A THREE STEP NOx REDUCTION PROGRAMME: "ACHIEVEMENTS WITH THE SINGLE ANNULAR LOW-NOx COMBUSTOR FOR THE BR 700 ENGINE FAMILY"

Norbert Brehm, Stephen J. Baker, and Steven P. Jones  
BMW Rolls-Royce AeroEngines, Eschenweg 11.D-15827 Dahlewitz

ABSTRACT

The social responsibility for the environment, in conjunction with the threat of more stringent emissions regulations requirements, initiated a comprehensive NOx-emissions reduction programme in BMW Rolls-Royce. The achievements of the first step for NOx-emissions reduction by optimisation of the single annular combustor stoichiometry and mixing are presented. The combustor development programme is described, and rig and engine test results are compared. The NOx-certification levels achieved with the BR 710 single annular low NOx combustor are down to 55 % of the actual ICAO limit.

1. INTRODUCTION

As a result of public concern about nitrogen oxide (NOx) emissions on the atmosphere and the climate and not completely understood by the scientific community yet (Virginia Beach, 1996), low NOx emissions are already a major and continuously more important requirement for jet engines for commercial applications. Intensive worldwide research and development work is being conducted to reduce emissions. Three steps can be identified leading to continuously lower NOx exhaust levels, firstly in the short term, the improvement of the single annular combustor technology by optimisation of the mixing process between fuel and air, secondly the introduction of staged combustors in the medium term, and finally, staged combustors using premixing and prevaporisation technology in the long term (Brehm et al., 1994).

The social responsibility for the environment, the commercial requirements from the airlines, and the tightened ICAO emissions certification regulations led to a comprehensive low-NOx Combustor Programme in BMW Rolls-Royce for the BR 700 engine family.

With the launch of the core engine in 1991 the NOx reduction programme was started and was continued during the BR 710 engine development programme. The technology programme was launched in mid 1994, having the objective to demonstrate with a fuel staged double annular combustor 35 % NOx reduction, against the best available single annular combustor, in a core engine in 1998. In the long term, ultra low-NOx levels might be achievable with the Lean-Premixed-Prevapourized (LPP) technology. Although BMW Rolls-Royce is concentrating its efforts mainly on the NOx reduction in single and double annular diffusion type combustors, the step to ultra low-NOx is prepared by the participation in the European BritedEURAM LOW NOx III programme with high pressure rig demonstration of a fuel staged LPP combustor in 1998.

Presented at the International Gas Turbine & Aeroengine Congress & Exhibition  
Orlando, Florida — June 2–June 5, 1997
2. BR 700 SINGLE ANNULAR COMBUSTOR

The content of this paper is the description of the NO₅ reduction achievements with the single annular combustor which was certified with the BR 710 engine (fig.1) in August 1996. For a description of the main features, the basic layout of the combustor is shown in fig. 2. The volume is based on the Rolls-Royce design rules for altitude relight and the engine pull-away requirements at sub-idle. Wall cooling is achieved with Z-ring shaped cooling rings, and the flame tube is rear mounted, both systems adapted from the Rolls-Royce military engine technology. The combustor has 20 airblast fuel injectors for low carbon monoxide, unburned hydrocarbons and smoke. As the required low-NO₅ emissions technology was not available, the air distribution and mixing in the flame tube, as well as the fuel injector and the heat shield arrangement, had to be developed from this initial datum design, during the BR 710 engine development programme.

3. BR 710 DEVELOPMENT PROGRAMME

When the BR700 core engine development was started in 1991, and with the launch of the BR 710 in 1992, NOₓ reduction was a major objective for the combustor development programme. Although computational fluid dynamics (CFD) is a helpful tool, a comprehensive rig programme was needed to develop the combustor technology. A 2:1 scale perspex flow visualisation rig was used to optimise the flow in the diffuser and annuli around the flame tube. A 60 degree low pressure sector rig, equipped with quartz glass side walls, was used to study ignition, weak extinction and fuel spray characteristics of the combustor. A 90 degree high pressure sector rig with an exit traverse gear was used for emissions measurements. With this rig the basic understanding of the low NOₓ technology was developed in a number of tests, with combustor inlet temperatures up to 900 K and an air-fuel ratio (AFR) down to 35. In parallel, thermal paint tests led to an optimised design concerning the durability of the fuel injector, the heat shield and the combustor walls. The tests were restricted to a maximum pressure of 2 MPa due to facility limitations. Before the combustor design was used for a core or an engine, the selected configuration was tested in a full annular rig for full analysis of emissions, exit temperature traverse, pressure loss, material temperatures, and ignition and stability behaviour. This rig was equipped with a continuously moving traverse gear. Test pressures were restricted to 1.3 MPa due to the facility limitations. Also the altitude relight and pull-away characteristics of up to 35000 feet were evaluated in the full annular rig, at sub-atmospheric conditions.

The first combustor standard (datum) which was not optimised for low NOₓ, underwent an early core test with emissions measured up to the full engine pressure. During the BR 710 engine development programme emissions were measured in the second development engine and in the certification engine only. These engines had datum and low NOₓ combustors respectively.

Besides the emissions tests the combustor underwent the flight clearance for the first Gulfstream V flight in September 1995, the engine certification programme and a number of flight cyclic tests, totaling more than 3000 cycles. A combustor noise problem which arose during the development was solved by introduction of a new fuel injector standard. This is described by Konrad et al. 1996, in some detail.

3.1 Results of the NOₓ Reduction Programme

3.1.1 CFD Simulations

The NOₓ reduction potential of various configurations was investigated by simulations with the CFD code PACE (Jones and Whitelaw, 1982). The comparison with the measured data in fig 3 shows that the simulation results are generally higher. The reduction of El NOₓ from the datum combustor standard to the low NOₓ standards, selected for the BR 710 and the BR 715 engines, was correctly predicted. The attempt to further optimise the combustor by CFD failed, due to insufficient accuracy especially in predicting the fuel atomisation process and the primary zone flow. This may have various reasons, e.g. the known deficiencies of the k-ε turbulence model to describe swirling flows, the imprecisely known boundary conditions or the simplifications in modelling the fuel spray. This leads to the conclusion that, CFD gives the right order of magnitude in NOₓ emissions and is a helpful tool to support the NOₓ reduction design strategy, but that the detailed optimisation can only be achieved in an experimental programme. The design strategy for NOₓ reduction was based on the Rich burn-Quick quench- Lean burn concept (RQL). In fig 4 and fig 5 the calculated distribution of the fuel fraction for the datum standard and the certification standard are shown. The RQL design strategy of the certification standard is seen. The quick quench has lead to a weaker, more constant quench shape.

3.1.2 High pressure sector rig tests

The design changes for lower NOₓ emissions were first tested in the high pressure sector rig. The 90 degree sector incorporated 5 fuel injectors. The benefits against a full annular rig are lower costs for modifications of the combustor and for the operation. The disadvantages are the disturbance of the flow by side walls and the poor statistics from only 5 injectors, which affects CO, UHC and smoke measurements. 15 configurations were investigated at the four engine thrust points defined in the ICAO regulations for Aircraft Engine Emissions (ICAO Annex 16, 1993). The engine cycle used was that of an early BR 715 engine with a rated pressure ratio of 32. The 15 configurations tested attempted to optimise i) the position and manner of injection for the quench zone, and ii) the primary air was injected for optimum mixing of the rich primary zone. However, improved primary zone mixing was not achieved with the various wall ports investigated. The NOₓ reduction achieved is mainly caused by the improved quenching configuration in the secondary zone. In fig. 6 the measured emission index (EI) of NOₓ is plotted against the combustor inlet temperature, T30, for the datum standard, the standard certified in the BR 710-48 engine and the standard selected for the BR 715-58. The primary zone pressure dependence of EI NOₓ was defined between 1.2 MPa and 2 MPa. The result for the low NOₓ combustor is (p/po)°0.33. This exponent was used to extrapolate from rig to engine conditions.

3.1.3 Full annular rig results

The NOₓ reduction achieved in the high pressure sector rig was confirmed in the full annular rig. Design fundamentals such as combustor pressure drop, cooling flow and port flow were verified also at this stage, as well as details like port axial position to control the mixing zones and therefore the emissions. In fig 7 El NOₓ is...
plotted for the datum, the BR710 and the BR 715 standard against T30.

Due to side wall effects in the sector rig the CO and UHC measurements were assumed inadequate to characterise the changes in the different standards. This was conducted in the full annular rig. Fig 8 and fig 9 give the measured values for CO and UHC respectively. It is clear that there is a trade-off between NOx and CO2, arising from the cooler secondary zone. Due to modest primary zone AFR variations during the development, smoke emissions were mainly defined by the fuel injector AFR. Because of the low combustor inlet temperatures at idle, the CO/NOx trade-off was more important than the smoke-NOx trade-off. The selection of the fuel injector had a minor influence on the NOx emissions, but a strong influence on the low power emissions.

Therefore a fuel injector optimised for low CO and UHC emissions was developed for the low NOx flame tube. Together with the requirement for high stability, low CO and UHC emissions were achieved with a three stream fuel injector by optimisation of the air distribution and the swirl number. The smoke level in the engine exhaust was the most difficult emission to predict from a rig measurement that was restricted to 1.3 MPa only. The combustor and fuel injector standards were ranked based on HSU smoke measurements taken at full power. Configurations which gave high smoke levels in the rig were not considered as an option for the engine.

The BR 710 engine cycle did not allow the combustor standard with the lowest NOx emissions achieved in the rig to be selected due to constraints at the low power emissions range. For the BR 715 engine cycle however, the combustor with the lowest NOx emissions can be used.

3.2. BR 710 engine test results

During the certification programme of the BR 710-48 engine the low-NOx combustor had to demonstrate its flight worthiness and its durability. The engine tests included a relight test up to 12000 ft with a windmilling start down to 250 knots, a rain and a rain test according to the latest, more stringent requirements, a cold start test down to -32 °C, a rapid deceleration test to demonstrate the combustor stability, a 150 hours type-test at elevated operation temperatures and the emissions certification test according to the ICAO regulations (ICAO Annex 16, 1993). Together with the engine the combustor fulfilled all requirements and demonstrated its airworthiness.

3.2.1 Engine emissions tests

Two engine emissions tests were carried out according to ICAO Annex 16. The first, with the datum flame tube, and the second, with the low-NOx combustor. The emissions indices for NOx against the combustor inlet temperature T30 are plotted in fig. 11. The NOx reduction, which was achieved in the rig programme, was confirmed in the engine tests. The measurements were analysed according to the ICAO procedure at the four standardised thrust points. In fig. 12 the NOx emissions levels for the two engines are compared with the full annular rig results. A 30 % NOx reduction is achieved in the engine by optimisation of the stoichiometry and the mixing process. The improvement in NOx emissions is underpredicted in the full annular rig.

In fig. 13 the emissions certification values of all species are shown in absolute values and in relation to the ICAO certification limits. The comparison in the ICAO chart indicates a reasonable margin to the actual NOx certification limit and even to the more stringent limit proposed by ICAO in 1996 in the CAEP III meeting (fig 14). Hence the combustor of the BR 710 engine will not fall under any operational restriction for at least the next 11 years.

4. APPLICATION FOR THE BR 715 ENGINE

The BR 715 engine is based on a common core to the BR 710. The low pressure system consists of a 58 inch fan, a 2 stage booster and a 3 stage low pressure turbine. The thrust of the engine will be up to 22000 lbs with a pressure ratio of 35 at take off condition. The higher combustor inlet pressure and temperature make the NOx reduction task even more difficult. Therefore a combustor will be used, which is further optimised for low NOx emissions with a penalty for the CO emissions index. This penalty is possible without an adverse effect on the CO emissions level in the ICAO cycle due to the changed engine cycle. In fig. 15 the ICAO NOx levels based on full annular rig measurements are compared for the BR 710 combustor and the BR 715 combustor. The BR 715 should provide an acceptable margin to the certification limit despite the higher pressure ratio.

5. CONCLUSIONS

This paper describes a logical approach to an emissions reduction programme. Both sector and full annular rigs, and CFD were used, in a time and cost effective approach, which required only minimal engine testing. As a result, NOx emissions were reduced by 30 % in the programme. The single annular combustor is the most attractive concept due to its relative simplicity, low cost, low weight and highest reliability. This combustor shows a reasonable margin against the latest NOx certification limit, proposed by the ICAO for the year 2000. Indeed further development might yield further reductions.
REFERENCES:


Fig. 1: BMW Rolls-Royce BR 710 jet engine.
The engine has a rated thrust of 14750 lbf at a pressure ratio of 24.5.

Fig. 2: Annular combustor of the BR 700 engine family

correlation coding

nickel alloy without thermal barrier coating

optimised combustor volume

"Z" ring cooling
Fig. 3: EINOx measured in the high pressure sector rig compared to EINOx calculated by CFD.

Fig. 4: Fuel fraction distribution calculated by CFD for the datum combustor design at take off condition.
Fig. 5: Fuel fraction distribution for the BR 710 Low NO\textsubscript{2} combustor calculated by CFD at take off condition

Fig. 6: EI-NO\textsubscript{2} versus combustor inlet temperature measured in the high pressure sector rig at simulated engine conditions (maximum pressure 2 Mpa)

Fig. 7: EI-NO\textsubscript{2} versus combustor inlet temperature measured in the full annular rig at simulated engine conditions (maximum)

Fig. 8: EI-CO versus combustor inlet temperature measured in the full annular rig at simulated engine conditions

Fig. 9: EI-UHC versus combustor inlet temperature measured in the full annular rig at simulated engine conditions
Fig. 10: Trade-off between NOx and CO for the combustors investigated at the same simulated engine conditions for 7% idle and take off.

Fig. 11: NOx-emission indices versus combustor inlet temperature for the datum design and the low NOx design measured in the BR 710 engine.

Fig. 12: NOx-emissions levels according to the ICAO procedure from the full annular rig and the engine.

Fig. 13: Certification emissions levels for the BR 710 Low NOx Combustor.

Fig. 14: ICAO NOx-emissions level versus engine pressure ratio.

Fig. 15: ICAO NOx levels for the BR710 combustor in the rig and the engine, and for the BR715 combustor in the rig.