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Engineering Evaluation of Tactile Warmth for Wood

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Wood is a prospective resource from viewpoint of sustainable development. The engineering evaluation of tactile warmth is treated as a good point of wood. The relationship of the contact surface temperature and the thermal effusivity is derived from the theoretical analysis of heat transfer phenomenon and proposed as measures to evaluate the tactile warmth. The measures review some knowledge on tactile warmth of wood. It is found that the sensory warmth of wood has a high and positive linear correlation with the logarithm of the contact surface temperature and that the material with a lower thermal effusivity feels warmer than the material with a higher one. The relationship explains rationally why each wood has large difference of sensory warmth in spite of their small difference of material properties. The relationship also explains the reason why wood has good tactile warmth regardless of the season, which is different from metals.

Key Words : Sustainable Resource, Sustainable Development, Wood, Tactile Warmth,
Contact Surface Temperature, Thermal Effusivity

1 INTRODUCTION

Recently, wood has attracted our attention as a prospective material from a viewpoint of sustainable development, because it stores carbon dioxide against the environmental problem of global warming and it can be sustainable resource against the shortage of mineral resources in near future (Ref. [1]). The use of wood as resource for industrial materials will save the limited mineral resources as shown Figure 1. The increase of demand for wood will encourage the cycle of cutting down, planting and growing trees for the supply. The flow from cutting down trees to planting ones means to replace older trees with younger ones and to keep forest younger and more active with high ability to fix carbon dioxide (Ref. [2]). The longer use of wood will postpone its getting back into carbon dioxide. So the industrial technologies to improve bad points of wood and to evaluate its good points for its wider use and to recycle wood for its longer use are expected in order to promote the system shown in Figure 1.

Good tactile warmth is one of the better points of wood than the other materials. For example, a wooden exterior handrail has good tactile warmth regardless of the seasons but a metallic one is felt too hot in summer and too cold in winter to touch. Recently, a compressed wood has been used as an exterior handrail. It can be expected as a substitute of the metallic handrail because it has not only the good tactile warmth but also the enough strength. The engineering measures to evaluate tactile warmth of both wood and metals are needed to compare their tactile warmth objectively.

There have been some reports on the relationship between the tactile warmth and the physical quantities (Ref. [3-6]). Their measure of tactile warmth is based on statistics of the subjective judge of panelists. Some of their papers have paid their attention to the relation between the tactile warmth and the thermal conductivity. They pointed out that materials with smaller thermal conductivity were felt warmer. Okajima et al. treated building

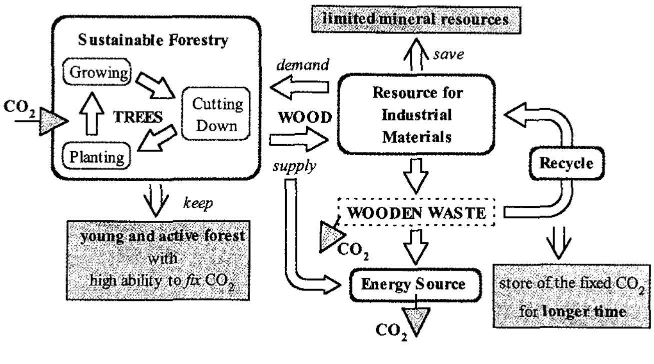

Figure 1 Better use of wood as resource for industrial materials and sustainable development.

materials containing wood and metals but they concluded that it was difficult to find out the simple expression to show the relation between the thermal conductivity and the sensory tactile warmth in Ref. [4]. Harada et al. reported that the sensory tactile warmth of wood has a high and negative linear-correlation with the logarithm of thermal conductivity (Ref. [6]). Their result has been generally accepted as a relation between the sensory tactile warmth and the physical quantities of wood (Ref. [7]). But it is impossible to compare the tactile warmth of wood and metals from their result because their measure of sensory tactile warmth is available in the closed group of materials that the experiment was done and it does not contain metals. It is also difficult to increase the number of test pieces with many woods and metals, because the enormous increase of sensory test rounds makes panelists tired and wald not give us the correct judges.

The aim of this study is to obtain the relation between the tactile warmth and the material properties from the theoretical analysis of the heat transfer phenomenon common to wood and other materials, and to establish the evaluation system of tactile warmth of materials. The measure of tactile warmth is expected to satisfy the following conditions:

1) It can be determined absolutely from physical quantities.
2) It can be available for not only woods but also other industrial materials.
3) It is easy to understand in order to explain the good point of wood to the end users.

We consider that the governing heat transfer phenomenon on the tactile warmth is the transient one-dimensional heat conduction problem when two semi-infinite bodies touch each other. We analyze the problem theoretically and derive the relationship between the contact surface temperature and the thermal effusivity. We review the sensory tactile warmth of wood in Ref. [6] with the contact surface temperature and thermal effusivity. We also discuss the other knowledge on tactile warmth with these properties. We propose the contact surface temperature as an engineering measure of tactile warmth as a result of such discussions.

2 THEORY

Let us consider the governing heat transfer phenomenon in the case that a human hand contacts with various materials. We have experienced sometimes that we separate our hand unconsciously and quickly from something too hot or too cold when we touch with it. It suggests that the tactile warmth is sensed sharply in a second just after bringing a human hand into contact with surfaces of various materials even when we feel good tactile warmth and keep our hand to touch with them. The human sensing points of warmth and coldness are also considered to be located at 0.4mm and 0.2mm below the human skin, respectively (Ref. [8]). The governing heat transfer phenomenon on tactile warmth occurs near the contact surface between the hand and the materials at the early portion of the transient. We can derive an analytical model for such transient response approximately with the transient one-dimensional heat conduction problem when two semi-infinite bodies, which have different material properties and different uniform initial temperatures, are placed in contact at their free surfaces. We call it the semi-infinite body contact model. We also analyze another model, which treats the contact of two plates, to judge the correctness of semi-infinite body contact model.

2.1 Semi-Infinite Body Contact Model

We consider that two semi-infinite bodies contact with each other at 0 in x-coordinate and the temperatures become same at the surfaces of both semi-infinite bodies. We assume that the hand is located at the minus side and the material at the plus side of the x-coordinate. Then the basic equations of transient one-dimensional heat conduction, the initial conditions and the boundary conditions are given as follows,

Basic equations:

$$\lambda_H \frac{\partial^2 T_H(t,x)}{\partial x^2} = C_H \rho_H \frac{\partial T_H(t,x)}{\partial t} \tag{1}$$

$$\lambda_M \frac{\partial^2 T_M(t,x)}{\partial x^2} = C_M \rho_M \frac{\partial T_M(t,x)}{\partial t} \tag{2}$$

Initial conditions:

$$T_H(0,x) = T_{iniH} \text{ at } t=0 \tag{3}$$

$$T_M(0,x) = T_{iniM} \text{ at } t=0 \tag{4}$$

Boundary conditions:

$$T_H(t,0) = T_M(t,0) = T_{cs}(t) \text{ at } x=0 \tag{5}$$

$$\left[\lambda_H \frac{\partial T_H(t,x)}{\partial x}\right]_{x=0} = \left[\lambda_M \frac{\partial T_M(t,x)}{\partial x}\right]_{x=0} \text{ at } x=0 \tag{6}$$

where T is the temperature, x is the coordinate, t is the time, λ is the thermal conductivity, C is the specific heat, ρ is the density, T_{ini} is the initial temperature before contact and T_{cs} is the contact surface temperature. The subscripts of H and M mean hand and material, respectively.

The procedure of analysis is well known and the contact surface temperature T_{cs} is given as follows (Ref. [9]):

$$T_{cs} - T_{iniM} = \frac{T_{iniH} - T_{iniM}}{1 + \eta_M/\eta_H} \tag{7}$$

where,

$$\eta = \sqrt{\lambda C \rho} \tag{8}$$

which is the thermal effusivity. We should note that T_{cs} in Eq. (7) is constant regardless of time.

2.2 Plate Contact Model

The basic equations and the initial conditions for the plate contact model are same to ones for the semi-infinite body contact model. On the boundary conditions, we added following ones to Eqs. (5) and (6) for the reverse side of contact surface:

$$T_H(t,-b_H) = T_{iniH} \text{ at } x=-b_H \tag{9}$$

$$T_M(t,b_M) = T_{iniM} \text{ at } x=b_H \tag{10}$$

where b_H and b_M are the thickness of hand and material, respectively. We can derive the contact surface temperature for this model as follows:

$$T_{cs}(t) - T_{iniM} = \frac{T_{iniH} - T_{iniM}}{1 + \lambda_M b_H/\lambda_H b_M} + 2\eta_M (T_{iniH} - T_{iniM}) \sum_{m=1}^{\infty} \frac{\tan\sqrt{p_m/\kappa_H}\, b_H}{\sqrt{p_m} F_d} \tag{11}$$

where

$$F_d = -\frac{b_H \eta_M}{\sqrt{\kappa_H}\cos^2\sqrt{p_m/\kappa_H}\, b_H} - \frac{b_M \eta_H}{\sqrt{\kappa_M}\cos^2\sqrt{p_m/\kappa_M}\, b_M}$$

Table 1 Thermophysical properties on tactile warmth.

No.	Materials	Face	λ [W/(m·K)]	C [kJ/(kg·K)]	ρ [kg/m^3]	η_M [kJ/(m^2·s$^{1/2}$·K)]	η_M/η_H
	Woods						
1	Balsa (*Ochroma lagopus*)	long.	0.070	1.633	130	0.122	0.096
2	Kiri* (*Paulownia tomentosa*)	long.	0.134	1.591	330	0.265	0.210
3	Hinoki* (*Chamaecyparis obtusa*)	long.	0.155	1.633	380	0.310	0.245
4	Karamatsu* (*Larix leptolepis*)	long.	0.203	1.633	490	0.403	0.319
5	Karamatsu* (*Larix leptolepis*)	end	0.313	1.674	510	0.517	0.409
6	Seraya (*Parahorea* sp.)	long.	0.190	1.633	560	0.416	0.330
7	Seraya (*Parahorea* sp.)	end	0.350	1.633	570	0.571	0.452
8	Buna* (*Fagus crenata*)	long.	0.230	1.633	700	0.513	0.406
9	Yachidamo* (*Fraxinus mandshurica*)	long.	0.229	1.633	710	0.515	0.408
10	Yachidamo* (*Fraxinus mandshurica*)	end	0.494	1.674	710	0.767	0.607
11	Kapur (*Dryobalanops* sp.)	long.	0.243	1.633	730	0.538	0.426
12	Kapur (*Dryobalanops* sp.)	end	0.394	1.674	740	0.699	0.553
13	Itayakaede* (*Acer mono*)	long.	0.262	1.633	760	0.570	0.451
14	Itayakaede* (*Acer mono*)	end	0.445	1.674	710	0.728	0.576
15	Shirakashi* (*Quercus myrsinaefolia*)	long.	0.330	1.633	1020	0.742	0.587
16	Shirakashi* (*Quercus myrsinaefolia*)	end	0.486	1.674	940	0.874	0.692
	Other materials						
17	polystyrene foam		0.034	1.340	12	0.023	0.018
18	polyurethane foam		0.048	1.800	27	0.048	0.038
19	epoxy resin		0.386	1.047	1180	0.690	0.547
20	cement mortar		1.419	0.921	2050	1.637	1.296
	Glass						
21	Pyrex		1.100	0.730	2230	1.338	1.060
	Rocks						
22	marble		2.8	0.810	2600	2.428	1.923
23	granite		4.3	1.100	2650	3.540	2.803
	Metals & Alloys						
24	bismuth		7.86	0.126	9800	3.115	2.467
25	manganese		7.82	0.479	7470	5.290	4.188
26	titanium		21.9	0.522	4506	7.177	5.683
27	steel		43	0.465	7850	12.53	9.920
28	aluminum alloy		193	0.893	2730	21.69	17.17
29	gold		315	0.129	19300	28.00	22.17
30	silver		427	0.237	10490	32.58	25.80
31	copper		355	0.415	8940	36.29	28.73
	Organs of human body						
32	palm		0.512	-	-	1.263	1.000
33	back of the hand		0.593	-	-	1.346	-
34	sole		0.407	-	-	1.012	-
35	instep		0.593	-	-	1.346	-

* Japanese names are used for these woods without corresponding English names.

Legend: λ; themal conductivity, C; specific heat, ρ; density, η; thermal effusivity

p_m is the eigen values to satisfy the following equation;

$$\tan\sqrt{p_m/\kappa_M}\,b_M/\tan\sqrt{p_m/\kappa_H}\,b_H=\eta_M/\eta_H,$$

and κ is the thermal diffusivity.

3 NUMERICAL RESULT AND DISCUSSION

3. 1 Numerical Conditions and Material Properties

Let us consider the situation that a human hand touches with the various materials at room temperature. Considering that a man feels moderate warmth when his skin's average temperature is 33-34℃ (Ref. [10]), we give the following initial temperatures to hand and materials:

$$T_{iniH}=32(℃),\quad T_{iniM}=T_{room}=20(℃)$$

T_{iniH} is 1-2 centigrade lower than the average skins temperature since the hand is an end organ in a human body. Table 1 shows thermophysical properties of the thermal conductivity λ, the specific heat C, the density ρ and the thermal effusivity η used for the numerical calculation in this work. The material properties of woods and other materials (No. 1-20) are referred to Ref. [6]. The sensory tactile warmth on many woods is studied in Ref. [6] in detail and we review it with the contact surface temperature and the thermal effusivity later. The Pyrex (No. 21) is selected as a material with similar thermal effusivity to one of a human palm (Ref. [11]). The rocks (No. 22-23), the metals and alloys (No. 24-31) are examples with much larger thermal effusivity (Ref. [11]). Each organ (No. 32-35) of human body has different material properties. We use the thermal effusivity and the thermal conductivity of human palms in Ref. [12] for the calculation.

3. 2 Comparison of Analytical Models

Figure 2 shows the contact surface temperatures. The symbols at 0.01 second are contact surface temperatures calculated by Eq. (7). The curved lines changing with time are ones calculated by Eq. (11). The thickness of hand b_H is assumed to be 0.2 mm, which is a distance between human skin and his sensing point of coldness. The thickness of material b_M is assumed to be 30mm, which is same to the thickness used in the experiment by Harada et al (Ref. [6]). All of the curved lines consist of three parts: 1) the initial constant state, 2) the transient state and 3) the constant steady state. Each contact surface temperature at the first part of the curved lines is coincident to one given by Eq. (7). Although it is difficult to know from Eq. (11) what material properties are concerned with the contact surface temperature in a second just after the contact, we can know it easily from Eq. (7) that only the thermal effusivity is. The time while both contact surface temperatures are coincident seems to be the time while the semi-infinite body contact model is available approximately. The times for various woods are about 10 seconds and we can apply the simple expression of Eq. (7) to know the contact surface temperatures within the time.

3. 3 Review of the Tactile Warmth on Woods with Contact Surface Temperature and Thermal Effusivity

Now we review the sensory tactile warmth reported in Ref. [6] with the contact surface temperature. Figure 3 shows the relationship between them. The sensory warmth has a high positive correlation with the logarithm of the contact surface temperature. The relationship is expressed as follows:

$$S \propto K_1 \log(T_{cs} - T_{room}) \propto K_2 \log(1 + \eta_M/\eta_H)^{-1} \tag{12}$$

where K_1 and K_2 are constants. Eq. (12) is coincident to the Fechner's formula, which shows a relation between state of mind S and stimulus R as follows:

$$S = K \log R \quad (K : \text{constant}) \tag{13}$$

It suggests that the contact surface temperature and the thermal effusivity can be measures of the tactile warmth.

On the other hand, Harada et al. proposed the following relationship between the sensory warmth of woods S and their thermal conductivities λ:

$$S \propto -\log\lambda \tag{14}$$

Let us consider the characteristics of wood in order to discuss the difference of Eq. (12) and Eq. (14). It is well known that specific heat of wood is almost same in spite of the difference of species as shown in Table 1. Also the thermal conductivity of wood is in proportion to the density. We assume the following relationship between the thermal conductivity and the density of wood against the well-known experimental formula which has the thermal conductivity of air when the density is zero (Ref. [13]).

$$\rho_M = K_3 \lambda_M \quad (K_3 : \text{constant}) \tag{15}$$

Then the thermal effusivity of materials is expressed as follows:

$$\eta_M = K_4 \eta_H \lambda_M \quad (K_4, \eta_H : \text{constant}) \tag{16}$$

The relationship between thermal effusivity and thermal conductivity for woods used by Harada et al. in Ref. [6] gives us the following expressions by the method of least squares:

$$\eta_M = 2.23\, \lambda_M^{1.18} \quad (\text{for longitudinal faces}) \tag{17}$$

$$\eta_M = 1.34\, \lambda_M^{1.01} \quad (\text{for end faces}) \tag{18}$$

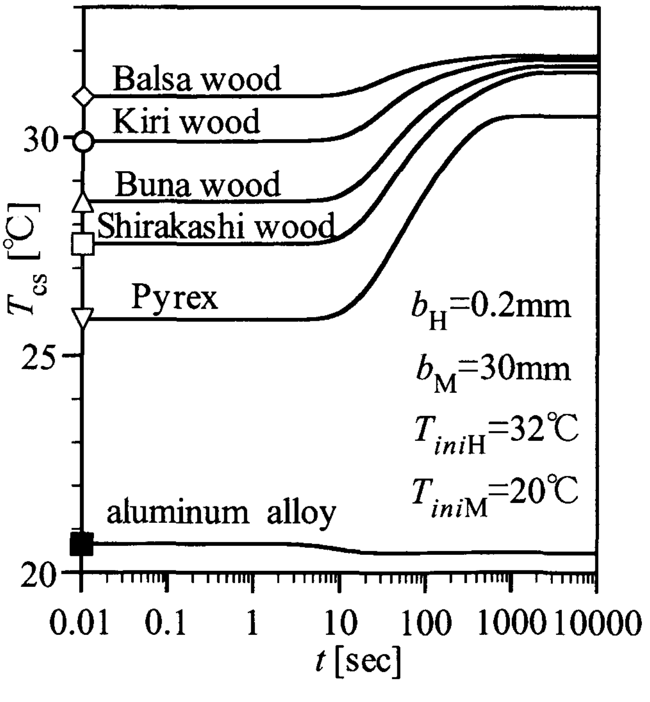

Figure 2 Comparison of contact surface temperatures obtained from two different analytical models.

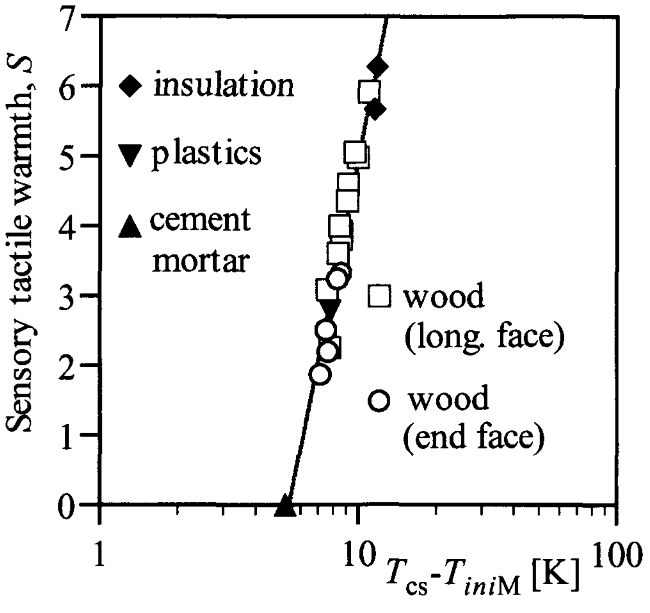

Figure 3 Review of sensory tactile warmth with contact surface temperature. (T_{iniH}=32℃, T_{iniM}=20℃)

Table 2 Comparison of thermal conductivity and thermal effusivity in evaluation of sensory tactile warmth for woods with mixed contact faces of end and longitudinal ones.

Materials	Face	S	λ [W/(m·K)]	η [kJ/(m^2·s$^{1/2}$·K)]
Seraya wood	long.	4.36	0.190	0.416
Seraya wood	end	3.25	0.350	0.571
Shirakashi wood	long.	3.09	0.330	0.742
Shirakashi wood	end	1.88	0.486	0.874

Legend: S; Sensory tactile warmth, λ; Thermal conductivity, η; Thermal effusivity

Eq. (17) and Eq. (18) agree almost with that Eq. (16) and Eq. (15) is proper. Finally, substitution of Eq. (16) into Eq. (12) yields the following relationship:

$$S \propto -\log(\lambda_M + 1/K_4) \quad (K_4 : \text{constant}) \tag{19}$$

Eq. (19) is similar to Eq. (14) that the sensory warmth is in proportion to the logarithm of thermal conductivity reported by Harada et al. in Ref. [6].

We can derive the change of contact surface temperature with the change of materials thermal effusivity as follows:

$$\frac{\partial (T_{cs}-T_{iniM})}{\partial \eta_M} = -\frac{T_{iniH}-T_{iniM}}{\eta_H[1+(\eta_M/\eta_H)]^2} \tag{20}$$

The value of Eq. (20) is minus whenever the human hand touches with materials with lower initial temperature than his hand. Then the contact surface temperature decreases with the increase of η_M and it increases with the decrease of η_M. It explains our knowledge that the material with smaller thermal conductivity and smaller density felt warmer, because thermal effusivity is defined as a root of product of thermal conductivity, specific heat and density.

Wood has an-isotropic thermal conductivities. The thermal conductivity in fiber direction is 2.25-2.75 times of the vertical one to it (Ref. [14]). Harada et al. reported that the touch to the end face of the wood felt colder than the touch to the longitudinal face of the same wood. But Table 2 shows that the order of the sensory tactile warmth does not correspond to the order of thermal conductivity in a mixed contact system of end and longitudinal faces for some woods. On the other hand, the order of thermal effusivity corresponds to the order of the sensory tactile warmth.

3. 4 Contact Surface Temperature for Woods and Other Materials

Figure 4 shows the relationship between the contact surface temperature and the thermal effusivity for not only woods but also other materials which are given in Table 1. The solid line represents the contact surface temperature when the thermal effusivity of palm is used as η_H. The line shows that the contact surface temperatures for woods are higher than ones for metals. It shows also that the difference of contact surface temperature for different species of wood is very large. The result explains our experience rationally that we can distinguish the difference of tactile warmth for

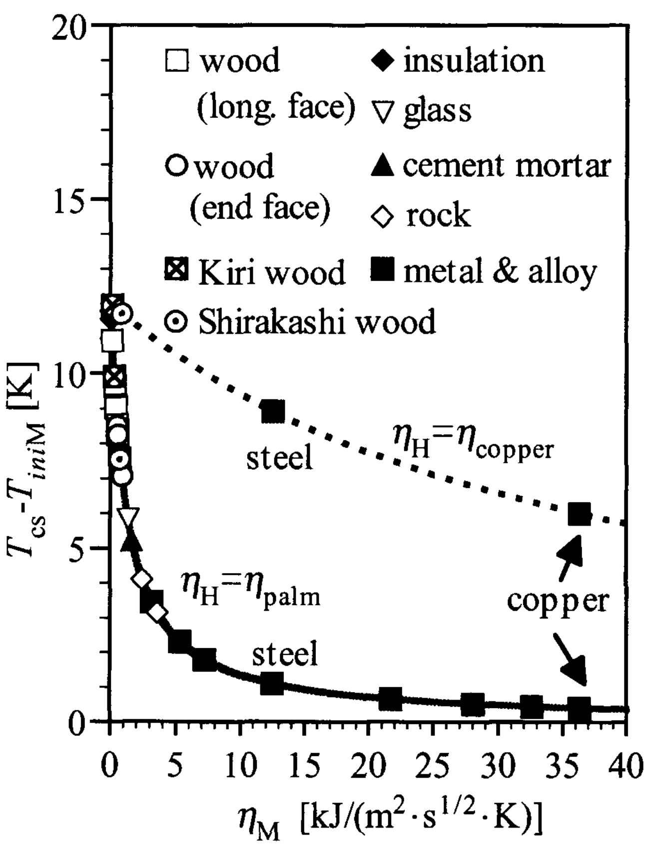

Figure 4 Contact surface temperature and thermal effusivitiy for various materials. (T_{iniH}=32℃, T_{iniM}=20℃)

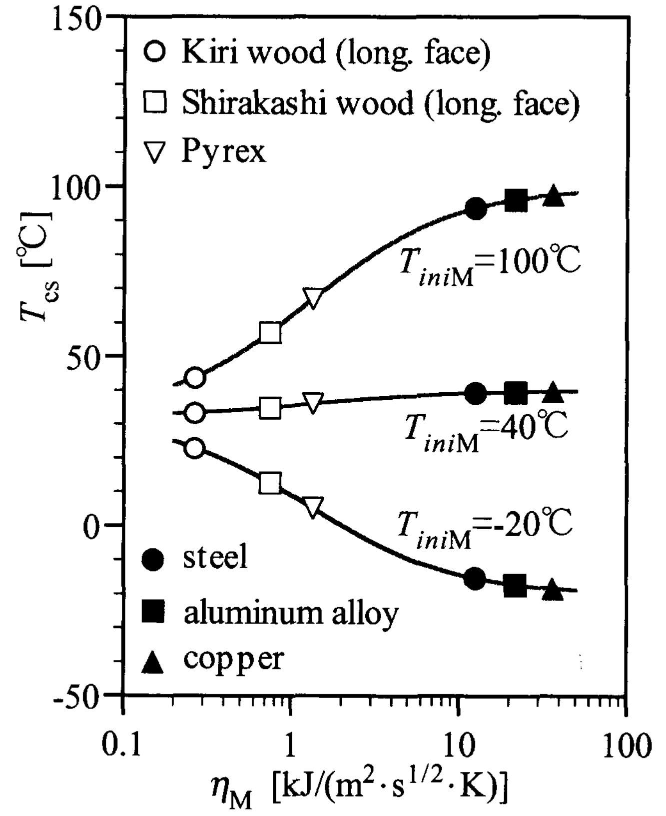

Figure 5 Contact surface temperature with various materials at higher and lower initial temperatures than room temperature. (T_{iniH}=32℃)

different species of wood in spite of the little difference in thermophysical properties. On the other hand, it is difficult to do it for metals, although the differences of their thermal effusivities are very large.

Copper is used as a heat source instead of human palm in many experimental works (Ref. [4,6]). The dotted line shows the contact surface temperature in the case that the thermal effusivity of copper is used as η_H instead of palm's one. Two woods on the dotted line are Kiri wood and Shirakashi wood which have the smallest thermal effusivity but one and the largest one in Table 1. It is difficult to distinguish the contact surface temperature of them in this case. On the other hand, two metals on the dotted line are steel and copper. We can distinguish their contact surface temperatures in this case. This result suggests that there is a proper heater that is most sensitive to measure tactile warmth for each material group. It also makes us aware that wood is very sensitive material for human beings from viewpoint of tactile warmth.

We treated the contact of hand with materials at room temperature in the previous discussions. Figure 5 shows the contact surface temperatures when the hand touches with various materials at the higher and lower initial temperature than the room temperature. Metals with high thermal effusivity are felt too hot at higher temperature and too cold at lower temperature. On the other hand, wood with low thermal effusivity has moderate tactile warmth in spite of the initial temperatures. It explains that the exterior handrail made of aluminum is too hot in summer and too cold in winter to touch but the wooden handrail has good tactile warmth without influence of seasons.

4 CONCLUDING REMARKS

We introduced that wood is a prospective material from viewpoints of sustainable development on resource and environment. We treated tactile warmth of wood in order to encourage wood in use more widely as substitute of other industrial materials. We give the concluding remarks as follows from the discussion on the evaluation of tactile warmth of wood and other materials.

(1) The relationship between the contact surface temperature and thermal effusivity was derived from the theoretical analysis of transient one-dimensional heat conduction problem for the contact of two semi-infinite bodies.
(2) The contact surface temperature decreases for the materials with higher thermal effusivity.
(3) The sensory warmth of wood is proportional to the logarithm of the contact surface temperature.
(4) The thermal effusivity evaluates sensory warmth properly in a mixed contact system of end and longitudinal faces of wood.
(5) The relationship of the contact surface temperature and the thermal effusivity explains rationally that woods are felt much warmer than metals. It also explains that each wood has large difference of tactile warmth from other species of wood in spite of the small difference of material properties.
(6) The relationship of the contact surface temperature and the thermal effusivity explains rationally that wood has good tactile warmth in spite of seasons, although metals are felt too hot in summer and too cold in winter to touch.

As a result of the above remarks, we propose the contact surface temperature and the thermal effusivity as the engineering measures to evaluate the tactile warmth of wood and other materials objectively

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