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Investigations on temperature distribution of satellite surfaces affected by solar absorptivity

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Abstract

Based on the Monte Carlo ray-tracing method, the network coefficients of thermal network model describing the radiation heat transfer among satellite surfaces is solved by considering the surface material optical characters. It is superiority to the conventional Gebhart's method in view of the grey body and the diffuse reflection assumptions. The zone leveling method is used to discrete the governing equations and the solar absorpivity is separated and considered to be an important correction parameter. Effects of the solar incidence round angle, the zenith angle and the ratio of absorpivity to emissivity (RAE) on temperature distribution are numerically simulated and discussed in detail. The higher or the lower the RAE may be lead to the alternative heating and cooling tend with a larger heating or cooling velocity of main body surfaces than the solar array surfaces. Furthermore, maximum temperature of main body is almost larger than solar arrays. Under the same RAE, solar incidence angle make a great effect on the uniform character of temperature distribution.

Keywords: Thermal network model; Satellite temperature; Solar absorptivity; Monte Carlo ray-tracing

1. Introduction

Transient temperature distributions of satellite surfaces are determined by the whole thermal environment in orbit, which consists of the three levels radiation–conduction coupled transfer. They are referred as the inner heat sources, the inner heat environments coupling with outer heat environments and the radiation heat transfer coupling with conduction among outer space, solar and space environments. Thermal network model method has been applied widely to solve the temperature field of satellite surfaces in last 20 years (Gilmore, 1994; Krisnaprakas, 1995; Min and Guo, 1998; Lee et al., 1999; Milman and Petrick, 2000). Some deficiencies due to the simplifying mathematical model and the selecting parameters inaccurately cause to the inevitable error between experimental data and simulated results (i.e. choosing appropriately heat conduct coefficient, contact thermal resistance and surface radiation parameters). Therefore, it must be corrected for application into the field of practical engineering.

Generally speaking, correction technique is classified into the two categories. One is the test correction method, which the network coefficients are corrected by experimental data. The other is the active correction method, which the network model is corrected using the perfect and comprehensive physical and mathematical model. As for the former method, Toussaint (1967) firstly established a system correcting approach on the basis of the thermal balance experimental data to correct the satellite thermal network model. Ishimoto and Pan (1969), Ishimoto and Gaski (1970), Ishimoto (1970), Shimoji and Oshima (1978) carried out a series of studies by means of the least

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Nomenclature

A	area
c	specific heat
D	network conduction coefficient
F	view factor
k	thermal conductivity of the material
L	length
m	mass
N	the number of nodes
q, Q	heat
R	network radiation coefficient
t	temperature
Greek alphabets	
α	absorptivity
β	solar incidence angle
δx, δy, δz	space distance
ε	emissivity
ρ	reflectivity
σ_0	Stenfen–Boltzman's constant
τ	time
Subscripts	
i, j, k, h	coordinates directions
E	earth
s	solar
E, W, N, S, T, B, P	east, west, north, south, top, bottom, position

square method, the Kalman filter method and the statistical regression method. These researches are limited by the number of discrete nodes for mathematical model. In order to overcome it, Weng and Pan (1995) and Weng et al. (1998) presented a general correction radiation coefficient method and Li (2004) proposed an improved correcting least square method. As for the latter method, Mantellim and Yovaovich (1998) established a compact analytical model to eliminate network heat conduct coefficient error, which comprehensively considered for the thermal resistance of bolted joints with a variable number of washers between plates, material and constriction resistance. Yang et al. (2004) proposed a three-dimensional equivalent conductivity model of cell plate, which combined the radiation–conduction heat transfer in folded solar array as a three-dimensional anisotropic conduction coefficient. Saidi et al. (2009) presented an inverse estimation of thermal parameters for the network model, Ji (2004) developed a global convergent algorithm for the solution of the network equation sets and Papalexandris and Milman (2001) derived an active control approach for the thermal network model.

As mentioned above, the combination of computational fluid dynamics and the more accurate simulation of radiation heat transfer is a potential ways for the further development of the heat transfer analysis (Ferziger and Peric, 1996). To date, a new correction method, referred as the alternating material optical characters has never been reported. In this study, solar absorptivity is separated from the governing equations on the basis of the Monte Carlo statistical analysis (Liu et al., 2004, 2009; Modest, 2003). It is considered to be an independent variable for correcting thermal network model rather than for the network conduction or for the network radiation coefficients. The detailed study is performed by directly solving the solar incidence area, the solar transfer coefficients and the combining solar absorptivity and emissivity.

2. Mathematical model and correction technique

2.1. Thermal network model

Thermal network approach is derived from the energy balance equations, which is equivalent to a particular finite difference discretion method of the underlying heat-transfer equation. Unsteady state thermal network equation is defined by

$$\sum_{j=1}^{N_D} D_{ji}(t_j - t_i) + \sum_{j=1}^{N_R} R_{ji}(t_j^4 - t_i^4) + Q_i = m_i c_i \frac{\mathrm{d}t_i}{\mathrm{d}\tau} \tag{1}$$

where D_{ji} is the linear conduction coefficients arising from conduction and convection, R_{ij} is the radiation exchange coefficients characterizing radiation heat transfer within the system and Q_j is the total heat sources. N_R is the number of radiation network nodes, N_D is the number of conduct network nodes, c_i is the specific heat, m is the mass, t is the temperature and τ is the time. Conduction coefficients D_{ji} is computed using Fourier's law:

$$D_{ji} = k \cdot \frac{A}{L} \tag{2}$$

where k is the thermal conductivity of the material, A is the cross-sectional area through which the heat flows, and L is the length between nodes i and j.

R_{ji} can be calculated as follows:

$$R_{ji} = \sigma_0 \cdot RTC_{j,i}^{\mathrm{infra}} \cdot \varepsilon_j \cdot A_j \tag{3}$$

where σ_0 is the Stenfen–Boltzman's constant ($\sigma_0 = 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$), $RTC_i j^{\mathrm{infra}}$ is the infrared radiation transfer coefficient, which is solved by MCRT, ε is the emissivity.

Q_i is defined by

$$Q_i = Q_{\mathrm{outer}} + Q_{\mathrm{inner}} + Q_{\mathrm{net}} \tag{4}$$

Outer heat source Q_{outer} is:

$$Q_{\mathrm{outer}} = q_1 + q_2 + q_3 \tag{5}$$