Acta Astronautica 93 (2014) 13–22

Contents lists available at SciVerse ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Multi-objective design optimization of the transverse gaseous jet in supersonic flows

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ARTICLE INFO

Article history:
Received 18 February 2013
Received in revised form
18 June 2013
Accepted 22 June 2013
Available online 4 July 2013

Keywords:
Aerospace propulsion system
Transverse slot injection
Multi-objective design optimization
Variance analysis
Extreme difference analysis
Supersonic flow

ABSTRACT

The mixing process between the injectant and the supersonic crossflow is one of the important issues for the design of the scramjet engine, and the efficiency mixing has a great impact on the improvement of the combustion efficiency. A hovering vortex is formed between the separation region and the barrel shock wave, and this may be induced by the large negative density gradient. The separation region provides a good mixing area for the injectant and the subsonic boundary layer. In the current study, the transverse injection flow field with a freestream Mach number of 3.5 has been optimized by the non-dominated sorting genetic algorithm (NSGA II) coupled with the Kriging surrogate model; and the variance analysis method and the extreme difference analysis method have been employed to evaluate the values of the objective functions. The obtained results show that the jet-to-crossflow pressure ratio is the most important design variable for the transverse injection flow field, and the injectant molecular weight and the slot width should be considered for the mixing process between the injectant and the supersonic crossflow. There exists an optimal penetration height for the mixing efficiency, and its value is about 14.3 mm in the range considered in the current study. The larger penetration height provides a larger total pressure loss, and there must be a tradeoff between these two objection functions. In addition, this study demonstrates that the multi-objective design optimization method with the data mining technique can be used efficiently to explore the relationship between the design variables and the objective functions.

1. Introduction

The mixing of a sonic circular jet with a supersonic crossflow has been the subject of interest in many engineering applications, especially in the area of aerospace engineering [1,2], and this is due to the very short residence timescale for the mixture in supersonic flows, namely in the order of milliseconds [3,4]. At the same time, it is one of the very important issues for the design of the scramjet engine. The effective mixing between the injectant and the supersonic crossflow has an important impact on the improvement of the combustion efficiency in the scramjet combustor, and it results in higher heat release accordingly. Many experimental and computational approaches have been employed to investigation the flow field characteristics of the transverse jet, i.e. surface pressure measurement [5,6], Raman scattering measurement [7], Reynolds Averaged Navier–Stokes simulation [8–10], large eddy simulation [11–14], detached eddy simulation [15,16] and different turbulence models [17–20]. Additionally, the oblique shock wave can improve the mixing efficiency in the transverse injection flow field [21,22].

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0094-5765/$ - see front matter © 2013 IAA. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actaastro.2013.06.027

Recently, with the improvement of the computer capability, the combined CFD/MDO method has been employed successfully in various design optimization problems for scramjet components with multiple objective functions [23,24], and the data mining method has been applied in the aerospace engineering as well, namely the variance analysis method [25,26] and the extreme difference analysis method [27].

However, in the opinion of the authors, the information in the transverse gaseous injection flow field has not been explored comprehensively, especially the qualitative and quantitative evaluation, and the interaction between the objective functions is not clear. It is crucial to evaluate the information exists in the transverse injection flow field in order to improve the mixing process between the injectant and the supersonic crossflow. At the same time, the transverse injection flow field has rarely been optimized by the evolutionary algorithm in the open literature, but it is very useful for the design of the supersonic mixing scheme.

In this paper, the transverse slot injection flow field has been optimized by the non-dominated sorting genetic algorithm (NSGA II) coupled with the Kriging surrogate model based on the predicted results arranged by the orthogonal table, and the numerical method has been validated with the available experimental data in the open literature. In the optimization process, the injectant molecular weight, the slot width, the jet-to-crossflow pressure ratio, the injectant injection angle and the distance between the leading edge of the plate and the center of the slot have been chosen as the design variables. At the same time, the interaction between the objective functions has been evaluated by the variance analysis approach and the extreme difference analysis method. However, the consideration of the combustion is beyond the scope of this article, and the optimization of the reacting flow field will be carried out in the future.

2. Physical model and numerical method

2.1. Physical model

Fig. 1 shows the configuration of the transverse slot injection in supersonic flows, and the air flows from left to right. The configuration contains four main geometric parameters, namely the distance from the plate leading edge to the centerline of the slot (l), the slot width (w), the distance from the centerline of the slot to the exit boundary of the computational domain (s) and the injection angle (θ).

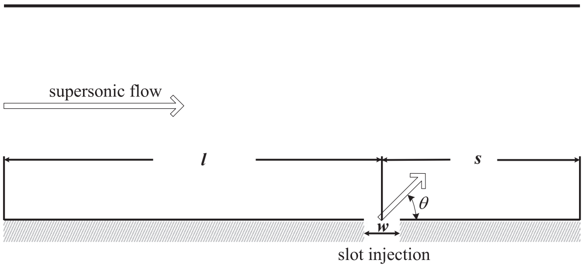

Fig. 1. Schematic of the transverse slot injection flow field.

In the current study, the distance from the centerline of the slot to the exit boundary of the computational domain (s) keeps constant, namely $s=68.58$ mm, and the other geometrical parameters are chosen as the design variables. At the same time, the air properties are set to a Mach number M_∞ of 3.5, a static pressure P_∞ of 3145 Pa and a static temperature T_∞ of 86.5 K. The jet flow Mach number M_j is set to be 1.0, with a static temperature $T_j=298$ K, and a jet-to-crossflow pressure ratio $P_j/P_\infty=8.74$, 17.12, 42.79 and 63.5. This means that the jet-to-crossflow pressure ratio is taken as one design variable as well. At the same time, the injectant type has a great impact on the transverse injection flow field in supersonic flows [28,29]; thus, the injectant molecular weight is also chosen as one of the design variables, and the hydrogen (H_2), nitrogen (N_2), methane (CH_4) and propylene (C_3H_6) are taken as the injectant in this paper. Both air and injectant are assumed to be calorically perfect with a constant specific heat ratio γ of 1.4.

The design of experiments methodologies is employed to arrange the numerical cases, and it is proved to be efficient in the optimization process [25,26,30]. There are five design variables as aforementioned, namely l, w, θ, P_j/P_∞ and the injectant molecular weight. Each design variance has four levels, i.e. $l\in\{100$ mm, 150 mm, 200 mm, 250 mm$\}$, $w\in\{0.1$ mm, 0.2 mm, 0.3 mm, 0.4 mm$\}$, $\theta\in\{30^\circ, 45^\circ, 60^\circ, 90^\circ\}$, $P_j/P_\infty\in\{8.74, 17.12, 42.79, 63.5\}$, and injectant$\in\{H_2, N_2, CH_4, C_3H_6\}$, and the specific experimental arrangement is given in Table 1. Table 1 shows the experimental design and turbulence models for the physical models, and the test cases are arranged by the orthogonal table $L_{16}(4^5)$.

2.2. Numerical method and code validation

In the current study, the two-dimensional Reynolds-averaged Navier–Stokes (RANS) equations are solved with density based (coupled) double precision solver of Fluent [31], and three different turbulence models, namely the Spalart–Allmaras, the RNG k–ε and the SST k–ω turbulence models, are employed to simulate the transverse slot

Table 1
Experimental design and turbulence models for the physical models.

	Injectant	w(mm)	P_j/P_∞	θ (deg)	l (mm)	Turbulence model
Case 1	H_2	0.1	8.74	30	100	RNG k–ε
Case 2	H_2	0.2	17.12	45	150	SST k–ω
Case 3	H_2	0.3	42.79	60	200	Spalart–Allmaras
Case 4	H_2	0.4	63.5	90	250	SST k–ω
Case 5	N_2	0.1	17.12	60	250	SST k–ω
Case 6	N_2	0.2	8.74	90	200	RNG k–ε
Case 7	N_2	0.3	63.5	30	150	SST k–ω
Case 8	N_2	0.4	42.79	45	100	Spalart–Allmaras
Case 9	CH_4	0.1	42.79	90	150	Spalart–Allmaras
Case 10	CH_4	0.2	63.5	60	100	SST k–ω
Case 11	CH_4	0.3	8.74	45	250	RNG k–ε
Case 12	CH_4	0.4	17.12	30	200	SST k–ω
Case 13	C_3H_6	0.1	63.5	45	200	SST k–ω
Case 14	C_3H_6	0.2	42.79	30	250	Spalart–Allmaras
Case 15	C_3H_6	0.3	17.12	90	100	SST k–ω
Case 16	C_3H_6	0.4	8.74	60	150	RNG k–ε