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Transient thermal protection of film covering circular aperture by sublimation and weak decomposition

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HIGHLIGHTS

- Precise sublimating layers can provide protection in transient thermal environments.
- Sensitivity analysis shows that the uncertainty in properties has modest influence.
- It is likely that methane layers are a good choice for IFE targets.

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ABSTRACT

Unwanted heating of sensitive surfaces in harsh thermal environments can be prevented by precise application of sacrificial materials such as sublimation layers and pyrolyzing films. The use of sublimation for the protection of circular polyimide membranes subjected to brief (∼100 ms) heating by infrared radiation and hot (6000 K) inert gas convection is analyzed. Selection of sublimation material and sublimation layer and membrane thickness is considered with emphasis on providing sufficient thermal protection yet negligible unwanted material remaining at the end of a specified heating period. Though the analysis here is general, the motivation is protection of the polyimide films covering the laser entrance holes on IFE (inertial fusion energy) hohlraums being injected into the hot gas (xenon) protecting IFE reactor chambers. Both one and two dimensional thermal models are used to develop a robust thermal concept. Sensitivity analyses (SA) methods are exercised to show where the design may be vulnerable and which input parameters have the greatest effect on performance and likelihood of success. For the design and conditions considered, methane sublimating layers are probably preferred over xenon or pentane.

1. Introduction

Unwanted heating of sensitive surfaces in harsh thermal environments is observed at the ends of high power lasers, on the front of planetary probes on reentry, on the interior of viewports in plasma coating vessels and in numerous other applications. In an IFE application, polyimide membrane is used for the laser entrance hole (LEH) window positioned at the leading and trailing surfaces of an inertial fusion confinement target shown in Fig. 1 [1]. The target is designed to be injected into a fusion chamber containing hot, low pressure xenon gas (6000 K, 23 Torr). In addition to the convective heating from the gas, there is an additional radiative heat load from the 900 K fusion chamber wall. The target is filled with helium gas at a density of about 1 mg/cm^3 and at a temperature of about 18 K which cools the inner surface of the polyimide membrane. Successful fusion implosion requires that the DT in the capsule at the center of the target remain in solid form and that, in fact, the temperature of this solid remain within about 0.1 K of the design temperature. It is therefore critical that the LEH window remains intact and not permits hot gases to contact the inner capsule. For this and other applications, transient one-time use or transient periodic protection techniques are sometimes preferable. Forced convection cooling and abbreviated operation can be the transient thermal protection system at high power laser windows. Pyrolysis, blowing into the boundary layer and charring of the substrate are often the protection mode for the extreme surface heating on earth reentry. In other systems no protection method may be used and viewports or other hardware may be periodically discarded and replaced. Alternatively, precise knowledge of heating conditions and duration can permit precise application of sacrificial materials such as sublimation layers and pyrolyzing materials for transient applications in some technologies.

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Nomenclature

A	constant in decomposition expression
a	transformed frame item
b	body force
C	specific heat (J/kg K)
C_1–C_3	constants in Antoine equation
D	stoichiometry matrix
D_1–D_4	constants in suppression function
E	constant in decomposition expression
F	force term
g	load vector
h	enthalpy (J/kg)
I	inertia matrix
k	reaction rate constant (#/m^2 s)
L	number of surface species
l	surface species index
m	mass (kg)
$\dot{m}$	mass flux (kg/m^2 s)
M	molecular weight (kg/kmol)
Nu	Nusselt number
N_o	Avogadro's number (#/kmol)
P	pressure (N/m^2)
Pr	Prandtl number
Q	number of surface reactions
$\dot{q}$	heat flux (J/m^2 s)
q	chemical species index
Re	Reynolds number
R	universal gas constant (J/kmol K) or (J/gmol K)
r	net forward reaction rate (#/m^2 s)
s	species index
s	surface recession
T	temperature (K)
u	displacement vector
W	number of gaseous species
w	gaseous species index
X	mole fraction of gaseous species
Y	stiffness matrix
α	fraction reacted in decomposition expression
Γ	forcing functions
ρ	density
β	constant in decomposition expression
μ	stoichiometric coefficient of gaseous products
ν	stoichiometric coefficient of gaseous reactants
λ	stoichiometric coefficient of surface products
η	stoichiometric coefficient of surface reactants
κ	thermal conductivity
ζ	spatial coordinate in transformed frame
θ	surface species population fraction
ε	emissivity
ε	parameter in surface species reaction constant

Subscripts

ab	ablation
bot	bottom side
cov	cover gas
dec	decomposition
diff	diffusion
emittradn	emitted radiation
f	forward
f	formation
flcondn	fluid conduction
incradn	incident radiation
n	constant in decomposition expression
nspec	number of species
p	pressure
pyrol	pyrolysis
q	reaction index
refIradn	reflected radiation
s	species index
solcondn	solid conduction
sub	sublimation
top	top side
T	temperature
und	underside
vap	vapor
w	wall

Superscripts

o	formation
dot	rate

Analysis of earth reentry dating to the 1950s includes many of the relevant phenomena for a consideration of protection of optical and other films built into terrestrial applications such as laser windows and viewports. Milos et al. [2] have reviewed surface heating, ablation, pyrolysis and charring effects as applied to space applications. Additional work on pyrolysis and on the breakdown of polyimide and other membranes is applicable to both space and terrestrial systems requiring transient protection [3–6]. Sublimation is a special case within surface chemical effects with the capability of protecting a wide range of surfaces with minimal impact on other aspects of device performance. Sublimation of carbon [7] and several other materials [8,9] may be well understood under many conditions but the influence of non-sublimating and non-condensing cover gases on the sublimation rate of the protective sublimating layer is not clear [10–12]. In some cases cover gases can suppress sublimation and in others they can enhance it. Here, we analyze the use of sublimation for the protection of circular polyimide membranes subjected to brief (~100 ms) heating by infrared radiation and hot (6000 K) inert gas convection. Selection of

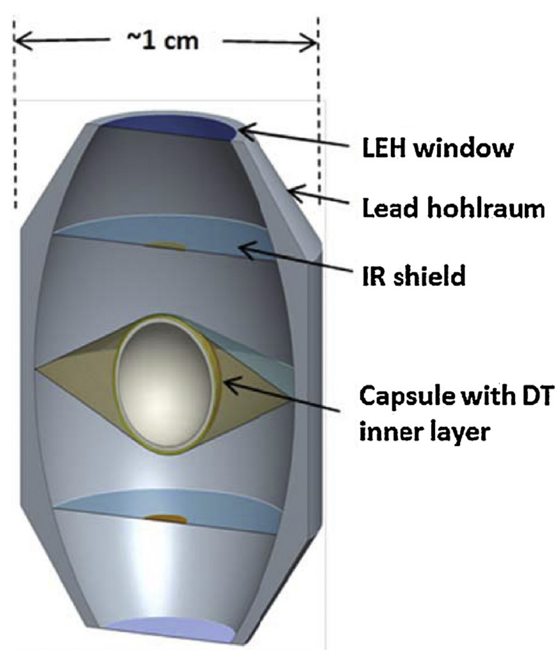

Fig. 1. The sketch of an inertial fusion confinement target.