THE IMPACT OF FUEL PREPARATION ON GAS TURBINE COMBUSTOR TRADE-OFFS

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ABSTRACT

The projected growth in civil aviation has strengthened the green lobby for continued reductions in gas turbine emissions. This focus combined with competitive pressures and the prospect of ever increasingly stringent legislation has driven unprecedented activity in combustion research over the last two to three decades.

This paper recounts the advances in combustor architecture and fuel injection technology over this period and defines the level of understanding in the critical physical processes required to deliver the cleaner technology of the 21st century.

1. INTRODUCTION

The legislative requirements have bestowed "market entry" status on engine emissions. Primary focus has been on the levels of oxides of nitrogen (NOx) emitted in the exhaust, but limits also exist for unburned hydrocarbons (UHC), carbon monoxide (CO) and smoke. The competitive edge provided by low emissions technology goes beyond green credentials in the market place by virtue of the relatively recent advent of airport landing charges, calculated on the basis of the level of pollutants emitted. NOx is essentially a high power by-product whereas control of UHC and CO is a low power issue. The challenge to the combustion engineer is enhanced further in that the solution to the emissions problem over the power range of the engine must be created within the constraints of other practical design considerations and conflicting requirements. An appreciation of this conflict management exercise is deemed warranted to establish the context and contribution of spray technology.

2. COMBUSTOR DESIGN CRITERIA

The combustion chamber is located in the high pressure core of the engine between the compressor and turbine (Figure 1).

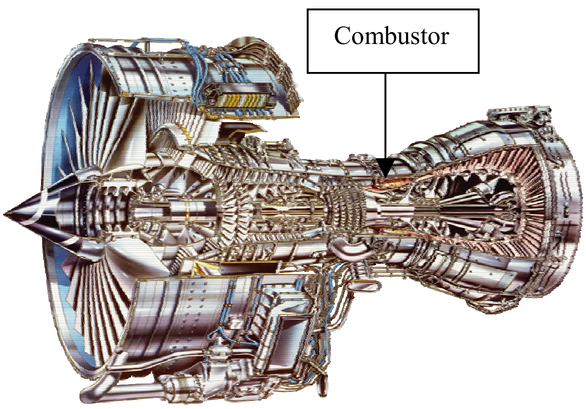


Figure 1 Trent 500 Engine

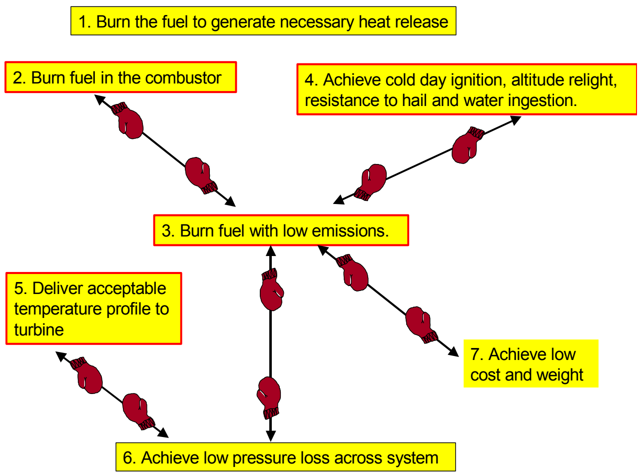


Figure 2 Combustor Design Criteria

The prime function of this component is to burn large quantities of fuel (approximately 5 litres per second at take-off conditions) to generate the heat release to drive the turbine. The principal design criteria for the combustor are captured in Figure 2.

The first and foremost requirement is that the combustion process take place within the confines of the flametube. It must be appreciated that the flame temperatures experienced are several hundred degrees higher than the melting point of the nickel based superalloys used in the construction of the hardware. To contain this extremely hostile environment, considerable attention is devoted to the provision of cooling air to maintain the liners at temperatures sufficiently low to survive for many thousands of hours in service. Typically 30-40% of the air delivered by the compressor is used to cool the combustor. Herein lies the first area of conflict in the design process because the quest for low emissions demands maximum utilisation of the available air for mixing with the fuel prior to combustion. Accordingly, the advancement of cooling technologies, capitalising on the sophisticated schemes adopted on high pressure turbine aerofoils, has been over the years and will continue to be a fertile field of research.

Emissions from aviation gas turbine engines are regulated by the International Civil Aviation Organisation (ICAO) Committee on Aviation Environmental Protection (CAEP). As stated above the primary focus continues to be on NOx, produced predominantly at the high power conditions. Control of this pollutant is achieved by minimising flame temperatures and the residence time of the fuel/air mixture within the combustor. The progress in terms of NOx reduction in the past decade, together with the legislative requirements and technology targets for the next generation of combustor technology is shown in Figure 3.

The parameter regulated by ICAO is the sum of the total emissions produced over the landing and take-off cycle divided by the take-off thrust of the engine. It can be noted from the increasing slope of the legislative limits that alleviation is granted with increasing engine pressure ratio. This reflects the impact of temperature on the NOx formation process as the combustor inlet air temperature rises with the engine pressure ratio. A significant step-change reduction in NOx emissions was achieved in the mid 90's by the phase 5 combustor technology that features in all Rolls-Royce Trent engines. Intensive effort is underway to deliver the next step change technology required for entry into service by the end of this decade.

The next design requirement to consider is cold day ignition on the ground and restart at altitude if combustor flame-out is experienced. The latter requirement is particularly arduous bearing in mind the ambient air conditions at 10,000 meters. At these conditions the fuel preparation/evaporation challenge calls for relatively long residence times for the fuel/air mixture to achieve an ignitable state. This is the key criterion in sizing the combustor volume. Here we confront the next trade-off. As stated above, minimum residence time is required to control NOx emissions. Ideally, to settle this issue two combustor volumes would be required, one with long residence time to favour altitude relight and another with low residence time to minimise pollution. This indeed is the design intent of staged combustion chambers as exemplified by GE in their GE90 engine [1] (Figure 4). However, the Rolls-Royce phase 5 combustor achieves an equitable balance in these design parameters in the much simpler, lower cost, lighter weight and more reliable single annular architecture.

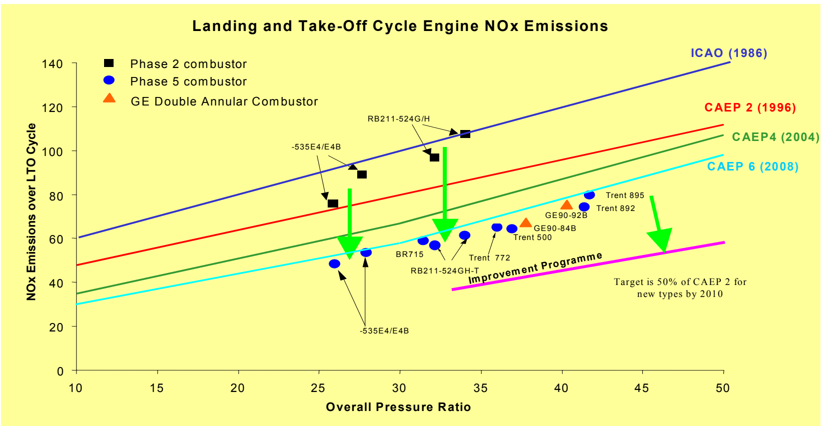


Figure 3 Engine NOx Emissions

GE 90 **Rolls-Royce Trent**

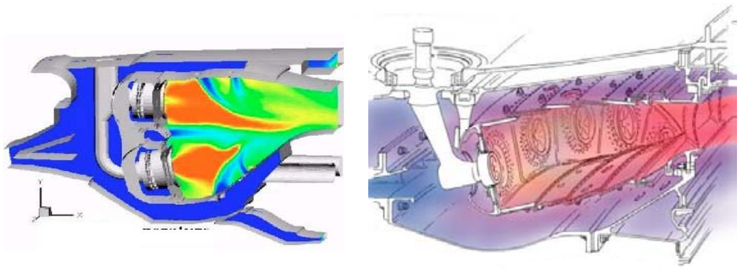


Figure 4 Low Emissions Combustor Architecture

Moving on, the next factor to consider is matching the temperature profile of the combustor exit gases to the turbine system design needs. This interaction results in a specification to the combustion engineer in terms of overall temperature uniformity around the annulus (seen by the static guide vanes) and a circumferentially averaged radial profile (seen by rotating aerofoils).

The above requirements must all be met within a prescribed pressure loss budget. Pressure loss across the combustion system adversely impacts the specific fuel consumption of the engine. This constraint conflicts directly with the low emissions and temperature profile challenges both of which are eased as pressure loss increases. The higher the pressure loss, the higher the momentum of the air jets introduced progressively down the liner to control zonal stoichiometries and achieve vigorous mixing with the reacting flametube flowfield.

Last but not least vital factors to consider throughout the design process are the cost and weight implications of the solution to the technical challenges. Direct conflict between these attributes and the quest for low emissions is apparent as the next generation technology evolves. A step change reduction in NOx will demand a significant increase in the amount of air introduced via the fuel injection device, and fuel staging within the nozzle, required to achieve a solution to the trade-offs, discussed above, will add to the complexity (Figure 5). This will more than double the cost and weight of these components.

The importance of fuel injection technology and the need to carefully match the spray characteristics to the aerodynamic flowfield cannot be overstated. The residence time within a typical flametube is less than 10 milliseconds, allowing no time to recover from a poor start to the combustion process.

Figure 5 Fuel Injector Comparison

3. COMBUSTOR ARCHITECTURE/FUEL INJECTION TECHNOLOGY EVOLUTION

Following initial concerns about aircraft emissions being raised in the late 1960's, particularly pertaining to air quality local to airports, the landing and take-off cycle basis for measurement was defined by the USA Environmental Protection Agency. First came smoke regulation, followed by unburned hydrocarbons, and then carbon monoxide and NOx limits. The increasing momentum behind the regulatory process stimulated unprecedented research activity which delivered highly impressive reductions in pollution levels (see Figure 3). The path from the capability available on the RB211 engines of the early 1980s to the phase 5 technology in production today is detailed below.

3.1 RB211 phase 2 Combustor

The incumbent combustor architecture in the RB211 engines was the phase 2 standard depicted in Figure 6 .

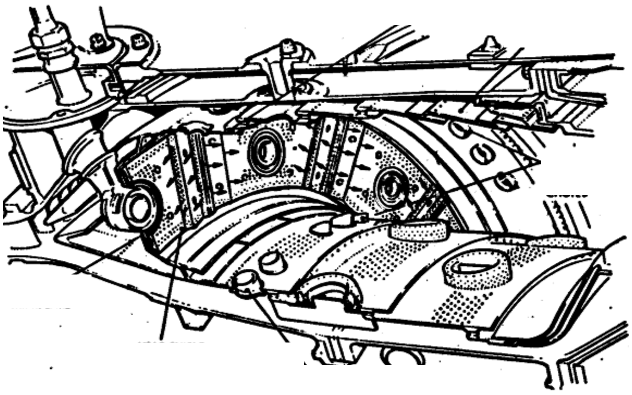
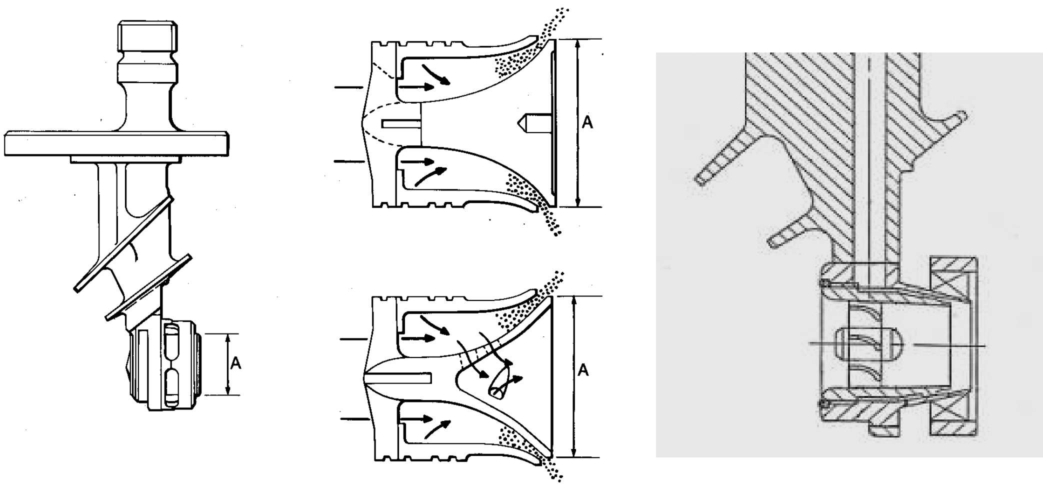


Figure 6 RB211 Phase 2 Combustor

The initial fuel injector was the low swirl, low shear, pintle flame stabilised design shown in Figure 7. This concept proved vulnerable to carbon build-up on the pintle face and was replaced by a high swirl, high shear design featuring a prefilmer device sandwiched between counter swirling air passages.



a. low swirl, pintle

b. high swirl, prefilming

Figure 7 Phase 2 Fuel Injector Designs

3.2 Vaporising Combustor Architecture

The effectiveness of the vaporising fuel injection system as demonstrated in the Olympus 593 (in Concorde), the Pegasus (in Harrier) and RB199 (in Tornado) engines qualified this concept as a candidate architecture for wider civil application. The principal features of the annular vaporiser chamber are depicted in Figure 8.

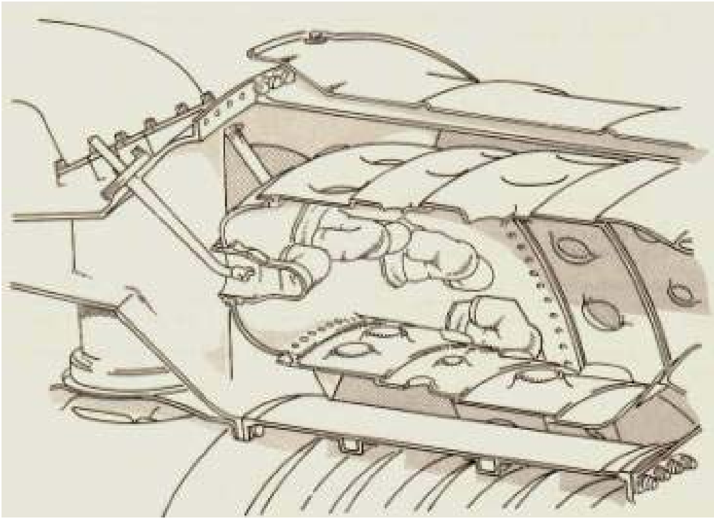


Figure 8 Annular Vaporiser Combustor

The insensitivity of combustor performance to fuel injector location, and the insensitivity of dump diffuser performance to combustor head position, sanction a one-piece, rear mounted construction free from sliding joints. Compatibility with dump diffusion permits the use of a low cost single skin combustor head cooled on the outside by compressor delivery air and on the inside by a fuel rich region resulting from the upstream injection of the fuel by the vaporiser. A crucial design criterion for this style of combustor is the vaporiser stoichiometry at the take-off condition. Early development work, underpinned by a spark photographic study of a vaporiser efflux over a range of combusting conditions (Figure 9) defined a satisfactory corridor of operation regarding this critical parameter [2]. Deviation on the lean side deprives the vaporiser tube of adequate cooling leading to oxidation and loss of vaporiser material, whereas overfuelling leads to high smoke and in the extreme, carbon accretion in the head of the combustor. As combustor inlet temperatures and pressures rise, this corridor narrows and ultimately limits the use of this technology. This fundamental principle was demonstrated to exclude application to future, low emissions civil engines, leaving the solution to be found in the more traditional airspray technology.

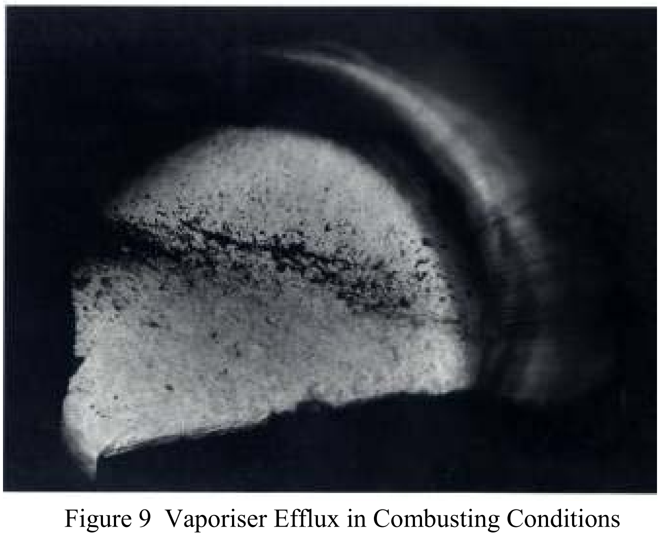


Figure 9 Vaporiser Efflux in Combusting Conditions

3.3 Trent phase 5 Combustor

The phase 2 system shown in Figure 6 was the result of significant development effort, but had limited growth potential. The cycles being considered for the next generation of engines featured increased temperatures and pressures to meet improved fuel consumption targets. The combination of the advanced cycles and the need for a step-change reduction in emissions called for a radical improvement in combustion technology. There was also a strong desire to reduce cost and weight, demanding a major overhaul of the combustor architecture. The solution was provided by the phase 5 design shown in Figure 4.

The major change to the fuel injector was the addition of a third air swirler (Figure 10) to weaken the fuel air mixture into the primary zone and control smoke production. To combat the potential for increased NOx formation in the weaker primary zone, rapid quench immediately downstream of the primary zone was achieved. This highly successful integrated design solution evolved from an extensive programme of experiment and modelling. Optimisation of the fuel injector performance proved a critical element of this effort.

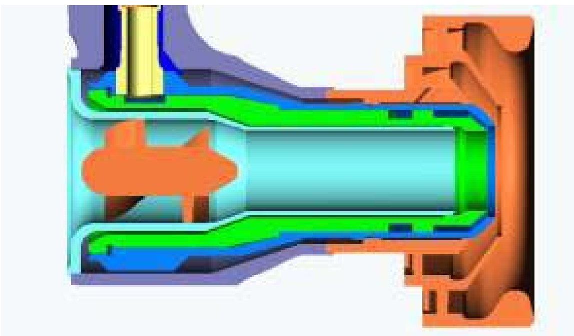


Figure 10 Trent phase 5 Fuel Injector

4.0 MODELLING AND VALIDATION

The creation of a combustion system solution for a particular engine requirement, meeting all aspects of performance discussed above in section 2, relies increasingly on a detailed characterisation of the fuel spray from both analytical and experimental perspectives. Fuel spray measurements, detailed below, provide the boundary conditions required for reliable CFD predictions of the reacting flow.

4.1 Sprays Measurements

When a new design is produced a standard set of measurements is performed to characterise the fuel spray nozzle performance. These include flow number, overall effective area, fuel placement, droplet size distribution, droplet velocities and air velocities. Characterisation of the fuel spray usually takes place with the nozzle mounted in an airbox (Figure 11) to simulate the air feed it experiences when mounted in the combustion system. This testing is normally carried out at ambient air pressure, but it can also be carried out at pressures above and below atmospheric pressure. The conditions of airbox based testing are scaled to the engine design point of interest. The fuel spray patterns delivered by a nozzle can change significantly from the maximum thrust to idle or sub-idle cases. In order to replicate the cone angle and fuel placement in the airbox simulation, the ratio of fuel to air momentum and absolute air velocity are usually conserved. If the fuel droplet size is the primary interest then the nozzle air/fuel ratio (AFR) and absolute air velocity can alternatively be conserved. The droplet size is dictated largely by the relative velocity between the fuel and the air. In practice the air to fuel relative (slip) velocity is close to the engine condition whichever matching is used since the larger air velocity is always conserved.

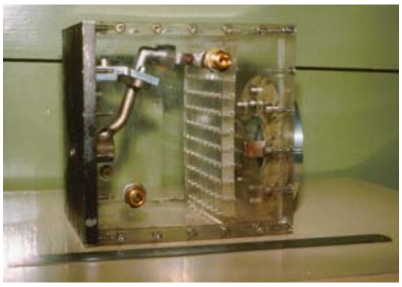
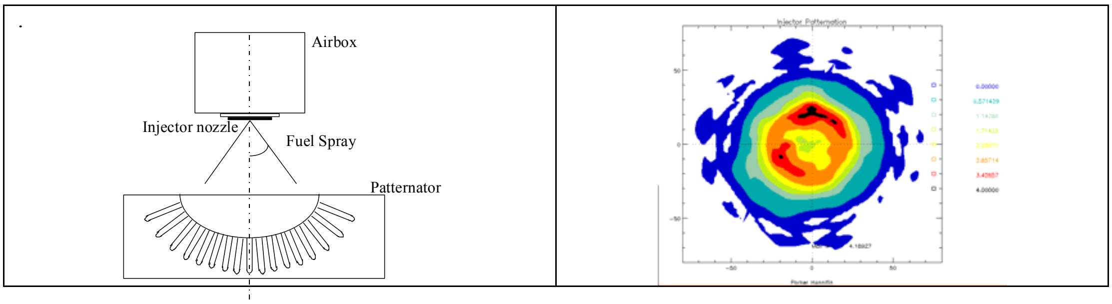


Figure 11 Typical Airbox for Spray Characterisation



Mechanical Patternation

LIF of a Phase V style injector

Figure 12 Cone Angle Measurement Systems

The fuel placement prescribed by a nozzle is measured by either a mechanical patternator collection device or laser induced fluorescence (LIF) as indicated in Figure 12. Narrow cone angle sprays such as those seen on early standards of RB211 engines using the pintle style of injector can be measured by either LIF or patternator. Wide cone angle sprays such as those used in the Trent phase 5 combustion system can only be measured using LIF. It is recognised when using the LIF patternation technique, that measurements suffer from inaccuracies due to light absorption, but reliably indicate significant non-uniformities in the spray as shown in Figure 13. The image normally undergoes post-processing to correct for incident and collected light absorption. Radial LIF images are normally recorded at a number of rotational nozzle positions to verify non-uniformities. These images are again post processed to correct for light absorption. The distance of the laser sheet from the injector face is dependant on the particular nozzle and spray density. Downstream measurement planes provide more information on the spray development, but at distances of more than 20mm from the face the spray in the combustor is strongly influenced by flametube mixing jets and by evaporation making measurements somewhat academic. However, the data may well be collected to validate CFD models.

Qualitative phase 5 LIF Image of Fuel Concentration

Section through LIF image showing asymmetry

Figure 13 LIF as a Spray Diagnostic Tool

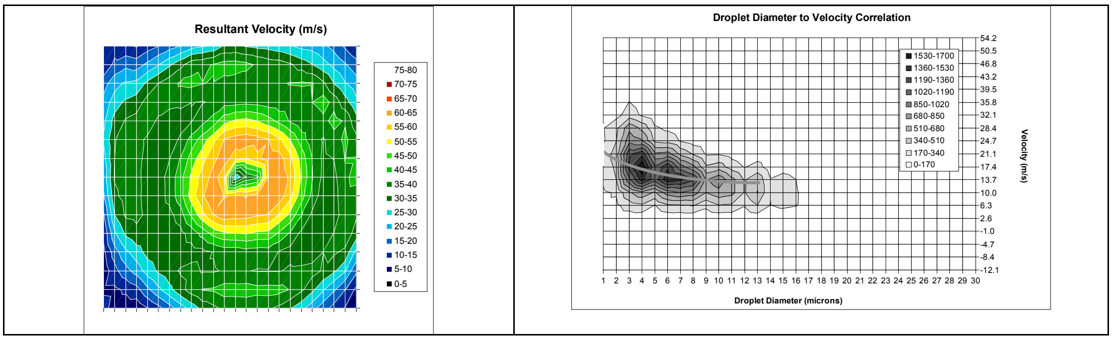


Figure 14 Air Velocity Based on Extrapolated Drop Size Data

The droplet velocity distributions in two components can be determined simultaneously with droplet size measurements using the Phase Doppler Anemometry (PDA) technique. PDA traverses are performed along at least two orthogonal diameters through the spray and the third component of velocity is measured by repeating the traverses. This results in one component of velocity being measured twice and provides a useful assessment of repeatability.

The air velocities downstream of a fuel spray nozzle can be approximated by analysing the same PDA traverse data [3], (Figure 14). Estimates of the air velocity can be found from looking at small droplets (< 5 microns) or extrapolating the size velocity correlation to find the velocity of zero sized droplets. However, there are inaccuracies in this technique due to the PDA measurements only taking account of the air that is transporting fuel. This results in low absolute air velocities but plausible profiles. Improved accuracy and data rate can be achieved by seeding the air to enhance measurements in regions of low fuel flow. The velocity profiles can be compared against CFD predictions if modelled under similar conditions and domain.

4.2 Spray Modelling

There are a number of different elements of modelling the fuel injector accurately, including sheet break-up, droplet transport and subsequent evaporation rate.

The approach adopted by Rolls-Royce follows the empirically based method described in [4]. The secondary break-up is modelled, but there has also been some success in applying the model to primary break-up regimes. The deformation and break-up of a liquid droplet by aerodynamic forces can be described by two dimensionless numbers (Weber Number, We and Ohnesorge Number, Oh) which are a measure of the relative strength of aerodynamic, surface tension and viscous forces . As the droplet is exposed to increasing relative velocity, significant deformation starts to occur distorting the droplet into a disc shape. Three distinct secondary mechanisms are then observed depending on the intensity of the aerodynamic forces. These are bag break-up, multi-mode break-up and shear break-up, all of which differ in the size and number of droplets after the break-up event (Figure 15).

This model is then further refined by the inclusion of a distillation curve treatment [5]. This caters for the multi-component nature of the fuels burned in gas turbine engines and allows for the boiling point temperature to increase with time as the lighter hydrocarbon species evaporate ahead of the heavier ones. In addition the molecular weight of the fuel evolves as the droplet evaporates representing the multi-component nature with reasonable accuracy without the need to implicitly model the different components of the fuel, a computationally expensive pursuit.

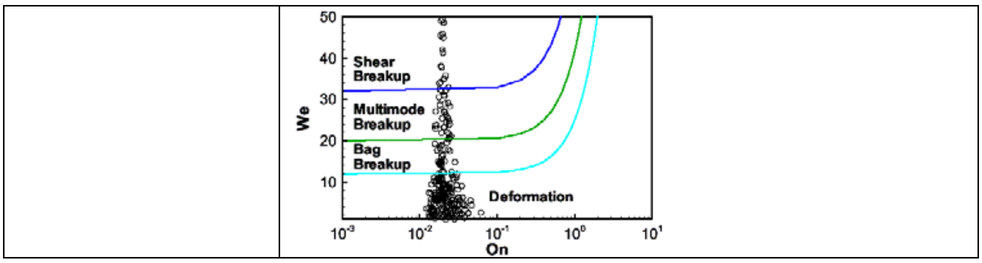


Figure 15 Droplet Break Up Mechanisms

4.3 Application in CFD

The application of the above methods has enabled very detailed CFD predictions of the Trent phase 5 combustor to be performed (Figure 16). Rigorous mapping of the fuel injector boundary conditions from both air and fuel flow perspectives has contributed significantly to the successful simulation of combustor performance.

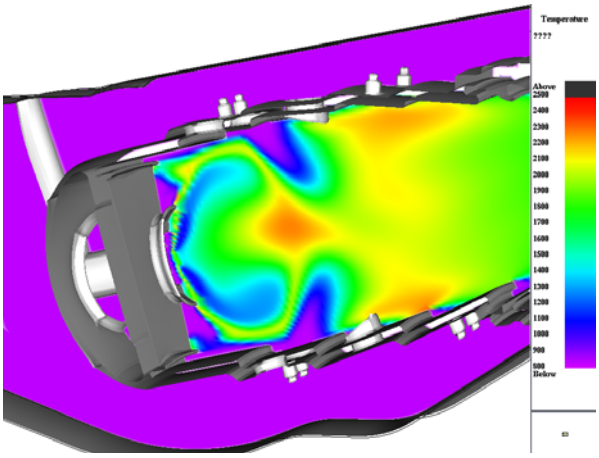


Figure 16 CFD Simulation of Trent Phase 5 Combustor

5.0 FUTURE INJECTION SYSTEMS

The fuel injector of tomorrow will be a radical departure of those flying today. Over the last fifteen years many investigators have been researching the next generation of technology to meet the NOx requirements. A common feature of all designs is the significant increase in airflow relative to the phase 5 style nozzle. The success criterion for this high airflow concept is the degree of mixedness of the fuel and air as delivered to the burning zone.

5.1 Lean Premixed Prevaporised (LPP) Concept

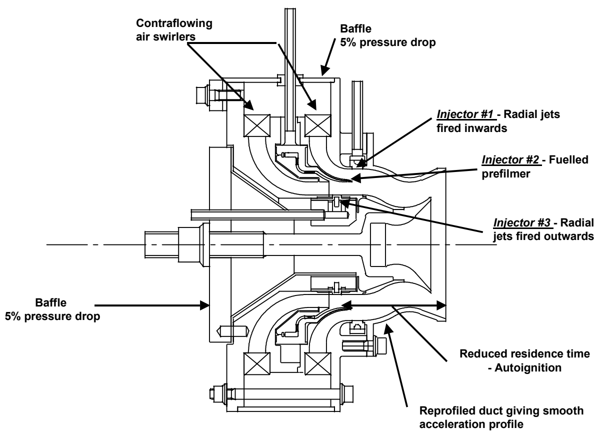
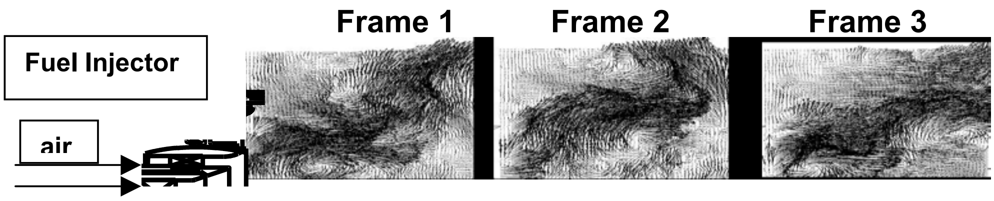


Figure 17 LPP Research Injector

This injector (Figure 17) is the evolution of a number of years work featuring a very short premix duct and has the flexibility to introduce fuel from a number of different locations within the premix passage. The (LPP) technology is unlikely to be used in the large civil engine cycle due to the risk of autoignition in the premix passage, but this technology may find use in niche applications where the pressures and temperatures are lower.

5.2 Lean Direct Injection

The concept of Lean Direct Injection (LDI) has been widely studied in recent years, overcoming the autoignition problem with the deletion of premix passages. The experimentation that has taken place in Rolls-Royce on LPP systems has demonstrated that efficient mixing can take place in extremely short ducts, pointing to the potential success of LDI. One of the main mechanisms for improving the mixing of fuel and air is turbulence. This turbulence can be promoted inside the pre-mix passage or outside the passage, pre the burning zone. In Figure 18 below, the turbulence at a fuel nozzle exit is captured via Particle Image Velocimetry (PIV). These pictures give an insight into the mechanism that drives the mixing of the fuel and air of a LDI fuel injector and to how these designs can achieve low NOx emissions. It is only by the use of advanced laser techniques in the time domain that the full understanding of modern fuel injection systems can be made.



8 PIV Images of Injector Efflux

6. CONCLUDING REMARKS

It is clear from the detail shown in Figure 18 and the fashionable Large Eddy Simulation (LES) CFD studies of reacting flows that the time averaged approach to measurements and calculations provides an incomplete description of the fuel/air mixing and combustion processes. The appetite for progress in this science will call increasingly for the employment of advanced diagnostic tools and simulation methods to capture the detailed time dependent nature of these critical physical processes. Combustion research will continue to provide a challenging and rewarding career for many years to come.

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