JOURNAL OF PROPULSION AND POWER
Vol. 25, No. 6, November–December 2009

Quasi-One-Dimensional Model of Hydrogen-Fueled Scramjet Combustors

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DOI: 10.2514/1.43716

A computationally efficient, quasi-one-dimensional, supersonic combustion ramjet (scramjet) propulsion model has been produced for use in hypersonic system design studies. The model solves a series of ordinary differential equations using a fourth-order Runge–Kutta method to describe the gas dynamics within the scramjet duct. Additional models for skin friction and wall heat transfer are also included. The equations are derived assuming an open thermodynamic system with equilibrium or simplified-chemistry combustion models. The combustion is also assumed to be mixing-limited rather than kinetically limited. This assumption allows simplification of the modeling and is justified when the model is compared against experimental results. Three test cases are used to validate the performance of the scramjet propulsion model: 1) a reflected-shock-tunnel hydrogen-fueled scramjet experiment, 2) a continuous-flow hydrogen-fueled scramjet ground test, and 3) a segment of the HyShot II flight test. The results show that the model simulates scramjet propulsion with a reasonable degree of accuracy.

Nomenclature

A = geometric area of the duct, m^2
$a_{1\text{–}6}$ = series of constants
c = speed of sound, m/s
c_f = skin-friction coefficient
c_h = Stanton number
c_p = specific heat, kJ/kgK
D = chemical species
$\mathcal{D}$ = hydraulic diameter, m
d = number of moles of species D
d = constant
d_f = diameter of fuel injectors, m
FAS = stoichiometric fuel/air ratio
f_c = fuel-mixture fraction along a centerline
$\bar{h}$ = mean specific enthalpy of a mixture, kJ/kg
h_i = specific enthalpy of the ith species, kJ/kg
K_p = equilibrium constant
K^* = proportionality constant
k = constant
L = length, m
M = Mach number
Mc = convective Mach number
MW = molecular weight, kg/kmol
$\dot{m}$ = mass flow rate, kg/s
N = number of moles
Pr = Prandtl number
Pr^* = modified Prandtl number
P_w = perimeter of duct cross section, m
p = pressure, Pa
$\mathcal{R}$ = universal gas constant, kJ/kgK
Re = Reynolds number
T = temperature, K
U = velocity, m/s
x = location along duct, m
Y = mass fraction
α = variable
γ = ratio of specific heats
δ = compressible turbulent mixing layer, m
δ_i = incompressible turbulent mixing layer, m
η_m = mixing efficiency
θ = momentum thickness, m
κ = constant
ρ = density, kg/m^3
ϕ = equivalence ratio
ω = ordinary-differential-equation solution

Subscripts

a = air
aw = adiabatic wall
f = fuel
fo = fuel at the injectors
i = species
inj = injection conditions
mix = mixing conditions
mix, i = incompressible mixing conditions
w = wall

I. Introduction

THE development of supersonic combustion ramjet (scramjet) propulsion systems is accelerating, with recent flight-test successes demonstrating their viability [1,2]. This activity has renewed interest in predicting the performance of complete hypersonic vehicles using scramjet combustors, such as single-stage-to-orbit launch systems, long-range cruise vehicles, and missiles. The accurate prediction of vehicle performance early in the design process is vital if conceptual vehicles are to be successfully developed into complete systems in a timely manner. In addition, hypersonic vehicle performance calculators are useful for system analysis studies. To facilitate these activities, accurate and computationally efficient models of all aspects of the vehicle are required.

Quasi-one-dimensional modeling has been used in previous design and performance studies [3,4]. These models use a series of ordinary differential equations (ODEs) to model the flowfield and incorporate chemical kinetics as part of their thermodynamic description of the flow. Results from these studies show that scramjet performance is extremely sensitive to small changes in design, thermodynamic, and mixing parameters. It has been concluded from these studies that it is much better to design a scramjet to operate

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Presented as Paper 4314 at the 18th AIAA Computational Fluid Dynamics Conference, Miami, FL; received 9 February 2009; accepted for publication 23 July 2009.

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