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Effects of Design Parameters on Cooling Air Requirement in a Gas Turbine Combustor

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Nomenclature

A_f = flame tube cross-sectional flow area
A_{ref} = casing cross-sectional flow area
D_f = flame tube diameter
L_f = flame tube length
M_{ref} = combustor reference Mach number
M_∞ = flight Mach number at zero altitude
$\dot{m}$ = total combustor air mass flow
$\dot{m}_{cf}$ = combustor cooling air mass flow
OPR = overall pressure ratio
s = cooling film slot height
TIT = turbine inlet temperature
T_{wmax} = maximum allowable wall temperature
η_{cp} = compressor efficiency

Abstract

THE purpose of this paper is to show the effects of design parameters on the cooling air requirement in a typical can-annular aircraft gas turbine combustor. Works in this field have been reported earlier, for instance by Whittaker,[1] showing how wall temperatures in different combustion zones depend upon various parameters. The objective of this work is the opposite, i.e., to prescribe a maximum allowable wall temperature and to calculate the total amount of cooling air required in order not to exceed this temperature at any location.

Contents

Calculation Procedure

A computer program for the preliminary design of aircraft gas turbine combustors was used for the present parametric study. The program is based upon established methods for wall temperature calculations.[2,3] Main dimensions, airflow distribution, and cooling air requirements are automatically calculated for a typical aircraft gas turbine combustor (Fig. 1), which is considered to consist of three zones, primary, secondary, and dilution. Each zone is treated separately, starting with the primary zone, and outlet conditions from one zone become inlet conditions for the next zone. When each zone has been optimized, any remaining airflow is fed to the dilution zone as "dilution air." In order to permit simple wall temperature calculations, each zone is characterized by one single effective mean temperature and one single representative air mass flow which is considered to flow uniformly in a downstream direction.[2]

A flow chart that describes the calculation procedure is shown in Fig. 2. It is assumed that the sea level static combustor conditions are known and the program starts to calculate the main dimensions from these data. The design conditions pertaining to the wall cooling requirement in a typical military jet engine are then calculated by assuming that the "worst case," i.e., the highest combustor inlet tem-

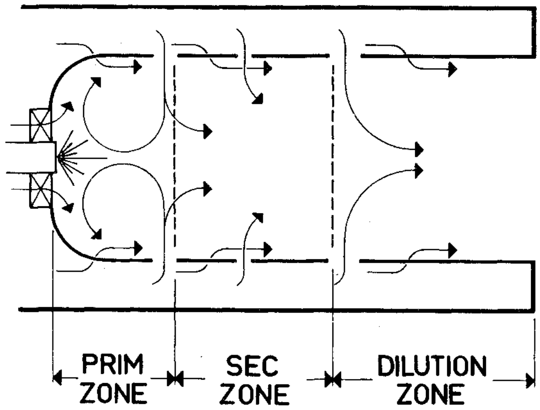

Fig. 1 Typical aircraft gas turbine combustor.

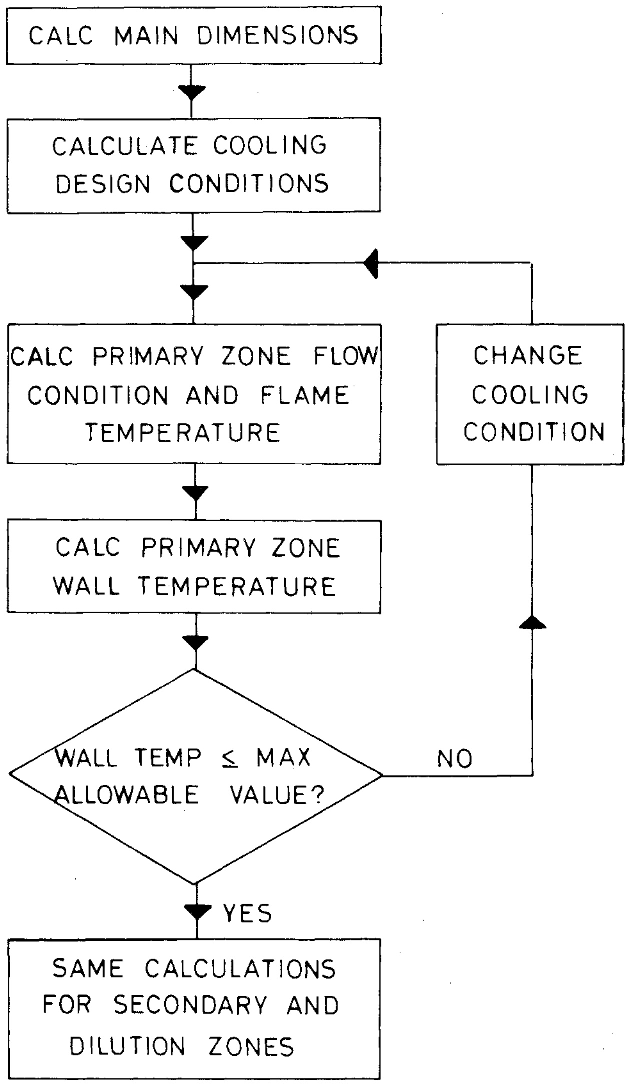

Fig. 2 Computer program calculation procedure.

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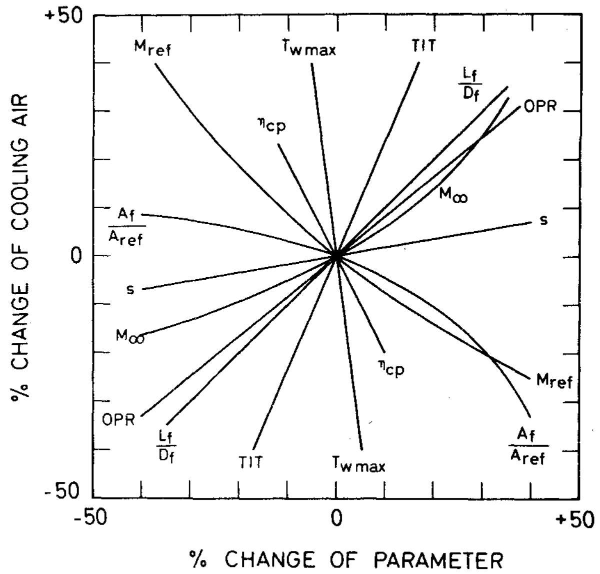

Fig. 3 Summary of parametric study.

perature and pressure level, occurs at zero flight altitude and maximum flight Mach number. The cooling air requirement is calculated in the following way: the calculations start with one cooling film in each zone and a minimum value of the cooling film/main stream mass velocity ratio, which is well below the anticipated optimum. This ratio is then, if necessary, increased in small steps to an upper value, which is well above the anticipated optimum. In each step the wall temperature is calculated and compared with a maximum allowable value. If the requirement is not satisfied by modifying the cooling film/main stream mass velocity ratio, the number of cooling films is increased from one to two and the procedure is repeated until an acceptable wall temperature is achieved in each zone. Cooling film effectiveness and heat transfer coefficient are calculated according to Ref. 3.

Parametric Study

The computer program was applied to a typical can-annular aircraft gas turbine combustor defined by the following data:

OPR $=17$ $\qquad$ $M_\infty = 1$
TIT $= 1350$ K $\qquad$ $\dot{m}_{cf}/\dot{m} = 0.34$
$\dot{m} = 70$ kg/s

A parametric study was carried out where one parameter was varied while maintaining the others. For each case the percentage of cooling air was calculated. Only "external" parameters directly affecting the dimensions and the geometrical design were varied. "Internal" parameters involved in flow and temperature calculations were kept constant. Although the results are valid for the chosen reference combustor and engine cycle only, they are considered to offer a general guide to the trends. A summary of the parametric study is given in Fig. 3, showing the relative effect of each of the parameters varied.

It is found that the cooling air requirement increases with increasing cooling film slot height(s). On the other hand, the number of cooling films decreases at the same time. Thus the choice of the slot height will be a compromise between the demands for a small amount of cooling air and a low number of cooling films. The computer program automatically finds the optimum value of the cooling film/main stream mass velocity ratio. Normally this ratio falls within the range of 1.0-1.5.

Increase in either the combustor reference Mach number (M_{ref}) or the ratio between the flame tube and the casing cross-sectional areas (A_f/A_{ref}) decreases the cooling air requirement. In both cases the result is mainly attributed to improved convective cooling in the annulus. On the other hand, the cooling air requirement increases with increasing flame tube length/diameter ratio (L_f/D_f). This is a result of the larger surface area that has to be cooled. Increase in the maximum allowable wall temperature (T_{wmax}) causes a dramatic reduction in the cooling airflow.

The effects of increasing overall pressure ratio (OPR) or flight Mach number (M_∞) are essentially the same. The cooling air requirement increases due to a combined effect of a higher combustor inlet temperature and a higher pressure level. Similarly the cooling air increases with decreasing compressor efficiency (η_{cp}) because the combustor inlet temperature goes up. Finally it is found that the cooling air requirement increases with increasing turbine inlet temperature (TIT). A higher TIT means a greater temperature rise and hence more air is needed in the combustion zone. In order to maintain the optimum value of the cooling film/main stream mass velocity ratio, the cooling airflow must increase. A higher turbine inlet temperature also means a hotter dilution zone which requires more cooling air.

Calculations were also carried out for a number of combinations of overall pressure ratios and TIT's. Within the region of interest the cooling air requirement could be approximated by the following power function

$$\frac{\dot{m}_{cf}}{\dot{m}} \sim \mathrm{TIT}^{2.4}\mathrm{OPR}^{0.85} \qquad (1)$$

which is particularly illustrative when showing how the current trend toward higher overall pressure ratios and higher TIT's aggravate the cooling situation. Eq. (1) can be used to obtain rough extrapolations for the cooling air requirement of any given combustor, while bearing in mind that it is obtained from one particular reference combustor.

Acknowledgments

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