A STUDY ON THE OPTIMIZATION OF JET ENGINES FOR COMBAT AIRCRAFTS

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Abstract

In the paper the optimization of jet engines for combat aircrafts is discussed. This optimization is referred to the selection of the values of the fan pressure ratio or by—pass ratio; maximum turbine inlet temperature; overall pressure ratio and maximum reheat temperature which optimize the specific fuel consumption and the ratio of the thrust to the nozzle throat area, assuming this last parameter to be an indicative of the thrust/weight ratio. The selection is carried out taking into account the aircraft missions for which the engine design is optimized.

Nomenclature

a	altitude
M	Nach number
T_{CC}	combustion chamber outlet temperature
T_{RH}	reheat outlet temperature
λ	by-pass ratio
π_{FN}	fan pressure ratio
π_{OV}	over-all pressure ratio

k Introductions Scope of the Work

The present work is devoted to the study of the optimization of the principal functional variables of a typical modern military engine for combat aircrafts. This optimization is referred to the fundamental engine characteristics: thrust/weight ratio and specific fuel consumption.

Unlike comercial aircrafts, which always fly at practically the same conditions; combat aircrafts are designed to operate at very different flight conditions, and the optimization of their engines greatly depend on the type of missions for which the aircraft is optimized.

Jet engine for modern combat aircraft are of the turbofan type, with reheat and a convergent or convergent-divergent exhaust nozzle of variable area.

During development optimization is an important task and it consists in the selection of the principal variables of the thermodynamic cycle: by-pass ratio *or* fan pressure ratio, combustion chamber outlet temperature, overall pressure ratio and maximum reheat temperature.

Selection of the values of these variables is carried out in order to optimize the thrust/weight ratio and the specific fuel consumption according to the missions for which the engine is optimized. The thrust/weight ratio depends not only on the cycle characteristic but also on the specific details of the engine design and on the engine size. From the cycle point of view it may be taken as representative of that variable the ratio of the thrust to the nozzle throat area.

Other important engine characteristics, such as life cycle cost, maintainibility and reliability have to be taken into account. However, they are outside of the scope of the present work.

II- _Missions

Among the great number of missions assigned to combat aircrafts, there are two specially significant with respect to engine optimization: they are the interception missions and the air strike or ground attack mission. In the first of these missions, typical of a combat or air superioity fighter, the aircraft takes off, climbs at optimum climb speed and flies at maximum or near maximum horizontal speed to intercept the target at full reheat conditions. In this mission up to 75-85% of the fuel may be consumed with the reheat burning and, therefore, fuel consumption in the reheat is of fundamental importance. On the other hand, in the strike missions the reheat is utilized only for take off and for attacking the target, and less than 10% of the fuel may be consumed when the reheat is operating.

In this last mission, and in missions of long range or long loiter; dry conditions of the engine (reheat off) at high altitude and in subsonic or supersonic cruise, become specially important in the process of the engine optimization.

II1^___Assumptions

a) The engine is assumed to be a two shafts turbofan, with reheat and a convergent nozzle.*

b) Typical adiabatic efficiencies of compressors and turbines are taken and assumed to be constant. Typical pressure-losses coefficients will also be taken for

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* The case of a convergent-divergent nozzle will be treated separately.

the combustion chamber, reheat, by-pass duct and nozzles, as well as for the mixing process of primary and secondary flows at the reheat inlet.

c) The complex cooling system of a high temperature military engine is treated in a simplified way. The cooling flow rates of turbines, reheat and exhaust nozzle are related to the combustion chamber outlet temperature and to the reheat temperature respectively; and it is assumed a partial recovery of the energy of the cooling flows in both turbines.

d) Average values will be taken *of* the exhaust area of the nozzle, for both on and off reheat conditions.

e) Average values of the specific heats are taken in each phase and for each individual case. Combustion processes are treated numerically utilizing hydrocarbon combustion tables.

With all these assumptions, calculations are simple and suitable to be treated with a computer programme.

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IV.1 By Pass Ratio and Fan Pressure Ratio

By equalizing the pressures of the primary and secondary flows at the reheat inlet, a relationship is obtained among the four variables: by-pass ratio, A fan pressure ratio $*_{F''}$. combustion chamber outlet temperature T„_ and over-all pressure ratio *ov* External conditions: altitude a and fligh Nach number M influence that relationship.

Fig. 1 showB results for K=0 and a=0 for different temperatures T„_.

Large fan pressure ratios are essential in order to obtain high values of the thrust/weight ratio, and low values of the specific fuel consumption, when the reheat is working (Figs. 2, 3 and 4), which implies low values of the by-pass ratio according to Fig. 1.

These low values of A give good supersonic flight conditions, but it deteriorates subsonic cruise conditions (Fig. 5); due to the fact that the optimum value of A that minimizes specific fuel consumption occurs at very high values of this parameter (Fig. 6), even higher that those normally utilized in turbofan engines for commercial aircrafts.

As a consequence, engines optimized for interception missions or combat aircrafts, must have small values of the by-pass ratio, of the order of 0.20-0.50 in practice. The minimum possible value of A is determined by a minimum air flow required to have combustion in the secondary flow and by the cooling requirements of reheat and nozzle. This minimum value of A is of the order of 0.10-0.20.' •'

Engines optimized for strike fighters or for aircrafts that require long range missions at subsonic speeds, higher values of the by-pass ratio have to be selected, of the order of 0.5-1.

IV. 2 Combustion Chamber Outlet Temperature

Combustion chamber outlet temperature does not influence directly the thrust/weight ratio when the reheat is operating, but it allows the selection of larger values of the fan pressure ratios (Figs. 1 and 2). On the other hand, it does influence directly the thrust/weight ratio at dry conditions.

High T temperatures improve the specific fuel consumption when the reheat is operating (Fig. 4) at supersonic conditions, but it deteriorates subsonic cruise conditions, specially at low by-pass ratios (Fig. 5). *

High temperatures T are always desirable in engines for combat aircrafts. At todays level of materials technology, those high temperatures are made feasible by means of large turbines cooling flows, which may offset further gains above a certain limit. Actually, maximum inlet turbine temperatures are of the order of 1800-2000 K; but there are research programmes in progress to increase these temperatures up to near the stoichiometric level by developing new types of materials.

IV.3 Overall Pressure Ratio

For a given by-pass ratio, there is a value of the overall pressure ratio $*Q_V$ for which the fan pressure ratio x_{FN} is maximum (Fig. 7), and then the specific fuel consumption is minimum at reheat operating conditions. However the specific fuel consumption is not a very sensitive function of *QV above that minimum value (Fig. 8).

On the other hand, at dry conditions the specific fuel consumption has a minimum value as function of *ov> which occurs at very high values (40 or even higher) of this variable, at subsonic flight conditions (M=0.85), as occurs in engines for commercial aircrafts. The value of »$_{ov}$ that minimizes the specific fuel consumption is considerably smaller at supersonic flight conditions.

It has also to be considered that high values of »Q_V would create severe temperature problems in the high pressure compressor at supersonic flight conditions.

' At very large by-pass ratios results would be inverse.

In practice, moderate values of the overall pressure ratio (of the order of 25) are a good compromise for combat aircrafts that do not require the capability of cruising at supersonic speeds at dry conditions.

If supersonic cruise is required without reheat lower values («15-20) of »$_{ov}$ appear to be more suitable.

IV.4 Reheat Maximum Temperature

Increasing the reheat maximum temperature T_RJJ directly increases the thrust/weight ratio, at the cost of a less important increase in the specific fuel consumption (Figs. 2 and 4).

Maximum values of TRH are limited, on one hand, by the cooling problems of the reheat and the exhaust nozzle, and on the other hand, because when TRH approaches the adiabatic combustion temperature, combustion instabilities problems (buzzing and screeching) become more severe. In practice, limiting values of 2000-2200 K are not surpassed.

Nozzles

The optimization studies have been carried out, for simplicity, on engines with convergent nozzles, and considering that results would have been very similar with convergent-divergent nozzles.

However, most modern engines for combat aircrafts utilize convergent divergent nozzles. With the high nozzle pressure ratios, typical of these engines at supersonic flight and at high altitude conditions; ideal thrust gains of the order of 25-30% may be obtained, with similar reductions in the specific fuel consumption.

In practice, thrust gains are lower, due to losses, additional cooling air and especially due to geometrical constraints typical of axi-symmetrical nozzles made of a certain number of sliding petals.

These convergent-divergent nozzles require also an important optimization process according to the missions for which -the engine design is optimized.

For each flight conditions (Mach number and altitude), there are optimum values of the exhaust and throat areas of the nozzle giving maximum values of the thrust gain. However, this requires considerable variations of the ratio of the exhaust area to the throat area, when the nozzle- changes from conditions adapted, for example, at full reheat (combat) at high .altitude and high Mach number, down to typical cruise conditions (Fig. 9). Petals constraints may limit such large variations of the nozzle area ratio.

On the other hand, if optimum values of the exhaust and throat areas would be adapted for each flight condition, each area would change independently and it would require two independent actuation systems, with an important penalty in weight and cost.

Convergent-divergent nozzles with only one actuation system are Bimpler and widely utilized in practice. Some sort of mechanical link between the convergent and the divergent petals is utilized, giving a relationship between the exhaust and the throat area. The selection of this relationship is the basis of the optimization process of the nozzle according to the missions.

Fo example, a law of variation such as A-A (Fig. 9) would give priority to high altitude combat conditions in detriment of range, and it would be suitable for an aircraft optimized for interdiction missions. On the other hand, a law of variation such as B-B, would be more suitable for a long range fighter or for a strike aircraft.

Bi-dimensional nozzles, which are being developed, overcome some of the aforementioned problems, at the cost of being more voluminous, probably heavier and with difficult sealing problems. However, their main asset is the possibility of thrust vectoring, which increases the maneuverability of the aircraft.

VI^__5££S£«S£*£

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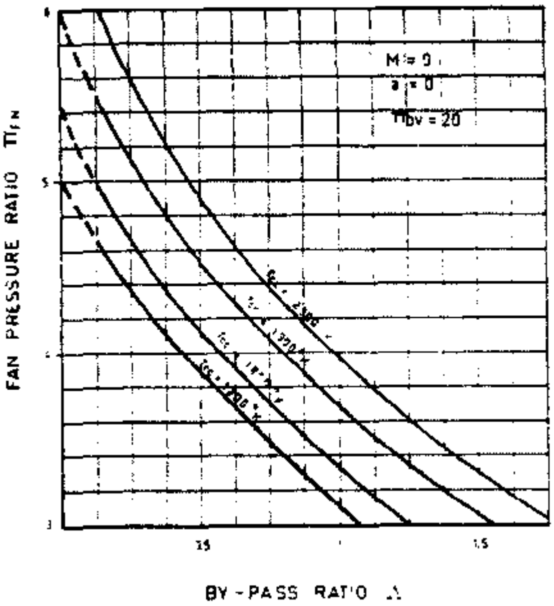
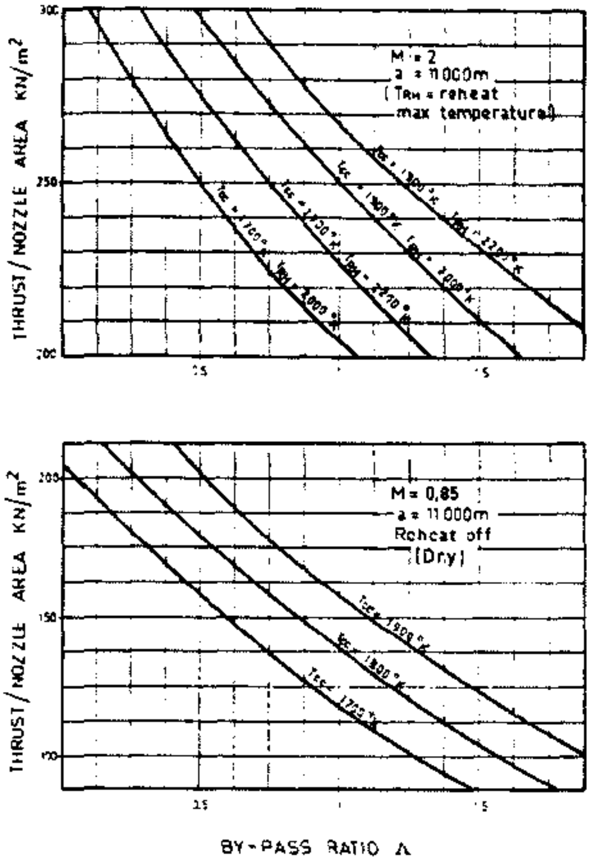
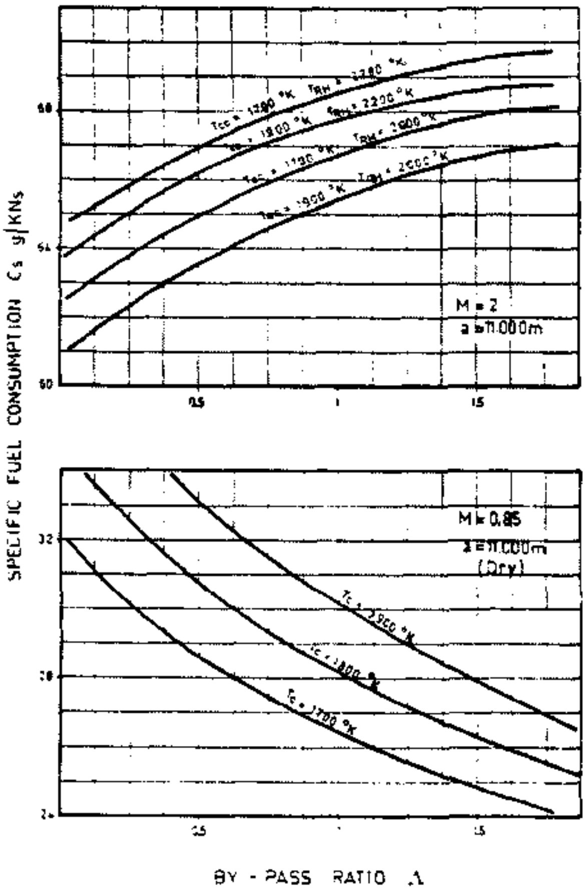


Fig. 1.- Fan pressure ratio as function of the by-pass ratio.



Figs. 2 and 3.- Thrust/nozzle area ratio as function of the by-pass ratio. Reheat on and off.



Figs. 4 and 5.- Specific fuel consumption as function of the by-pass ratio. Reheat on and off.

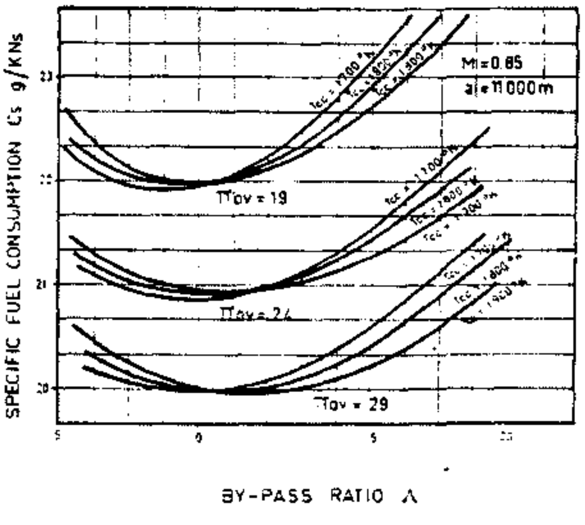


Fig. 6.- Specific fuel consumption as function of the by-pass ratio at subsonic speed.

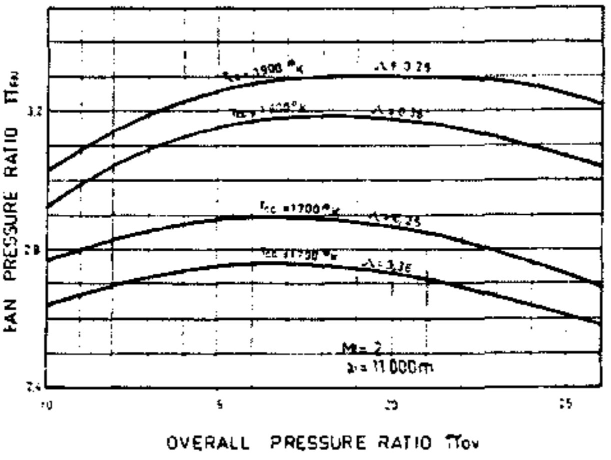


Fig. 7.- Fan pressure ratio as function of the overall pressure ratio, showing the maximum value of π_{FN}.

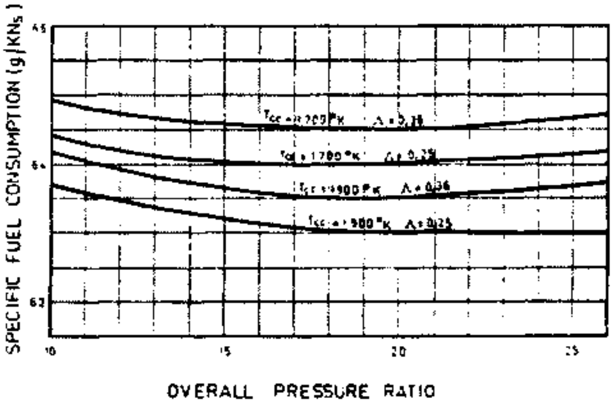


Fig. 8.- Specific fuel consumption as function of the overall pressure ratio.

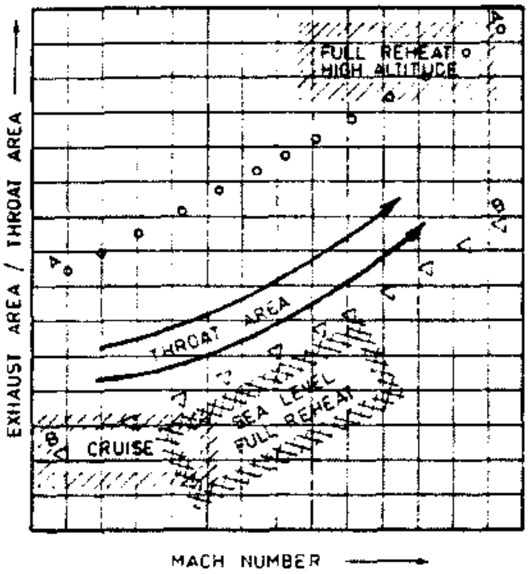


Fig. 9.- Convergent-divergent nozzles. Laws of variation of the ratio of the exhaust area to the throat area.