Directional Characteristics of Radiation Reflection on Rough Metal Surfaces with Description of Heat Transfer Parameters*

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Directional distribution of bidirectional reflectance ρ for visible laser irradiation is investigated experimentally on rough metal surfaces. The reflection is found to be far from perfect-diffuse. Relationship of reflection characteristics and rms surface roughness Σ is not simple in case Σ is of an order of the wavelength of incident radiation. It is recommended to analyze the reflection characteristics on $(\rho \cos \theta_R)$, where θ_R is the zenithal angle of reflection. What has been called 'off-specular' peak does not appear in this case. A reflection model for describing the directional distribution is presented for heat transfer applications. The model can evaluate the values of the specular component R_s and the perfect-diffuse component R_d of the hemispherical reflectance R_H for directional incidence. It is interesting that calculated values of the specularly reflected energy ratio (R_s/R_H) do not always fit with our impression on the specularity in the directional distribution of ρ .

Key Words: Heat Transfer, Thermal Radiation, Thermophysical Property, Spectroscopic Measurement, Bidirectional Reflectance, Hemispherical Reflectance, Radiation Energy Exchange, Real Surface, Surface Roughness

1. Introduction

In thermal engineering systems, in which radiation heat transfer should be considered, radiation is incident onto a surface from various directions. The surface absorbs a part of the radiation and reflects another part of the radiation to various directions. This directional characteristics of radiation absorption, reflection and emission are properties of individual surfaces. Particularly, the directional characteristics of reflection on surfaces range from optically smooth and specular to rough and perfect-diffuse. On the other hand, the emission of radiation depends on the direction of emission weaker than the reflection.

The heat transfer calculations for evaluating radiative energy exchange among surfaces are compli-

cated and take long computation times in most cases, a crude technique using configuration factors has been adopted traditionally with three assumptions on surface characteristics: (1) perfect-diffuse incidence of radiation, (2) perfect-diffuse reflection irrespective of incident radiation, and (3) perfect-diffuse emission. But, recently, in many engineering systems for radiation heat transfer evaluation, highly or partially specular surfaces and/or highly directional radiation are involved, as are the case in semiconductor processes and/or in laser manufacturing processes. The assumptions (1) and (2) of the three are not always realistic for such modern engineering systems. Also, with a backup of the development in computer technology, a little more sophisticated technique for radiation energy exchange calculations, in which a specular reflection component and a perfect-diffuse component of the hemispherical reflection of the surface are managed in parallel, was examined⁽¹⁾. But, no good idea has been presented for interpreting the directional characteristics of reflection of individual surfaces into the parameters in such heat transfer calculations.

There has been an experimental technique for

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investigating the directional distribution of bidirectional reflectance in detail⁽²⁾. The technique offers us too fine data of the reflectance in a form of matrices of numerical values particularly on the reflection in the incident plane, and it is not useful for the heat transfer calculations. Also, the specular reflection to very exactly defined specular direction is meaningless for most engineering applications. A new idea is required to establish a simple and quantitative technique to deal with this problem so that all the energy reflected hemispherically would be readily divided into the specular and the perfect-diffuse components.

In the present study, we investigate directional distribution of bidirectional reflectance of rough metal surfaces for visible laser irradiation experimentally, and present a new technique to interpret such characteristics to a couple of input parameters to the heat transfer calculations.

Since real surfaces are generally more or less diffuse and more or less specular, we adopt, in this paper, adjective terms of 'perfect-diffuse' and 'perfect-specular' for ideally diffuse and ideally specular characteristics, respectively.

Nomenclature

- A : maximum value of $(\rho \cos \theta_R)$ in reflection model in section 4.3, sr^{-1}
 F : objective function defined by Eq.(17), sr^{-1}
 I : intensity of radiation, $\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$
 l : length from specimen surface to detector, m
 q : radiation energy flux, $\text{W} \cdot \text{m}^{-2}$
 R_d : perfect-diffuse reflection component of R_H
 R_H : hemispherical (energy) reflectance for directional incidence
 R_s : specular reflection component of R_H
 w : weight defined by Eq.(18)
 ΔA : specimen surface area of radiation incident, m^2
 ΔS : effective area of detector, m^2
 θ : azimuthal angle, rad
 $\theta_{R \max}$: azimuthal angle at which $(\rho \cos \theta_R)$ takes the maximum in reflection model in section 4.3, rad
 $\theta_{R \max}^+$: azimuthal angle at which experimental value of ρ is the maximum, rad
 $\theta_{R \max}^*$: azimuthal angle at which experimental value of $(\rho \cos \theta_R)$ is the maximum, rad
 ρ : bidirectional reflectance, sr^{-1}
 ρ_d : perfect-diffuse reflection component of ρ , sr^{-1}
 ρ_s : specular reflection component of ρ , sr^{-1}
 σ : representative value of peak width in reflection model in section 4.3
 Σ : root-mean-square roughness, m

z_0 : self-correlation length, m

ϕ : zenithal angle, rad

Ω : solid angle, sr

Subscripts and Superscripts

calc: calculated value

d : perfect-diffuse

exp: experimental value

i : i -th point of directional measurement

I : incidence

R : reflection

s : specular

2. Bidirectional Reflectance

Consider radiation is incident on a surface from a solid angle $\Delta\Omega_I$ in a direction of a zenithal angle θ_I and an azimuthal angle ϕ_I . The incident energy per a unit surface area is $q_I [\text{W} \cdot \text{m}^{-2}]$. The intensity of reflected radiation in a direction of a zenithal angle θ_R and an azimuthal angle ϕ_R is denoted by $I_R [\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}]$. Bidirectional reflectance ρ is defined as a ratio of I_R to q_I ⁽³⁾ by,

$$\begin{aligned} \rho &= \rho(\theta_I, \phi_I, \theta_R, \phi_R) \\ &= I_R / q_I \\ &= \frac{I_R}{\int_{\Delta\Omega_I} I_I \cos \theta_I d\Omega_I} \end{aligned} \quad (1)$$

The unit of ρ is sr^{-1} . Hemispherical (energy) reflectance R_H for directional incidence is given by,

$$\begin{aligned} R_H &= R_H(\theta_I, \phi_I) \\ &= \frac{\int_{\text{hemisphere}} I_R \cos \theta_R d\Omega_R}{\int_{\Delta\Omega_I} I_I \cos \theta_I d\Omega_I} \\ &= \int_{\text{hemisphere}} \rho \cos \theta_R d\Omega_R \\ &= \int_{-\pi}^{\pi} \int_0^{\pi/2} \rho \cos \theta_R \sin \theta_R d\theta_R d\phi_R \\ &= \int_0^1 \int_{-\pi}^{\pi} \rho \cdot (\sin \theta_R d\phi_R) \cdot d(\sin \theta_R) \end{aligned} \quad (2)$$

3. Experimental Procedure

3.1 Principles of experiment

In the present study, we investigate the reflection characteristics of isotropically rough surfaces whose reflectances are independent of the azimuthal angle ϕ_I . That is,

$$\begin{aligned} \rho &= \rho(\theta_I, \theta_R, \phi_R) \\ R_H &= R_H(\theta_I) \end{aligned}$$

in this case. Figure 1 explains the principle of the measurement of bidirectional reflectance ρ . In this figure radiation is incident on the surface area ΔA from a solid angle $\Delta\Omega_I$ in the direction of θ_I . The incident energy on the surface is $(q_I \cdot \Delta A) [\text{W}]$. A detector of an effective area ΔS , which is set in a distance of l from the specimen surface, measures the

Fig. 1 Principle of bidirectional reflectance measurement

reflection energy $(q_R \cdot \Delta A)$ [W] in a solid angle $\Delta\Omega_R$ in the direction of θ_R and ϕ_R .

$$(q_I \cdot \Delta A) = I_I \cos \theta_I \cdot \Delta A \cdot \Delta\Omega_I \quad (3)$$

$$(q_R \cdot \Delta A) = I_R \cos \theta_R \cdot \Delta A \cdot \Delta\Omega_R \quad (4)$$

$$\Delta\Omega_R = \Delta S / l^2 \quad (5)$$

Reflectance ρ is determined by measuring $(q_I \cdot \Delta A)$ and $(q_R \cdot \Delta A)$ and by,

$$\rho = I_R / q_I = \frac{(q_R \cdot \Delta A)}{(q_I \cdot \Delta A)} \cdot \frac{1}{\cos \theta_R} \cdot \frac{l^2}{\Delta S} \quad (6)$$

where the measured quantity $(q_R \cdot \Delta A)$ is proportional to $(\rho \cos \theta_R)$.

3.2 Experimental apparatus

In the experiment of the present study, we should measure the distribution of diffuse radiation reflected over the hemisphere, and the measurement should be made with high precision. It is desirable to investigate the reflection characteristics in the visible wavelength region, in which strong incident radiation is available and a sensitive detector is available. So that, in the present experiment, we measure the directional distribution of bidirectional reflectance ρ for visible radiation. It is noticed that the spectral and directional characteristics of surface reflection depend to each other, on which a theoretical study has been examined⁽⁴⁾.

Figure 2 shows a schematic sketch of the optical subsystem of our experimental apparatus. A helium-neon laser/1/ is used for radiation incidence. It emits linearly polarized radiation whose wavelength in vacuum is $0.6328 \mu\text{m}$ and the beam diameter is 1.3 mm. The output energy instability of the laser is $\pm 0.5\%$. The laser beam is transformed to a parallel flux of 30 mm in diameter by a laser beam expander /2/. A central part of the flux of 3 mm in diameter, which is homogeneous in intensity, is led through an aperture just after the expander to an optical chopper /3/. The chopper modulates the radiation to chopped one to be incident onto a specimen surface /4/. The specimen is set on a specimen holder unit with an optical detector arm. This unit can rotate with a three dimensional

Fig. 2 Schematic sketch of optical subsystem of experimental apparatus

freedom corresponding to θ_I , θ_R and ϕ_R . The detector /5/ is a silicon photodiode detector, whose effective area is $\Delta S = 34(\text{mm})^2$. The length l from specimen surface to the detector is kept at $l = 200 \text{ mm}$. The zenithal angles of radiation incident on the specimen surfaces are set at $\theta_I = 0, 20, 40$ and 60° . Reflection angles for the measurement of $(q_R \cdot \Delta A)$ are chosen in principle by every 20° of θ_R and ϕ_R , and by every 5° in the directions of $\pm 20^\circ$ around the specular reflection direction. In the measurement of $(q_I \cdot \Delta A)$, the optical detector is set so that it can receive the laser radiation incidence normally. Directional distribution of ρ is calculated by Eq. (6). Since the specular reflection for $\theta_I = 0^\circ$ can not be measured by this experimental apparatus, and that for $\theta_I = 0.5^\circ$ is measured to substitute the datum to that for $\theta_I = 0^\circ$.

3.3 Specimen surfaces

Six kinds of rough surfaces are prepared of JIS-SS41 mild carbon steel plates and of JIS-SUS304 austenite stainless steel plates to choose representatively rough metal specimen surfaces. These surfaces are hand-ground isotropically by a wet-grinding technique with grinding powders of JIS-meshes 240, 800 and 1500. Microprofiles of the rough surfaces are measured one-dimensionally by a stylus technique. This measurement is made on each of the six specimens and on two directions perpendicular to each other. The measured profile data are analyzed to specify the values of root-mean-square (rms) roughness Σ and self-correlation length τ_0 of the surfaces. Figure 3 shows the results of the measurement. Variation of Σ and τ_0 for the measured direction is within an order of 10%. In this meaning, microprofile of every specimen surface is isotropic. The 28 points in Fig. 3 for Σ - τ_0 relationship are those for two kinds of materials and the above-mentioned two directions in the profile measurement. In spite of that, a strong 1st-order correlation is noticed between Σ and τ_0 . The correlation coefficient reaches 0.97. It suggests us

Table 1 Angles of maximum reflection and hemispherical reflectances (measured)

Specimen No.	Σ μm	τ_0 μm	θ_I $^\circ$	$\theta_{R\max}^+$		$\theta_{R\max}^*$		s	R_H	
				s $^\circ$	p $^\circ$	s $^\circ$	p $^\circ$		p	n
1	1.49	5.38	0	0	0	0	0	0.75	0.75	0.75
			20	25	30	20	20	0.73	0.72	0.73
			40	80	40	40	35	0.74	0.71	0.72
			60	80	80	60	55	0.74	0.67	0.70
2	0.60	3.18	0	0	0	0	0	0.63	0.63	0.63
			20	30	25	20	20	0.60	0.62	0.61
			40	55	55	40	40	0.59	0.60	0.59
			60	75	75	65	55	0.68	0.55	0.62
3	0.30	3.14	0	0	0	0	0	0.80	0.80	0.80
			20	30	20	25	15	0.66	0.75	0.70
			40	55	40	40	40	0.68	0.72	0.70
			60	65	60	65	60	0.89	0.72	0.81

Fig. 3 Σ - τ_0 correlation in rough surface profiles

a direction for choosing representative specimens of rough surfaces for radiation characteristics investigation. We can put rough surfaces in order by considering only the roughness Σ .

In the reflectance measurement, we investigate reflection characteristics of surfaces of specimens 1, 2 and 3 of the above six surfaces. Aluminum of 99.99% in purity is vacuum-deposited thickly on the surfaces. Table 1 shows the values of the root-mean-square roughness Σ and the self-correlation length τ_0 averaged over the measured two directions. The surfaces are rough in order of Specimen Nos. 1, 2 and 3.

4. Experimental Results and Discussion

4.1 Bidirectional reflectance ρ

Figures 4, 5 and Table 1 present experimental results of bidirectional reflectance ρ . Figure 4 shows examples of the reflection characteristics directly measured in the experiment, where s- or p-polarized radiation is incident on the surface of specimen 3 from the direction of $\theta_I = 40^\circ$. In the experimental course, 21 curved surfaces as those shown in Fig. 4 are measured on the three rough specimen surfaces, four kinds

(a) s-polarization (b) p-polarization
Fig. 4 Examples of reflection characteristics for polarized radiation in incidence (measured)

of incident angles θ_I and two kinds of polarized radiation. Table 1 summarizes the measured results on s- and p-polarized radiations. Characteristics for natural radiation incidence which is polarized isotropically are averaged ones over those for the s- and p-polarized radiation incidence. Figure 5 shows the ρ characteristics for natural radiation incidence, which are obtained through such a procedure.

In Figs. 4 and 5, radiation is incident from the direction of $\sin \theta_R < 0$ and $\phi_R = 180^\circ$. Cross points of longitude and latitude lines on the curved surfaces in the figures correspond to the measurement directions (points) of the zenithal angle θ_R and the azimuthal angle ϕ_R of reflection. As is clear in Eq. (2), the volume between the curved surface and the $(\sin \theta_R - \phi_R)$ plane results in the hemispherical reflectance R_H . In the case of the perfect-diffuse perfect-reflecting surface, ρ forms a column of height $(1/\pi)$ on the plane. Numbers with the curved surfaces for $\theta_I = 60^\circ$ imply the maximum values of ρ .

Since radiation characteristics of material are results of 'interaction of radiation and matter', reflectances ρ and R_H depend on the surface roughness Σ , the polarization and the incident angle θ_I of radiation. The experimental results shown in Figs. 4, 5 and Table 1 suggest roughly that the peak on the curved surface of ρ is higher and sharper and the reflection to the backward of $|\phi_R| > 90^\circ$ is weaker in the case where

the roughness Σ is smaller, and the incident angle θ_i is larger for oblique incidence, and in the case of the p-polarization than the s-polarization. We call this tendency in reflection characteristics here 'specular-reflecting'. The direction of at which bidirectional reflectance ρ is the maximum is in the incident plane of $\phi_R = 0^\circ$, but the zenithal angle $\theta_{R \max}^*$ of the maximum reflection is larger than that of the specular reflection (Table 1). The 'off-specular' reflection, which has been found before⁽¹⁾, is observed. This phenomenon is clearer in the case of the s-polarized radiation incidence.

Table 1 includes values of reflectance R_H which are calculated by using experimental data of ρ . The symbol n in the table denotes the natural radiation. The R_H value, which represents all the energy reflected, does not monotonously decrease with an increase of the surface roughness Σ . Particularly, R_H of specimen 2, whose roughness Σ is of an order of the wavelength of the incident radiation, is lower than those of specimens 1 and 3 for every incident angle θ_i . This tendency has been found in preceding works^{(4),(5)}. As far as the incident angles of $\theta_i \leq 60^\circ$ and the p-polarized radiation incidence of the present study, reflectance R_H decreases with an increase in the incident angle θ_i . On the other hand, R_H for the s-polarized radiation incidence is low at $\theta_i = 20^\circ$ or 40° . Accordingly, the tendency of R_H characteristics for natural radiation incidence can not be described simply.

4.2 ($\rho \cos \theta_R$) Characteristics

The 'off-specular' reflection in ρ characteristics

Fig. 5 ρ characteristics for natural radiation incidence (measured)

does not fit with our daily life sense. It is because reflectance ρ is on the radiation intensity of a unit of ($\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$), while the pupils of our eyes have an approximately constant size and catch the energy corresponding to the radiation flux of a unit of ($\text{W} \cdot \text{m}^{-2}$) rather than the intensity. The measured quantity ($q_R \cdot \Delta A$) in the experiment is proportional to ($\rho \cos \theta_R$). Then, we investigate the directional characteristics of ($\rho \cos \theta_R$) such as that in Fig. 6(a). This figure is on the same specimen 3 as that for Fig. 4 and for the natural radiation incidence at $\theta_i = 40^\circ$. In Fig. 6(a) and in Table 1 which shows the zenithal angle $\theta_{R \max}^*$ of the maximum ($\rho \cos \theta_R$), the reflection is found not to be 'off-specular', but the angle $\theta_{R \max}^*$ of the maximum energy reflection is near to that of the specular reflection in both cases of the s- and p-polarized radiation incidence. Figure 6(b) shows the contour lines corresponding to $0 \leq \phi_R \leq 180^\circ$ region of the curved surface of ($\rho \cos \theta_R$) in Fig. 6(a). It is suggested in Fig. 6(b) that the reflection characteristics are described by a simple function of the reflection angles θ_R and ϕ_R for each incident angle θ_i . The directional distribution of reflection seems to be described by the superimposition of two components: the perfect-diffuse component of constant intensity, and the specular component for which ($\rho \cos \theta_R$) is modelled by an anisotropic body of rotation of normal distribution function.

4.3 Model of directional distribution of reflection

We present here a series of equations to describe the directional distribution of reflection:

$$\begin{aligned} \rho &= \rho(\theta_i, \theta_R, \phi_R; \theta_{R \max}, A, \sigma, \rho_d) \\ &= \rho_s(\theta_i, \theta_R, \phi_R) + \rho_d(\theta_i) \end{aligned} \quad (7)$$

Fig. 6 Example of ($\rho \cos \theta_R$) characteristics for natural radiation incidence (measured)

$$\rho_s \cos \theta_R = A \exp\left(-\frac{f^2}{2\sigma^2}\right) \cos\left\{\frac{\pi}{2}\left(\frac{f}{g}\right)^2\right\} \quad (8)$$

$$\text{at } (\theta_R, \phi_R) = (\theta_{R \max}, 0), \quad f=0, \quad g = (\text{real number}) \neq 0 \quad (9)$$

$$\text{at } (\theta_R, \phi_R) \neq (\theta_{R \max}, 0), \quad f = (p^2 + q^2)^{1/2} \quad (10)$$

$$g = \frac{1}{f} \{-kq + (f^2 - k^2 q^2)^{1/2}\} \quad (11)$$

$$p = \sin \theta_R \cos \phi_R - \sin \theta_{R \max} \quad (12)$$

$$q = \sin \theta_R \sin \phi_R \quad (13)$$

$$k = \sin \theta_{R \max}$$

The four constant values (parameters) $\theta_{R \max}$, A , σ and ρ_d in Eqs.(7)-(13) mean, respectively, the zenithal angle of the maximum ($\rho \cos \theta_R$), the maximum value of ($\rho \cos \theta_R$), the representative value of the peak width in the ($\rho \cos \theta_R$) curved surface, and the perfect-diffuse reflection component of ρ . The specular component R_s and the perfect-diffuse component R_d of hemispherical reflectance R_H which corresponds to all the energy reflected are calculated by,

$$R_H = R_s + R_d \quad (14)$$

$$R_s = R_s(\theta_I) = \int_{-\pi}^{\pi} \int_0^{\pi/2} \rho_s(\theta_I, \theta_R, \phi_R) \cdot \cos \theta_R \sin \theta_R d\theta_R d\phi_R \quad (15)$$

$$R_d = R_d(\theta_I) = \int_{-\pi}^{\pi} \int_0^{\pi/2} \rho_d(\theta_I) \cos \theta_R \sin \theta_R d\theta_R d\phi_R = \pi \rho_d(\theta_I) \quad (16)$$

4.4 Procedure of experimental datum analysis

In the analysis of experimental data for determining the above four kinds of parameters, we adopt an objective function F for a least squares processing,

$$F = [\sum_i w_i \{(\rho \cos \theta_R)_i^{\text{calc}} - (\rho \cos \theta_R)_i^{\text{exp}}\}^2]^{1/2} \quad (17)$$

$$w_i = (\Delta \Omega_R)_i / \sum_i (\Delta \Omega_R)_i = (\sin \theta_R \Delta \theta_R)_i (\Delta \phi_R)_i / (2\pi) = \{\Delta(-\cos \theta_R)\}_i \cdot (\Delta \phi_R)_i / (2\pi) \quad (18)$$

where $(\rho \cos \theta_R)_i^{\text{exp}}$ is an experimental value and

$(\rho \cos \theta_R)_i^{\text{calc}}$ a calculated value by Eqs.(7)-(13). Function F is the standard deviation between the experimental and calculated values, w_i the weight, and $(\Delta \theta_R)_i$ and $(\Delta \phi_R)_i$ correspond to a solid angle which represents each measurement point i in a reflection direction. In this analysis we adopt a condition so that the calculated value of R_H should be equal to the experimental value. The angle $\theta_{R \max}$ is taken as an unknown parameter. After the values of the four kinds of parameters are determined in this analysis, the experimental data of the distribution of the bidirectional reflectance ρ on each surface and each incident angle are reduced to a set of the four values.

4.5 Results of analysis

Table 2 presents determined values of the four kinds of parameters. The value of σ , which represents the sharpness of the peak in the directional distribution of ρ , is small for oblique incidence of $\theta_I = 60^\circ$. Figure 7 shows the ρ characteristics for the natural radiation incidence which are calculated by using the determined parameters. Fig. 7 is to be compared with Fig. 5. Agreement between the two figures is excellent for the purpose of the present work. In Table 2, the maximum deviation between the curved surfaces in Figs. 2 and 4 is 0.02 sr^{-1} in F . Table 2 also shows the values of the hemispherical reflectance R_H , the specular component R_s and the perfect-diffuse component R_d of R_H , and the specularly reflected energy ratio (R_s/R_H). These values can be input parameters into heat transfer calculations. As mentioned in section 4.4 experimental and calculated values of R_H agree exactly to each other. The ratio (R_s/R_H) is 0.5 or less in every specimen. The ratio (R_s/R_H) is smaller in the case of the most rough specimen 1. It is noticed that this ratio is rather independent of the incident angle θ_I , and that the value of the ratio does not fit with our impression of 'specularity' in the curved surfaces of ρ in Figs. 5 and 7.

Table 2 Values of parameters for radiation heat transfer computation

Specimen No.	Σ μm	τ_0 μm	θ_I $^\circ$	$\theta_{R \max}$ $^\circ$	A sr^{-1}	σ	ρ_d sr^{-1}	F sr^{-1}	R_s	R_d	R_H	R_s/R_H
1	1.49	5.38	0	1.0	0.170	0.49	0.156	0.005	0.24	0.51	0.75	0.32
			20	22.0	0.176	0.55	0.144	0.007	0.26	0.47	0.73	0.36
			40	40.0	0.212	0.46	0.151	0.009	0.23	0.49	0.72	0.32
			60	62.0	0.314	0.41	0.135	0.018	0.27	0.44	0.70	0.38
2	0.60	3.18	0	3.5	0.201	0.51	0.099	0.005	0.32	0.32	0.63	0.50
			20	20.0	0.187	0.60	0.093	0.004	0.31	0.30	0.61	0.50
			40	40.5	0.232	0.50	0.097	0.006	0.28	0.31	0.59	0.47
			60	61.5	0.371	0.37	0.105	0.021	0.28	0.34	0.62	0.45
3	0.30	3.14	0	4.5	0.299	0.43	0.124	0.008	0.40	0.40	0.80	0.50
			20	18.0	0.265	0.49	0.107	0.008	0.35	0.35	0.70	0.50
			40	38.5	0.332	0.37	0.130	0.014	0.28	0.42	0.70	0.40
			60	62.0	0.636	0.23	0.137	0.003	0.36	0.44	0.81	0.44

Fig. 7 ρ characteristics for natural radiation incidence (calculated)

The following consideration is given on this point.

It is preferable to consider the partially-specular and partially-diffuse reflection in radiative energy exchange calculation by dealing the reflection characteristics with only two parameters of R_s and R_d , or R_H and (R_s/R_H) . But, it should be considered in this case that the system for the calculation must not be divided into too fine elements of surfaces so that the specularly reflected energy represented by R_s would not be concentrated in a particular small element. The surface division should be rather rough. Values of R_s and R_d obtained in this work are recommended to be used with such a consideration.

The present technique may be modified in correspondence with the required accuracy of R_s and R_d , so that we can apply the present reflection model to the case when we have measured data of reflection only in the incident plane.

5. Conclusions

We have investigated directional distribution of bidirectional reflectance ρ of rough metal surfaces for visible laser irradiation experimentally, and have presented a new technique to determine radiation heat transfer parameters for representing the reflection characteristics. Concluding remarks are summarized as follows:

(1) Root-mean-square-roughness Σ and self-correlation length τ_0 of wet-polished rough metal surfaces have a strong relationship. The surface

microgeometry is represented by Σ in this case.

(2) Rough metal surface is not perfect-diffuse. When Σ is of an order of the wavelength of incident radiation, the relation between directional characteristics of radiation reflection and Σ and/or incident angle is not simple.

(3) It is desirable to investigate $(\rho \cos \theta_r)$ in the study of directional characteristics of radiation reflection of rough metal surfaces. The 'off-specular' reflection is not observed in this case.

(4) Directional characteristics of radiation reflection on rough metal surfaces can be described by a series of simple equations. These equations are effective to evaluate values of the specular reflection component R_s and the diffuse reflection component R_d of hemispherical reflectance R_H in heat transfer calculations.

(5) The determined values of the specularly reflected energy ratio (R_s/R_H) does not fit our impression of 'specularity' in the ρ characteristics.

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