Aerospace Science and Technology 50 (2016) 31–43

Contents lists available at ScienceDirect

Aerospace Science and Technology

www.elsevier.com/locate/aescte

Numerical prediction of nozzle flow separation: Issue of turbulence modeling

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ARTICLE INFO

Article history:
Received 21 July 2015
Received in revised form 12 December 2015
Accepted 14 December 2015
Available online 17 December 2015

Keywords:
Shear stress transport model
Nozzle flow separation
RANS simulation
Turbulence modeling
Jet spreading

ABSTRACT

Numerical simulation of separated flows in rocket nozzles is challenging because existing turbulence models are unable to predict it correctly. This paper addresses this issue with the Spalart–Allmaras and Shear Stress Transport (SST) eddy-viscosity models, which predict flow separation with moderate success. Their performances have been compared against experimental data for a conical and two contoured subscale nozzles. It is found that they fail to predict the separation location correctly, exhibiting sensitivity to the nozzle pressure ratio (NPR) and nozzle type. A careful assessment indicated how the model had to be tuned for better, consistent prediction. It is learnt that SST model's failure is caused by limiting of the shear stress inside boundary layer according to Bradshaw's assumption, and by over-prediction of jet spreading rate. Accordingly, SST's coefficients were empirically modified to match the experimental wall pressure data. Results confirm that accurate RANS prediction of separation depends on the correct capture of the jet spreading rate, and that it is feasible over a wide range of NPRs by modified values of the diffusion coefficients in the turbulence model.

1. Introduction

Convergent–Divergent (C–D) nozzles are used in rocket engines to produce thrust as a reaction to the acceleration of hot combustion chamber gases in the opposite direction. The rocket nozzles operate, usually over a wide range of altitudes, from sea-level to high altitudes with very low ambient pressures. To maximize the engine performance at high altitudes, large area ratio, *bell-shaped* or *contoured* nozzles are used. Different types of nozzle contour designs are applied to increase the performance of today's launch vehicles. Truncated Ideal Contour (TIC) nozzles are used in Viking, the Russian RD-0120 and the Japanese LE-7 engine. Thrust-Optimized Parabolic (TOP) nozzles, also known as Thrust-Optimized Contour (TOC) nozzles are used in the American J-2S rocket engine and the Space Shuttle Main Engine (SSME), and in the European Vulcain engine.

Furthermore, to get an optimum performance over the entire flight trajectory, the nozzles are designed for an intermediate pressure ratio (NPR) of chamber to ambient pressure, p_c/p_a, at which the exhaust flow is adapted in pressure to the ambient. This results in an off-design overexpanded condition at lower altitudes. The overexpanded condition is when the nozzle exit pressure p_e is lower than the ambient pressure. The nozzle flow adjusts to the ambient pressure through a shock. If the wall pressure p_w is much lower than the ambient pressure, an oblique shock is located inside the divergent portion of the nozzle. The boundary layer is unable to withstand the pressure rise associated with the shock, and consequently flow separation is induced. Downstream of the separation, the pressure further rises gradually along the nozzle wall to adapt with the ambient pressure.

Two distinct flow separation phenomena, namely, free-shock separation (FSS) and restricted-shock separation (RSS) were demonstrated by several experimental studies performed on either subscale [9,12,22,25,28,35] or full-scale [5] optimized nozzles, and also by different numerical simulations [5,7,11,18–20,25]. In FSS, the separated flow continues as a free jet and a back flow region exists downstream of the separation location due to entrainment of ambient air by the separated jet flow. This pattern is observed in any type of overexpanded nozzle. Whereas, RSS has been reported to occur only in TOP and Compressed Truncated Perfect (CTP) nozzles at certain range of pressure ratios. In RSS, the separated flow reattaches to the nozzle wall, thus forming a separation bubble and the pressure downstream of the separation point exhibits an irregular behavior and reaches values above the ambient pressure.

Flow separation in rocket nozzles is considered undesirable because asymmetry in the flow separation can cause large aerodynamic side loads which, in the past, have caused structural failures

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http://dx.doi.org/10.1016/j.ast.2015.12.016
1270-9638/

Nomenclature

a_1	turbulence structural parameter
A	area
A_s	realizability constants
F_2	blending function
k	turbulence kinetic energy
L	length of nozzle divergent portion
M	Mach number
p	static pressure
r	radial coordinate
Re	Reynolds number
S	invariant measure of the strain rate, S_{ij}
S_{ij}	strain rate tensor
t	time
T	temperature
y^+	wall-normal mesh spacing in turbulence coordinates
x	axial coordinate

Greek letters

ϵ	turbulence dissipation rate
ε_E	nozzle expansion- or area-ratio
γ	ratio of specific heats
μ	molecular viscosity
μ_t	turbulent- or eddy-viscosity
ω	specific dissipation rate
ρ	mass density
σ	diffusion coefficient
τ	shear stress
τ_{ij}	Reynolds shear stress

Subscripts

a	ambient or atmospheric
e	nozzle-exit
r	radial component
sep	separation
t	turbulence
w	wall
x	axial component

Superscripts

-	mean value
′	fluctuating value

Abbreviations

AUSM	Advection Upstream Splitting Method
C–D	Convergent–Divergent
CFL	Courant–Friedrich–Lewy
CTP	Compressed Truncated Perfect
DLR	German Aerospace Center
EVM	Eddy Viscosity Model
FSCD	Flow Separation Control Devices
FSS	Free Shock Separation
JPL	Jet Propulsion Laboratory
LEA	Laboratoire d'Etudes Aérodynamiques
MOC	Method of Characteristics
NPR	Nozzle Pressure Ratio (p_0/p_a)
RANS	Reynolds-Averaged Navier–Stokes
RSS	Restricted Shock Separation
SA	Spalart–Allmaras
SST	Shear Stress Transport
TIC	Truncated Ideal Contour
TOC	Thrust-Optimized Contour
TOP	Thrust-Optimized Parabolic
VAC	Volvo Aero Corporation
2-D	Two-dimensional
3-D	Three-dimensional

of the rocket engines. Hence accurate prediction of flow separation in rocket nozzles is important. Since flow separation in rocket nozzles is an unsteady phenomenon induced by shock, it is essential to simulate accurately the locations of the separation shock and flow separation in order to accurately predict the aerodynamic loads caused by shock-motion.

Several researchers have tried various turbulence models and have realized that accurate prediction of flow separation over a range of NPRs is challenging. Some models over-predict the separation location while some under-predict. The two eddy-viscosity based turbulence models, Spalart–Allmaras model and Shear Stress Transport (SST) model, are well known to predict separation location better than other eddy-viscosity models, but with moderate success. They fail to predict the separation location correctly, exhibiting sensitivity to the range of nozzle pressure ratios and to the type of nozzle. In 2006, a CFD workshop on the prediction of steady-state separation location in the DLR-TIC nozzle was organized by the European Flow Separation Control Device (FSCD) group in collaboration with the French ATAC group [31]. The Shear Stress Transport (SST) model was found to under-predict (upstream of the actual location) separation location for NPR $= 25$. But a modified value of the realizability constant A_s in the formulation of eddy viscosity, as suggested by Östlund, improved the separation location by moving the shock system downstream. Even better agreement with the experimental data was found by using the Spalart–Allmaras (SA) model, the Wilcox k–ω model and the k–ω model with Sarkar's compressibility correction. But, during assessment of four two-equation turbulence models in the simulation of the VAC-S1 nozzle (a TOP nozzle) [24], the SST model performed relatively better than the Wilcox k–ω model for NPR $= 12$, but by over-predicting (downstream of the actual location) the separation location. This is similar to the over-predictions in the simulations of the LEA-TOC nozzle [23] for NPR < 23.9 and in the simulations of the LEA-TIC nozzle [26] for NPR < 34.7. So, for lower NPRs, the SST model over-predicts separation location in the VAC-S1, the LEA-TOC and the LEA-TIC nozzles whereas it under-predicts in the DLR-TIC nozzle. And, it is not certain that the Wilcox k–ω performs always better than the SST model.

In another DLR-TIC nozzle with shorter divergent length [30], the SA model over-predicts the separation locations for NPRs < 25 and under-predicts for NPRs ≥ 25. In the RANS simulations of the VAC-S6-short nozzle (a TIC nozzle), using the SA model [16], the separation locations are slightly under-predicted for all NPRs and yet in good agreement with the experimental data. It is noticed that the results of these simulations match exactly with the results of the DES simulations [17] based on a modification to the SA model. It is also reported that there was no significant difference in the performances of the SA and the SST model in the simulations of the CTP nozzle [38].

Because of such indeterminism in correctly predicting flow separation by using the existing turbulence models, differences in the predictions are verified in this work. The performances of the SA and SST models, in terms of predicting separation location and pressure recovery, are compared with each other and evaluated against experimental data for one conical and two differently contoured subscale rocket nozzles. Causes of turbulence modeling failure in predicting nozzle flow separation correctly are investigated. The objective of this paper is to identify the underly-