

A Thermal Method for the Determination of Solar Absorptance

and Thermal Emittance of Spacecraft Coatings

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I. ABSTRACT

For the determination of the solar absorptance s and the thermal emittance preferably optical methods are utilized. To these methods belong spectral reflectance α_s and ε measurements and / or emission measurements (only ε), whereby for α_s must be measured in the common range $0,3 \mu\text{m}$ to $2,5 \mu\text{m}$ and in the range $5 \mu\text{m}$ to $35 \mu\text{m}$ with an essentially better resolution than 10 nm . Besides so-called integrated reflectance measurements are known, for which special detectors are used, in the above indicated spectral ranges. These optical measuring procedures are relatively exact. They deliver also information about a perhaps spectral selective behaviour of surfaces, however, special measuring equipment is required.

The known thermal (or calorimetrical) methods [1] require, that the test surfaces are in the thermal balance with their environment and at least for the s determination a suited solar simulator is required with high constance of the irradiation intensity during the entire measuring phase. Since these measuring phases up to the reaching of the thermal equilibrium are very long, this is a fundamental disadvantage of the thermal method. The work presented in this paper demonstrates possibilities, to neglect for the determination of completely and to shorten the irradiation times for the α_s determination drastically whereby the requirement of the long time constance of the solar irradiation intensity does no longer play a dominant role.

II. FUNDAMENTELS OF THE THERMAL METHODS

The requirements for these measurements are: The measuring object must be located in a vacuum chamber and may be in contact with its isothermal environment (heat sink via radiadion). For the absorption measurements a solar simulator is required, which must be capable of reaching the sun spectrum (Johnson curve) as close as possible.

As measuring object special prepared plain test samples (measuring target) are used. These samples are rotatable suspended in a solar simulation facility such, that alternatively the comparison side (F_v) or the measuring side (F_m) is viewing the "sun". Important is that the target consists of well heat conducting material and an electrical heater as well as several thermocouples are integrated in the target. The measuring and comparison foils on the target can changed and must be so thin, that their influence on the thermal mass of the target is neglectible.

Under the assumption, that the comparison side of the measuring target is sufficiently black (α_s and $\varepsilon = 1$) following balance equations are valid:

Case 1: " Sun "on F_m with irradiation intensity E_s

$$(1) Q_{m_{zu}} = \alpha_m F_m E_s$$

$$(2) Q_{m_{ab}} = (1 + \varepsilon_m) \sigma F_m (T_m^4 - T_u^4)$$

Case 2: "Sun" on F_v with irradiation intensity E_s

$$(3) Q_{v_{zu}} = F_v E_s$$

and

$$(4) Q_{v_{ab}} = (1 + \varepsilon_m) F_v (T_v^4 - T_u^4)$$

when the temperature equilibrium is reached.

It is possible to derive from EQ (1) through EQ (4) for the determination of α_m :

$$(5) \alpha_m = T_m^4 - T_u^4 / T_v^4 - T_u^4$$

From the measured equilibrium temperatures T_m , T_v and T_u α_m can then be calculated according to EQ (5), without knowledge of E_s ! Disturbance sources (windows and others) are eliminated by the comparison measurement with its "black" side. It is demanded however, that during the entire measuring procedure the irradiation intensity remains constant ($E_s = 0$).

The conditions for this procedure are very difficult to assure: Neither $E_s = 0$ nor $T = 0$ is exactly achievable. In the tests, which were accomplished for the examination of the procedures it was planned that T should be considered zero if $T / t \geq 2,7 * 10^{-4}$ (K / s). This resulted in very long measuring times ,so that also the solar simulator had to assure a irradiation intensity constance of far better than 1%. Repetition measurements for α_m according to this procedure showed clearly this problem, so that one had to look for a procedure improvement.

For the determination of the emission coefficient ε_m of the prepared test object the measurement was made with help of the electric heater power. (This power can be stabilized sufficiently well without large expense with regard to measuring times). The "sun" is not required. The installed heater power Q_H belonging to the thermal equilibrium can be described with

$$(6) Q_H = (1 + \varepsilon_m) \sigma F (T_H^4 - T_u^4)$$

from which ε_m with

$$(7) \varepsilon_m = (Q_H / \sigma F (T_H^4 - T_u^4) - 1$$

can be calculated, if the heating power and the equilibrium temperatures T_H and T_u are measured. Most important is that the power fluctuate during the measuring phase only less than 1%.

Provided that the measuring target was approximately in a "cold" thermal equilibrium with the surrounding heat sink, we see in the starting phase of a heating process a quasi linear increase of the temperature, before then the emission function begins to dominate ending in the so-called "warm" thermal equilibrium. For α_s this means, that in the start phase -i.e. as long as the temperature increase is linear with time relative to the measuring precision - the balance equations for the "sun heating" of the target

$$(8) m_T c_T = (dT_m / dt) \alpha_m F_m E_s - (1+\varepsilon_m) \sigma F (T_m^4 - T_u^4)$$

and

$$(9) m_T c_T = (dT_v / dt) F_v E_s - (1+\varepsilon_m) \sigma F (T_v^4 - T_u^4)$$

can be replaced with good approximation by

$$(10) m_T c_T = (\Delta T_m / \Delta t) \alpha_m F_m E_s$$

and/or

$$(11) m_T c_T (\Delta T_v / t) = F_v E_s$$

From that equation we then get after some calculations

$$(12) \alpha_m = \Delta T_m / \Delta T_v$$

for the same heating time Δt

and/or

$$(13) m = \Delta t_v / \Delta t_m$$

for the same temperature increase ($\Delta T_m = \Delta T_v$)

Particularly for the EQ (13) is given following justification:

As long as the heating process (in consequence of the irradiation with the solar simulator) displays assuming quasi linear temperature increases in time, EQ (8) and / or EQ (9) can be replaced by

$$(14) m_T c_T (\Delta T_m / \Delta t_m) = \alpha_m F_m E_s - \Delta Q_m^s$$

and

$$(15) m_T c_T (\Delta T_m / \Delta t_v) = F_v E_s - \Delta Q_v^s$$

Because the heating process is interrupted at T_m the terms $\Delta t \Delta Q^s$, which consider the emission losses are equal for both measurements. It is therefore

$$(16) \Delta t_v \Delta Q_v^s = \Delta t_m \Delta Q_m^s$$

Combining EQ (14) through EQ (16), i.e. considering also emission losses which had been ignored when explaining EQ (13) above, one obtains the same EQ (13) formulation for α_s determination. As a consequence, however, following boundary conditions have to be kept when applying the said method:

1. The measurements must begin in the proximity of the environmental temperature ("cold equilibrium").
2. Measuring time and/or measuring range are to be chosen such, that the temperature increase remains linear (control criteria).

III. THE EXPERIMENTAL VERIFICATION OF THE THERMAL METHOD FOR THE DETERMINATION OF α_s AND ϵ

Measuring requirements - the measurements were made in a solar simulation facility. A scheme of this facility, its essential technical parameters and the test rig are presented in the figures 1 and 2.

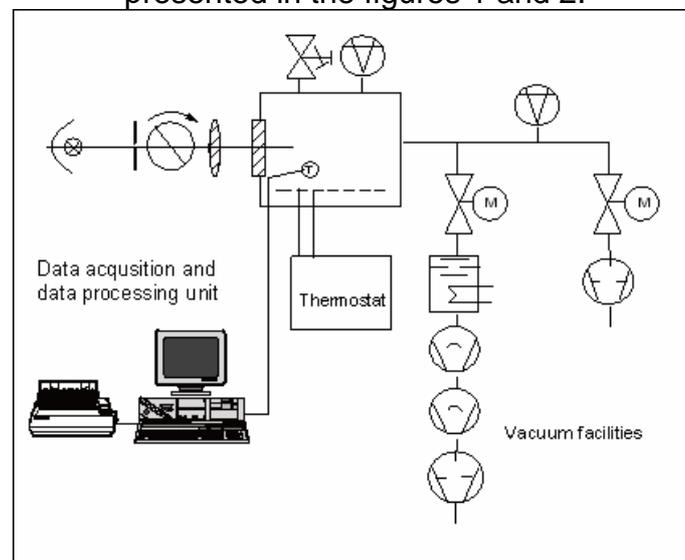


figure 1: scheme of test facility

useful volume : $0,45 \text{ m}^3$

max. possible diameter of testobject : $0,7 \text{ m}$

final pressure : $1,33 \cdot 10^{-3} \text{ Pa}$

temperature of cold shroud

(liquid nitrogen) : $T_u < 100 \text{ K (IN}_2 \text{) ; } \alpha_s > 0,95$

solar simulator : $0 \dots 2,8 \text{ kW / m}^2$ at 150 mm diameter

collimator angle : $< 5^\circ$

spectral range : $0,2 \dots 2,5 \text{ } \mu\text{m}$

data acquisition : thermocouples or transistors, resolution $< 0,1 \text{ K}$

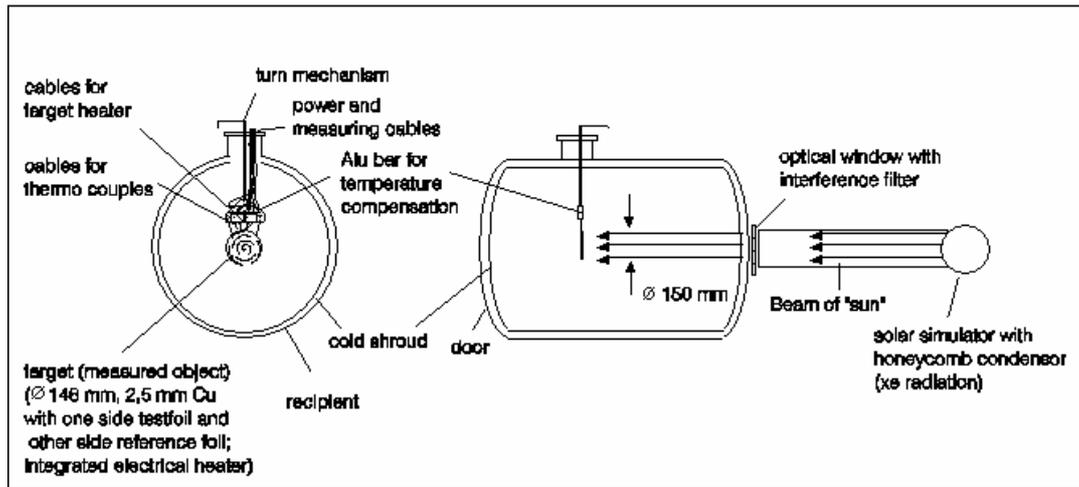


figure 2: solar simulation facility and test rig

The equilibrium temperatures T_H were measured for different power of the integrated electric heater for the determination of ε . During short-term irradiation of both target sides (measuring and comparison side) with the solar simulator were measured for the α_s determination the respective temperature rises starting from the proximity of the "cold equilibrium". For the appraisal of the quality of the procedures measurements were performed first with foils, from which the properties α_s and ε are sufficiently well known (e.g. from optical measuring procedures with fourierspectrometers in the range from 380 to 17000 nm).

As "black" foil Kapton XC was applied. As test sample a vacuum deposited aluminium foil, Kapton HN was used. Both foils are 25 m thick. In a second run then "yellow chromated Al foil", as it is foreseen as coating material for the dust sensor of the CASSINI mission has been subjected to the said measurement procedure. To avoid systematic errors, in the balance equations the edge zone of the target must be considered, so that EQ (7) now has following form:

$$(17) \quad \varepsilon_m + \varepsilon_v = Q_H - Q_{Rand} / \sigma F (T_H^4 - T_u^4)$$

Q_{Rand} considers the emission losses of the edge of the target whilst for ε_v , the value measured with optical methods is used.

For the determination of α_s according to the temperature rise method instead of EQ (13) now

$$(18) \quad \alpha_m = (\Delta t_v / \Delta t_m) \alpha_v$$

The edge of target has no influence on the α_s measurement.

Measurement Results - results obtained following the described methods are tabulated below.

Table 1:

Comparison of thermal method results with optical measurements

	Kapton	XC	Kapton	HN
	optical	thermal	optical	thermal
α_s	0,93	/ ¹⁾	0,089	0,089
ε	0,875	0,8753 ²⁾	0,035	0,0351

1) no value due to EQ (18)

2) because EQ (17) this is the sum $\varepsilon_m + \varepsilon_v$

Table 2

Comparison of measurement results of yellow chromated Al foil

	measured by ESTEC according ESA PSS-01-709	ISST
α_s	0,21	0,213
ε	0,17	0,176

The error analysis shows, that the maximum procedure errors for our thermal methods are about 5% for α_s and less than 7% for ε . The somewhat higher error for results from the measurement tolerances of the sample dimensions to be used in the determination equation. Interesting is also, that for the gross determination of α_s the temperature rise method can be used under normal lab conditions; that means no high vacuum, no cryogenic shroud, only short-term irradiation of the two target sides successively with the solar simulator. The value determined in such way is only about 10% different from the value determined under exact measuring conditions.

IV. CONCLUSIONS

The presented method appears as welcome enrichment of the measuring possibilities for the determination of the thermo-optical properties α_s and ε particularly if the corresponding simulation facilities are already available. It is possible with slight technical expense to expand the usage possibilities of such facilities by the presented procedure.

V. APPENDIX

Nomenclature

Parameters:

Q = power [W]

α = solar absorption of a surface

ε = thermal emission of a surface

F = surface size [m^2]

E = irradiation intensity [W / m^2]

T = temperature [K]

m_T = mass of the target [kg]

c_T = heat capacity of the target [Wh / kg K]

σ = Boltzmann constant [$\text{W} / \text{m}^2 \text{K}^4$]

t = time [h]

Indices:

ab = output

zu = input

H = heating

T = target

m = measuring side of the target

v = comparison side of the target

u = environment

s = radiation / sun

Abbreviations:

ESTEC European Space Research and Technology Centre

ISST Institute for Space Sensor Technology

ESA PSS European Space Agency Procedures, Standards and Specifications

References:

[1] W.B.Fussel, j.j. Triolo and J.H. Henninger

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