Analytical Study of Swirler Effects in Annular Propulsive Nozzles

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Abstract

THIS paper presents an analytical performance prediction methodology for annular propulsive nozzles with swirl introduced ahead of the combustor that feeds the nozzle. The methodology is applied to investigate the effects of swirler design on nozzle performance. Four types of swirlers are investigated: free vortex, constant angle, forced vortex, and Rankine vortex swirlers. Discharge coefficients and specific impulses are presented.

Contents

Introduction

Recent studies indicate that the introduction of swirl in axisymmetric dump combustors can have very beneficial effects on the combustion process. Buckley et al.[1] found that swirl both reduced the reattachment length of the combustor flowfield (thus reducing the overall combustor length needed for good performance) and helped eliminate destructive very low-frequency instabilities.

Conley et al.[2] presented an analytical and experimental investigation of the performance of annular propulsive nozzles without swirl. Kornblum et al.[3] extended that methodology to include the effects of swirl introduced ahead of the combustor for free vortex swirlers. The present work is an extension of the latter methodology to include constant angle swirlers, forced vortex swirlers, and Rankine vortex swirlers.

Performance Prediction Methodology

The geometric model considered in this investigation is presented in Fig. 1. Air enters at station A and flows through a swirler where tangential momentum is transferred to the air to give the desired tangential velocity distribution at station B. Station B is followed by a sudden expansion dump into the combustor at station C. Combustion takes place between stations C and D, where the stagnation temperature rises due to the combustion energy release and the stagnation pressure decrease due to friction, mixing, and heat addition. The combustion products accelerate in the nozzle, choke at the nozzle throat at station E, and accelerate supersonically from station E to F.

The concern in the present study was the effect of swirl on the performance of the nozzle (i,e., the mass flow rate, thrust, and specific impulse). Consequently, the swirler, the sudden expansion dump, and the combustor are not modeled in detail. Emphasis is placed on the nozzle flowfield. The swirl introduced by the swirler is assumed to flow through the combustor and nozzle unchanged in magnitude.

The swirler is a set of axial flow guide vanes that imparts the desired tangential velocity distribution to the air as it passes through the swirler, i.e., from section A to section B in Fig. 1. Buckeley et al.[1] experimentally investigated four types of tangential velocity distributions at the swirler exit. They are the following:

Free vortex: $$w = C_1/y \tag{1}$$

Constant angle: $$w = C_2 u = u \tan\alpha \tag{2}$$

Forced vortex: $$w = C_3 y \tag{3}$$

Rankine vortex: $$w = (C_4/y)\,[1 - \exp(-y^2/Y_2^2)] \tag{4}$$

where w is the tangential velocity, u is the axial velocity, the constants $C_1 - C_4$ are specified to achieve the desired tangential velocity distribution, y is the radial coordinate, and Y_2 is the wall radius. In the present study, all four swirler types were considered. The effects of swirl were correlated with the mass-averaged swirl $\overline{yw}$

$$\overline{yw} = \frac{1}{\dot{m}} \int_{Y_1}^{Y_2} yw \, \mathrm{d}\dot{m} = \frac{1}{\dot{m}} \int_{Y_1}^{Y_2} yw\rho u 2\pi y \, \mathrm{d}y \tag{5}$$

where Y_1 is the inner radius of the flow passage.

The swirl distribution at the nozzle inlet, station D, was determined from the swirl distribution at the swirler exit, Station B, by an approximate analysis that neglected viscous effects. That analysis required the swirl yw to remain constant on a streamline, neglected the radial velocity component, assumed radial equilibrium, and assumed known values of the stagnation pressure and temperature at the swirler inlet, station A. These conditions were combined with the velocity distributions described by Eqs. (1-4) to determine the swirl distributions at the nozzle inlet, station D.

Flowfield Model

The flowfield model is based on the following assumptions: 1) steady axisymmetric flow, 2) inviscid nonconducting fluid, 3) no body forces, 4) thermally and calorically perfect gas, and 5) empirical separation and base pressures. A subsonic/transonic solution is required to define the mass flow rate and throat thrust, while a supersonic solution is required to define the cowl, plug, and base thrusts.

The finite-difference code developed by Marcum and Hoffman[4] was used to calculate the subsonic/transonic flowfield. That program solves unsteady, three-dimensional, inviscid flowfields in superelliptical nozzles with centerbodies. An option exists for calculating unsteady axisymmetric swirling flowfields in axisymmetric nozzles. The direct marching method of characteristics code developed by Kornblum and Thompson[5] was used to calculate the supersonic flowfield. The base pressure on the face of the truncated plug was computed from the empirical correlation

$$P_{\text{base}} = 0.846. \ P_F/M_F^{1.3} \tag{6}$$

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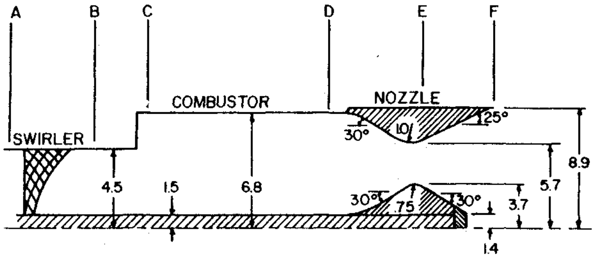

Fig. 1 Nozzle geometry.

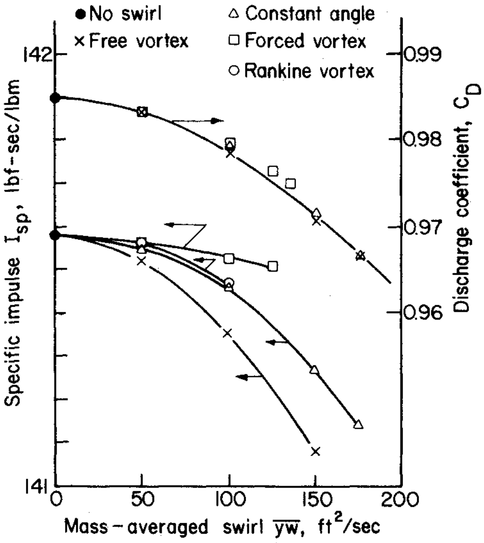

Fig. 2 Discharge coefficient and specific impulse.

where M_F and P_F are the Mach number and static pressure of the flow approaching the base. Equation (6) fits measured data only when the base area is small. It gives unrealistically high values for highly truncated plugs.

Results

Nozzle flowfields were computed for 13 cases. Figure 1 defines the flowfield geometry for all 13 cases. The swirl strength was characterized by selected values of the mass-averaged swirl $\overline{yw}$. Values of $\overline{yw}$ of 0 (the no-swirl case), 50, 100, and 150 ft^2/s for the free vortex swirler, of 50, 100, 150, and 175 ft^2/s for the constant angle swirler, of 50, 100, and 125 ft^2/s for the forced vortex swirler, and of 50 and 100 ft^2/s for the Rankine vortex swirler were analyzed. The stagnation temperature and pressure at the nozzle inlet were 2500°R and 35 psia, respectively. In all cases, the specific heat ratio $\gamma = 1.40$ and the gas constant $R = 53.35$ (ft-lbf)/(1bm-R). These values of swirl cover the practical range of interest for the geometry and temperature considered in this study. Higher values of swirl result in supersonic Mach numbers at the swirler exit and were therefore not considered.

The mass flow rate was determined by integrating across the initial-value line that is generated from the results of the transonic analysis. The zero-swirl discharge coefficient (0.9853) reflects the two-dimensional nature of the flowfield and is a function of the transonic geometry. The discharge coefficients are presented in Fig. 2 as a function of the mass-averaged swirl. The values decrease with increasing swirl in a smooth, consistent manner and correlate very well for all four swirler types.

The thrust was determined by integrating the momentum and pressure thrusts across the transonic initial-value line, the pressure thrusts along the wall and centerbody, and the pressure thrust on the face of the truncated plug. The corresponding specific impulse is also presented in Fig. 2 as a function of mass-averaged swirl. The results indicate that the decrease in the vacuum specific impulse is a function of swirler design and is least for forced vortex swirlers and greatest for free vortex swirlers. In fact, the decrease for the forced vortex swirlers is very small. This result suggests a preference for forced vortex swirlers as far as nozzle performance is concerned, all other factors being equal. The specific impulses of the constant angle and Rankine vortex swirlers lies between the value for the forced and free vortex swirlers. However, the maximum decrease in the specific impulse is only 0.35%.

In most cases of interest for ramjet or turbojet applications, the values of the mass-averaged swirl $\overline{yw}$ are no more than about 100 ft^2/s, and the effect of swirl on the nozzle performance is small and can probably be neglected in preliminary design and overall performance calculations.

Conclusions

An analytical performance prediction methodology for predicting the effects of swirl in annular propulsive nozzles has been developed. The computed results indicated that swirl decreases the discharge coefficient, the thrust, and the vacuum specific impulse. The decrease in the discharge coefficient correlates with the mass-averaged swirl $\overline{yw}$ for all four types of swirlers. The decrease in the vacuum specific impulse is a function of the swirler design and is least for forced vortex swirlers and greatest for free vortex swirlers.

Acknowledgments

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