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Numerical Analysis of Film Cooling in Advanced Rocket Nozzles

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The key demand on future space transportation systems is the concurrent reduction of Earth-to-orbit launch costs and increase of launcher reliability and operational efficiency. A common way of slightly improving performance of gas-generator open-cycle engines is the injection of the turbine exhaust gas into the nozzle divergent section, which is also used for wall film cooling. The present study focuses on a numerical parametric analysis of the film-cooling efficiency in dual-bell nozzles. The secondary gas injection is made in the first bell, and it is found that the expansion fan originating from the inflection helps the film to better protect the wall. The results of fully-attached-flow simulations are also used to study the influence of film cooling on the expected behavior of nozzle side loads during operation with separated flow in the second bell.

Nomenclature

A	=	cross-sectional area
a	=	speed of sound
c_p	=	constant-pressure specific heat
g	=	gravity constant
l	=	length
M	=	Mach number
$\dot{m}$	=	mass flow rate
p	=	pressure
R	=	gas constant
Re	=	Reynolds number
r	=	radius
s	=	slot height
T	=	temperature
u	=	flow velocity
V	=	flight velocity
x	=	abscissa
α	=	change of wall angle at inflection
β	=	blowing ratio, $(\rho u)_f/(\rho u)_m$
ϵ	=	area ratio, A/A_t
η	=	film-cooling effectiveness
λ	=	nondimensional axial distance from inflection, l/r_t
μ	=	viscosity
ξ	=	nondimensional abscissa, x/r_t
π	=	nondimensional pressure, p/p_c
π_ξ	=	nondimensional wall pressure gradient, $\mathrm{d}\pi/\mathrm{d}\xi$
ρ	=	density
σ	=	nondimensional slot height, s/r_t
τ_{sl}	=	nondimensional side-load time
Φ_{sl}	=	nondimensional side-load force
χ	=	secondary-to-primary mass flow rate ratio, $\dot{m}_f/\dot{m}_m$

Subscripts

a	=	ambient
b	=	base, value at the end of the base
c	=	combustion chamber
e	=	extension, nozzle exit
f	=	film flow, film injection cross section
fb	=	film breaking
i	=	inflection region
m	=	main flow
o	=	overall nozzle
r	=	recovery value
s	=	separation point
t	=	throat
w	=	wall

I. Introduction

THE key demand on future space transportation systems is the concurrent reduction of Earth-to-orbit launch costs and increase of launcher reliability and operational efficiency. A common way of slightly improving performance of gas-generator open-cycle engines is the injection of the turbine exhaust gas (TEG) into the main nozzle. The role of TEG injection is twofold: in addition to the performance increase, it provides a low-temperature gas that is able to create an insulating film that reduces the convective heat transfer rate from the hot-gas stream to the exposed nozzle surface. To get advantages from both sides, the TEG injection system must be properly designed. In particular, several studies on film cooling [1–3] have shown that the highest efficiency is obtained when the coolant fluid is injected parallel to the primary stream to minimize the mixing, which tends to break down the insulating film, thus reducing coolant efficiency. In addition, it has been shown that film cooling is much more efficient in supersonic than in subsonic flows, because the former presents a thinner boundary layer, smaller turbulent length scales, and thus a lower mixing rate than the latter [3].

The basic studies on TEG injection have addressed cooling properties and nozzle performance during design operations in conventional nozzles. However, following the recent development in advanced nozzle studies [4,5], a further aspect to investigate is the role of film injection in nozzles designed to operate with steady separated flow during the first part of the launch. To this goal, a first study has been carried out by the authors [6] regarding a parametric analysis of the film cooling of a subscale dual-bell nozzle (Fig. 1). The divergent section of this advanced nozzle features two bells with different exit areas to allow safe operation with separated flow at low altitude [5,7,8].

This work aims to study the efficiency of the film cooling in a hot full-scale dual-bell nozzle, with the injection made upstream of the inflection point between the two bells. This analysis is carried out in the simpler case of high-altitude operation, which shows attached flow in the whole nozzle, considering the effect of secondary mass flow rate and of the height of the film-cooling slot. The results suggest

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