Selection of a Suitable Combustion System for a Small Gas Turbine Engine

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ABSTRACT

Experimental studies on a straight and a reverse flow annular combustion chamber to select a suitable combustion system for a small gas turbine engine are presented. One straight flow annular combustor with simplex fuel injector and three sector models of the reverse flow annular combustor with simplex, airblast and vapouriser type of fuel injectors were fabricated and tested, retaining the same maximum outer casing diameter. The paper presents the basic design procedure, the three types of fuel injection system and the performance comparison of these models. An attempt has been made to develop a correlation to compare the performance of the models. It has been concluded that with the available data, for small gas turbine engines, reverse flow annular combustor with vapouriser is the best from overall considerations.

NOMENCLATURE

– a parameter based on operating conditions of the combustion chamber

CV – calorific value

M – Mach number

η_{cc} – combustion efficiency

θ – Lefebvre's airloading parameter

f/a – fuel air ratio

P_{in} – inlet total pressure of the combustor

– total pressure loss as a percentage of inlet total pressure

ΔP_{inj} – delivery head of the fuel injector

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PF	–	pattern factor (temperature traverse quality)
PPP	–	a parameter describing the performance in terms of combustion efficiency pressure loss, pattern factor and equivalence ratio
ϕ	–	equivalence ratio
HRR	–	heat release rate of the combustor
L_L	–	length of the combustor liner
D_L	–	diameter of the combustor liner
V_L	–	volume of the flame tube
ϕ_p	–	air loading parameter in $1/\theta$ form
PLF	–	pressure loss factor
q_{ref}	–	reference dynamic head
ΔP_{ft}	–	flame tube pressure drop

1. INTRODUCTION

Reliable operation of gas turbine engines with high turbine entry temperature and high cycle efficiency pose severe conditions on their combustion chambers. The high surface to volume ratio of small engine combustors give rise to more severe heat transfer problems. To meet the above challenges a straight flow or a reverse flow combustor can be selected depending on engine operating parameters, choice of compressor, turbine, etc. and length limitations. Further, for small gas turbine combustors, it is realised that relatively larger number of fuel injectors are required to uniformly disperse the fuel and to provide a satisfactory temperature distribution at entry to the turbine. In the case of a reverse flow combustor the problem becomes more severe than in a straight flow combustor because of lesser flame tube width.

With a view to select the right type of combustor for a small gas turbine engine two alternate configurations, a straight flow and a reverse flow combustors were designed and tested for a wide range of possible operating conditions. The reverse flow combustor was fabricated with three different fuel injection systems, namely the simplex, airblast and vapouriser type of atomisers. A correlation was developed to compare the performance of the various models and to arrive at the final configuration.

2. EVALUATION OF COMBUSTION SYSTEM

The combustors both straight flow and reverse flow were designed in the following lines[1-8]

Overall specification of the combustors is based on sea level (ISA) static performance (Table 1).

From the component constraints and design specifications a preliminary layout of the combustor is made using a semi-empirical method.

The mass flow fractions and the pressure loss of the combustor are predicted using the airflow analysis program[9].

The liner wall temperature distribution is predicted, using the heat transfer analysis program[10,11].

The combustion efficiency distribution and air mass flow distribution along the length of the combustion chamber are predicted using the analytical method[12] based on reaction rate considerations and compared with the flow predictions using the flow analysis program.

The combustor fabricated based on the above geometry is rig tested. Any performance improvement bcsed on rig test results is incorporated and the model is cleared for the engine.

Table 1 Combustor design specification ISA SLS condition

Sl. No.	Parameter	Straight flow	Reverse flow
	Entry pressure	4.34 kg/cm^2	5.356 kg/cm^2
	Entry temperature	464 K	510 K
	Entry air mass flow	5.847 kg/s	5.2 kg/s
4.	Pressure loss	7% of inlet total pressure	7% of inlet total pressure
5.	Combustion efficiency	96%	96%
6.	Fuel air ratio	0.0207	0.0196
	Turbine entry temperature	1200 K	1200 K
8.	Leading dimensions		
	Maximum outer casing dia.	330 mm	330 mm
	Minimum inner casing dia.	104 mm	104 mm
	Length of CC	230 mm	142 mm
	Mach no at entry	0.445	0.32

3. BRIEF DESCRIPTION OF THE COMBUSTORS

The straight and reverse flow annular combustor configurations are shown in Fig. 1. The straight flow combustor consists of an outer casing assembly, an inner casing assembly and a flame tube assembly each individually fabricated and assembled with sixteen simplex atomisers for fuel supply, with provision for fuel flow division for starting.

Similarly the reverse flow combustor houses an outer casing, an inner casing, a flame-tube assembly and a dual manifold assembly for fuel supply. One manifold with four simplex atomisers supplies the fuel for starting purposes, while the other supplies the fuel for other eight atomisers which could be a simplex or vapouriser or airblast type. Figure 2 shows the three types of fuel injectors that were tested.

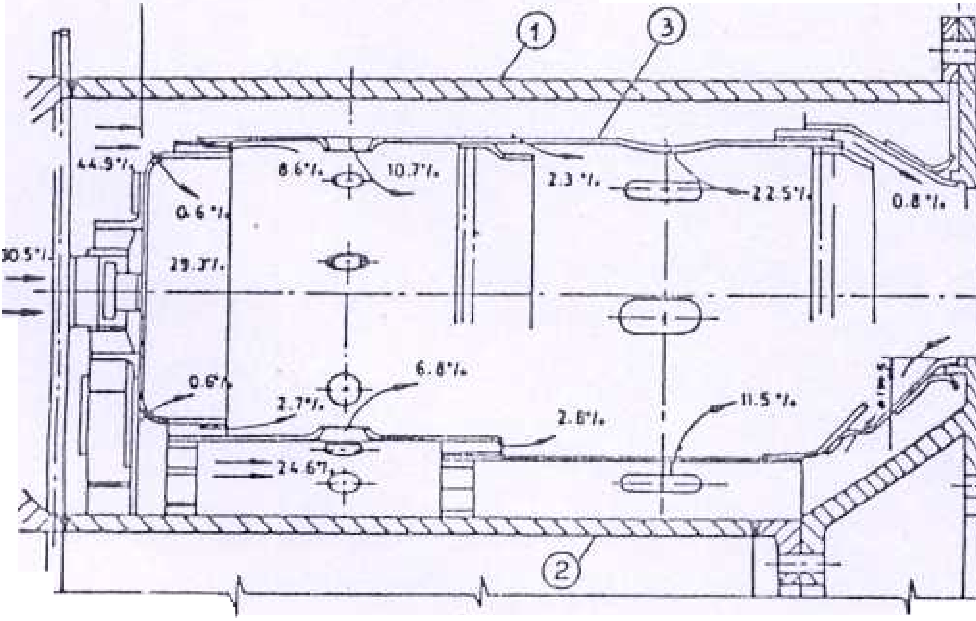

Figure 1(a). Straight flow annular combustor.

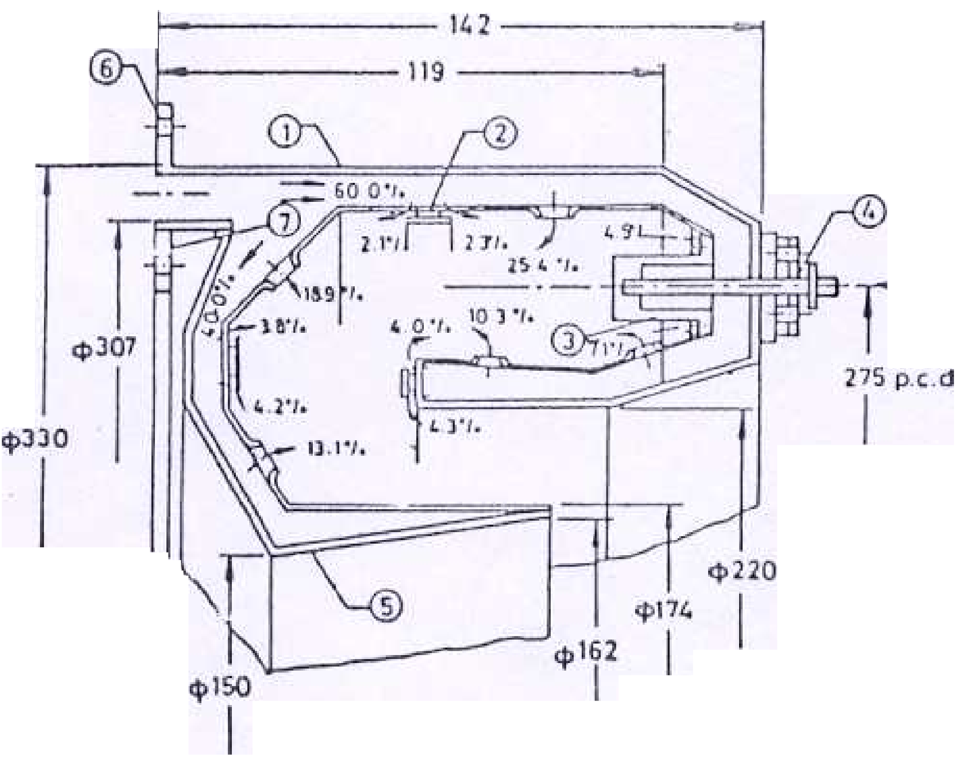

Figure 1(b). Reverse flow annular combustor.

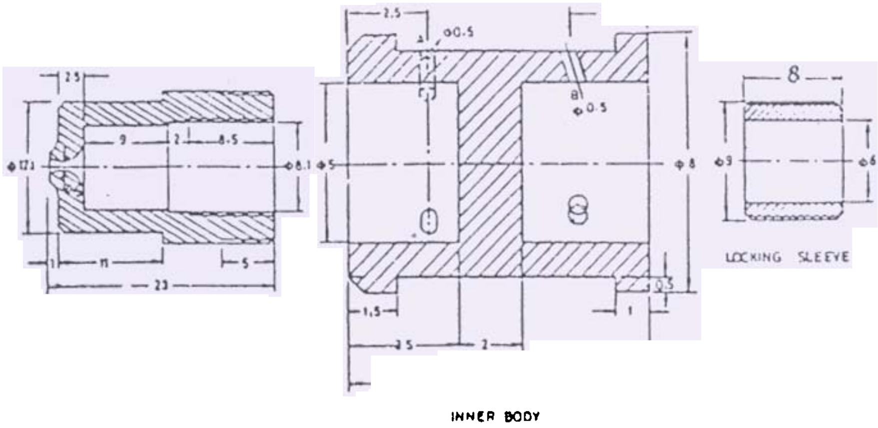

Figure 2(a). Simplex inje

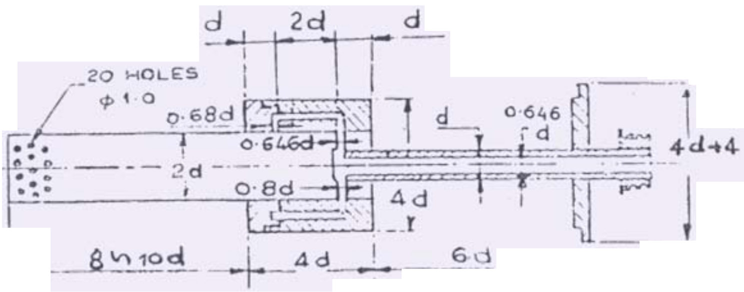

Figure 2(b). Airblast atomise

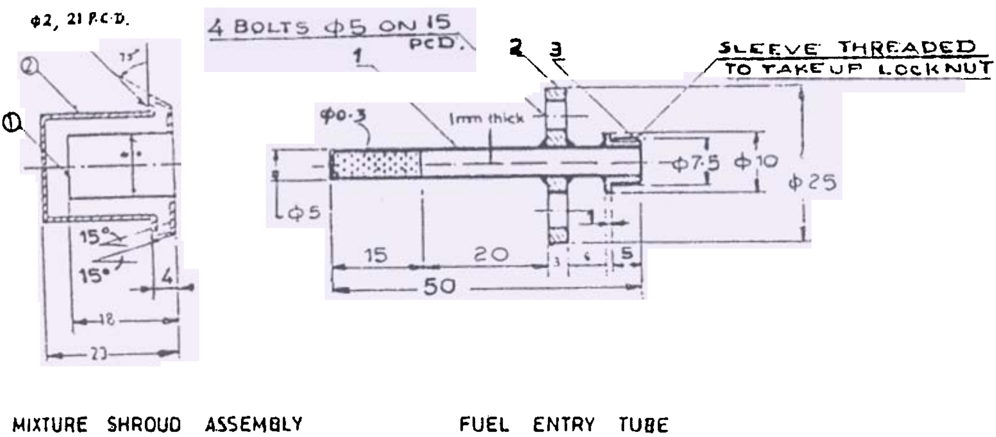

Figure 2(c). Vaporiser.

4. EXPERIMENTAL RESULTS

The comparison of the straight flow and reverse flow combustors are presented in Table 2 and the results of the experimental investigation are presented in Figs. 3 & 4 and in Tables 3 & 4 respectively.

Table 2. Comparison of straight and reverse flow combustors

Sl. No.	Parameter	Straight flow	Reverse flow
1.	Length	377 mm	142 mm
2.	Diffuser	needs longer diffuser (147 mm)	shorter diffuser (20 mm)
3.	Diameter (overall max.)	330 mm	330 mm
4.	Inlet Mach No. at SLS	0.445	0.32
5.	Expected pressure loss	7%	7%
6.	Achieved prossure loss	7.5% at $M_{in} = 0.445$	7% at $M_{in} = 0.32$ for ABA and simplex 7% at min=0.15 for vapouriser
7.	Combustion intensity (kcals/M^3/hr atms)	0.55×10^8	1.3×10^8
8.	Radial pattern factor	0.1	0.05
9.	Weight (approx.) kg.	7.5	6.1

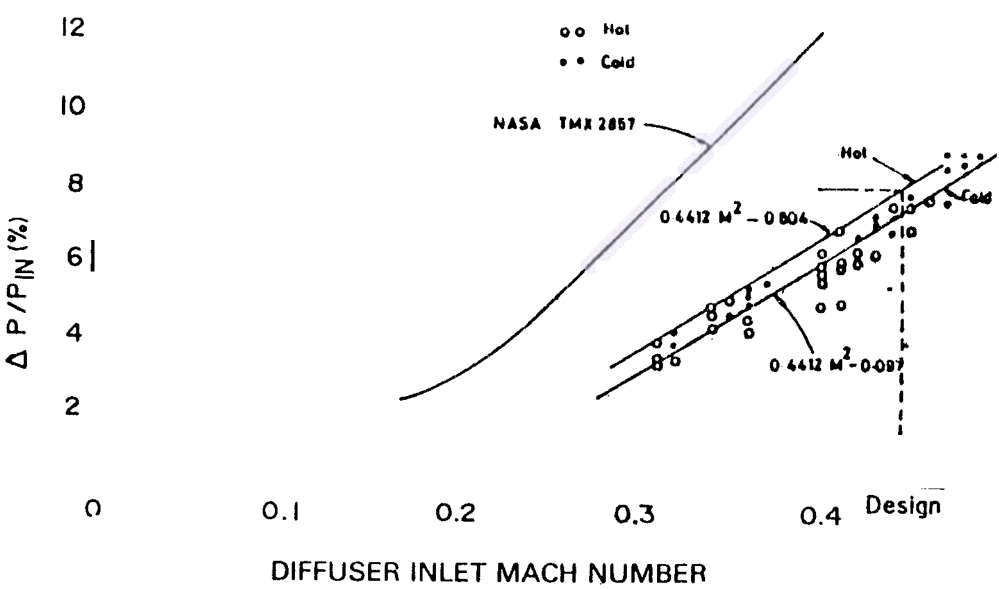

Figure 3(a). Total pressure loss.

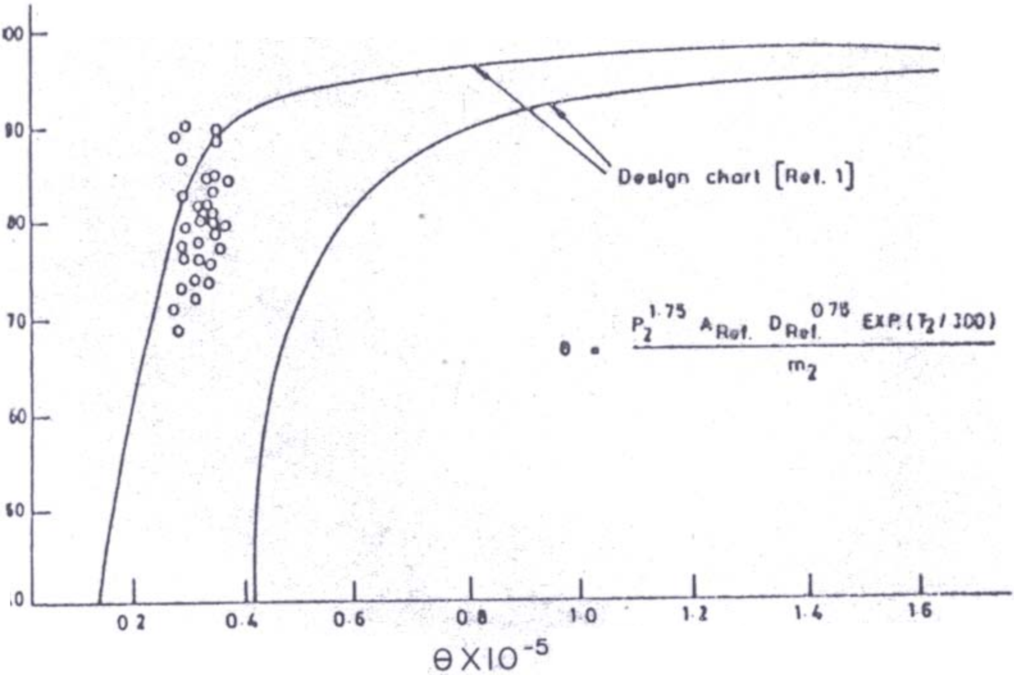

Figure 3(b). Combustion efficiency vs. θ parameter.

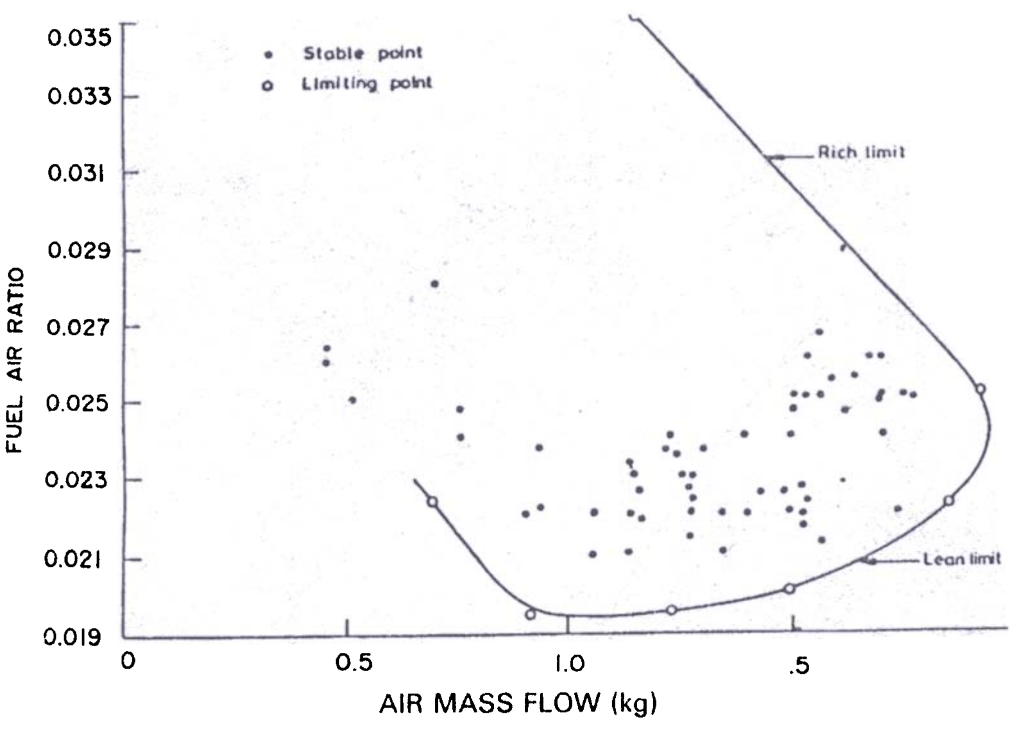

Figure 3(c). Stability loop

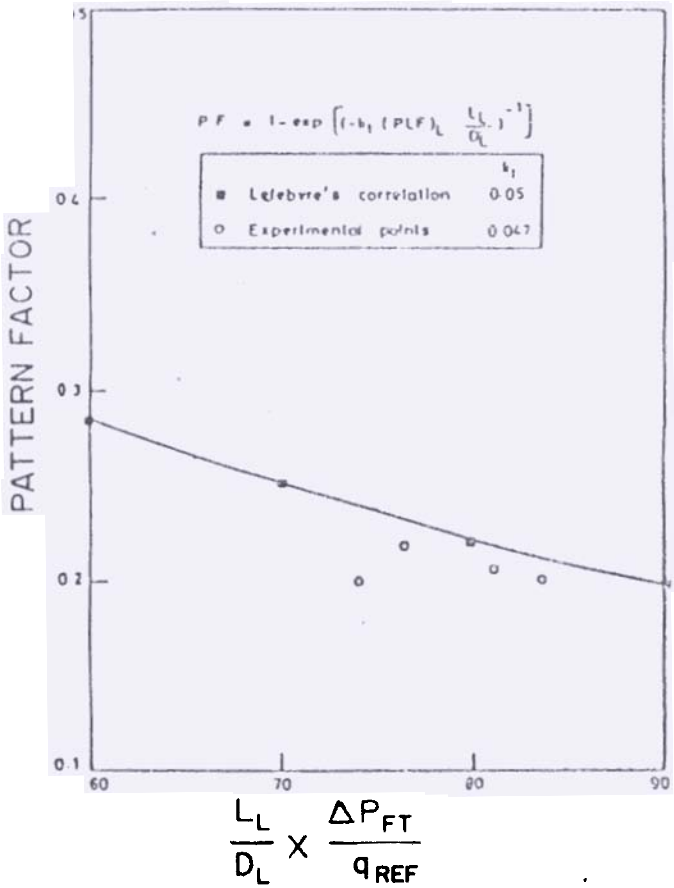

Figure 3(d). Pattern factor correlation for straight flow annular combustors.

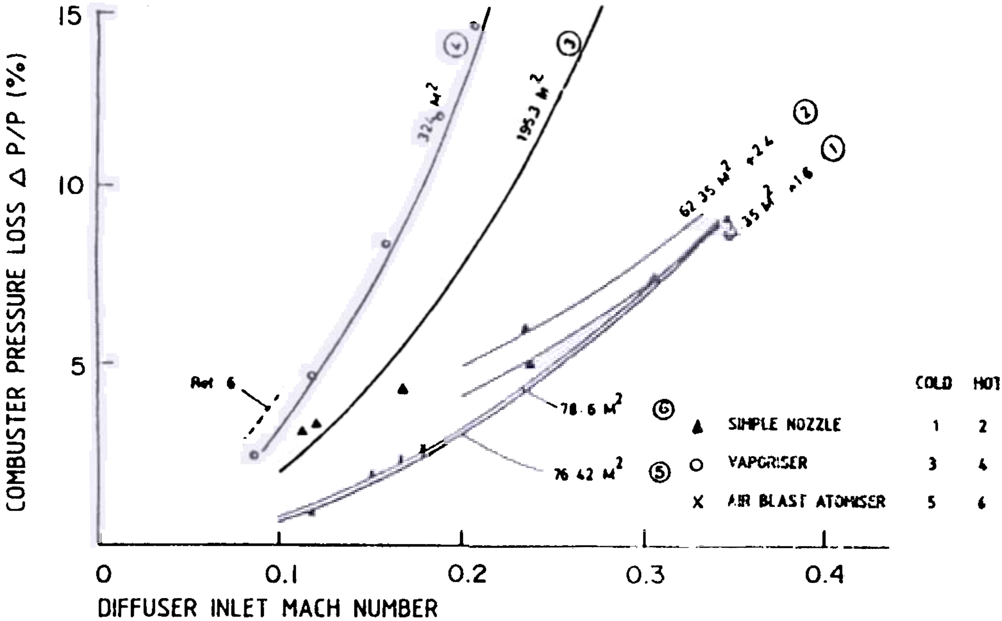

Figure 4(a). Variation of total pressure loss with diffuser inlet Mach number

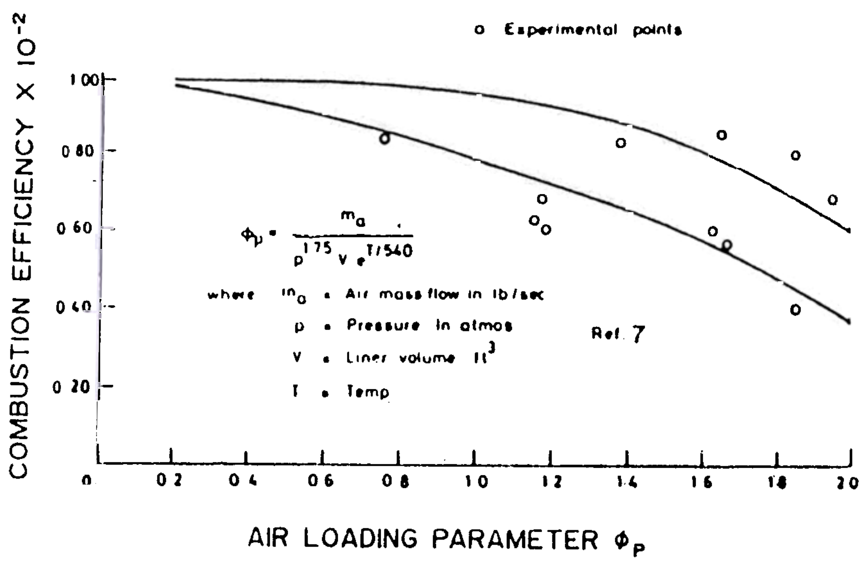

Figure 4(b) Combustion efficiency variation

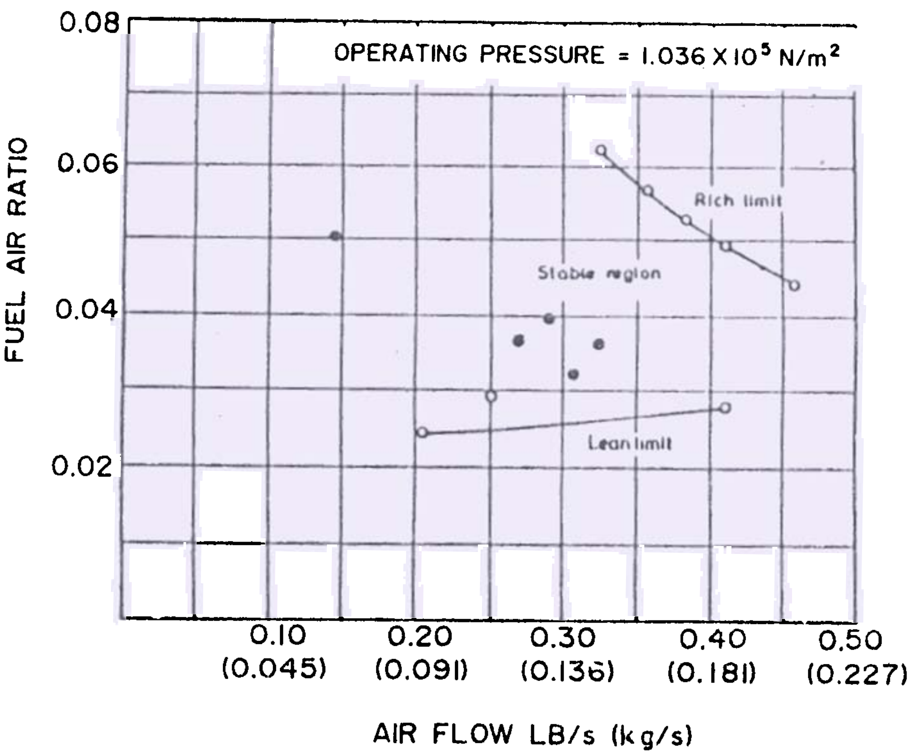

Figure 4(c). Stability loop

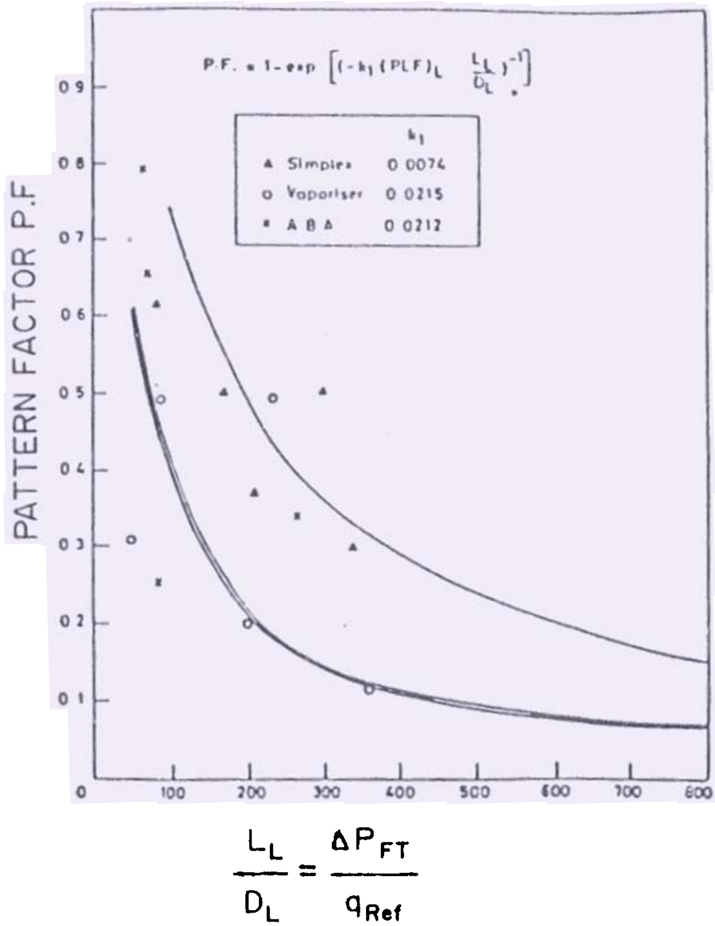

Figure 4(d). Pattern factor correlation for reverse flow annular combustors.

It can be seen that a reverse flow combustion system offers high combustion intensities, lower size and weight compared to a straight flow combustor. It can also bring down the weight of the engine shaft resulting in saving in over all size and weight of the engine, a factor much needed for smaller engines. An added advantage will be reduction in shaft vibrational problems.

5. DEVELOPMENT OF A CORRELATION FOR COMPARISON OF PERFORMANCE

To compare the two combustors or a given combustor with different fuel injectors, a correlation is derived as follows. It can be shown that :

Combustion efficiency $\eta_{cc} \propto (\theta, f/a)$

Total pressure loss $\dfrac{\Delta P}{P} \propto M^2$

Pattern factor $PF \propto \left(\dfrac{L_L}{D_L}\right)\left(\dfrac{\Delta P_{ft}}{q_{ref}}\right)\left(\dfrac{1}{HRR}\right)$

Table 3. Results of the experimental investigation of straight flow combustors

Sl No.	Performance characteristic	Effect of change in operating parameter	Remarks
1.	Total pressure loss Fig. 3(a)	(a) Increase in inlet Mach No. M	Total pressure loss increases. Maximum allowable pressure loss occurs at M = 0.45. So operation of this combustor is limited to this Mach No.
		(b) Decrease in inner annulus area	No appreciable change in total pressure loss. Slight decrease in the hot condition.
	Radial temperature profile at combustor exit	(a) Increase in inlet Mach No. M	Except between M = 0.31 and 0.35, temperature profiles behave as expected. In this range, the peak of the profile shifts towards the hub because of shift from 8 to 16 burner operation.
		(b) Shift in velocity profile towards tip	20 to 50% change shifts peak of the temperature profile from 40% to 50% of the annulus height.
		(c) Decrease in inner annulus area	Inlet velocity profile shifts towards the tip. Temperature profile shifts towards the hub by nearly the same amount.
	Circumferential temperature profile at exit		Hottest regions occur near the centre of the exit annulus. One hot spot was observed between 285 and 330° due to over fuelling of two burners
4.	Combustion efficiency Fig. 3(b)		In the θ range of 0.25–0.35 × 10^{+5}, η_{cc} falls between 70% to 90% which is within the accepted band
5.	Combustion stability Fig. 3(c)		Combustor operation is stable between f/a 0.019 to 0.029 for air mass flows less than 1.9 kg/s. Lean limit can be extended by resorting to operation with reduced fuel injectors.
6.	Pattern factor Fig. 3(d)		Experimental values are in good agreement with Lefebvre's correlation[1].

Table 4. Results of the experimental investigation of reverse flow combustors.

Sl. No.	Performance characteristic	Change in operational parameter	Remarks
	Total pressure loss Fig. 4(a)	Increase in inlet Mach No. M	Experimental total pressure loss increases, as estimated except for the vapouriser type in which case, increase is more rapid, because of a fabrication error and perhaps due to larger blockage in the mixture shroud assy.
2.	Radial velocity profile at the exit	Increase in inlet Mach No. M	At cold conditions, the profile is centre peaked as for a pipe flow. At hot conditions, velocity and temperature profiles are found to be similar.
3.	Radial temperature profile at the exit	(a) Inlet velocity profile	A tip peaked inlet velcity profile produces hub peaked exit velocity and temperature profiles.
			A centre peaked inlet velocity profile produces tip peaked exit velocity and temperature profiles.
			A hub peaked inlet velocity profile produces a temperature profile with peaks at both near the tip and hub.
		(b) Increase in inlet Mach No. M	This increases the value of the peak temperature.
4.	Circumferential temperature profiles		Sector models produce a lower temperature on the side walls due to wall effect
5.	Combustion efficiency Fig. 4(b)		Values of η_{cc} lie within or above the prescribed band shown in the figure.
	Stability loop Fig. 4(c)		Limits of stable operation of this combustor are similar to those of the straight flow combustor. However lean limit cannot be extended any further by reducing the number of burners.
7.	Pattern factor Fig. 4(d)		This is same, more or less for all the three combustor models under similar operating conditions.

Heat release rate $$HRR \propto \left(\frac{\Delta P_{inj}}{P_{in}} \right) \times \frac{CV}{V_L} \tag{4}$$

Grouping the LHS quantities of Eqns. (1–3) a performance parameter called *PPP* parameter is evolved thus

$$\eta_{cc} \Big/ \left[\left(\frac{\Delta P}{P} \right) (PF) \phi \right] \tag{5}$$

Similarly grouping the RHS quantities of these equations an operating airloading parameter can be obtained. Calling this parameter as Aerodynamic Design parameter, *AD*,

$$AD = \frac{\theta}{M^2} \times \frac{HRR}{\left(\frac{L_L}{D_L} \times PLF_L \right)}$$

Substituting *HRR* by Eqn. (4),

$$AD = \frac{\theta}{M^2} \times \left(\frac{CV}{\frac{L_L}{D_L} \times PLF_L \times V_L} \right) \times \frac{\Delta P_{inj}}{P_{in}} \tag{6}$$

(a) For a given combustion chamber using the same fuel but operating with different fuel injectors, $\left(\frac{CV}{(L_L/D_L) \times PLF_L \times V_L} \right)$ is a constant. Therefore Eqn. (6) can be written as

$$AD = \frac{\theta}{M^2} \times \frac{\Delta P_{inj}}{P_{in}} \tag{7}$$

(b) For combustors operating under cold conditions, the terms corresponding to combustion efficiency, pattern factor and equivalence ratio are taken as unity and the terms corresponding to heat release rate, θ parameter and the pressure loss factor are deleted. This is due to the fact that under cold conditions, the only parameter that defines the performance is the pressure loss which is proportional to the square of the Mach number.

Hence Eqns. (5) & (6) become as

$$PPP = (1/(\Delta P/P)) \tag{8}$$

and $$AD = 1/M^2 \tag{9}$$

A curve showing the variation of PPP^* with AD^* is plotted in Fig. 5. PPP^* and AD^* values are obtained after dividing the *PPP* and *AD* values by respective parametric values representing the operating conditions corresponding to a datum value. In this case the datum corresponds to the design condition values of the straight flow combustor operating with a simplex atomiser at a pressure of $35 \times 10^5 N/M^2$ (500 psi).

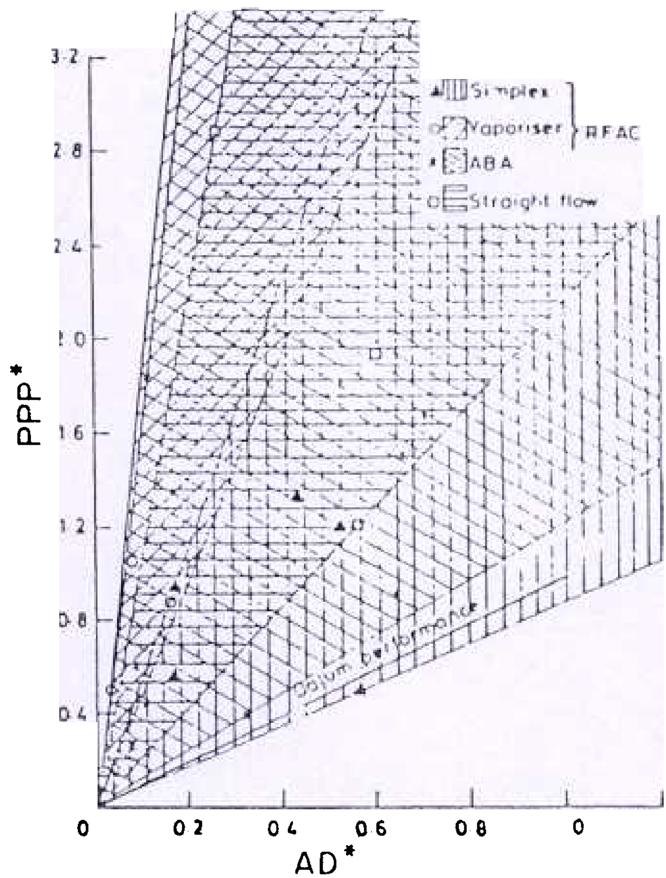

Figure 5. Comparison of performance of combustor

It can be seen that the performance points for these models lie within a band bounded by lines emanating from the origin (0, 0). It can also be seen that the bands are overlapping showing the regions where all the models perform equally. Based on this figure, the order of merit can be established as : (a) Reverse flow combustor with vapouriser, (b) Straight flow combustor with simplex, (c) Reverse flow combustor with airblast atomiser, and (d) Reverse flow combustor with simplex.

6. CONCLUSION

From the investigations presented, the general conclusions which can be drawn are : (a) A viable combustion chamber can be developed using the proposed design technique, (b) A correlation for meaningful comparison of the combustor models is arrived at, (c) Investigations show that for a small gas turbine, reverse flow combustor with a vapouriser is the best from overall considerations.

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