9	[MJ/(m^{3}K)]
Heat capacity of tobacco $(C_p\rho)_t$	0.9	[MJ/(m^{3}K)]
Emissivity of ash ϵ_a	0.9	—
Emissivity of paper ϵ_p	0.9	—
Emissivity of tobacco ϵ_t	0.9	—

Table 4.
Effect of paper thermal properties on cigarette static burning rate (predicted by mathematical analysis based on the proposed model)

Property	Cig static burning rate
Thermal conductivity of ash λ_a ↑	↑
Thermal conductivity of paper λ_p ↑	↓
Heat capacity of ash $(C_p\rho)_a$ ↑	—
Heat capacity of paper $(C_p\rho)_p$ ↑	—
Emissivity of ash ϵ_a ↑	—
Emissivity of paper ϵ_p ↑	↓

Table 5.
Properties of sample papers for the porosity study
(basis weight: 30 g/m^2, potassium citrate: 0%)

Porosity (CU)	Filler content (%)
10	29
29[a]	32[a]
60	35
88	36
185	34

[a]Control cigarette.

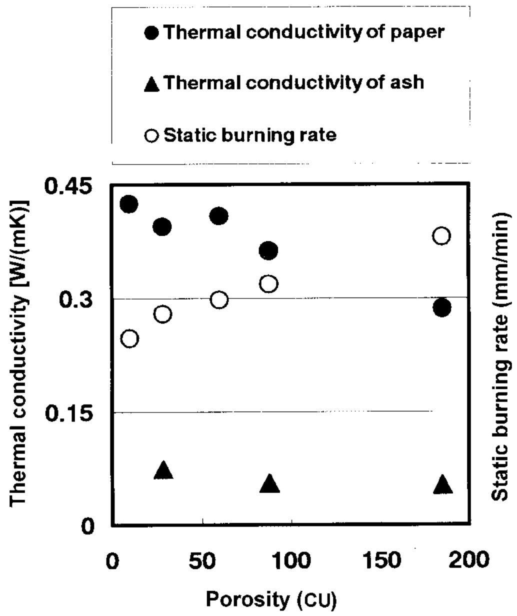

Figure 13.
Effect of paper porosity on cigarette static burning rate and thermal conductivity of paper

Verification of the effect of paper properties on cigarette static burn

The effects of paper properties on the cigarette static burning rate were verified by using the proposed burning propagation model and the assumptions outlined above. Sample papers were used in which each parameter was changed individually. The properties of the sample papers for the porosity study are shown in Table 5. The effect of paper porosity on the static burning rate and the thermal conductivity of the paper is shown in Figure 13. The cigarette static burning rate increases as the porosity increases. The thermal conductivity of the paper decreases as the porosity increases. The change in porosity slightly affects the thermal conductivity of the paper ash. These results agree with the prediction by the model, which predicts increasing that the thermal conductivity of the paper decreases the static burning rate.

The properties of the sample papers for the filler content study are shown in Table 6. The effect of the filler content on the static burning rate and the thermal conductivity of the paper is shown in Figure 14. The cigarette static burning rate increases as the filler content increases. The thermal conductivity of the paper decreases as the filler content increases. The change in filler content slightly affects the thermal conductivity of the paper ash. These results also agree with the predictions by the model. The effects of porosity and filler content on the cigarette static burning rate could be due to an effect of the thermal conductivity, as shown in Figure 15. The increase in thermal conductivity reduces the static burning rate, as predicted by the model. The thermal conductivity increases as both the porosity and filler content of the paper decrease.

The effects of potassium citrate level on the static burning rate and the thermal conductivity of the ash are shown in Figure 16. The properties of the sample papers for the potassium citrate study are shown in Table 7. The addition of potassium citrate above about 5% resulted in a decrease of static burning rate. The thermal conductivity of the paper ash shows a similar trend as the static burning rate. The static burning rate increases as the thermal conductivity of the ash increases, again as predicted by the model. The effect of the addition of potassium citrate on the static burning rate is more significant

Table 6.
Properties of sample papers for the filler content study
(basis weight: 30 g/m^2, potassium citrate: 0%)

Porosity (CU)	Filler content (%)
26	14
29[a]	32[a]
25	40

[a]Control cigarette.

Table 7.
Properties of sample papers

Basis weight (g/m^2)	Porosity (CU)	Filler content (%)	Citrate (%)
30[a]	29[a]	32[a]	0.0[a]
31	34	32	0.9
32	31	31	4.9
33	29	30	8.9
36	27	28	16.8

[a]Control cigarette.

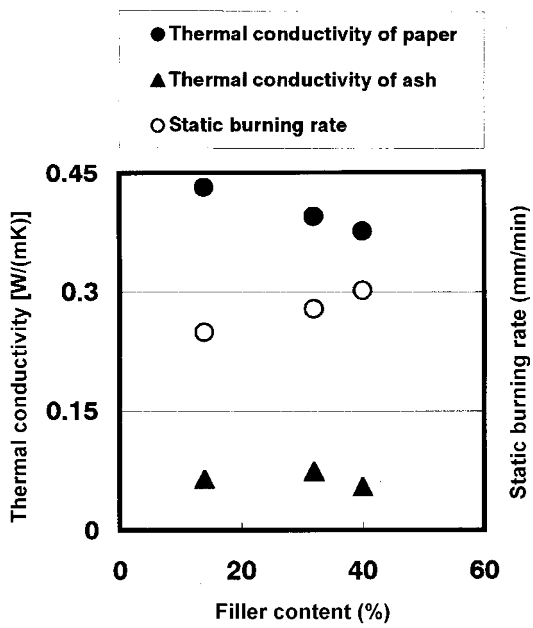

Figure 14.
Effect of paper filler content on cigarette static burning rate and thermal conductivity of paper

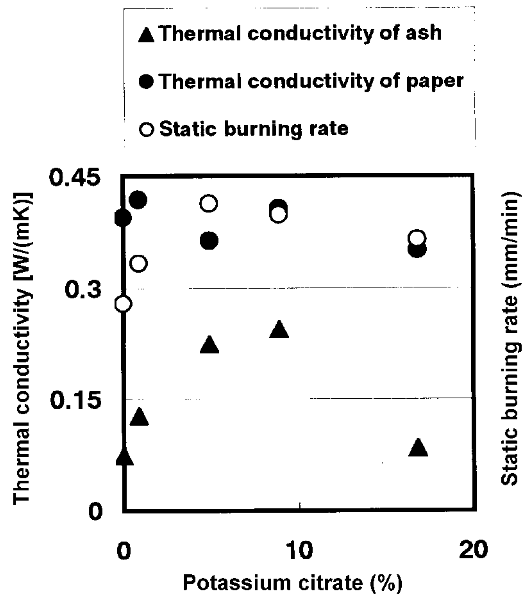

Figure 16.
Effect of potassium citrate on cigarette static burning rate and thermal conductivity of paper ash

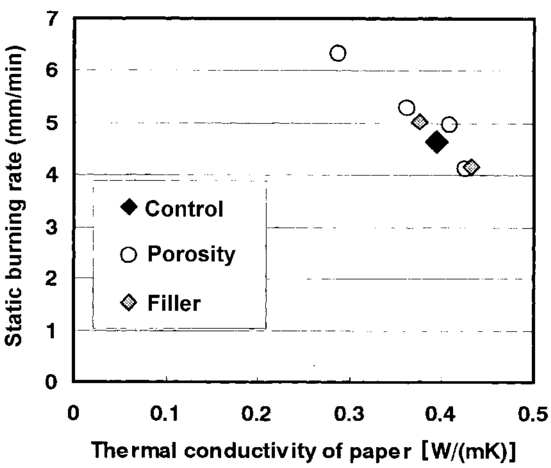

Figure 15.
Static burning rate of cigarette *vs* thermal conductivity of paper

than that of the porosity and the filler content. The effect of the ash thermal conductivity on the static burning rate is more significant than that of the paper thermal conductivity. We also observed that the addition of a small amount of potassium citrate causes the formation of a solid ash while the addition of a large amount causes char to remain in the ash. We assume that the addition of potassium citrate affects the paper ash structure, which causes a change in the thermal conductivity of the ash.

In Figure 17, static burning rates are plotted *vs* the thermal conductivity of the paper along with additional data. The property range of the sample papers is shown in Table 8. These measured data agree with the results of the modeling, in which the cigarette static burning rate increases with a decrease of the thermal conductivity of the paper and/or an increase of the thermal conductivity of the ash. It is thus verified that the thermal conductivity of the paper and ash are the dominant factors regulating the cigarette static burning rate.

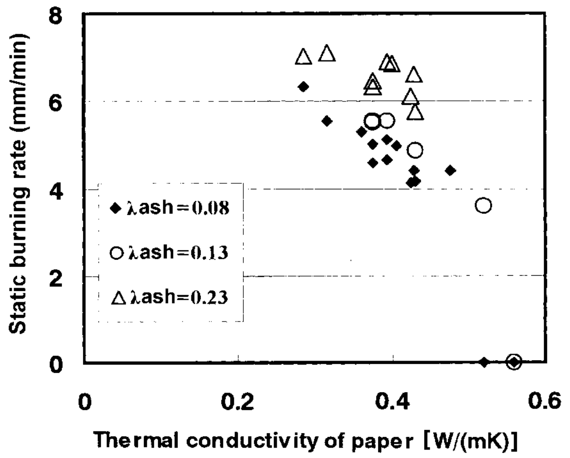

Figure 17.
Effect of thermal property of paper on cigarette static burning rate

CONCLUSIONS

The propagation of cigarette static burn is characterized by the intermittent burning of the cigarette periphery. The cigarette paper shows a periodical flash burn, and the cigarette static burning rate depends on the time between the extinction and the re-ignition of the paper. We propose a model of the burning propagation at the cigarette periphery. In this model, the paper and tobacco are ignited alternately, and the cigarette paper is the medium of heat transfer. Analysis of the measured temperature of the paper near the char line reveals that the rate-determining step of cigarette static burn is the length of time required to re-ignite the char line by the burning tobacco. We estimated the effects of the thermal properties of the cigarette on the char line temperature by calculating heat transfer during the paper heating period. We determined that the thermal conductivity of the paper ash, the thermal conductivity of the paper, the heat capacity of the tobacco, the emissivity of the paper, and the emissivity of the tobacco affect the cigarette static burning rate. Measured results obtained by varying the paper burning properties show good agreement with the model results. We have shown that the thermal properties of the cigarette are the dominant rate-limiting factors of the cigarette static burn.

Table 8
Parameter ranges for the sample papers

Property	Range	Unit
Porosity	8–185	CU
Filler content	0–45	%
Citrate	0, 1, 5	%
Basis weight	23–45	g/m^2

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