A Methodology for Afterburner Evaluation

J.J. Isaac [*]**, N.R. Ramesh** [*]**, V.S. Krishnakumar** [*]**, C. Rajashekar** [*]**, S.R.Shyamsundar** [*]**,
A.P. Haran** [+] **and V.Sundararajan** [+]

Abstract:

A preliminary investigation of the performance of an afterburner module proposed by the Gas Turbine Research Establishment, Bangalore for the Kaveri engine has been carried out. The investigation, which was both theoretical and experimental, evaluated the afterburner configuration on the basis of flame stability, combustion efficiency and total pressure loss. An evaluation methodology, which was formulated, has been employed to arrive at design modifications for improved performance.

INTRODUCTION

In order to achieve better take-off characteristics, higher rate of climb and meet performance demands during tactical maneuvers, the thrust of an aeroengine has to be augmented by employing an afterburner. The main advantages of using the afterburning gas turbine cycle is that the weight and size of the augmented engine are much less than that of a turbojet engine which can produce the same maximum thrust periodically. Afterburning consists of the introduction and burning of kerosene fuel between the engine turbine and the jet propelling nozzle. Due to structural limitations, the maximum gas temperatures approaching the turbine are limited to around half the adiabatic flame temperature. Consequently, the gas leaving the turbine will still contain a considerable proportion of oxygen. Secondary burning of fuel in the afterburner leads to increased exit velocity and thrust.

The current trend towards high turbine discharge temperature and the requirement for satisfactory operation over extended fuel/air ratios and flight maps has complicated the application of conventional afterburner technology to modern jet engines. Weight penalties dictate a short afterburner. Hence, the flame holder/fuel injector configuration has to be chosen as a compromise between acceptable ignition/good flame stability characteristics and low total pressure loss / high combustion efficiency for the stipulated afterburner length (Ref.1). Fuel atomisation/ mixing, flame stabilisation and flame spreading are yet not fully understood. Consequently, the selection of the best flame holder geometry, width and blockage, fuel injector geometry and location, fuel injector-flameholder separation and afterburner length is a time consuming exercise (Ref.1).

----
 * National Aerospace Laboratories, Bangalore
+ Gas Turbine Research Establishment, Bangalore

1

It is clear that the successful design/development of an efficient afterburner requires a good knowledge of the coupling of complex fluid flows with chemical reaction processes. The complexity of the aerothermodynamics and chemical processes that occur together in an afterburner does not allow the adoption of a purely analytical approach to component design and performance prediction. In practice, a semi-empirical treatment is always adopted.

A methodology for afterburner evaluation is presented. It has been employed to evaluate an afterburner module for the Kaveri engine.

METHODOLOGY

The approach has been to devise/develop rapid screening and evaluation methods with which to check out afterburner configurations (typically fig.1) and to restrict actual testing only to those promising configurations. The strategy has been to adopt a three pronged attack.

The afterburner module was checked out analytically employing semi-empirical
.

methods.. Particular emphasis was placed on flame stability, combustion efficiency and the optimum geometric blockage and after burner length. Computer graphics studies of flame holder configurations were carried out on an IRIS workstation of the CSIR Centre for Mathematical Modelling and Computer Simulation (C-MMACS).

Extensive flow visualisation studies of afterburner models were then carried out in the water tunnel of the Experimental Aerodynamics Division, National Aerospace Laboratories (NAL). A specially set-up fuel spray rig was used to study the spray qualities of different types of fuel injectors in the Combustion Laboratory, Propulsion Division.

Detailed model tests with combustion were then carried out in the Combustion Laboratory of the Propulsion Division, NAL. The tests included checking satisfactory ignition determining the flame stability characteristics as well as measurement of combustion efficiency and cold and hot pressure losses. All inlet conditions were chosen to conform to those stipulated by GTRE
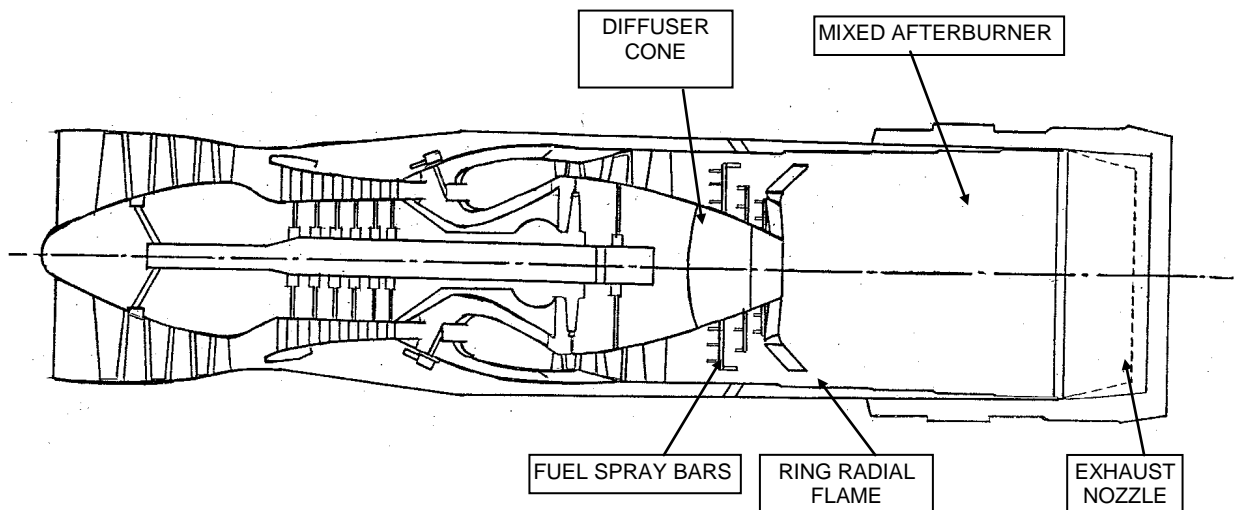

Fig. 1. Kaveri Engine

ANALYTICAL STUDIES

Total pressure loss

The afterburner is typically used for the time limited operation of takeoff, climb and combat maneuvers. Hence, the diffuser flame holder/fuel injector system should be so designed to achieve high performance in the afterburning phase and to give rise to low dry loss in the non-afterburning phase.

The total pressure loss of an afterburner is mainly composed of that due to the diffuser, the drag of the flame holder/fuel injector system and the combustion process. It is recognized that it is necessary that a system total pressure loss has to be incurred in order to achieve design objectives such as large temperature rise, wide temperature modulation, high efficiency, short duct length and to affect a stabilizing effect on combustor aerodynamics. However, this total pressure loss has a serious impact on engine thrust. Typically, a 1% increase in total pressure loss will result in a 1% decrease in thrust.
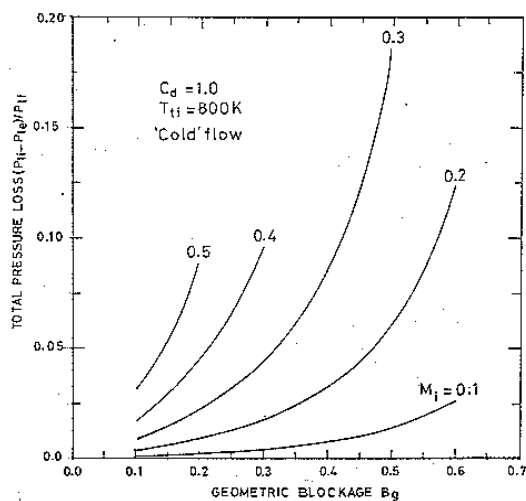

Fig. 2. Total pressure loss-effect of geometric blockage and inlet Mach number

Fig. 2 shows that serious efforts should be made to reduce the afterburner inlet Mach number and characteristic flame holder blockage and drag coefficient to keep total pressure losses down to permissible levels. The maximum heat that can be added increases and the total pressure loss decreases as the inlet Mach number decreases. Moreover, stabilisation of flames becomes easier as the inlet Mach number decreases. Hence, it is conventional practice to incorporate a diffuser between the turbine exit plane and the afterburner combustion zone. These theoretical estimates were arrived at by considering the afterburner section as a constant area duct with simple heating and internal drag corresponding to a weighted equivalent flame holder/fuel ring assembly geometric blockage and drag coefficient.

Flame holder blockage

Flame stabilisation in a high velocity stream of a combustible mixture is readily accomplished by introducing a bluff body which produces in its wake a low velocity recirculatory flow. Although the mechanism of flame stabilisation is still not fully understood, adequate experimental data is available for its behaviour to be predicted accurately. An examination of the flame stability correlating equation $V_{bo}/PD^nT^m = f(\varnothing)$ would reveal that an increase in the characteristic dimension D or a decrease in the velocity V_{bo} past the flame holder would improve flame stability. An increase of pressure P, temperature T as well as operation at equivalence ratios ($\varnothing$) close to unity would lead to improved flame stability. However, an increase in D and hence in flameholder blockage would increase the velocity past the flameholder for a given duct size. This would impair flame stability. Hence, there is an optimum value of the flameholder size for a given approach stream velocity for which peak flame stability is attained
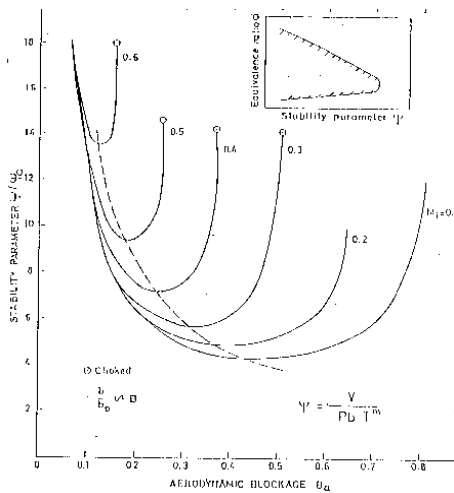
3

Fig. 3 . Variation of stability parameter with aerodynamic blockage - 2D

The aerodynamic blockage of a flameholder has been shown to have a significant effect on flame stability (Fig.3). The variation of the aerodynamic blockage with the flameholder geometric blockage has been determined (Fig.4). It is seen that the aerodynamic blockage is no longer directly proportional to the geometric blockage at high blockages. From a knowledge of the optimum aerodynamic blockage for a given flameholder shape, the corresponding geometric blockage could be deduced and practical flameholder sizes chosen at the design stage. The optimum aerodynamic blockage is seen to decrease with an increase in approach Mach number (Fig.3).

In order to minimise weight, the diffuser is kept as short as possible without flow separation from the inner cone. The flame holder/fuel injector system is also located very close, if not, partially inside the diffuser passage. Relatively large diffuser divergence angles can be used as the flame holder/fuel injector system acts as a diffuser augmentation device and reduces the tendency of the flow to separate.

Typically, for annular and radial gutters, the optimum aerodynamic blockage for an approach Mach number of about 0.3 is seen to be around 0.3 (Fig.3). However, the trough is quite flat and without a serious loss in flame stability,

aerodynamic blockages in the range 0.25 to 0.40 could be chosen to suit other considerations. It would be logical for the choice to tend to the higher values from flame spreading considerations. Fig.4 shows that the corresponding geometric blockages should lie in the range 0.20 to 0.30.
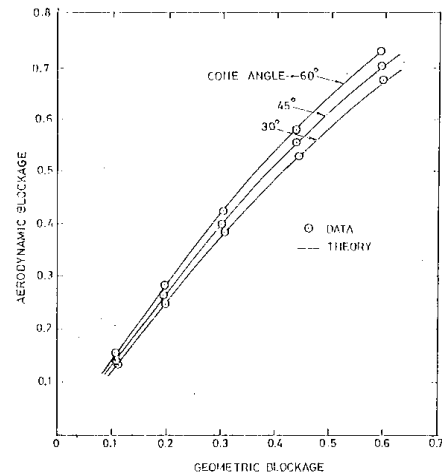

Fig. 4. Variation of aerodynamic blockage with geometric blockage-conical flame holders

Quasi-morphological studies

In conventional practice, flameholder systems employed in turbofan afterburners consist of `Vee' gutter arrays arranged in the form of rings or radials or a combination of both. At present, a general methodology is not available for the selection of the flameholder array geometry to achieve optimum flame coverage and hence combustion efficiency in the stipulated afterburner duct length.

In practice there is a large variation in the configuration types. It is essentially a mix of radial and ring gutters. Essentially, it remains a task to select the optimum flameholder shape to achieve maximum burning area and hence attain maximum combustion efficiency in a given afterburner length. It must be stressed that the flame stability should not be impaired at any cost. To ensure this, the gutter width is restricted to its mini-

4

mum size. It has been experimentally observed by Wright and Zukoski (Ref.4). that flame spreading from bluff bodies is remarkably independent of approach velocity, temperature, fuel/air ratio and fuel type for subsonic, turbulent flow. Hence, if the flame spread angle is known, then the inverse problem of seeking a gutter shape to achieve full flame coverage at the end of the afterburner can attempted. If such a flame spreading approach is correct, the variation of combustion efficiency with length should be linear for an annular gutter. This has been observed in practice.
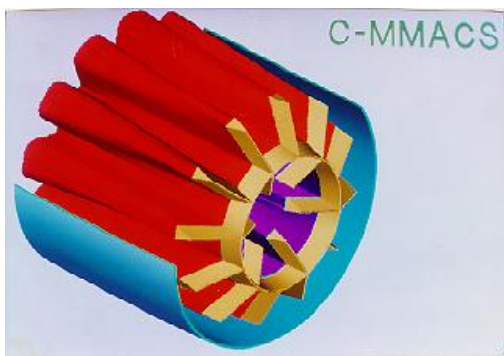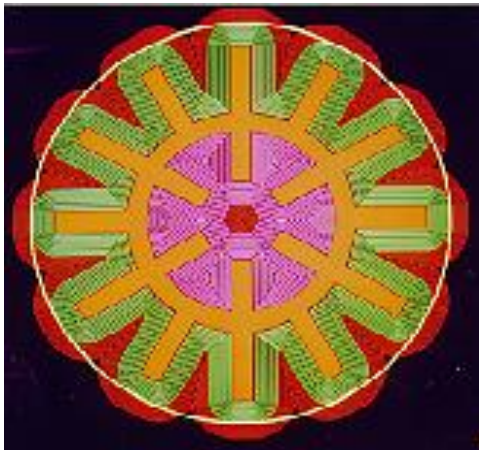

Fig. 5. Flame growth - Isometric view

Fig. 6. Flame growth - Ring with 12 outer radials and 6 inner radials, L/D = 1.4.

Fig. 7. Restricted flame growth - Ring with 12 outer radials and 4 inner radials, L/D = 1.4

A computer graphics study of the flame spreading characteristics of typical afterburner flame holder geometries has been carried on the IRIS workstation of C-MMACS. The effect of flameholder geometry has been examined and a design criteria evolved for the selection of turbofan afterburner flameholder geometry to obtain adequate combustion efficiency. For the gutter geometry considered, the flame growth, as obtained by computer graphics, is shown in Figs. 5,6,7. It is seen that 4 inner radials (Fig.7) will be adequate to ensure good flame coverage instead of the 6 inner radials (Fig.6) presently provided. The annular ring is seen to be not necessary for flame spreading. Flame growth from the ring has been deliberately suppressed to bring out this effect (Fig.7). However, the ring will be necessary for conveying the ignited flame kernel around the flameholder petal network. A hollow stream-lined annular passage could perhaps be considered to reduce drag losses. A similar study using fuel spreading characteristics was carried out to check the location and type of the fuel injectors so as to ensure good fuel spread. This fuel is injected from 3 rings - primary, secondary-1 and secondary-2 depending on the fuel scheduling scheme.

FLOW VISUALISATION

5

Water flow visualisation

Aerodynamic processes play a vital role in improving the performance of afterburners. When a good aerodynamic design is coupled to a matching fuel injection system, a trouble free afterburner, that requires only nominal development, is virtually assured.

Flow visualisation is a powerful tool to study complex flow- fields such as those which occur in afterburners. Observing the whole flowfield can lead to a better understanding of complex flow phenomena and can very often save many hours of developmental work. Testing of afterburners is costly and difficult when investigating a large number of design options. However, studying the simulated flow in an afterburner, by using a transparent model with water as the fluid medium, would reveal the basic flowfield features under `cold' flow conditions.

Observations

Water flow visualisation using a hydrogen bubble streak technique was employed as a diagnostic tool to assess various afterburner configurations. The immediate task was to locate the flame stabilizer, which consisted of a simple annular ring with twelve outer radials and six inner radials, so as to create a favourable diffuser/flame holder interaction. In order to minimise the weight, the diffuser is kept as short as possible without flow separation from the inner cone. The flame holder/fuel injection system is also located very close, if not partially inside the diffuser passage. Relatively large diffuser divergence angles can be used as the flameholder/fuel injector system would act as a diffuser augmentation device and reduce the tendency of the flow to separate. Fig. 8 shows the `cold' flow simulated pattern using a hydrogen bubble streak photographic technique for a configuration in which the flame

stabilizer/fuel ring assembly was within the annular diffuser.

A Vee gutter flame holder incorporates flow separation by design to aid the flame stabilisation process. Flame holders serve not only as flame stabilisers, but in an afterburner combustion zone help to proportion the air flow and to introduce turbulence necessary for good mixing of hot and cold gases during the combustion process. The separated regions and the intense turbulent mixing zones are clearly seen in Fig.8.

Fig. 8. Flow pattern - Flame stabiliser/fuel ring assembly within annular diffuser

A trapped vortex can also be seen between the smallest (primary) fuel ring and the vertex of the annular ring (Fig.8). The annular Vee gutter ring is in the aerodynamic `shadow' of the primary fuel ring and this will, as is well known, lead to a lowering of the overall drag, depending on the gap width. However, there is also a large separated region at the base of the cropped diffuser. This will lead to flow losses depending on the extent of sudden expansion. If the afterburner has a pilot ignition system, it may be necessary to retain a certain degree of diffuser cropping to house it.

Hence, a necessity to shift the flameholder/fuel ring assembly downstream to reduce the sudden expansion effect and to decrease the separated region at the cropped diffuser base by

6

energising the adjacent region was indicated. The flame stabilizer/ fuel ring assembly has to be treated as an integral unit to retain the same fuel atomisation, vaporisation and flame stability characteristics.

Fig.9 shows the flow pattern when the flameholder/ fuel ring assembly was located far downstream of the diffuser. The diffuser had stalled. Not withstanding the associated stall losses, the fuel-air distribution could also be significantly altered and the area near the centre of the duct will be starved of fuel, particularly the inner radials. Clearly, the flame holder/fuel ring assembly acts as an effective passive diffuser augmentation device to prevent stall.

Fig. 9. Flow pattern - Flame stabiliser/fuel ring assembly far downstream

Fig. 10. Flow pattern - Flame stabiliser/ fuel ring assembly in optimum position

Fig. 10 shows the flow pattern when the flameholder/ fuel ring assembly was located in the optimum position. The vertex of the annular ring was in the same plane as the cropped diffuser base. It is seen that the flow was well proportioned, the diffuser was not stalled and the sudden expansion losses would have been reduced as signified by the virtual disappearance of the separated region at the cropped diffuser base due to energisation by the deflected flow. A favourable interaction between the diffuser and flameholder/fuel ring assembly has been created. The effective geometric blockage and drag coefficient of the flameholder/fuel ring assembly, as related to the total pressure loss, has been reduced while at the same time retaining the necessary blockage to obtain the desired flame stability and flame spreading characteristics. Estimates indicate that the total pressure loss in this position is about 70% of that when the flameholder/fuel ring assembly is within the annular diffuser.

Fuel spray studies

The primary objective of a liquid fuel injection system is to produce a specified distribution of fuel in the gas stream entering the afterburner. The fuel injection parameters must be carefully chosen to ensure that the fuel/air ratio in the vicinity of the flameholder is close to stoichiometric as this will lead to desirable ignition and combustion characteristics.

A fuel spray rig was specially set-up which included a Goblin chamber for supplying heated air. A comprehensive series of experiments were conducted in the fuel spray rig and the penetration and spreading characteristics of fuel sprays determined for various approach stream velocities, temperature, injector types (plain orifice and swirl atomisers) and fuel injector pressures. Fig. 11 shows the spray envelope of a swirl atomiser in opposed flow and Fig. 12, that of a plain orifice injector in opposed flow.
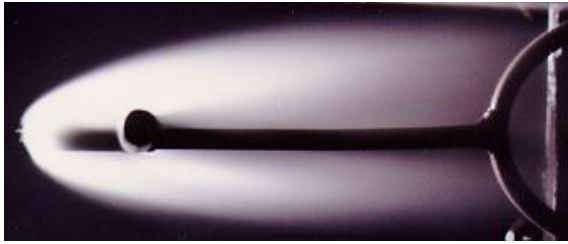
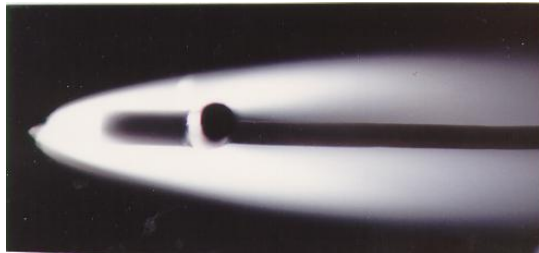Fig. 11. Spray envelope - swirl atomiser in opposed flow, P_{inj} = 10 bar, g

Fig. 12. Spray envelope - Plain orifice injector (with stem) in opposed flow, P_{inj} = 10 bar,g.

It is seen that good atomisation and penetration/spreading characteristics are obtained with both plain orifice and swirl injector types. Hence, there is no justification in using swirl injectors in contra-stream mode when considering its complexity in contrast to a simple plain orifice injector. It may be advantageous to use a channel anvil plain orifice injector to ensure good fuel coverage and elimination of any fuel spread asymmetry depending on the inlet flow conditions. The penetration and spreading for a given injector diameter were found to be significantly affected by the fuel to air momentum ratio (Fig.13-15). With this knowledge of penetration and spreading, it is possible to select the proper location of the fuel injector to obtain near stoichiometric conditions at the plane of the flameholder.
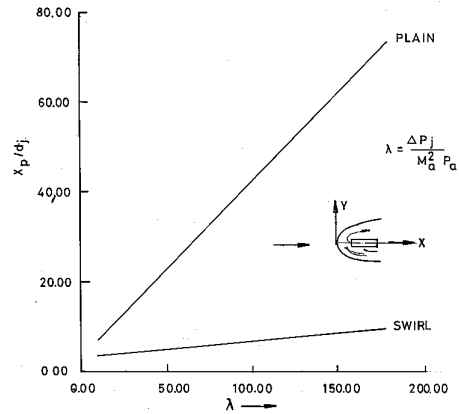
Fig. 13. Opposed injection (Plain and Swirl) - upstream penetration
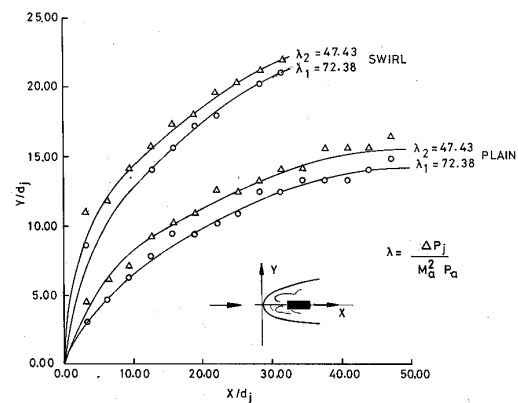

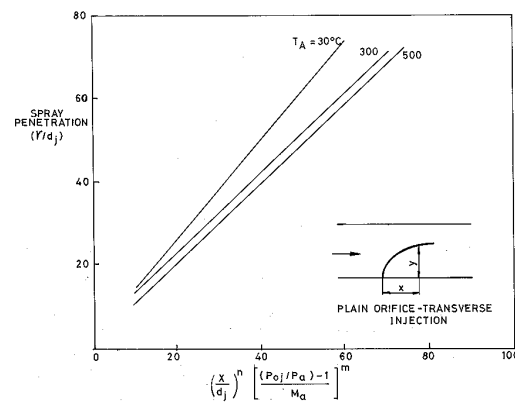Fig. 14. Opposed injection (Plain and Swirl) -transverse penetration

Fig. 15. Spray penetration characteristics

8

As expected, plain orifice injectors have higher penetration (Fig. 13) and lower spread (Fig. 14) than swirl atomisers. The overall effect is a superior fuel influence zone for a plain orifice injector. Fig.15 shows the penetration characteristics of a plain orifice injector in transverse flow. The effect of temperature is seen to apparently reduce the penetration. An evaporation effect should not be overlooked. It may be advantageous to have a combination of opposed and transverse fuel jets.

COMBUSTION TESTS

Facility

The Propulsion Division has a well equipped Combustion Laboratory in which continuous air flow up to 5kg/sec at upto 10 atmospheres is available. There are also provisions for obtaining unvitiated heated air at temperatures upto 600K at flow rates upto 4.5 kg/sec and vitiated air at temperatures upto 1000K at flow rates upto 5 kg/sec. The facility layout is given in Fig. 16 and view Fig.17 .
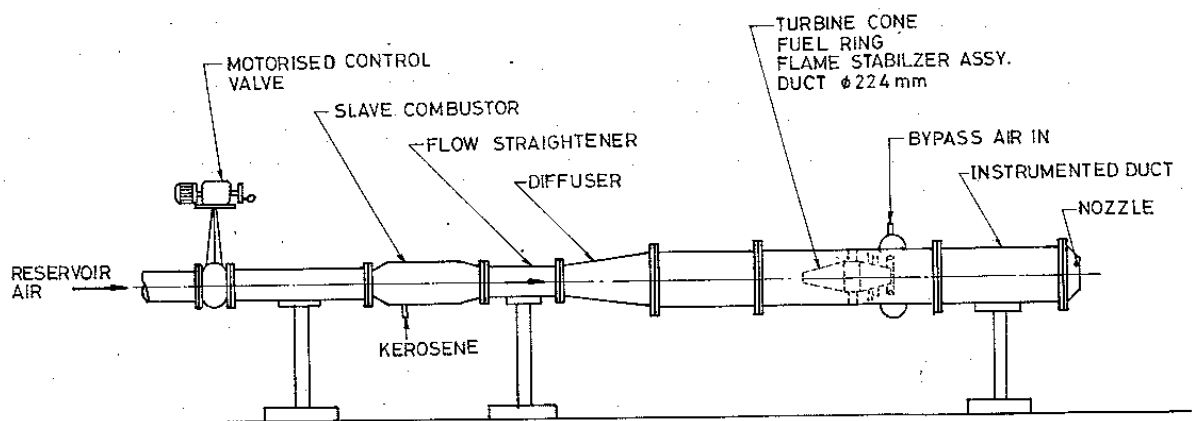

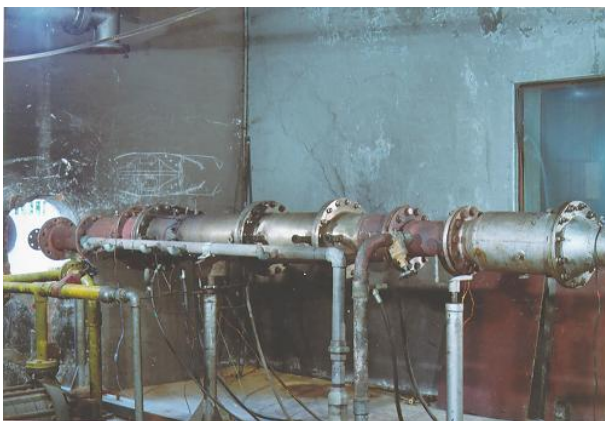Fig. 16. Schematic of afterburner test facility

Fig. 17. Afterburner test facility

Fig. 18. End-on view of the V- gutter

Tests were carried out on a 1/3 scale model of the Kaveri afterburner module (Fig.16-18). The model was generally tested at inlet conditions corresponding to flight Mach number 0.8, altitude 11 km with the `PD' scaling rule operating.

General considerations

Based on the water flow visualisation studies, the gutter was shifted downstream to the optimum position for the tests. Plain orifice injections were employed in contrastream mode, instead of swirl atomisers. This decision was based on the results of the fuel spray rig tests. The circumferential pitch of the holes were chosen in conformity to the results of the computer graphics studies.

By-pass air was introduced through chutes. It was determined that lower pressure loss would be incurred this way than if the by-pass air was introduced through a large number of 3 mm diameter holes in the duct wall. The number of chutes (36) was chosen to be in conformity with the number of injector ports in the outermost injector ring. An anti-screech liner consisting of 3 mm diameter holes was located in the vicinity of the flameholder. Gutter end plates were incorporated as it was found that there would be a serious deterioration in flame stability due to ingestion of relatively cold air via the gutter ends thus destroying the effectiveness of the recirculation zone .

Experimental

Extensive combustion tests to determine flame stability, combustion efficiency and total pressure loss characteristics were carried out. The experiments were conducted in the rig shown in Fig. 16,17. The afterburner channel consisted of a cylindrical chamber 224 mm dia, equipped with adequate water-cooled and air cooled jackets. This channel contained the diffuser, injectors and flameholders (Fig.16). An ORPHEUS slave combustor (Fig.17) was employed to ensure inlet air temperatures around 600 to 1000K. The model details

are shown in Fig.1, 16. An afterburner flame viewing system was designed and a typical end on view of the flame is shown in Fig. 19. A typical lean stability characteristic is given in Fig. 20.
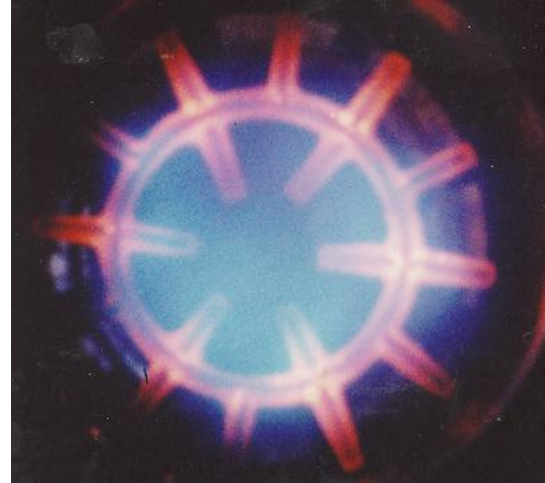

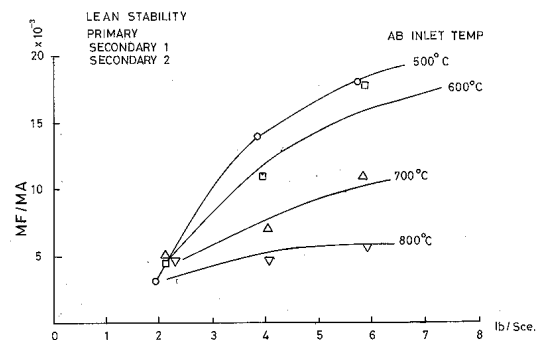Fig. 19. Typical afterburner flame viewed end on

Fig. 20. Lean stability characteristics

The air mass flow was measured with an orifice plate as well as with a vortex flow meter, the kerosene flow rate with turbine flow meters and a `Micromotion' unit. Pressures and temperatures were acquired on an Orion data logger and backed up by a PC. Pressures were obtained with the help of Scanivalves. Afterburner ignition was achieved by momentarily increasing the air inlet temperature with the aid of the Orpheus slave combustor. Afterburner ignition was generally found to be smooth.

The effectiveness of combustion can be determined by analysing its effect on the wall static pressures in a afterburner duct of constant area cross-section. When combustion is complete, the only process which causes a pressure decrease is friction. A typical variation of duct wall pressure with length is shown in Fig. 21,22 for both the afterburner off and on cases. It is seen that the combustion is complete by the end of the chosen duct length as indicated.
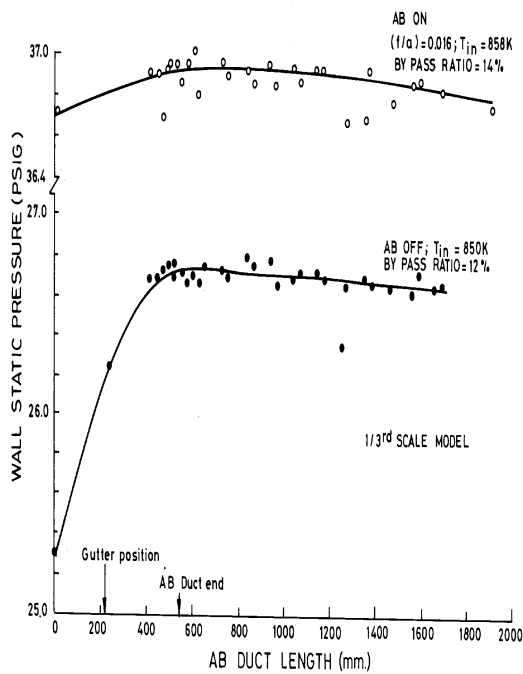

Fig. 22. Wall static pressure - afterburner duct length variation
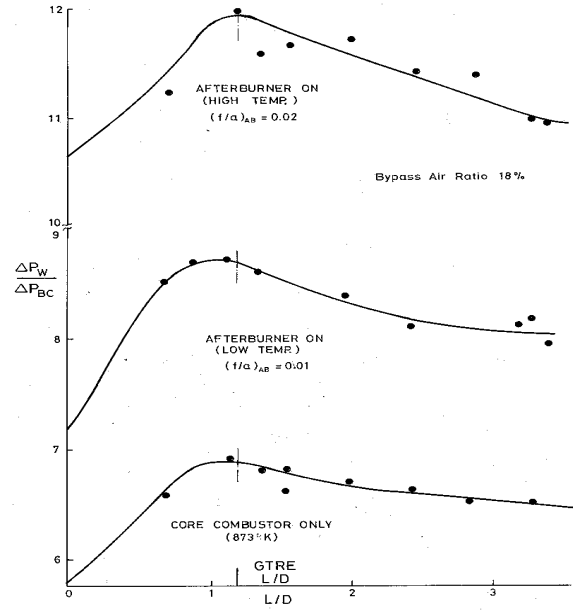

Fig. 21. Wall static pressure - afterburner duct length variation

Heat addition to a subsonic flow at an abrupt change in cross section is akin to the combustion process in an afterburner. The equations of gas dynamics have been solved. The ratio of outlet wall static pressure to inlet static pressure was found to decrease with heat addition.

This is seen to be true in actual practice (Fig.21). In all the cases tested, the duct terminated in a choked nozzle. Hence, if the outlet static pressure is measured, from a knowledge of the nozzle area ratio, the thrust weighted outlet total pressure can be estimated. The inlet total pressure was measured and hence the total pressure loss was estimated (Table 1) for various bypass ratios. Table 1 also gives the estimated combustion efficiencies from temperature measurements. From Fig. 23, it is seen that for annulus Mach numbers of 0.5 to 0.6, the total pressure losses, as extrapolated, are those which conform to the design target, both for hot and cold flows. Fig. 23 shows that the simple heat addition theory is seen to predict the stagnation pressure loss fairly accurately.
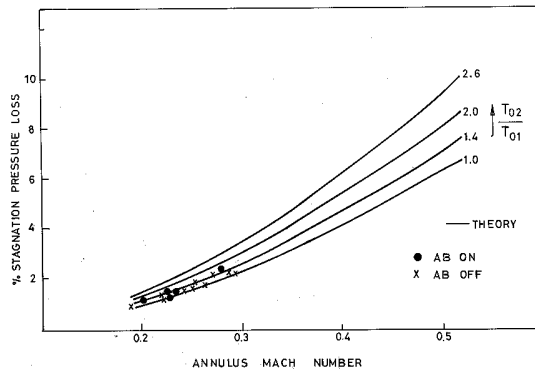
11

Fig. 23. Pressure loss characteristics

CONCLUSIONS/ RECOMMENDATIONS

The detailed afterburner design evaluation has shown that the performance as characterised by flame stability, combustion efficiency and total pressure loss is reasonably satisfactory.

The following suggestions/ modifications may be considered for incorporation in the final design:

(1). The gutter should be shifted away from the diffuser annulus to reduce the total pressure loss.

(2). The gutter blockage could be reduced by removing two inner petals to reduce total pressure loss.

(3). The gutter annular ring is not necessary for flame spreading and could be redesigned as a streamlined tube which acts as a communication passage for the ignited flame kernel to travel. Hence, the drag and corresponding pressure loss can be reduced.

(4). Contrastream operation of swirl injectors is not necessary as plain orifices would suffice. A channel anvil could be incorporated to ensure uniform fuel spreading.

(5). The circumferential pitch and number of injector ports has to be modified to allow for proper fuel distribution.

(6). The bypass air should be introduced through chutes, the number of which should be in consonance with the number of injection points in the secondary 2 - fuel ring.

(7). The partial use of the anti-screech liner for by-pass air addition may not be desirable.

(8). End plates should be incorporated at the radial ends of the gutter to avoid impairment of flame stability.

(9). The length/diameter ratio of the afterburner duct appears to be adequate.

(10). The combustion efficiency and total pressure loss characteristics appear to be satisfactory at the flight point simulated.

(11). A methodology for evaluation of afterburners has been formulated and shown to be reasonable.

ACKNOWLEDGEMENTS

REFERENCES

1. Zukoski, E.E., `Afterburners' in `The Aerothermodynamics of aircraft gas turbine engines', AFAPL-TR-78-52, Air Force Aero Propulsion Laboratory, July 1978.

2. Isaac, J.J., Prediction of the effective blockage of flame stabilisers, NAL Technical Memorandum TM-PR-202-1176, May 1976.

3. Lefebvre, A.H., A method of predicting the aerodynamic blockage of bluff bodies in a ducted airstream, CoA Report No. 180, College of Aeronautics, Cranfield, Nov. 1965.

4. Wright, F.H. and Zukoski, E.E., Flame spreading from bluff body flameholders, 8th Intl. Comb. Symp., 1960.,pp973.