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A probabilistic sizing tool and Monte Carlo analysis for entry vehicle ablative thermal protection systems ☆

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ABSTRACT

Implicit ablation and thermal response software was developed to analyse and size charring ablative thermal protection systems for entry vehicles. A statistical monitor integrated into the tool, which uses the Monte Carlo technique, allows a simulation to run over stochastic series. This performs an uncertainty and sensitivity analysis, which estimates the probability of maintaining the temperature of the underlying material within specified requirements. This approach and the associated software are primarily helpful during the preliminary design phases of spacecraft thermal protection systems. They are proposed as an alternative to traditional approaches, such as the Root-Sum-Square method. The developed tool was verified by comparing the results with those from previous work on thermal protection system probabilistic sizing methodologies, which are based on an industry standard high-fidelity ablation and thermal response program. New case studies were analysed to establish thickness margins on sizing heat shields that are currently proposed for vehicles using rigid aeroshells for future aerocapture missions at Neptune, and identifying the major sources of uncertainty in the material response.

1. Introduction

One of the greatest challenges in designing aerospace structures is determining the internal thermal field, which is generated by aerodynamic heating during the atmospheric flight phase of a space vehicle. Ablative heat shields are commonly used for single mission spacecraft. Upon absorbing heat, the ablative material sublimes and forms a gas layer whose temperature is remarkably lower than that of the bow shock. In this way, the entering heat flux is reduced. Before the advent of reusable surface insulations, such as those used in the NASA's Space Transportation System, the utilisation of ablative materials was the only approach adopted for the Thermal Protection System (TPS). In fact, to date, ablative materials remain the primary thermal protection for a variety of aerospace applications. Past and present trends have been to develop atmospheric entry vehicles and cosmic return capsules that are protected by ablative heat shields. The present work focuses on a statistical analysis of the thermal response of an ablative TPS and the repercussions of its application to design.

The first step was to develop an integrally original numerical code, which is based on an implicit finite difference scheme, to perform the ablative thermal problem's analysis. The selected thermo-physical model accounts for a large variety of phenomena and conditions, such as heats of formation, decomposition kinetics, simplified surface chemistry, pyrolysis, substructure presence, and effects of surface recession. All thermal and physical properties depend on the temperature, pressure, and the state of the ablative material.

Moreover, it is possible to choose among several initial temperature distributions and boundary conditions for both the internal and external surfaces.

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Nomenclature

A	see Eq. (10)
A_i, B_i, C_i, D_i	coefficients; see Eq. (16)
a, b	exponents, dependent on ρ_{atm} and V
B	activation temperature, K
C_c	constant, dependent on the atmosphere
C_r	constant, dependent on the atmosphere
c_P	specific heat, J/(kg K)
dt	integration time step, s
F	exterior view factor
$f(V)$	function, dependent on the velocity
H_d	pyrolysis enthalpy, J/kg
h	enthalpy, J/kg
$\overline{h}$	partial heat of charring, J/kg
h_w	wall enthalpy, J/kg
h_0	total enthalpy, J/kg
i	node index [1−N]
J	material index
j	sample index [1−M]
K	collision frequency factor, kg/(m^3 s)
k	thermal conductivity, W/(m K)
M	number of samples
$\dot{m}_c$	char removal rate, kg/(m^2 s)
$\dot{m}_g$	pyrolysis gas mass flow rate, kg/(m^2 s)
N	number of nodes
n	decomposition reaction order
$\dot{Q}_{in}$	net total heat flux at surface, W/m^2
$\dot{q}_{c,blow}$	net hot wall convective heat flux, W/m^2
$\dot{q}_{comb}$	combustion heat flux, W/m^2
$\dot{q}_{c,w}$	cold wall convective heat flux, W/m^2
$\dot{q}_R$	internal radiative heat flux, W/m^2
$\dot{q}_{rad}$	radiative heat flux, W/m^2
r_n	vehicle nose radius, m
S	surface recession, m
$\dot{S}$	char recession rate, m/s
T	temperature, K
T_{abl}	ablation (start) temperature, K
T_{char}	charring temperature, K
T_w	wall temperature, K
T_∞	freestream temperature, K
t	time, s
V	velocity, m/s^2
x	mobile coordinate system, $y-S$, m
y	fixed coordinate system, m
ΔH_c	heat of combustion per unit weight, J/kg
ΔX	node thickness, m
α_c	weighting factor for char mass loss
α_g	weighting factor for pyrolysis gases
ε_w	surface emissivity
ρ	density, kg/m^3
ρ_{atm}	atmospheric density, kg/m^3
σ	standard deviation; or Stefan–Boltzmann constant in Eq. (9), W/(m^2 K^4)
τ	mass fraction of virgin material

Subscripts

BL	bond-line
c	char
g	pyrolysis gas
v	virgin material

Superscripts

$-$	mean value
$'$	value at time $t+dt$

Finally, the results for several types of missions can be obtained by entering the estimated heat fluxes (via data bases) or through classic correlation formulas. The core of the program, flexible and modular, is the thermal ablative problem solver. It has been integrated with a management "monitor" that calculates statistical series based on the Monte Carlo methodology. These series are then used for a sensitivity and uncertainty analysis of the results. The main purpose is to estimate the probability that the temperature of the bond-line (T_{BL}), i.e., the adhesive junction layer between the heat shield and the substructure, is within the design specification temperature.

The sensitivity and uncertainty analysis is used to evaluate the thickness probability distribution for the ablative layer and to estimate the contribution of the various input uncertainties on the uncertainty of the same thickness. These evaluations are based on the randomness that is relevant to the operational aerothermal environment and on the uncertainties of the thermal characteristics for both the ablative and substructure materials.

Identifying the ablative material properties, which proves to have the greatest impact on the TPS sizing due to its indeterminateness, can provide suggestions to improve the performance of the same material. Thus, by improving the performance of the materials used, the heat shield mass fraction can be significantly reduced. Chen et al. presented this approach [1] as an alternative to traditional methodologies, like the Root-Sum-Square method, to evaluate thickness margins; it is particularly helpful during the preliminary TPS vehicle design phases.

The developed computational tool was validated with two case studies from the corresponding literature that are related to the statistical sizing of thermal shields and based on industry standard high-fidelity software. The results were successfully verified by comparing them to the values that are found in Ref. [1] for the TPS of both the Stardust and Mars Exploration Rovers capsules, which were obtained from the source code "Fully Implicit Ablation and Thermal" (FIAT) of the NASA Ames Research Center.

The third case study was application oriented. It determined the thickness margins for rigid cell vehicles, which are currently proposed for future aerocapture missions at Neptune. Again, the results agreed well with the design estimates that are found in the literature [2].