

Heat Flux Duplication Between Ground Facility and Hypersonic Flight

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DOI: 10.2514/1.35808

The development of reentry space vehicles requires a precise qualification of their thermal protection system materials. The material catalytic properties should be determined for test conditions relevant to the real flight mission program. However, perfect reproduction of the flight environment in a ground facility is practically impossible for reacting flows and one is obliged to resort to a partial simulation. In an attempt to overcome such an issue, we present a methodology that allows establishing under which hypothesis and approximations the flowfield inside a ground facility is equivalent, regarding the heat flux load, to the real flowfield experienced by a space vehicle. The analytical results of the theory are compared with numerical predictions and agree favorably with them.

Nomenclature

c	=	mass fraction
\mathcal{D}_{ij}	=	binary diffusion coefficient between species i and j , m^2/s
f	=	Blasius function
g	=	$h_0/h_{0\delta}$, nondimensional mixture total enthalpy
h	=	enthalpy, J/kg
h_0	=	$h + \frac{1}{2}u^2$, total enthalpy, J/kg
k_b	=	Boltzmann constant
k_w	=	wall catalytic speed, m/s
Le	=	Lewis number
l_0	=	$\rho\mu/\rho_\delta\mu_\delta$, Chapman–Rubesin parameter
M	=	Mach number
M^M	=	mixture molar mass, kg/mol
M_i^M	=	molar mass of species i , kg/mol
m	=	mass of particle, kg
N_s	=	number of species in the mixture
Pr	=	Prandtl number
p	=	pressure, Pa
q	=	heat flux, W/m^2
r	=	distance from body axis, m
R	=	body nose radius, m
\mathcal{R}	=	universal gas constant, J/(mol K)
R_g	=	specific gas constant, J/(kg K)
T	=	mixture temperature, K
u, v	=	tangential and normal velocity components, m/s
\dot{w}	=	mass chemical production rate, $\text{kg}/(\text{m}^3\text{s})$
x, y	=	Cartesian coordinates, m
x_i	=	mole fraction of species i
γ	=	wall catalytic recombination probability
η	=	transformed y coordinate
θ	=	mixture nondimensional temperature
μ	=	mixture viscosity, m^2/s
ξ	=	transformed x coordinate
ρ	=	mixture density, kg/m^3

Subscripts

A	=	atoms
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M	=	molecules
s	=	stagnation point
w	=	wall surface
δ	=	boundary-layer outer edge
∞	=	freestream

Superscripts

f	=	flight
t	=	ground facility

I. Introduction

THE determination of the catalytic properties of thermal protection system (TPS) materials is crucial for the design of an optimal flight strategy of aerospace vehicles: as a matter of fact, the heat flux for a fully catalytic wall can be more than twice the heat flux for a noncatalytic wall. Furthermore, TPS material catalytic behavior can be influenced by the local gas temperature, pressure, and chemical composition [1]. This situation requires ground facilities that are able to provide representative testing conditions for the evaluation of the material performances, because TPS materials should be tested in real flight conditions, to safely rely on their catalytic properties. However, for reacting flows, the wide range of real flight conditions cannot be fully reproduced in the existing experimental ground facilities [2,3]. The usual strategy to overcome such a problem is to resort to some kind of partial simulation: only some characteristics of the flight environment, which are of interest in the specific experiment, are reproduced.

In this contribution, we present a methodology that allows establishing which hypothesis and approximations make the flowfield inside a plasma wind tunnel able to reproduce the real flowfield experienced by a specific part of a reentry vehicle. The focus is on heat flux duplication between flight and ground facility. In [4] we presented a methodology for local heat flux duplication in the stagnation region; here, we extend the previous work to the whole boundary layer downstream of the stagnation point.

II. Local Heat Flux Duplication Concept

In this section, we derive an analytical expression for wall heat flux that will be used to establish the conditions needed for heat flux duplication between real flight and wind tunnel.

We suppose that a boundary layer exists and the flow is laminar, two-dimensional, or axisymmetric and made of N_s chemically reacting perfect-gas species. These assumptions exclude fully three-dimensional or turbulent flows, but are consistent with the goal of deriving an approximate analytical solution of boundary-layer equations, which is subsequently used to establish the heat flux duplication criteria.

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