JOURNAL OF PROPULSION AND POWER
Vol. 25, No. 5, September–October 2009

Technical Notes

Multi-Objective Optimization of Rocket-Based Combined-Cycle Engine Performance Using a Hybrid Evolutionary Algorithm

Dario Pastrone* and Matteo Rosa Sentinella†
Politecnico di Torino, 10129 Turin, Italy

DOI: 10.2514/1.41327

Nomenclature

A = ejector-mixing-duct area
A^* = rocket throat area
c^* = rocket characteristic velocity
I_s = specific impulse
$\mathcal{M}$ = molecular mass
M = Mach number
$\dot{m}$ = mass flow rate
p = pressure
$\mathcal{T}$ = temperature
T = thrust
T/A = thrust to area ratio
u = flight speed
w = velocity
$\mathbf{x}$ = design parameters vector
α = ejector-to-primary-nozzle-throat area ratio
β = primary-to-secondary total pressure ratio
β_n = nozzle expansion ratio
γ = specific heat ratio
δ = ramjet-fuel-to-primary mass flow rate
ε = nozzle area ratio
μ = secondary-to-primary mass flow rate
ν = primary-to-secondary molecular mass ratio
ν_3 = mixed-to-secondary molecular mass ratio
τ = primary-to-secondary total temperature ratio
τ_3 = mixed-to-secondary total temperature ratio
Φ = overall equivalence ratio
φ = rocket chamber mixture ratio
χ = ejector operation parameter

Subscripts

ck = secondary-flow choking
e = engine exit
$M3$ = ejector-exit choking
p = primary flow
s = secondary flow
0 = upstream/ambient
$1, 3, 7$ = engine stations, see Fig. 1

Superscript

o = total

I. Introduction

ROCKET-BASED combined-cycle (RBCC) engines promise low-cost space access. They combine airbreathing and rocket propulsion elements into a single integrated engine which is capable of multimode operation and can be used from ground takeoff up to space. In this study a RBCC engine called an ejector-ram-rocket (ERR) engine is considered. In such an engine (Fig. 1) a rocket is used as the primary of an ejector from static conditions up to about Mach 2 or 3 to augment the pure ramjet thrust. At higher flight Mach numbers the rocket is shut off and the engine is operated as a ramjet. The same rocket is then reignited and used alone when the flight Mach number exceeds 6. This kind of engine presents interesting features, because it provides good thrust augmentation at low speeds while having mechanical simplicity [1]. When the flight Mach number is above sonic conditions the engine operates in ram rocket or air augmented rocket mode: The air entering the engine is determined by flight Mach number and inlet geometry, unless the engine determines subcritical/unstarted inlet conditions. On the other hand, at low flight Mach numbers, the engine is said to be operating in ejector rocket mode because the amount of air being entrained into the engine depends on numerous factors within the ejector itself and the evaluation of the flowfield results to be more intriguing. Moreover, at low flight speeds the dynamic pressure is low and high thrust to area ratio must be obtained with affordable propellant consumption: A multi-objective optimization problem should be solved, considering both thrust to area ratio and specific impulse.

A large number of works concerning numerical and experimental RBCC engine investigation can be found in the literature [2]. Some works focus on ejector performance such as entrained air and total pressure ratio [3,4]. Even if some authors consider the effects due to molecular weight [5], other ejector performance parameters that influence thrust augmentation, such as the total temperature and specific heat of the flow exiting the engine, are not usually considered. The best is to consider thrust as compared to propellant consumption and engine size. Parametric studies can be found which investigate ejector thrust augmentation [6]. Jahingir and Huque [7] used computational fluid dynamics modeling and neural network to search for the ejector design variables that maximize a desirability function which includes bypass ratio, compression ratio, and ejector nozzle efficiency.

The present study goal is to develop and demonstrate a multi-objective design optimization method for RBCC engines. Discontinuous or concave Pareto fronts can be a real concern for mathematical programming techniques. Therefore, a method based on evolutionary algorithms (EAs) has been developed and proved. Because the model used to evaluate the ejector's performance will be recalled several times by the optimization procedures, a control-volume approach is used, similar to those used by other authors [4,5,8–10], in order to have a reasonable computation time. With respect to previous studies the model is here improved. The effects of the gas properties, which depend on the primary rocket propellant combination and mixture ratio and on the ramjet equivalence ratio, are taken into account. Moreover, the ejector operation constraints are properly highlighted.

Presented as Paper 5170 at the 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Hartford, CT, 21–23 July 2008; received 30 September 2008; revision received 26 May 2009; accepted for publication 26 May 2009.

*Associate Professor, Dipartimento di Energetica, Corso Duca degli Abruzzi, 24. Senior Member AIAA.

†Research Assistant, Dipartimento di Energetica, Corso Duca degli Abruzzi, 24.