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Low Emission Commercial Aircraft Engine Combustor Development in China: From Airworthiness Requirements to Combustor Design

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Abstract

The development of International Civil Aviation Organization (ICAO) requirements of aircraft engine emission is reviewed in this paper with special focus on the influence on commercial aircraft engine combustor design. As the reason of NO_X emission as the primary critical issues for combustion organization scheme during the combustor R&D, the development status of several classical low emission combustors in the word is referred in this paper. Based on the current technology and the future certification standards, the design perspective of the Chinese next generation low emission commercial aircraft engine combustor is also discussed in this paper.

Keywords: ICAO, commercial aircraft combustor design, NOx emission requirements, low emission combustor

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Nomenclature

ϕ	Equivalent ratio
CAEP	Committee on Aviation Environment Protection
ICAO	International Civil Aviation Organization

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IES	Independent experts
LDI	Lean direct injection
LPP	Lean premixed prevapourised combustor
LT	Long term
LTO	Landing and Take-off
MT	Middle term
NO_X	Nitrogen oxides
RQL	Rich-burn/ quench/ lean-burn combustor
TAPS	Twin annular premixing swirler
TRL	Technology readiness level
UEET	Ultra efficient engine technology program
UHC	Unburned hydrocarbons

1 INTRODUCTION OF CAEP STANDARDS

With much more concerning on the living environment and health for humanity in recent years, the regulations and standards of emission control are launching respectively. As we know, the emission standards of gas turbine engine are issued by the International Civil Aviation Organization (ICAO), while the activities of environmental protection in ICAO are organized by Committee on Aviation Environment Protection (CAEP).

For the better understanding of the restrictions for the gas turbine engine design especially of combustor design, this paper introduces some latest emission requirements of ICAO CAEP. In the year of 2007, ICAO CAEP had held a CAEP/7-WP/11 meeting by inviting the experts of industry, university, government and relative association in Europe and America to authorize the new regulation for the new generation engine. During that meeting, the future commercial aircraft engine emission goal and the future 10 years to 20 years NO_X emission technical goal of commercial engine had been discussed. From the publications released from this meeting, we can see that more stringent standards than the NO_X emission requirement of CAEP/6 in 2004 have been established. ICAO CAEP had held a CAEP/8-WP/10 meeting and reports a review by IEs of the NO_X goals which set in 2007.

The time our commercial aircraft engine finishing the airworthiness certification is close to the estimate LT technical goal reaching time, and the suggested NO_X technology goal in WP/11 has far-reaching influence to our commercial aircraft engine low emission combustor development.

2 READING OF ICAO CAEP EMISSION REQUIREMENTS

According to the provisions of ICAO CAEP, the emission pollutants of gas turbine engine are CO, UHC, Smoke and NO_X. Emission calculation is defined by LTO cycle.

The ICAO CAEP had established eight emission requirements for aircraft engines from CAEP/1 to CAEP/8. What the emission requirements that CAEP provided are the recommended practice, not the certification regulations. Now most of the countries choose the CAEP/2 emission requirements as the aircraft engine certification standard.

In the 6th meeting of ICAO CAEP, the NO_X emission requirement has been more stringent, the emission requirement is what we called CAEP/6 requirement.

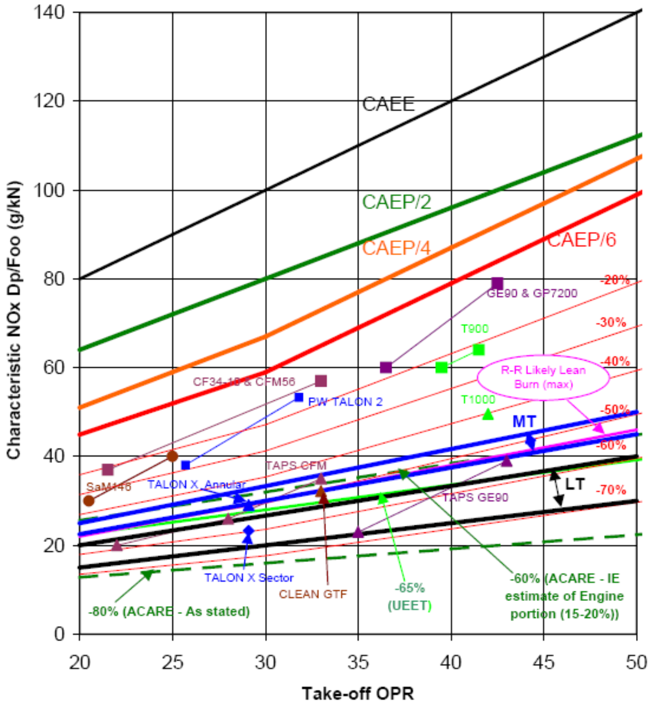


Figure 1: The MT and LT goals of NO_X emission (CAEP/7)[2]

The CAEP/7-WP/11 meeting had offered medium (MT, 10 years) and long term (LT, 20 years) technology goals for NO_X emission. The MT and LT technology goals for NO_X emission separately decrease 45% and 60% relative to CAEP/6 requirements (in Fig 1). The new technology goals of NO_X emission had put forward great challenges to commercial aircraft engine combustor low emission combustion technology.

The CAEP/8-WP/10 meeting do not change the MT and LT technology goals which set in 2007, the seventh meeting of ICAO CAEP. And the eighth meeting of ICAO's CAEP recommends more stringent Nitrogen Oxides (NO_X) emission standards on large engines certified after 31 December 2013.

3 LOW EMISSION COMBUSTION PRINCIPLE AND REGULATORY MEASURES

According to the CAEP emission standard, the NO_X emission requirement is more and more stringent while smoke number and other gaseous pollutants limits are not change. The low emission combustor critical difficulty point is NO_X. In order to describe the low emission combustion regulatory measures, the NO_X formation principle will be reviewed as follows.

3.1 NO_X FORMATION MECHANISM IN COMBUSTION

Nitric oxide can be produced by four different mechanisms: thermal NO, nitrous oxide mechanism, prompt NO, and fuel NO.

Thermal nitric oxide is produced by the oxidation of atmospheric nitrogen in high-temperature regions of the flame and in the post flame gases. The process is endothermic and it proceeds at a significant rate only at temperatures above around 1850K. Most of the proposed reaction schemes for thermal NO utilize the extended Zeldovich mechanism[5].

Nitrous oxide mechanism is when combustion temperature decrease and pressure increase, the reaction temperature less than 1500K, the nitrous oxide (N_2O) formed and then oxidized to NO.

Prompt NO is produced by high-speed reactions at the flame front.

Fuel NO is produced by oxidation of nitrogen contained in the fuel. This portion will be ignored as a result of the nitrogen content in the fuel is very low.

For conventional combustors, in the take-off, climb and cruise operation phase, NO_X formation is mostly from thermal nitric oxide. From the above NO formation mechanism analysis, thermal nitric oxide plays a dominant role when equivalent ratio is approximate 1. Nowadays the pressure ratio of the in-service dominating commercial turbofan engine is about 30~40, combustor inlet temperature is about 800~900K, outlet temperature is about 1600~1700K at take-off operation phase. The equivalent ratios of primary zone at take-off, climb and cruise operation phase are all about 0.8. In order to reduce the NO_X production, the primary zone should achieve homogeneous combustion and avoid the partial combustion of equivalent ratio being 1.

3.2 LOW NO_X CONTROL METHOD

The main factors controlling emissions from conventional combustors may be considered in terms of: primary-zone temperature and equivalence ratio, degree of homogeneity of the primary-zone combustion process, residence time in the primary zone, liner-wall quenching characteristics and fuel spray characteristics.

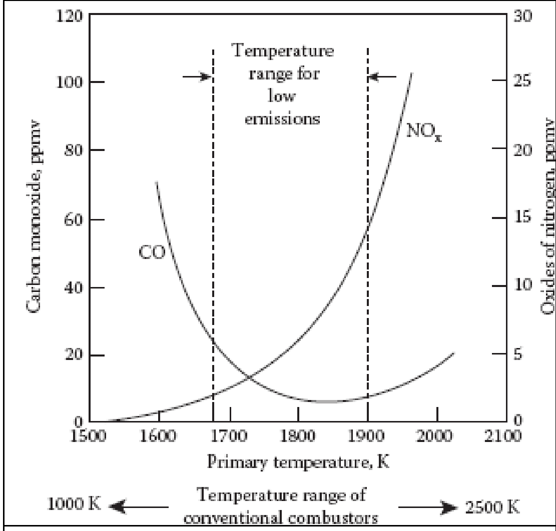


Fig 2: Influence of primary-zone temperature on CO and NO_X emissions [5]

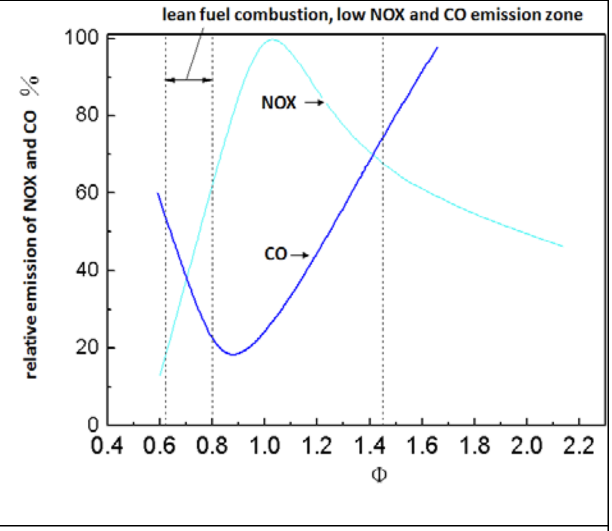


Fig 3: Influence of equivalent ratio on CO and NO_X emission [1]

Of all the factors influencing pollutant emissions from gas turbine combustors, the most important by far is the temperature of the combustion zone. Figure 2 shows that too much CO is formed at temperature 1670 K, while excessive amounts of NO_X are produced at temperatures higher than 1900 K. Only in the fairly narrow band of temperatures between 1670 K and 1900 K are the levels of CO and NO_X below 25 and 15 ppmv, respectively.

Figure 3 shows that in the narrow band of equivalent ratio the emission level of both CO and NO_X are simultaneity low. There are two measures to reduce all the pollutant emissions. One is through controlling the whole combustion zone equivalent ratio to control the combustion temperature to ensure the low emission. The other is to control the local equivalent ratio, which is the homogeneity of the equivalent ratio, to ensure the low emission. To intensify the mixing of fuel and air, minimize the liquid fuel particular size after the atomization; strengthen the evaporation even using the prevaporization.

Table 1: Comparison among three combustion methods

Low emission method	LPP	RQL	LDI
NOX emission	Extremely low	Very low	Very low
Combustion efficiency	Extremely high	high	high
Combustion stability	Flash back Combustion unstable Spontaneous combustion	No flash back	Combustion unstable
Smoke	Extremely low	High	Low
configuration	Short length Complex dome	Long length	Short length Complex dome
Development prospect	Common	Good	Best

From fig 3, it is easily concluded that there are two methods to reach the low emission target: lean fuel combustion and rich fuel combustion. From the two combustion methods, which LPP (Lean Premixed Prevaporized Combustion), LDI (Lean Direct Mixing Combustion) and RQL (Rich burn - quench - lean burn) generated.

Currently the characteristics of combustors which design according to the above low emission control methods are comparing in table 1.

4 CLASSICAL LOW EMISSION COMBUSTORS DESIGN REVIEW

In the CAEP/7-WP/11 meeting, the MT band is supported by the combination of TALON X (P&W P21), TAPS 2 (GE P20), and the lower portion of the R-R likely lean burn projection (R-R P18). Perspective is established by the R-R T1000 target (787application) for 2008 certification. This product to be certified nearly a decade before the timeframe of the MT band is only 10% above the MT band midpoint. The MT band is narrow (+/- 2.5%) because of the quantity of near term efforts targeted for product, giving confidence in its achievement.

The LT band is supported by TAPS 3, R-R 2020 target, TAPS CFM and UEET. This band is considerably wider (+/-5%) due to the uncertainty caused by an additional 10 years, and the reduction in the number of supported efforts, estimates/targets, and committed funding for this time frame.

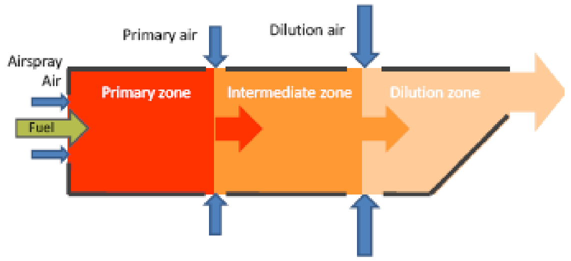


Fig 4: RQL combustor schematic [3]

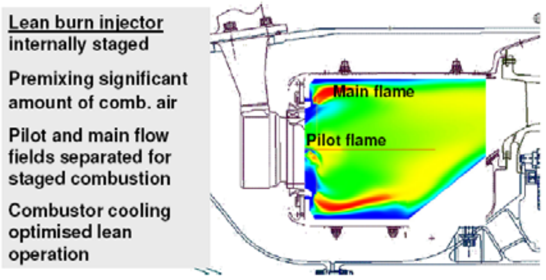


Fig 5: RR LDI combustor schematic

Engine manufacturers are aware of aviation's growing impact on the environment, continue to develop and introduce into service cleaner and more fuel-efficient engines.

To address this environment concern, Pratt & Whitney has continued aggressive development of the TALON family of combustors that employ advanced RQL technology (see Fig 4).

R-R develops the low emission combustor using LDI technology. The combustor is a single annular combustor and its NO_X emission decreased 50% compared with CAEP/6 emission requirements. The LDI technology combustor (see Fig 5) will be used into Trent 1000 engine.

GE's GEnX-1B (using TAPS 1(see Fig 6) staged lean burn combustor technology) appears very close to achieving the MT goal according to its certification data.

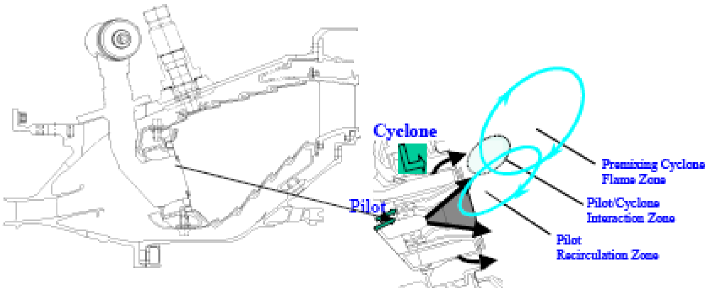


Fig 6: GE TAPS combustor schematic [4]

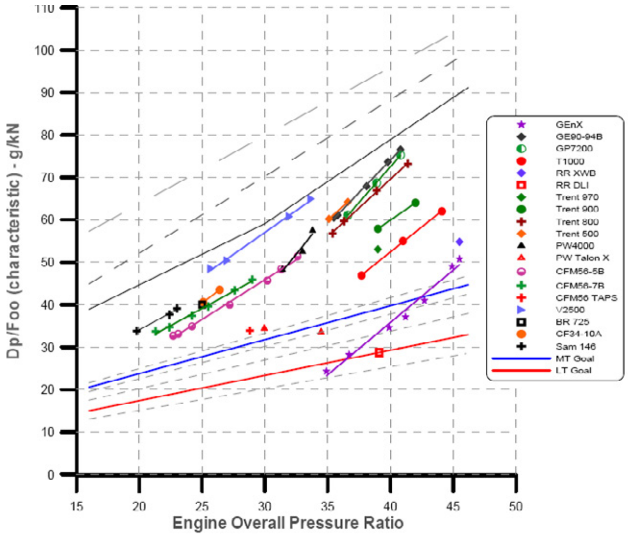


Fig 7: Historical engine data points, recent certification s, uncertified engines and high TRL tests and demonstrations' NO_X emission level [3]

To meet the MT and LT emission goals of CAEP/7, GE has started the development work of TAPS 2 and TAPS 3 combustor. The new technology's major feature is having used the much more enhanced mixing approach.

Fig 7 develops the data identifying engine types both certificated and uncertified, and has been extended to include the high TRL demonstrators and predictions.

5 THE ROAD OF CHINESE NEXT GENERATION LOW EMISSION COMBUSTOR

5.1 EMISSION TARGETS

From CAEP/1 to CAEP/8, the NO_X emission is more and more stringent and other pollutants emission requirements are not changed in the last several meetings. Now most country's certification is based on CAEP/2 requirements. CAEP/6 requirements decrease 26% relative to the current certification standard when OPR is around 30.The Buildup of Chinese commercial aircraft Engine Company triggers up the national wide study upsurge of the low emission combustor design. According to our commercial aircraft engine development schedule, the first demo-engine will be succeed in developing in these years, so our aircraft engine combustor's NO_X emission target directly aims to the goals of more than 45% decreasing compared to CAEP/6 requirements.

5.2 LOW EMISSION COMBUSTOR DESIGN DEVELOPMENT

The low emission combustor development should follow two basic principles. One is to meet the requirements of the combustor; and the other is to follow the basic principle of low emission combustion [1].

In the combustor combustion technology design, we can choose the LPP, RQL, fuel or air staging technology to meet the CAEP emission requirements. The RQL technology has the possibility to decrease the NO_X emission further, but the lean burn technology is more potential than RQL technology for NO_X decreasing in the long run.

The combustor design is a trade-off process of stability requirements, emissions requirements, performance requirements, reliability requirements, weight requirements, altitude re-light and starting requirements, etc. However, the safety must be the top one what we consider the most important requirements.

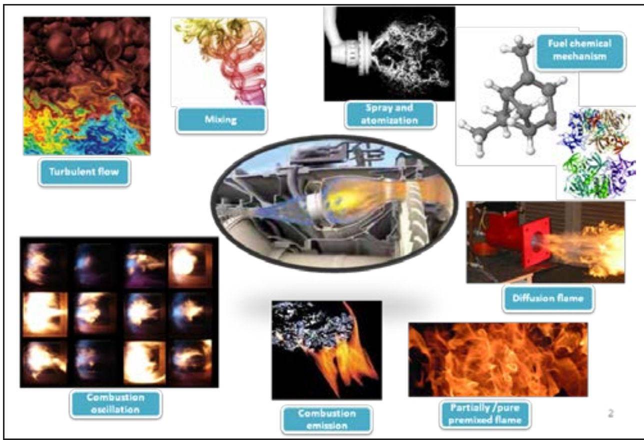


Fig 8: CFD requirement of low emission combustor

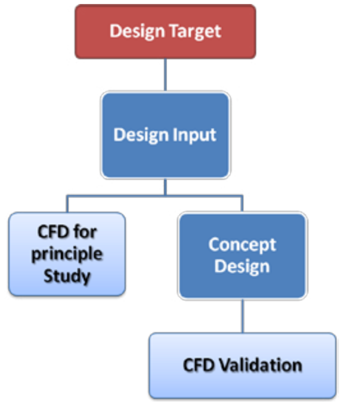


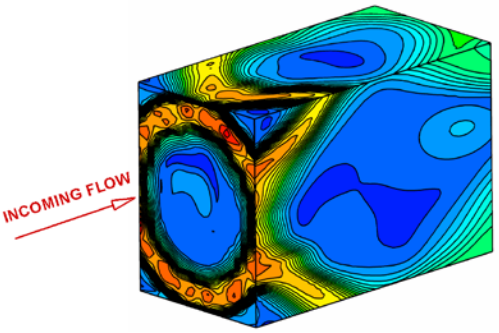
Fig 9: Design loops of the product development involved with CFD

Developments in computational fluid dynamics (CFD) techniques and supercomputers have enabled more complicated engineering cases to be simulated. The numerical approaches to turbulent spray reacting flow are rapidly developing in the context of the studies of aircraft combustor over the years. However, to obtain reliable results, numerical approaches must resolve the difficulties and challenges of modeling some complex physical processes, including turbulence, droplet clusters momentum, energy transfer under the influence of vortices, reaction of hydrocarbon fuels and combustion oscillation. So far, numerical studies of liquid fueled aircraft combustor are mostly carried out using Reynolds averaged Navier-Stokes (RANS) methods in industry application[8], while large-eddy simulation (LES) approaches to the detailed reacting mechanism study (see fig 8).

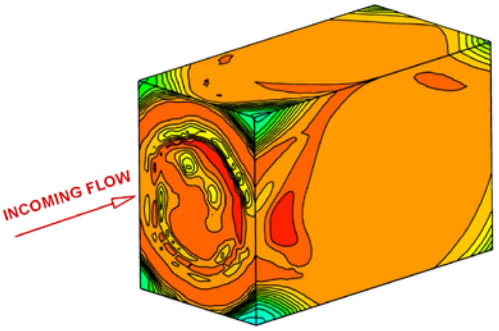
In most industrial company, CFD plays two important roles in the design process of the combustor R&D, as shown in fig 9. Before the combustor design, CFD will accumulate the data base for the design input, while as the validation tools after the product concept design.

To optimize the combustor design, both empirical analytical methods and advanced numerical simulation method are required to provide insight into the combustion and emission prediction, see Fig

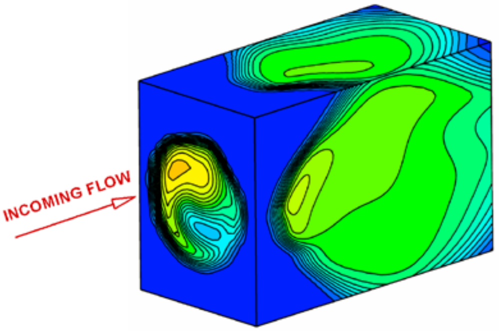
10.With the powerful product development tools, both the inner fluid motion and the NOx generation mechanism could be reviewed clearly. This approach will increase the efficiency of the combustor development.



(a)Velocity field



(b) Temperature field



(c) NOx emission field

Fig 10: Numerical simulation as useful method to predict temperature and emission distribution during combustor design.

6 CONCLUSION

Our commercial aircraft engine aims to the civil aviation market. The low emission is the inevitable choice. The combustor is required to be designed and developed to achieve low emission performance while maintaining safety requirements first. We should place great emphasis on the change of ICAO CAEP emission requirements and low emission combustion technology.

The following are what should pay more attention to:

a. Carry out the intellectual property and patent study ;
b. Develop the airworthiness compliance verification technology study, especially in emission test compliance technology investigation, get ready for the future entire engine certification;
c. Carry out the CFD investigation work;
d. Carry out lots of experimental investigation work.

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