Theoretical Evaluation of Rigid Baffles in Suppression of Combustion Instability

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Theme

THE stability improvement of combustors implemented with rigid, injector-face baffles has been experimentally verified[1]; however, the reliability of this damping device has been limited since a few combustors have failed to gain stability improvement. Previous analytical attempts at modeling the involved unsteady confined flow have failed in that they predict a destabilizing effect with the addition of a baffle to a combustor. The purpose of this work is to examine a possible fluid dynamic mechanism for the damping produced by the baffle. This analysis incorporates viscous and turbulence effects in a dissipation model which is used in a stability evaluation of baffled combustors having a concentrated combustion source at the injector and a short, constant Mach number nozzle.

Results of this study agree qualitatively with experimental observations and show that sufficient energy dissipation exists at the baffle blade tips to indicate that the primary mechanism of the damping is indeed a fluid dynamic loss. The response of the dissipation model to varying oscillation amplitude, wave character, and baffle blade length is presented.

Contents

The linearized partial differential equation governing the unsteady confined flow (refer to Fig. 1) is represented as

$$\nabla^2\phi' - \phi'_{tt} = 2M\phi'_{tz} + M^2\phi'_{zz} \tag{1}$$

where M is the steady-state mean flow Mach number, and ϕ' is the perturbed velocity potential represented with the time dependence $\phi' = \phi(r)e^{i\omega t}$. The corresponding equation for the perturbed pressure is thus

$$P' = -\gamma\phi'_t - \gamma M\phi'_z \tag{2}$$

Bounding the solution at the injector and nozzle entrance are gain/loss relationships. It is assumed that the combustion is concentrated on the injector surface, and using Crocco's time lag theory[2] the following boundary condition is obtained

$$(MP'/\gamma + \phi'_z)|_{z=0} = Mn(P'(t) - P'(t-\bar{\tau}))|_{z=0} \tag{3}$$

where n and $\bar{\tau}$ are, respectively, the interaction index and the sensitive time lag.

At the opposite end of the chamber the unsteady flow is assumed to enter a constant Mach number nozzle,[3] and the nozzle entrance boundary condition becomes

$$\phi'_z|_{z=L} = M\frac{(\gamma-1)}{2\gamma}P'|_{z=L} \tag{4}$$

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On the remaining surfaces (including the baffle blade surface) hard wall boundary conditions are imposed, and the normal component of velocity vanishes along these surfaces.

Because of the discontinuous geometry of this problem, separate solutions are found for the baffle cavities and the main chamber. A matching of these solutions at an artificial interface connecting these regions produces the complete solution. The solution within the baffle cavities is represented using an eigenfunction expansion which satisfies the boundary conditions at the baffle blade surfaces and the injector face gain/loss condition. Within the main chamber the solution is represented with standing or traveling wave eigenfunctions which satisfy the nozzle entrance condition and the hardwall boundary condition along the cylindrical periphery. Continuity of pressure and axial velocity provide the matching requirements at the interface connecting the regions.

Since an eigenvalue problem is posed with the boundary conditions, an additional equation is obtained by normalizing the solution to a particular mode of oscillation within the main chamber. This equation is used to compute the frequency of the wave motion within the baffled combustor.

An iterative procedure is used to calculate the series coefficients, and the converged solution produces velocity and pressure profiles which are comparable to an earlier study.[4] These profiles also agree with experimentally determined wave motions presented in the previous analysis. Of most significance is the prediction of a strong flowfield which encircles the baffle blade tips ($z = z_B$). Unfortunately, the series solutions suffer severe convergence problems in these regions, and a more representative solution is required. A local polar coordinate system, depicted in Fig. 2, is set up at the baffle blade tips, and Eq. (1) is transformed accordingly. An asymptotic solution, valid for small ζ, is then found and is represented as

$$\phi' = [a(r)\zeta^{1/2}\cos\alpha/2 + k(r)]^{e^{i\omega t}} + O(\zeta) \tag{5}$$

The functions $a(r)$ and $k(r)$ are obtained by matching the solution with the outer series expansions at a fixed ζ_c.

This asymptotic solution indicates the singular nature of the velocity field, i.e., $\partial\phi/\partial\zeta \to \infty$ as $\zeta \to 0$. The possibility of significant energy dissipation is then investigated by incorporating the proper boundary-layer corrections. A time-averaged value of the mechanical energy dissipation due to unsteady flow which occurs locally at the baffle blade tips is

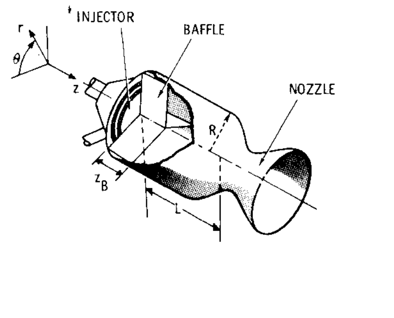

Fig. 1 The geometry of the baffled combustion chamber.

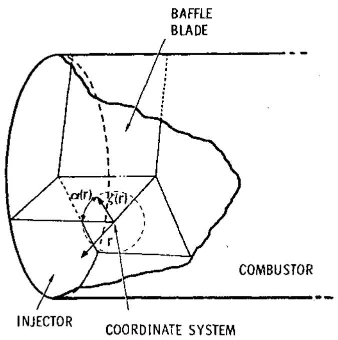

Fig. 2 The polar coordinate system at the baffle blade tips.

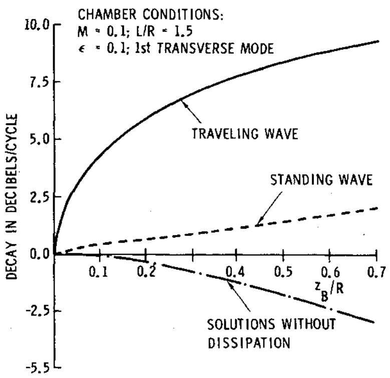

Fig. 3 The effect of wave amplitude on decay in decibels/cycle vs baffle blade length.

represented in the following integral relationship[5]

$$E_{\mathrm{dis}} \cong \langle \gamma \int_{S_B} \left(\frac{\mu\omega}{2}\right)^{1/2} \nabla\phi' \cdot \nabla\phi' ds \rangle \tag{6}$$

where the surface S_B is the surface which bounds the vortex region at the baffle blade tips. This region is characterized with a dimension which is of the order of the baffle blade thickness. The effects of the turbulent flowfield are included, in a gross sense, by modifying the viscosity term to one which is dependent on the local flow conditions. This effective viscosity[6] is represented as

$$\mu_{\mathrm{eff}} = c\langle (M^2 + \nabla\phi' \cdot \nabla\phi')\rangle^{1/2} \tag{7}$$

where the constant c is of the order 0.05.

Rather than correcting the boundary conditions at the baffle blade tips to account for this dissipation, as is done in acoustic theory, a more direct method of stability prediction is applied.[7] This choice of method is in the spirit of existing acoustic liner damping predictions in which nonlinear (amplitude dependent) damping mechanisms are combined with linear wave motion models. Mathematically, this relationship, correct to second-order, is given as

$$2\lambda\langle \int_V \left\{ \frac{P'^2}{2\gamma} + \gamma\nabla\phi' \cdot \nabla\phi' + M\phi'_z P' \right\} dV \rangle$$

$$= \langle \oint_S \left\{ P'\nabla\phi' + \frac{P'^2}{\gamma} Me_k \right\} \cdot ds \rangle \tag{8}$$

where λ is the decay rate of the oscillation. The surface integral physically represents the energy extraction (or addition) at the appropriate surfaces. Along the baffle blade surface this integral is directly equated to the dissipation integral, Eq. (6).

A combustor with length to radius ratio $L/R = 1.5$ is used with a evenly spaced 3 compartment baffle configuration. The blade thickness to chamber radius is chosen to be 0.05, and the parameters n and $\bar{\tau}$ are chosen so that a neutrally stable unbaffled combustor is referenced.

Figure 3 depicts the prediction of decay rate for various baffle blade lengths (nondimensionalized by chamber radius) for a combustor which has a mean flow Mach number of 0.1. Two wave amplitudes ($\epsilon = |\phi'| = 0.1$ and 0.2) are shown and indicate the trends of the experimental data.[1] It is noted that the damping ability improves with an increase in wave amplitude. This implies that the baffle is most effective in damping moderately large amplitude waves, and that a baffle can be designed (in a conservative sense) using a small amplitude theory.

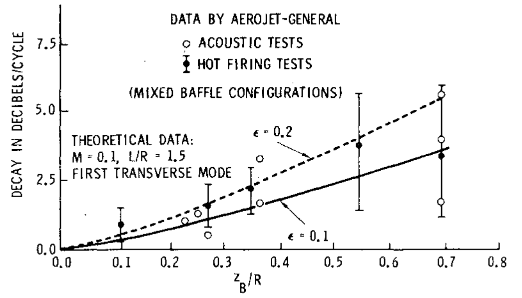

Fig. 4 The standing and traveling wave predictions of decay/cycle vs. baffle blade length.

Figure 4 compares the stability predictions for a standing wave solution and a traveling wave solution. It is seen that the traveling wave is most affected by the presence of the baffle and produces decay rates that are much greater than those of the standing wave solution. It is then apparent that the phasing between the oscillations in the main chamber and standing wave oscillations in the baffle cavities produce different stability results. This observation has been experimentally verified.[8]

Also included in this figure is the trend of the stability of the flow when the dissipation at the baffle blade tips is neglected. The importance of this dissipation is emphasized since a destabilizing effect (consistent with the Rayleigh criterion[9]) is produced when it is absent.

For the first time, a stabilizing influence for the baffle has been predicted, and results are placed within the trends of the experimental data. This analysis shows that sufficient energy dissipation exists at the baffle blade tips to indicate that the mechanism for the damping produced by the baffle is a fluid dynamic loss.

Acknowledgment

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