SOME ASPECTS ON THE JOINT GE/VOLVO DEVELOPMENT OF THE F404/RM12 AUGMENTOR

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Abstract

A derivative of the GE F404 augmented turbofan jet engine, called RM12, was developed in partnership with Volvo Flygmotor for the Swedish JAS 39 Gripen fighter aircraft. During the development, a half-scale plexiglass model was tested in a water tunnel and the commercially available computer code FLUENT was used to study the aerodynamic flowfield without and with combustion. In this paper, full scale engine development test results, water tunnel flow visualization results and corresponding computational results are presented revealing some of the interesting aspects of the development of the F404/RM12 augmentor. Especially the effect of inlet swirl on the augmentor performance is discussed.

Nomenclature

A	area
C_1, C_2	convection terms
D	flameholder disk width
H	enthalphy
i	stoichiometric mass ratio
$\dot{m}$	mass flow
ma	mass fraction
p	pressure
R	specific gas constant
R_1, R_2	radiation terms
T	temperature
u	mean axial velocity
w	mean tangential velocity
γ	ratio of specific heats
η	efficiency
$\emptyset$	fuel-air equivalence ratio

Subscripts

a	air
ab	afterburner
ef	effective
fu	fuel
gg	gasgenerator
id	ideal
in	inlet
ox	oxygen
pr	products
s	stoichiometric
th	thrust
w	wall

Introduction

A derivative of the GE F404 augmented turbofan jet engine was developed in partnership with Volvo Flygmotor AB for the Swedish airfighter JAS. This engine is designated the RM12 and is an improved performance version of the present F404-400/F18 model. Differences in augmentor operating conditions such as inlet pressure, temperature, velocities, swirl angles etc necessitated new design considerations for this application. The development process requires significant testing before a final configuration can be chosen, the so called cut and try method. However, today there also exist analytical tools such as three-dimensional computer codes which have proved to be helpful in the development process. In this work, the commercially available 3D-code FLUENT† was used. Besides applying the computer code, a half-scale plexiglass model of the augmentor was also built and tested in a water tunnel at Volvo Flygmotor.

Volvo and GE extensively analyzed the combustion flowfield with two-dimensional axisymmetric and three-dimensional FLUENT computational flow models of the augmentor. The effects of the augmentor flowfield boundary conditions were studied. In particular flow swirl angles were evaluated for their predicted effects on the augmentor performance. Liner wall temperatures were also calculated.

Development engine test results are compared with computer code analysis and water tunnel testing. Conclusions are drawn with regard to augmentor combustion pressure oscillations and augmentor thrust effective efficiency.

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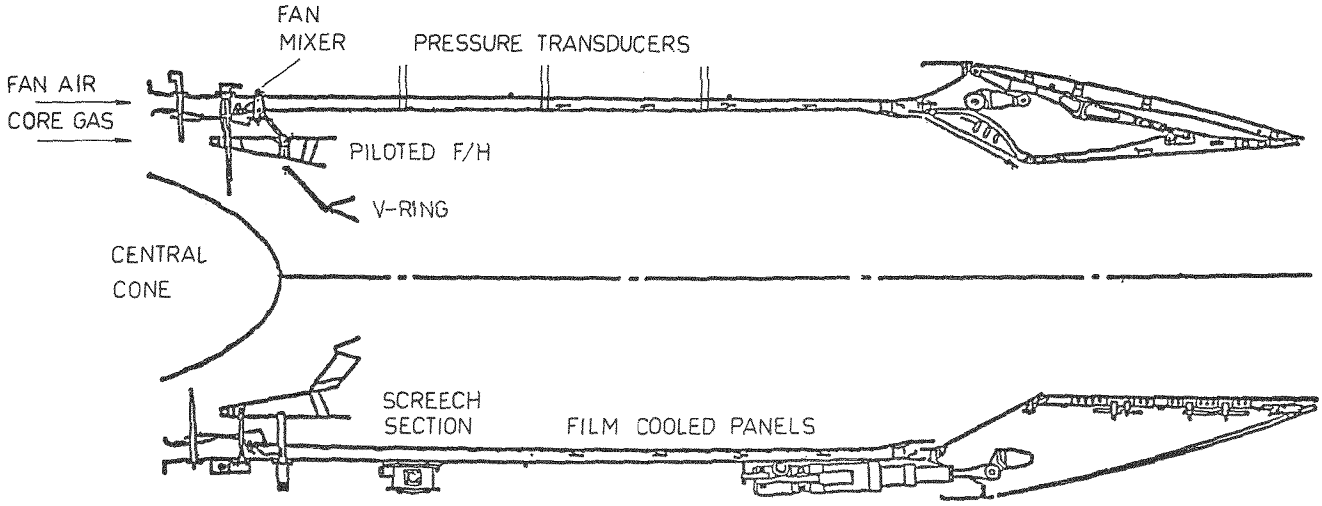

Figure 1. Augmentor and variable exhaust nozzle cross section.

The RM12 augmentor

The mixed flow RM12 augmentor cross section is shown in Figure 1. A large piloted flameholder system is located midstream, complemented on the inside by a V-ring for flameholding and flamespreading at high augmentor fuel-air ratios. The flameholder system and centerbody are selected to provide stable diffusion and uniform flowfield conditions in the augmentor.

During the development of a modern augmented turbojet/turbofan gas turbine engine, the following parameters must be considered when selecting the thrust augmentation system:

- The anticipated range of augmentor inlet gas stream pressure, temperature and velocity profiles throughout the flight envelope for all engine operating conditions.
- Required performance level and maximum augmentation ratio.
- The anticipated engine transient operating characteristics.
- Hardware life/durability requirements.

A key aspect in selecting and sizing an augmentor design, involves consideration of the fundamental stability characteristics of the flameholder system. This one has a characteristic fuel-air ratio versus loading parameter curve like that shown in Figure 2 (Ref 1). Typically, such test data was taken with well behaved inlet conditions, i.e. uniform pressure, temperature and velocity profiles. As gas turbines have become more compact for improved thrust-to-weight performance, the flameholding and diffusing functions have become integrated resulting in possible non-uniform flowfield conditions approaching the flameholder and undesirable

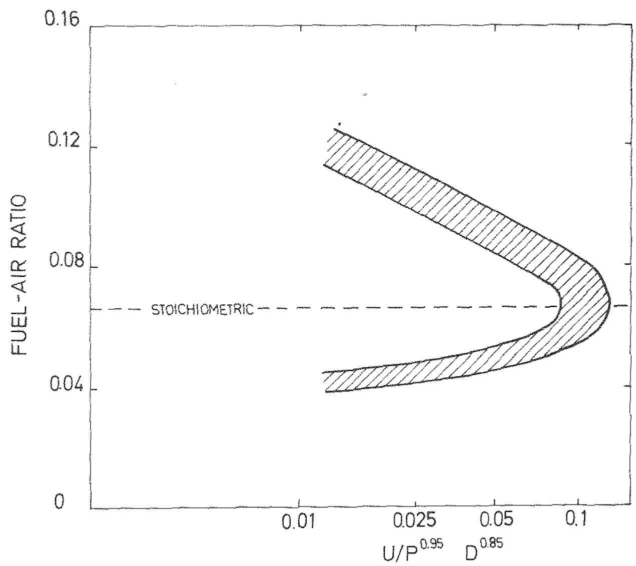

Figure 2. Typical flameholder stability loop.

secondary flows downstream in the augmentor. Additionally, as the fundamental stability limit of the flameholder system is approached, the combustion process may couple with one of the many acoustic resonant modes resulting in unacceptable levels of acoustic pressure oscillations known as augmentor screech or rumble.

Water tunnel

A half-scale plexiglass model of the augmentor was designed and tested in a water tunnel. The water tunnel enables visualization of the general flow pattern, makes it possible to study fuel injection by using colored water and also gives an idea about flow oscillations.

The effects of various geometry changes to the flameholder and centerbody on the augmentor flowfield were evaluated. Water tunnel inlet swirl angles were varied from 0 to 20 degrees. The water tunnel has been a helpful tool, especially the video recordings are useful. Although it does not give the whole thruth, it contributes to the understanding of the flow conditions in the augmentor. Most of the material is best shown on video, and thus information about the water tunnel tests in this paper is limited to a comparison with results from the analytical predictions in the next chapter.

Analytical tool

Models

There exist several commercial codes as well as company developed 2D and 3D computer codes for the analysis of combustors. In this work, version 2.99 of the commercial computer code FLUENT was used.

The complexities in evaluating reaction rates for practical fuels are such that in the near future the use of only a small number of finite-rate reaction mechanisms may be the only practical way. The simplest model available, and the one used in FLUENT, is to assume that the reaction proceeds via a single-step irreversable reaction of the form:

$$ma_{fu} + i\ ma_{ox} \rightarrow (1 + i)ma_{pr} \qquad (1)$$

The chemical reaction rate is controlled either by mixing of the eddies containing reactants or by an Arrhenius rate expression. The influence of turbulence on the reaction rate is taken into account by employing the Magnussen and Hjertager model[2]. Turbulence was described with a standard k-ε model.

The effect of radiation is modelled with a six-flux method and a grey-gas model using constant values for the absorption and scattering coefficients throughout the flow field.

The droplets are tracked in a Lagrangian frame of reference, where the path through each finite-difference cell is broken into a number of time steps. Droplet trajectories are calculated every tenth gas-phase iteration and the fuel mass evaporated is introduced into the gas-phase at the appropriate grid cell.

The governing partial differential equations are reduced to their finite difference form by integration over the computational cells into which the domain is divided. The set of simultaneous algebraic equations are solved with the SIMPLE-algorithm of Patankar and Spalding[3].

Boundary conditions

The amount of air (pure air) entering through the mixer, the screech holes and the film-cooling holes were calculated using a separate computer code which considers the casing and liner geometry as well as the pressure conditions at the outside and inside of the augmentor liner. The pressure distributions used in this augmentor 'annulus flow program' were based on measured values.

The air entering the augmentor via the gas generator has taken part in the combustion process in the main combustor and thus some of the oxygen has been consumed. The oxygen mass concentration at the inlet to the augmentor was calculated from:

$$ma_{ox} = \frac{0.233\ (1 - \phi_{gg}\ \eta_{gg})}{1 + \dfrac{\phi_{gg}}{15.045}} \qquad (2)$$

In order to introduce the liquid fuel into the computer code, knowledge of droplet sizes and droplet distribution as well as the fuel mass distribution is needed. Droplet sizes were calculated using standard empirical expressions and an idea of the fuel distribution and the fuel penetration was given by applying the work by Hojnacki[4].

Calculation

The augmentor was modelled in a two--dimensional axisymmetrical system using a grid of 47 cells in the axial direction and 37 cells in the radial direction. Calculations using a full three-dimensional grid have also been done and it was found that the difference of flow-pattern and temperature distribution with the 3D-case as compared to the 2D-case was negligible. Considering the geometry, it is only the spray bars that are really three-dimensional. The three-dimensional calculations with a non-uniform fuel distribution showed that fuel and air mixed well before reaching the combustion zone. A reason for this is that the droplet sizes were small and thus evaporation was quick, giving fuel and air plenty of time to mix. The results presented in this paper are from two-dimensional calculations.

Several different swirl-angles at the augmentor inlet were studied with the code and the water tunnel. Figure 3a and Figure 3b shows a comparison of the results with a uniform inlet swirl of 15 degrees. The calculated result shows the flowfield for a dry (non-burning) augmentor. In order to better illustrate the flow pattern, the velocity vectors shown in Figure 3b are not in scale. When performing calculations with combustion, the fuel was introduced at the location of the spray-bars and the local fuel-air ratio inside the main flameholder was chosen to the stoichiometric value. The remaining fuel was inserted outside the flameholder, and for an augmentor at full thrust this gives fuel-rich conditions at the location where the fuel is introduced. However, as fresh air enters through the screech and film-cooling holes the fuel-air ratio will decrease.

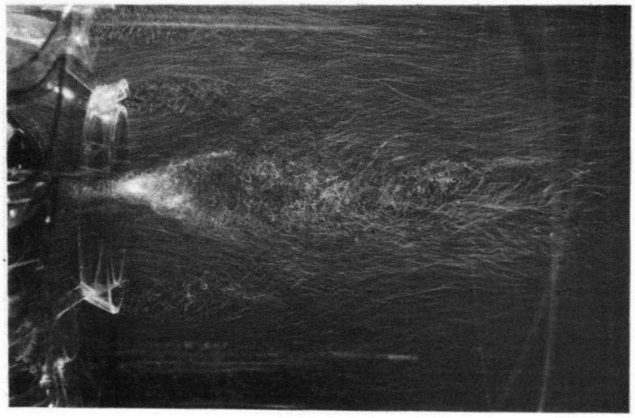

Figure 3a. Flow pattern from water tunnel test, inlet swirl 15 degrees.

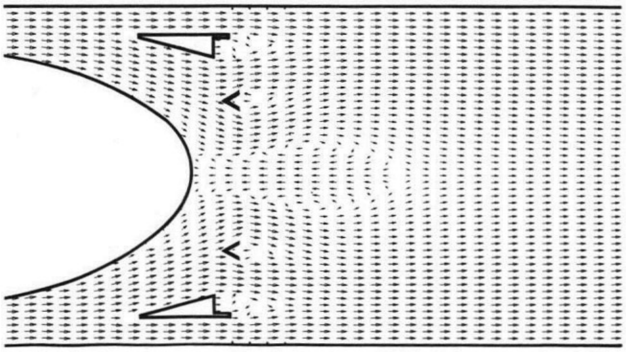

Figure 3b. Calculated flow pattern for a dry augmentor, inlet swirl 15 degrees.

In the present work, a single-step reaction mechanism was used. It is difficult to find reliable values on the constants in the reaction rate for such a global reaction. The fuel in the augmentor is JP4 and it consists of several fractions which makes the modelling even more difficult. The procedure applied in this work was to use measured inlet and outlet average temperatures and pressures, and adjust the preexponential factor in the Arrhenius expression until reasonable outlet values were achieved in the computer code. The chosen factor gave as a result that the molecular mixing is the controlling mechanism for combustion in most parts of the augmentor. However, along the combustion liner the kinetics control the chemical reaction because of low temperatures of the entering fan air. This is what one would expect.

Figure 4 illustrates the calculated temperature distribution for a wet augmentor (burning). The recirculation region behind the central cone is predicted to act as a flame stabilization zone.

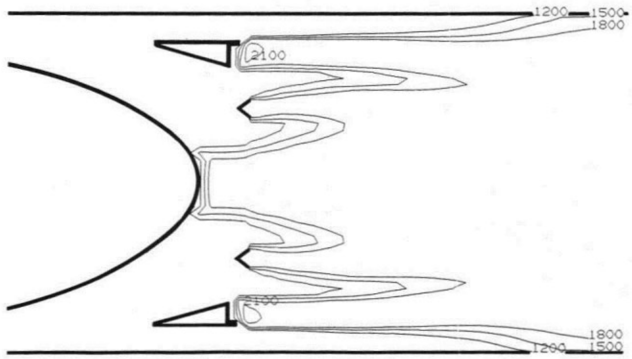

Figure 4. Temperature distribution for a wet augmentor, inlet swirl 15 degrees.

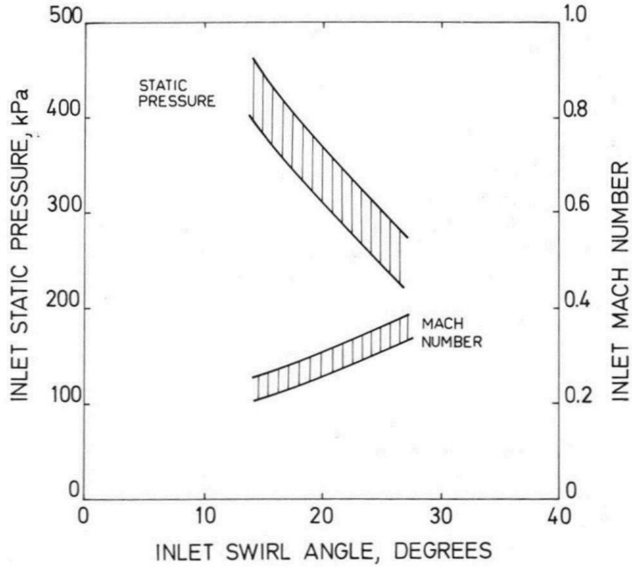

Figure 5. Augmentor inlet conditions.

Test results and analysis

Augmentor pressure oscillations

The effects of augmentor inlet swirl on combustion pressure oscillations were investigated. Average turbine discharge swirl angle and augmentor fuel-air ratio were varied on a sample of four engines by manipulating engine control schedules at fixed engine inlet conditions of 322 K to 344 K and 101 kPa. The range of augmentor pressure level and inlet Mach number as function of average discharge swirl angle are shown in Figure 5. These parameters are uniquely related to the swirl angle as shown. Hence, test results were plotted against swirl angle because it represents a unique value of the flameholder combustion stability parameter as shown in Figure 2. Augmentor dynamic acoustic pressure oscillations were measured in the combustion chamber as shown in Figure 1. The real time signal was analyzed on a Spectral Dynamics SD345 Fast Fourier Transform Analyzer.

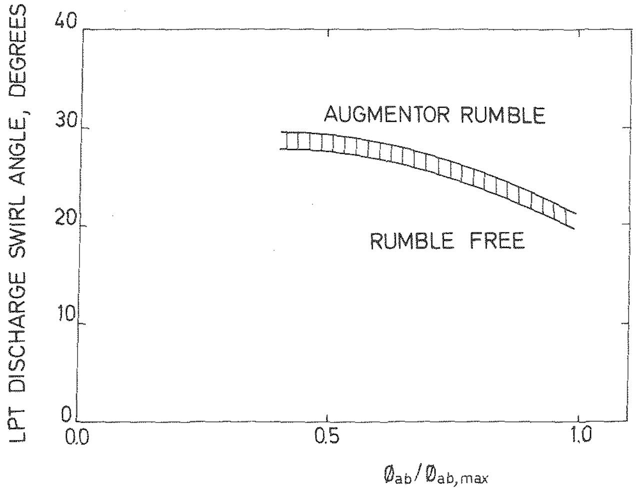

Figure 6a. Engine rumble experience.

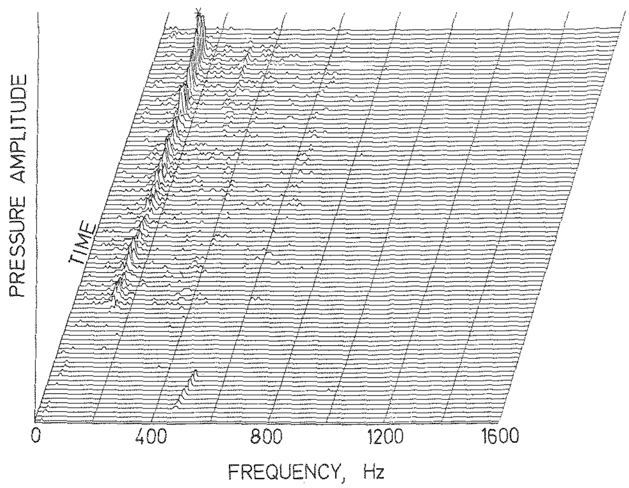

Figure 6b. Augmentor dynamic acoustic pressure oscillation.

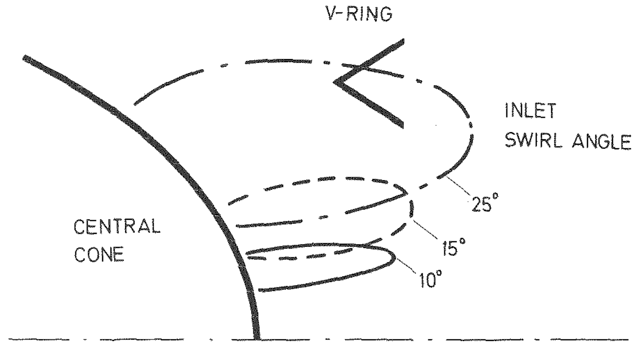

Figure 7. Region of high tangential velocity (W/U_{in} = 0.7).

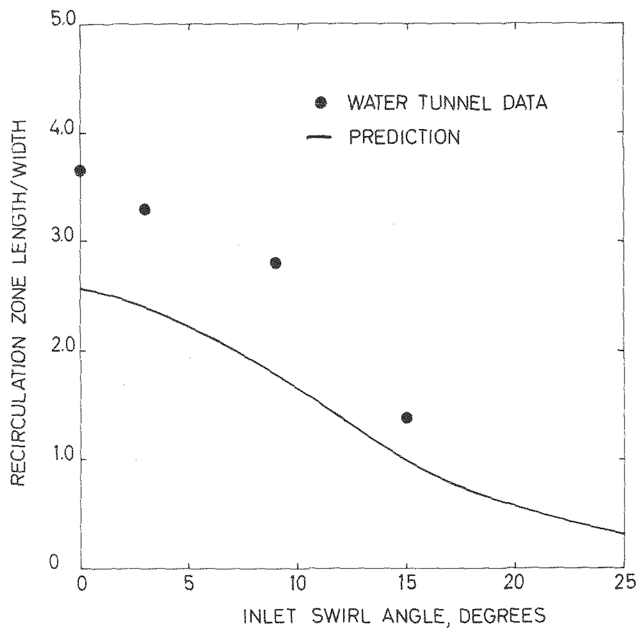

Figure 8. V-ring flameholder recirculation zone length.

The test results are summarized in Figure 6a. On the basis of the four engine samples, an augmentor 'rumble boundary' was defined as a function of turbine discharge swirl angle and augmentor fuel-air ratio. The boundary was defined at the fuel-air ratio at which discrete frequency activity at 170 Hz exceeded 7 kPa of peak-to-peak activity. Typically the amplitude would rise rapidly to a maximum of approximately 35 kPa as shown in Figure 6b. The 170 Hz rumble corresponds to excitation of the longitudinal mode of acoustic resonance which is the typical mode of oscillation at poor flameholding conditions.

Using the FLUENT results some conclusions can be drawn. Figure 7 illustrates how the region of high tangential velocity (arbitrarily defined as W/U_{in} = 0.7) changes with inlet swirl. The high tangential velocity region increases and moves out towards the inner V-ring flameholder as the swirl increases. This effect will lead to disturbances of the flow field behind the inner flameholder including a higher value of the loading parameter. At the same time, the recirculation region behind this flameholder will decrease as is shown in Figure 8. The combination of these effects can lead to unstable combustion.

Performance measurement

Augmentor efficiency is based on the 'thrust effective' average exhaust gas enthalpy which is derived from the actual measured thrust under controlled test conditions. The efficiency is then calculated by ratioing the 'thrust effective' enthalpy rise to the ideal enthalpy rise which assumes 100% chemical combustion efficiency and a completely mixed homogeneous mixture exiting the augmentor, i.e. a uniform exit temperature profile.

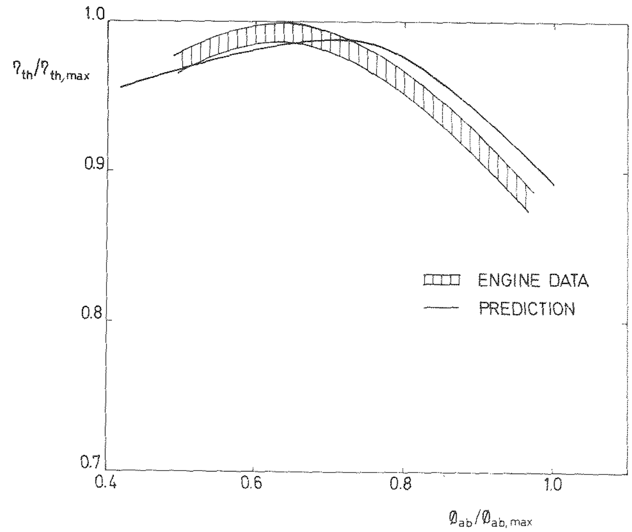

Figure 9. Measured and predicted thrust efficiency.

$$\eta_{th} = \frac{H_{th,ef} - H_{in}}{H_{th,id} - H_{in}} \qquad (3)$$

If the exhaust gas temperature, pressure and velocity profiles are known from measurements, or computer calculations, the 'thrust effective' average exhaust gas temperature is determined from integrating the momentum equation across the exhaust stream as follows:

$$T_{th,ef} = \left[\frac{\Sigma \dot{m}_i \sqrt{T_i}}{\Sigma \dot{m}_i} \right]^2 \qquad (4)$$

However, a simpler method is employed on gas turbines employing fixed conic nozzles. The thrust and flow coefficients are usually well known from lab experiments for a fixed geometry conic nozzle. The thrust and flow coefficients are defined as follows from conservation of momentum and continuity respectively:

$$C_{th} = \frac{T_{th}}{\dot{m} \quad T_0 \left(\frac{2 \gamma R}{g(\gamma - 1)} \left(1 - (p/p_0)^{\frac{\gamma-1}{\gamma}} \right) \right)^{1/2}} \qquad (5)$$

$$C_f = \frac{\dot{m} \quad T_0}{Ap_0 \quad \frac{\gamma g}{R} \left(1 + \frac{\gamma - 1}{2} \right)^{- \frac{\gamma + 1}{2(\gamma - 1)}}} \qquad (6)$$

Special water cooled total pressure rakes are used to measure the augmentor exit pressure (nozzle inlet). From the above equations, there are three possible solutions to the average exhaust temperature: the continuity equation, the thrust equation and by combining the thrust and continuity equations (eliminating nozzle inlet temperature from the equation) as follows

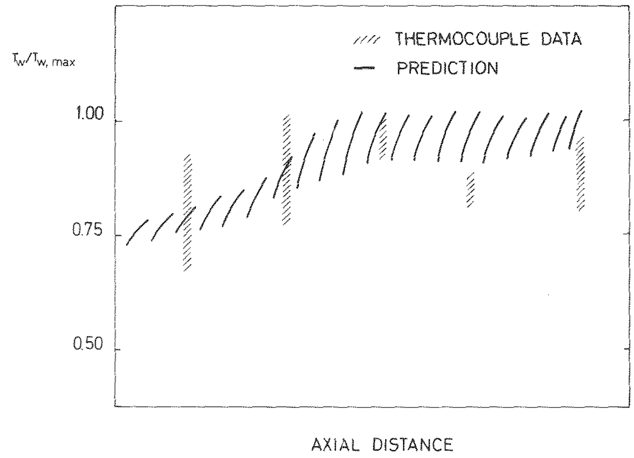

Figure 10. Measured and predicted liner wall temperature.

for the 'combined' solution:

$$C_f \frac{Ap_0}{\dot{m}} \sqrt{\frac{\gamma g}{R}} \left(1 + \frac{\gamma - 1}{2} \right)^{\frac{\gamma + 1}{2(1 - \gamma)}} =$$

$$= \frac{T_{th}}{C_{th} \, \dot{m}} \; \frac{1}{\frac{2 \gamma R}{g(\gamma - 1)} \left[1 - \left(\frac{p}{p_0} \right)^{\frac{\gamma - 1}{\gamma}} \right]} \qquad (7)$$

Nozzle inlet pressure is solved for iteratively from the above equation and then used to solve for nozzle inlet temperature from either the continuity or momentum equations.

Thrust efficiencies at different fuel-air ratio were also calculated using FLUENT, with the 15 degree inlet swirl as a baseline case. The equilibrium fuel-air equivalence ratio in the augmentor was calculated as:

$$\phi_{ab} = \frac{\dot{m}_{fu,ab} + (1 - \eta_{gg}) \dot{m}_{fu,gg}}{\left(\dot{m}_{fu} / \dot{m}_a \right)_s \dot{m}_a - \eta_{gg} \dot{m}_{fu,gg}} \qquad (8)$$

When changing this fuel-air ratio during computations, the fuel was reduced by the same percentage at the inside and the outside of the flameholder.

Augmentor efficiency was determined from synthesis of all the above methods during the development of the RM12. Comparison of measured and predicted augmentor efficiencies as determined by integrating the FLUENT predicted exit temperature profile, is shown in Figure 9. Although there is a slight difference between measured and predicted values it is interesting to note that it was possible to reproduce the general shape of the curve using the computer code.

Wall temperature calculation

A film cooled liner is incorporated in the augmentor design to protect the outer engine casing from the combustion process convection and radiation heat load. The liner wall temperature was calculated using the heat balance:

$$R_1 + C_1 = R_2 + C_2 \qquad (9)$$

The radiation to the outer casing, the value of the convection to the outer air and the effect of film-cooling, which is included in the term C_1, were all calculated using the expressions by Kretchmer and Odgers[5]. The value of the radiant flux from the flame to the liner wall, R_1, was taken directly from FLUENT. The local velocities and temperatures needed in the expression for cooling film effectiveness were also taken from the computer code.

The liner temperature is actually a boundary condition in the 3D code, so in order to get a good solution it is necessary to iterate between the 'wall-temperature program' and the combustion computer code. Usually this has only to be done a few times.

Figure 10 shows calculated and measured temperatures for the RM12 augmentor. The measured values were taken with a limited number of thermocouples located at the end of five cooling panels.

The variation of measured temperatures in the circumferential direction is due to the non-uniform temperature distribution in the augmentor combustion flowfield. There is also a non-uniform temperature distribution at the inlet to the augmentor. In the calculations so far only uniform inlet conditions were considered.

As indicated by the results, the film-cooling effectiveness is decreasing rapidly and thus permitting only short film cooling panels.

Conclusions

In this paper, some different augmentor performance data were studied and the following conclusions can be made:

- Augmentor pressure oscillations represent a very complex process of closed loop interaction between the combustion process and the acoustic modes of resonance on the augmentor combustion chamber. At present, there is no technique for reliably predict the onset of combustion in stability or the mode of resonance of a particular unstable combustion process. However, as more is learned about the combustion flowfield and experience is gained with particular modes of instability, the ability to design more stable system will improve. During the development work of the RM12 augmentor, computational analysis and water tunnel tests have been shown to be good complements to the engine tests. To get more accurate computer code predictions further data gathering is required via validation tests with sufficient instrumentation.
- A large value of the inlet swirl was found to give unstable combustion in the RM12 augmentor. This can be explained by a deteriorated flameholding capability at the inner V-ring.
- The 3D-code FLUENT qualitatively predicted the general flowfield characteristics as verified by water tunnel model testing. In particular the centerline vortex flowfield as predicted by the computer code was clearly illustrated in the water tunnel.
- The augmentor thrust effective efficiency characteristic versus augmentor equivalence ratio, was quantitatively predicted with FLUENT, and this is a significant step in prediction capability considering the complexity of the process contributing to the observed performance levels.
- Wall temperature predictions gave correct levels. However, measurements showed large variations in circumferential direction, which are not predictable at present.

Acknowledgment

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