Combustion Technology Challenges for Small Aviation Gas Turbines

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Abstract

Demands for small gas turbine technologies from the market place continue to evolve; for combustion systems this has resulted in advancements of design and manufacturing processes and tools to reduce design leadtimes and improve quality of first designs. Market feedback analysis and controlled engine/rig tests have been successfully used to validate new design processes and tools. New combustor technologies are addressing need for low emissions and high reliability as well as low cost manufacturing methods. Status of small engine combustor technology and innovation to meet current and future market challenges are discussed, along with developments in numerical tools and manufacturing methods. Results of association with Canadian universities and national laboratories are also highlighted.

Introduction

Small aviation gas turbines have responded to market demands for improved performance and reliability, cost and weight challenges, and the need for low emissions / noise signatures. These are being achieved in a complex market place comprising of Turbofan, Turboprop and Turboshaft powered applications for regional, corporate and business aircraft and for helicopters. Deregulation in the regional aircraft market has increased demands for aircraft in ' less than 100' passenger class and the powerplants have challenging requirements for fuel burn, reliability as well as operating costs. A whole new generation of small helicopters has entered the market place, with single or twin engines, where the challenges include weight, cost and simplicity of installation. Pratt and Whitney Canada (PWC) is a key player in all the abovementioned market segments and has introduced a number of new products in the last three decades to meet the industry demands (Figure 1) and is offering fully integrated power solutions to OEMs and Customers. Technology programs have been structured to address short and longer term industry requirements and key elements of technology are being validated with demonstrator engines, prior to being incorporated into new products.

"Point Designs", created very specifically for certain application(s), are increasingly determining product definitions of today whereas a common core approach was commonly used in the past years. This is illustrated in Figure 1, which shows three new centerline engines in the turbofan & turboprop sectors at P&WC in a five year time period to meet specific OEM requirements; although the thrust and overall sizes are comparable , the specific (OEM) requirements required new engine designs.. The market is also demanding accelerated product introduction in periods of three years or less, which demand "Design right first time" quality as well as fully integrated design to manufacturing processes working through Integrated Product Teams (IPT). Process improvements are key and the P&WC efforts in process improvement and technology integration have been previously published (Sampath & Hogg).

This paper addresses process advancements in the field of small aviation engine combustion systems and their impact on leadtime reduction and quality of first designs. Recent technology advancements in engineering and manufacturing are described and how they are addressing the short and medium term demands of the market place. The role of academia, national technical institutes, and their interactions with the product research teams (at PWC) are discussed .

Small Engine Challenges For Combustion Systems

Combustion technologies have kept pace with the requirements from engines for better performance and reliability. These include high temperature rise combustion, high altitude applications, low emissions minimizing tradeoffs in operability/ performance, and improved understanding of combustion dynamics issues. Materials and coating advancements as well as advancements in combustor construction methods, have advanced combustion system reliability to match those of larger engines. Advancements in numerical modeling and use of Market Feedback Analysis (MFA) data have made significant inroads into improving quality of first designs and reducing design elapse times. Operability challenges , especially with low emission combustion designs, have required innovative solutions involving both the air and fuel systems of the engine. Future challenges will continue to emphasize on compact combustion systems, lower emissions including those at engine cruise which are currently unregulated, higher altitude applications and even higher levels of reliability with continued emphasis on lower ownership cost.

Small engine combustion systems, including those on turboprops, turboshafts and small turbofans all have unique issues distinct from those with larger engines. Although the general requirements for a small turbine engine are similar to its larger counterpart, there are significant differences imposed by geometric scale render achieving these requirements more difficult with smaller engines. The flow geometry of many small engines include centrifugal final compressor stages and the most common combustor geometry embodies reverse flow combustors (Figure 2) whereas large engines use axial flow annular combustors. While problems resulting from combustion kinetics are similar to larger combustion systems, aerodynamic and manufacturing problems arising from the smaller sizes are distinct. For example, the surface to volume ratios of small engine combustors are in the range of 10 – 15 $ft.^{-1}$, whereas those from larger engines are much smaller (5 – 10 $ft.^{-1}$), resulting in increased wall quenching of combustion reactions at low powers such as idle. The larger surface areas of small reverse flow annular combustors (Figure 2) will require proportionally more cooling air and less air available for tailoring emissions or exit temperature quality. Also the air flows of small engine combustors typically require smaller sizes of orifices (or holes) in liner walls, and the ability of machining or drilling orifices does not scale down in size, and this can cause more variation in air flow distribution and hence performance/emissions from smaller combustors. This has partly been the reason that newer engine models are considering straight through combustor designs (Figure 2e), inspite of penalty of increased engine length with straight through combustors. Radial combustors are also attractive in this regard.

Demands for improvements to fuel burn (thermodynamic efficiency) are steadily increasing small engine pressure ratios and temperatures, and this trend will be limited only by availability of suitable materials for the combustor and high turbine stages of the engine. Improved cooling methods, and advanced materials are being incorporated into newer designs, as well refinements to combustor construction, such as 'P&W Floatwall' (Ref. – The PW6000 Engine) to small engines. New manufacturing technologies such as laser drilling have resulted in increased use of highly efficient effusion cooling for combustion liners (e.g. Figure 2e, PW 308) in a cost effective manner. Increased pressures and temperatures also result in higher emissions of Nitrogen Oxides (NOx). NOx is currently not regulated for small engines by ICAO, because of the negligible environmental impact from this class of engines and aircraft (Eatock & Sampath); however regulations down the road are possible and technology needs to be developed, which not only address emissions, but also other important issues such as weight, cost and reliability. Added motivation is the need to avoid landing fee surcharges for non complying engines from certain States, based on their local environmental needs and regulations.

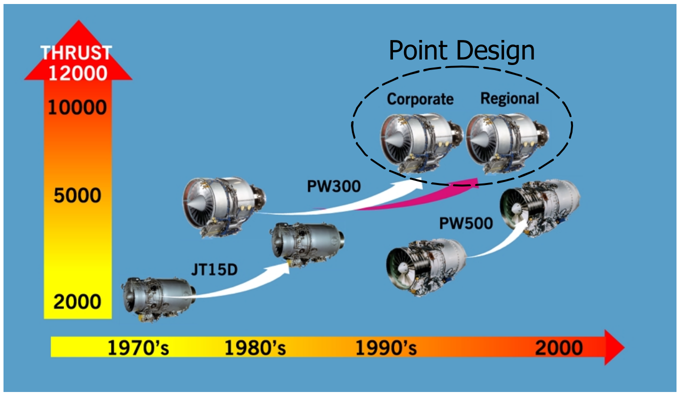

Figure 1a: P&WC Turbofan Evolution

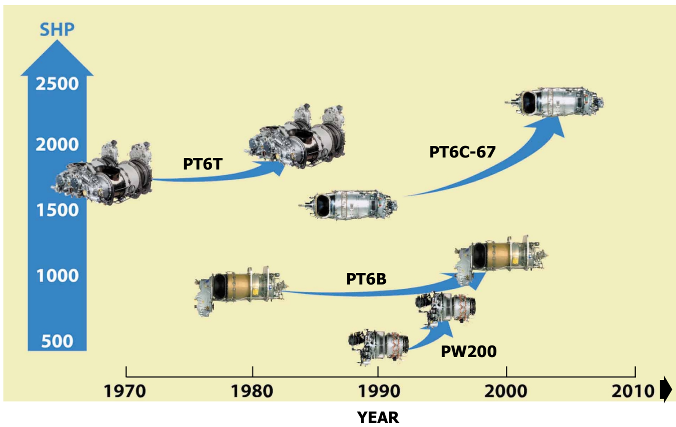

Figure 1b: P&WC Turboshaft Evolution

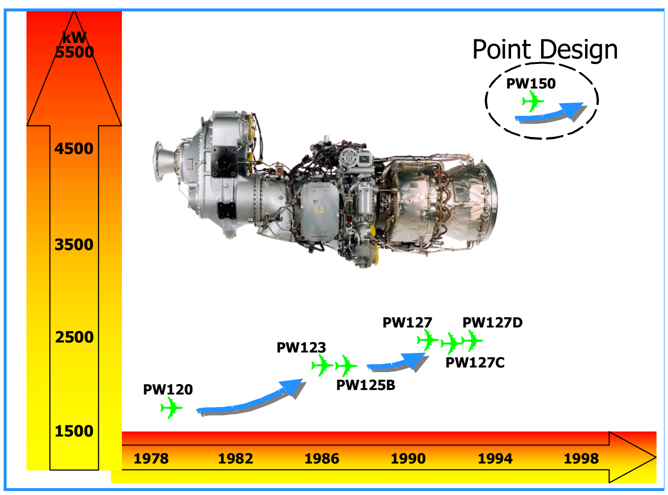

Figure 1c: P&WC Large Turboprop Evolution

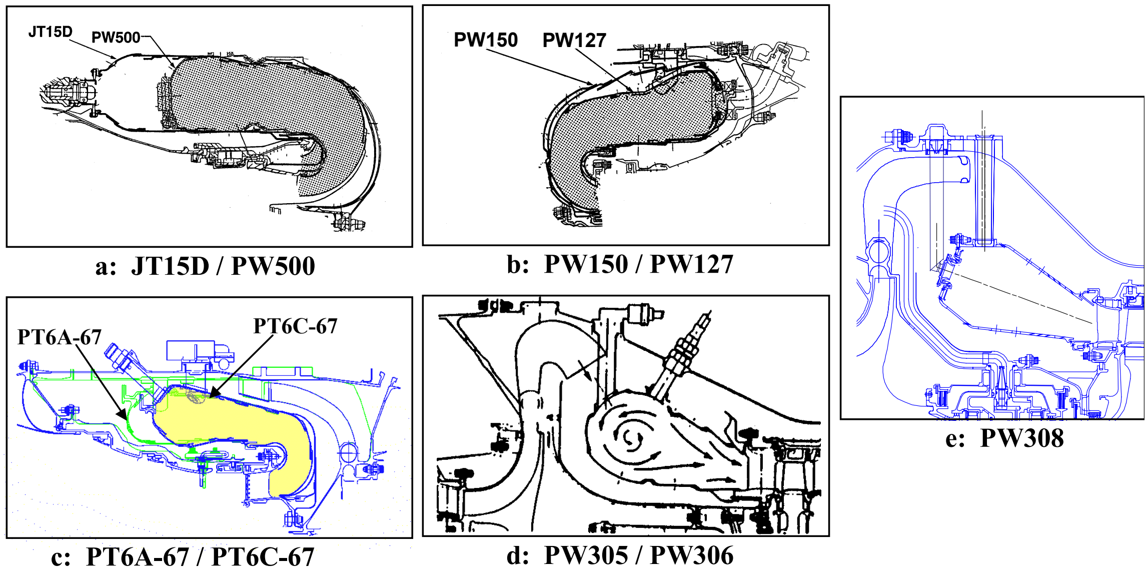

Figure 2: P&WC Combustor Geometries

Design Process Evolution

The design process used for combustion systems must address the dual requirements of meeting manufacturability and engineering requirements of the product. In the past the practice often was the engineering definition of a product to meet customer requirements without full consideration of manufacturability. Now the situation has changed where manufacturability and cost issues take equal emphasis as engineering issues are addressed concurrently and right decisions are taken to ensure Quality of First Design. Quality of First Design also requires clear definition of risks in a potential design, elimination of high risk areas and having risk mitigation plan for the rest. Market Feedback Analysis (MFA) and lessons learned are critically important in delineating the risks and taking corrective action early in the design cycle. Risk mitigation often requires institution of validation programs early in the product definition phase and where considered essential, providing for a back-up design. Research on a new design feature should be completed upfront or ahead of incorporation into product.

Leadtime reduction through design process improvement is presented in detail in the following section; in addition a comprehensive plan with an Integrated Product Team addressing risk areas in the design cycle will ensure leadtime commitments, which invariably demands reductions. Market feed-back analysis (MFA) occasionally reveal anomalies not noticed during design or validation phases of a program. One of these has been carbon generation in the field found on an engine at Pratt & Whitney Canada, which had not previously been observed during block, performance or IMIT endurance testing of the engine (Figure 3). IMIT or block test did not fully validate the combustor and information would not have been available without direct contact with the aircraft user. A revised validation process to include carbon formation test sequence was implemented as a process improvement. Lead time reduction requires efficient team work between disciplines and modules. In addition, more parallel analysis, addressing field issues with MFA, including suppliers upfront in the design process and capturing lessons learned are all good methodologies.

Risk reduction may require instituting demonstrated programs to address risk areas for such cases, careful planning and on-time execution are critical to the success of the program.

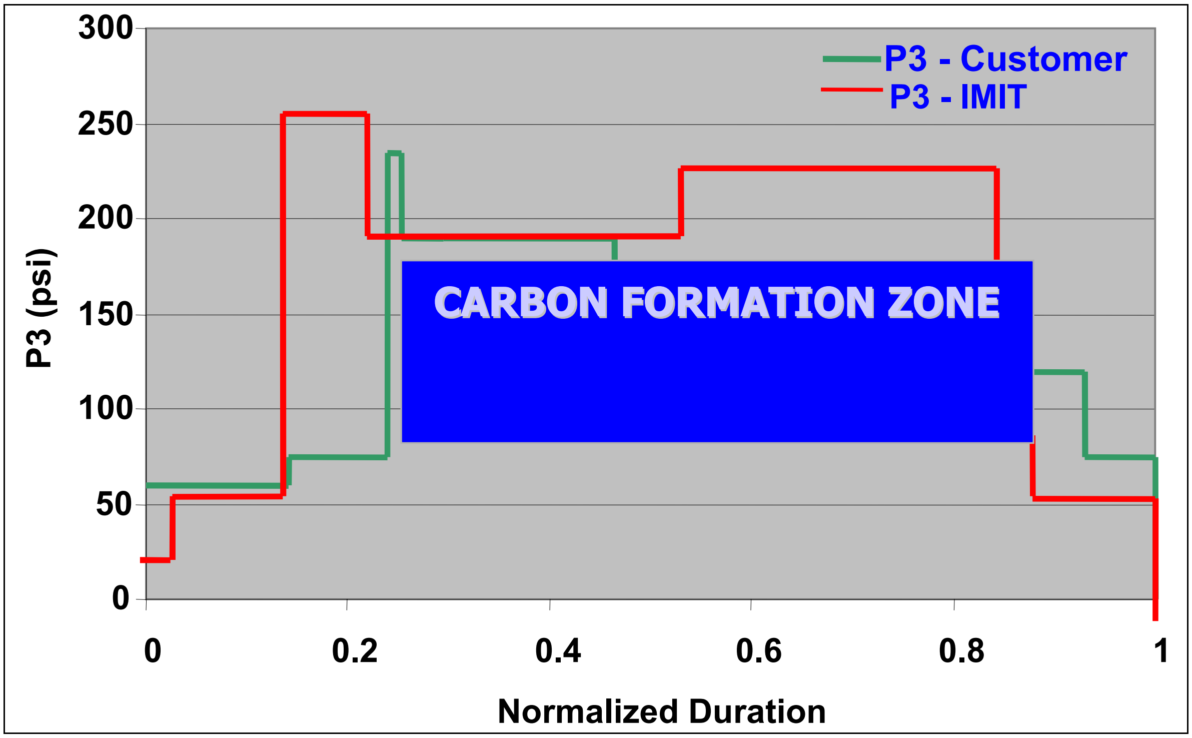

Figure 3: Mission Profiles

Design Process Improvement

Process management is the method at P&WC in which work is simplified and structured to ensure a quality product on time. Process improvement and waste elimination opportunities are immediately identified once a process is mapped. Process efficiency, effectiveness and adaptability can all be improved through process mapping. In addition to the lead time benefits described in the previous section, there are many quality improvement initiatives that benefit the engine program. Not only does process mapping provide a clear understanding of the process flow, but there is also a clear understanding of the responsibilities and ownership of all aspects of the process. In this way the company ensures that a customer-focused improvements prevail.

Scatter diagrams are often used on the process maps to provide an overview of where the trouble activities occur in the process. This scatter diagrams will provide instant information as to where the bottle-necks are in a given process. In this way, cross-functional teamwork can be greatly improved by focussing on the bottlenecks. Lessons learned are captured in the improvement process and overall business processes are thus improved.

Risk Reduction – Demo Programs

Risk reduction is a major part of technology readiness for future engine considerations. Running demonstrator programs for future engines not only reduce risk but ensures "Quality of first Design". Figure 4 shows that although the initial cost is greater, there is an overall cost saving associated with introducing a demo program.

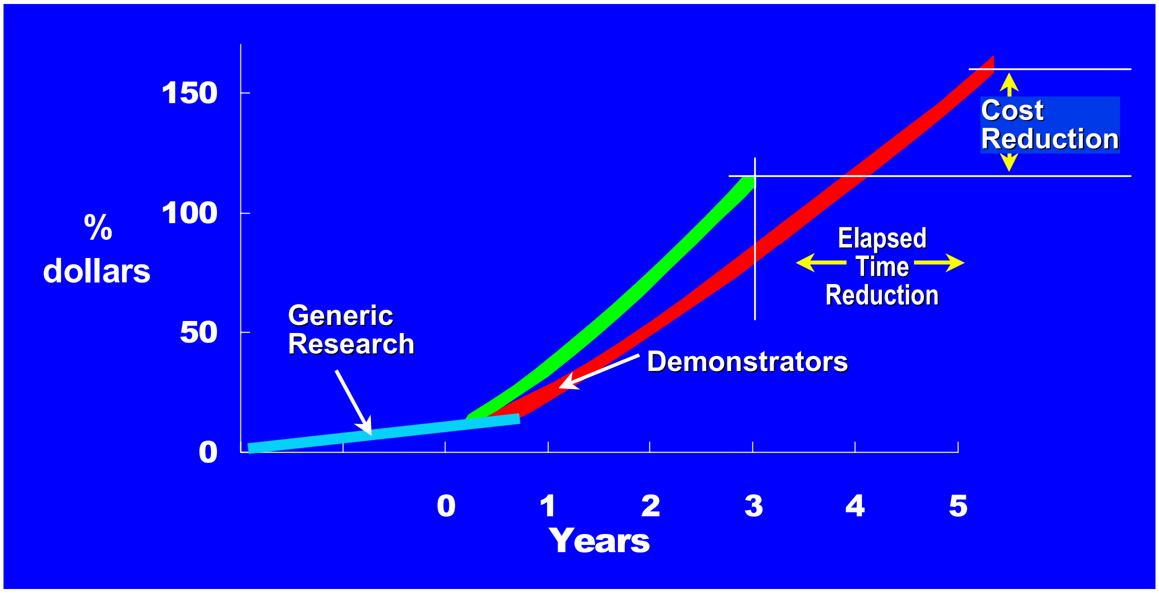

Figure 4: Cost Comparison of Engine Program With and Without Demo Program

Technology Advancements

The design of gas turbine engines that produce small amount of air pollutants is becoming an important objective of gas turbine engine manufacturers. Protecting and improving the global atmosphere continues to be key international issue at the turn of the third millennium to reduce and several countries are signatories to Kyoto charter on global warming. ICAO has recently added new regulations limiting pollutant emissions from gas turbine aircraft engines. Some local airports have based on their national legislation, and in accordance with national and regional clean air policies, introduced emission landing surcharges. They are based on emissions during a landing-take off duty cycle of the aircraft. Such emission regulations and airport landing surcharges have significantly changes design requirements of small gas turbine combustion system.

The future growth of aviation will depend heavily on global and regional economics, the demand of travel for leisure and business, the development of infrastructure to support air travel and available flight technology, the availability and cost of fuel [1]. However, increases in aviation traffic will not translate directly into increases in emissions. Changes in engine efficiency, airplane design, and operational practice are all expected to lead to more efficient use of fuel. Emissions of NOx, CO, and hydrocarbons depend strongly on combustor technology—particularly the mixing of fuel and air in the combustion chamber, as well as temperature and pressure.

To enhance fuel efficiency in gas turbine engines, higher and higher overall engine pressure ratios are being utilized in the engine cycles. This also leads to higher combustor inlet temperature and the corresponding exhaust temperature is expected to increase as well. As a result of the increasing pressure and temperature of a gas turbine engine, its thermodynamic efficiency, thrust-to-weight ratio will be improved. The increase in combustor gas temperature and pressure will lead to higher nitrogen oxides (NOx) emissions. Aircraft NOx emissions perturb a large chain of interconnected chemical reactions that has an end impact on ozone concentrations. The pressure for reducing emissions, especially NOx , has resulted in examination of improved mixing, fuel injection, ignition system, alternative cooling, advanced materials and innovative combustor configurations.

Combustor Design Challenges

The challenge of low emission combustor lies in the balancing act of providing sufficiently high temperatures for completion of hydrocarbon reactions to achieve low HC and CO emissions, short enough time and low enough temperatures to control the production of NOx to a minimum, and enough air through the fuel injector to avoid smoke production, yet no compromise to flameout margin or stability. The combustor front-end reference velocity should also be low enough for meeting altitude relight requirements of the customer, yet fast enough to improve fuel-air mixing in the primary zone for emissions, smoke and pattern factor controls. The often conflicting requirements are making significant changes in the methodology for optimizing the combustor geometry and flowfield.

Design of a conventional combustor normally experiences a trade-off between low NOx with high CO, HC and smoke. Many combustors in small gas turbine engines utilize single toroidal recirculation for flame stability and reverse flow duct that helps to shorten the engine overall length. With such combustor flowfield arrangement, the amount of air required for dilution is not adequate to achieve quick quenching of the chemical reactions for low emissions. As shown in Figure 5, the conventional combustor primary zone operates near stoichiometry at high powers. Cooling and dilution flows are added slowly to quench the reacting flows to a lean mixture. Going over the peak temperature region in the primary zone, high thermal NOx is produced.

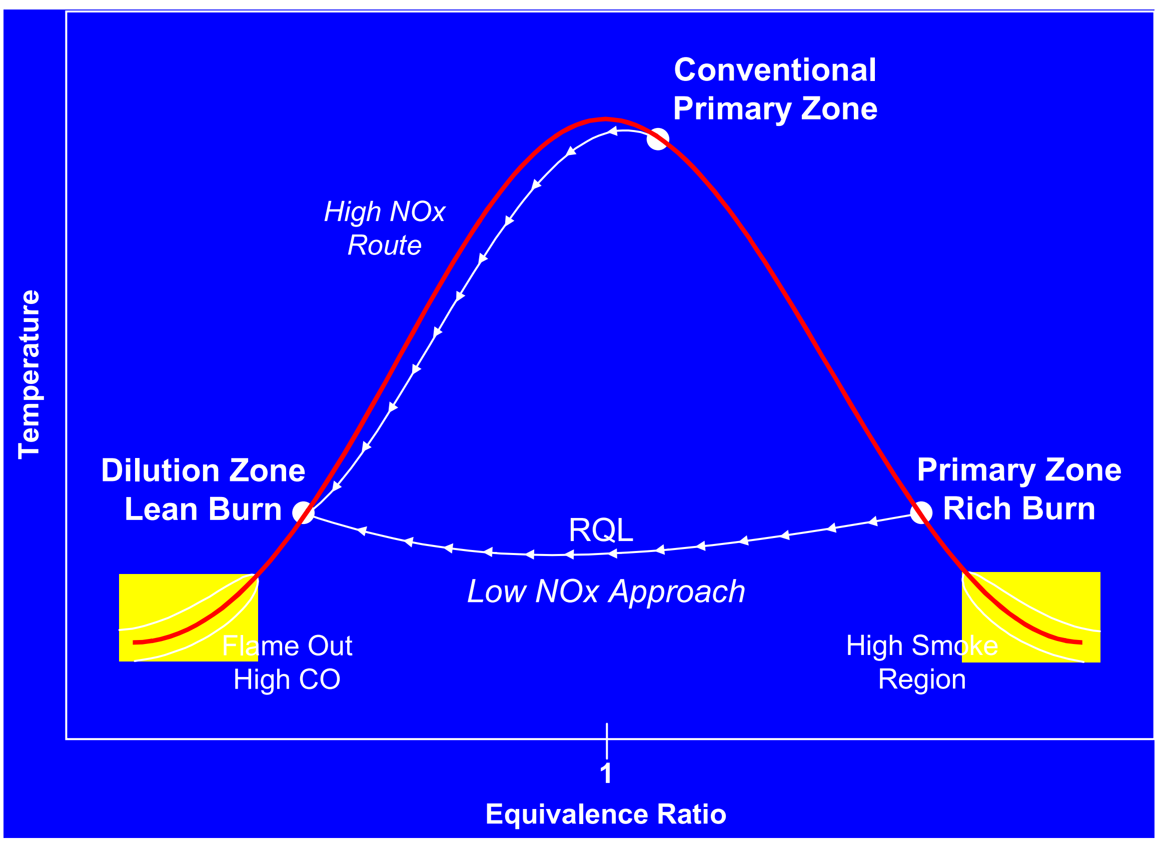

Figure 5: Low NOx Rich Burn Quick Quench Concept

One of the low emissions combustor concepts is the Rich-burn Quick-quench/Lean-burn (RQL) combustors using swirl stabilised front end. Here, the rich-burn zone (primary zone) is a fuel preparation zone and only partial oxidation results. The rich mixture is then quickly mixed with the remaining of the combustion air (dilution air) in the quench zone. Downstream of the quench dilution jets, the combustion mixture completes the combustion process and reactions at controlled low temperatures where thermal NOx production is kept to a minimum. RQL concept provides the benefit of low NOx emissions and flame stability due to the rich primary zone. With RQL, the combustor length is minimized to reduce the residence time for NOx. The trade-off for lower NOx may be a reduction in the altitude relight envelop.

Other low emission combustion concepts that are presently active in the research community are lean-premixed-prevaporized (LPP) and lean direct injection (LDI) combustors. LPP concept lies in providing a uniform premixed prevaporized fuel air mixture that burns at low temperatures where NOx formation is a minimum. This concept has the advantage of producing extremely low NOx that is close the theoretical minimum level, but it has the disadvantages of very narrow stability limits, potential for high CO, potential for auto-ignition and flashback with gaseous fuel system. The LDI concept injects all the combustion air through the front-end of the combustor. Fuel is injected directly into the combustion region of the combustor. Because the fuel-air mixture is lean, the combustion gas temperature is low and hence low NOx can be achieved. There is no dilution air used in this concept. Compared to the LPP concept, LDI has much wider flame stability margins. LDI may be an interesting future research topic combined with advanced continuous ignition system. The challenge combustion engineers face is to keeps a good balance on the many performance requirements of the combustor. Since conventional combustors cannot produce low emissions, innovative combustor concepts are needed.

Engine software and hardware changes also impact on combustion system operability. Software advancements in engine fuel control give unlimited options to fuel scheduling. New EEC enables low cost fuel systems to operate very efficiently by understanding fuel manifold fill times, combustion efficiencies at low and transient fuel and air flows, and fuel spray characteristics. Optimizing fuel control can have a benefit on many aspects of performance such as altitude relight, cold starting, and reducing engine rumble. New fuel flow control devices (mpfd) are being tested that allow for cheap fuel nozzles to be used throughout the engine operating line by compensating for nozzle inefficiency.

Fuel Injector Technology

Fuel-air control and mixing in a combustor, especially in the primary zone, are critical to achieve low emissions. Issues that fuel injector designers have to face are numerous. The requirements of the fuel injectors include proper droplet size range, fuel mass flow distribution, spray cone angle, circumferential uniformity, emissions and smoke controls. Droplet size is a key factor in controlling primary zone mixing, ignition, altitude relights and emissions. Fuel mass distribution together with cone spray angle has an impact on CO & HC emissions production at the wall due to quenching and radial temperature profile control. Circumferential uniformity can avoid streaks and voids that might cause hot streaks which reduce turbine blade life and cold spots at low power that might results in high HC & CO production. Higher fuel-air ratio at high power means higher fuel flow rate to the fuel injectors. If the fuel-air ratio at low power remains, the turn-down ratio for the fuel injector increases. High turn-down ratio during combustor operation can present performance and operability challenges to a combustor system. Higher fuel-air ratio operation will require front-end and fuel injector air adjustment to address smoke issues, which in turn can present operability problems because of proximity to flameout limit, as shown in Figure 6. Other consideration to take care of in fuel injector design is heat loading. Any increase in fuel temperature higher than acceptable level will lead to gum and carbon formation in tiny fuel passages. In small gas turbine fuel injectors, the fuel passages are very small. Demand for and achieving tight tolerance in fuel injector manufacturing are crucial.

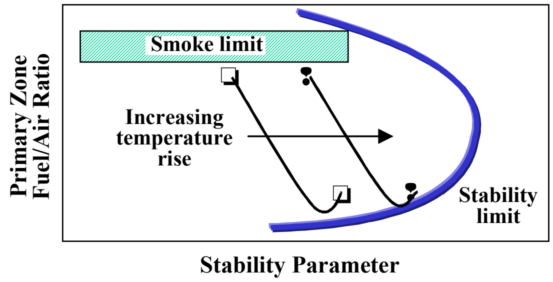

Figure 6: Influence of Turndown Ratio on Performance and Operability

Fuel nozzle technology at P&WC has evolved considerably over the past several years. Injector designs have migrated from cast, tubular and welded assemblies to more simple machined and brazed constructions to deliver one or more fuel streams to the nozzle tip. Fuel nozzle designs have focused on reduced piece part counts, optimising component material selection and utilizing high yield, advanced manufacturing technologies. This approach has proven to be very effective in significantly reducing injector cost, reducing development time and enhancing nozzle performance.

Using this 'design for cost and quality' approach, P&WC has successfully developed a number of high performance, advanced fuel injectors of the pure air-blast, air-assist (both single and dual orifice) and piloted air-blast (hybrid) varieties. All of these injectors employ the generic swirler similar to the one shown in Figure 7. This swirler includes a unique annular array of air passages (or multiple arrays which are spaced radially from the first array) that offer several performance advantages. This geometry allows for maximising air-flow through the fuel nozzle, while optimising mixing, hence leading to effective control of both smoke and emissions. This geometry also offers considerable flexibility in shaping the spray and tailoring the fuel distribution within the spray cone. By adjusting the jets from the swirler (both angle and offset) the spray can be easily tuned to a large range of specifications.

Many of these injector parameters are modelled and designed using the latest 3D numerical tools including CFD and FEM for aero, thermal, structural and dynamic analysis of the nozzle. Paramount to injector designs is avoiding excessive wetted wall temperatures that can lead to fuel coking and subsequent injector contamination. P&WC designs use the fuel extensively (as opposed to heat shields which increase piece part count and cost) to cool the injector internal passages and minimize wall temperatures. Passages are intentionally sized and arranged to maximize fuel velocities and swirl. This ensures optimum contact between the fuel and passage walls to minimise the temperature of the metal. Both CFD and FEM are used to accurately predict wetted wall temperatures (Figure 7).

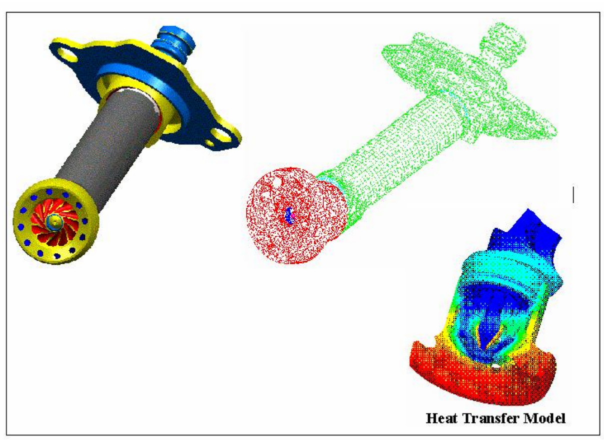

Figure 7: Example of P&WC Generic Fuel Nozzle

P&WC injector designs have also given significant consideration to the injector supporting structure. This structure, often overlooked must satisfy a number of requirements including, sealing high temperature - high pressure air within the engine casing, maintaining the fuel cool to prevent coking, sealing high pressure fuel within the injector, avoiding vibration induced resonance, accurate positioning of the injector tip within the combustor, capablility of enduring thousands of cycles and of course being light weight and low cost. These requirements often lead to a supporting structure that is a major portion of the overall fuel nozzle cost. A number of novel solutions have been developed to improve fuel nozzle stem designs. Advanced machining methods have played an integral role in allowing the development of superior stem support designs that are cost effective and meet the aformentioned performance criterion. The advent of multi-axis mill-turn equipment has permitted efficient, single set-up, machine from barstock, manufacturing of small, variable geometry parts typical of gas turbine engine fuel injectors including the supports. The result of this single set up, machine from solid approach is a more consistent part, machined in a fraction of the time incomparison to conventional machining processes, leading to premium quality at a lower cost. As recently as five years ago, geometries designed to be made on these mill-turn machines would not be pursued due to the lack of adequate technology to cost effectively produce the features required in these new style fuel nozzle stems.

The development efforts have proven to yield low cost, high quality components. Part consistency of both the spray and air flow through the injector has been outstanding - see Figure 8. Since the combustion chamber includes a plurality of fuel nozzles, the superior part repeatability has improved hot section durability by minimising hot spots and streaks. Building on recent successes, P&WC continues to push the envelope in developing innovative, cost effective fuel injection devices.

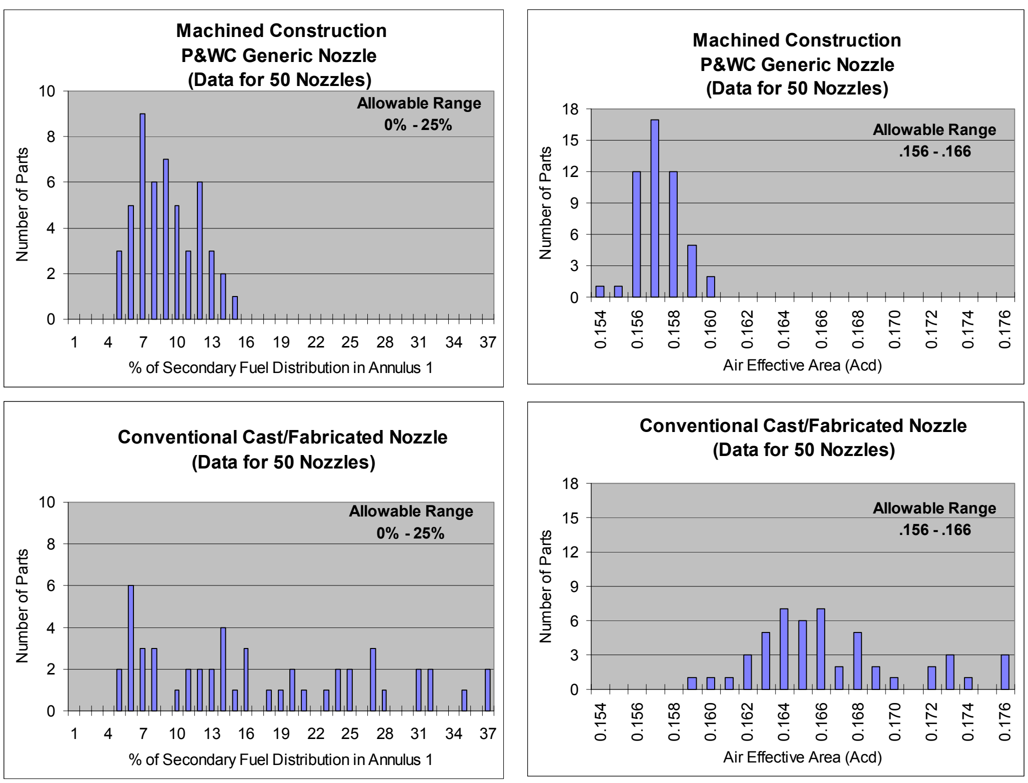

Figure 8: Patternation & Air Flow Comparison for Machined Construction and Conventional Designs

In the process of exploring ways to reduce cost and weight of the fuel manifold, internal fuel manifold with multiple fuel injector attached was proposed. By having all fuel injectors being pressure atomizer, one internal fuel passage is all that is required. However, there are quite a few challenges on using internal fuel manifold. The internal fuel manifold must be properly sealed to prevent any fuel leakage into the combustor outer annulus. There is a serious concern about fuel leakage since 3D CFD analysis showed local recirculation regions attached to the internal fuel manifold due to wake effect. High combustor outer annulus air and metal temperatures could create a flame with the leak fuel caught recirculating in the wake of the internal fuel manifold. There is also the challenge of starting using a single fuel manifold. Due to the high turndown ratio of the fuel pressure, the fuel flow rate is normally low during start and the droplet size is not adequate for flame propagation. Then there is the issue of fuel coking in the internal passages of the fuel injector. If there is fuel remains in the fuel manifold after engine shut down, the high stagnant temperature will be high enough to cause fuel coking and carbon formation inside the fuel nozzle passages. Despite all these challenges, internal fuel manifold offers very attractive saving in weight and cost.

Advanced Cooling Schemes

With conventional film cooling techniques such as splashed louvre and laser drilled Z-ring louvre, higher wall temperatures equates to more cooling air required for wall cooling and less for dilution air, which may run the risk of high radial and overall pattern factors. As the pressure ratio goes up combustor inlet temperature also increases, thus lowering the heat sink capability of the wall cooling air. Hence, high temperature materials, thermal barrier coatings and advanced cooling schemes are required for wall treatment.

Customer requirements of combustor life has grown over the years. Typical combustor life requirements before 1990's would be about 5000 mission hours. Requirements on more recent applications demanded high time before overhaul in the range of 6000 to 12,000 hours. Effusions and double-pass cooling techniques are good alternatives to one pass louvre. Small amount of front-side cooling flow can be introduced to address hot spots if needed. Panels of heat shield are mounted onto the hotside of the combustor liner by bolts and nuts. There are cooling pins on the underside of the heat shields that act as fins to enhance heat transfer. Cooling air goes through holes on the liner and impinges on the underside of the heat shields. The air then flows pass rows of pins and out into the combustor as louvre flow. A variation of the heat shield cooling technique is effusion on the hot-side instead of coming out as louvre flows. Advanced in laser drilling methods have enabled fast, accurate drilling of liner panels with shallow angle holes, which have good cooling effectiveness in a cluster. Small size systems are also seeing the needs of floating heat shields common in some large engine combustion systems.

Combustor Design Process

Over a decade ago, the design and development techniques had relied entirely on empirical design rules based on successful combustor design experience and database from water rigs, simplified 1D calculations, sector combustor rigs, atmospheric and high pressure test rigs. Assessment of the entire combustion system was then conducted on experimental and developmental engines. Such approaches were extremely costly, time consuming, and not providing full understanding of the combustor flowfield structures and key characteristics for the combustion engineers.

However in today's preliminary design stage, design process still starts off with empirical and 1D analysis to define the combustor volume based on NOx emissions, residence time, heat loading, combustion efficiency, altitude relight capability and pattern factor. Once the combustor volume has been defined, the outer annulus flow path between the combustor outer casing and the combustor can be established using 1D flow split analysis. Once the combustor volume and outer annulus path have been defined, 3D analytical tools are employed for detail design and analysis.

With the advancement in 3D numerical methods for combustion aerodynamics and structures as well as the exponential growth in the computing power, the design and analyses have evolved to highly computational-based system. Although computational methods do not take into account or have their shortcomings in modelling all the physical processes within practical combustors, they can be set up quickly and run to the proper operating conditions, providing valuable insights and data of the complex flowfield. The opportunity to modify the combustor model numerically to evaluate, optimize and arrive at a recommended configuration of the combustor design has, in fact, replaced the many rig tests in the design and development cycles. The number of rig tests over the last 25 years at P&WC, as illustrated in Figure 9, has dropped significantly with the number of detail 2D and 3D analysis performed. However, a fully integrated combustor design system can be achieved only with a computational-based design system that has been validated with laboratory data and improved upon with direct feedback from actual engine run and field data.

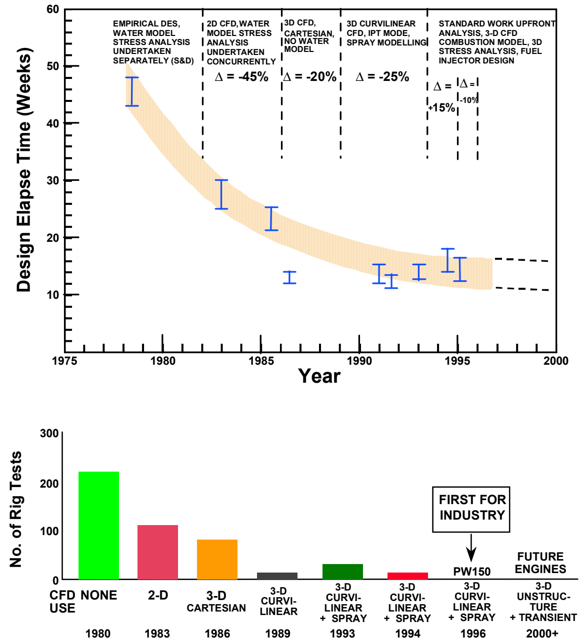

Figure 9: Combustor Analysis Evolution

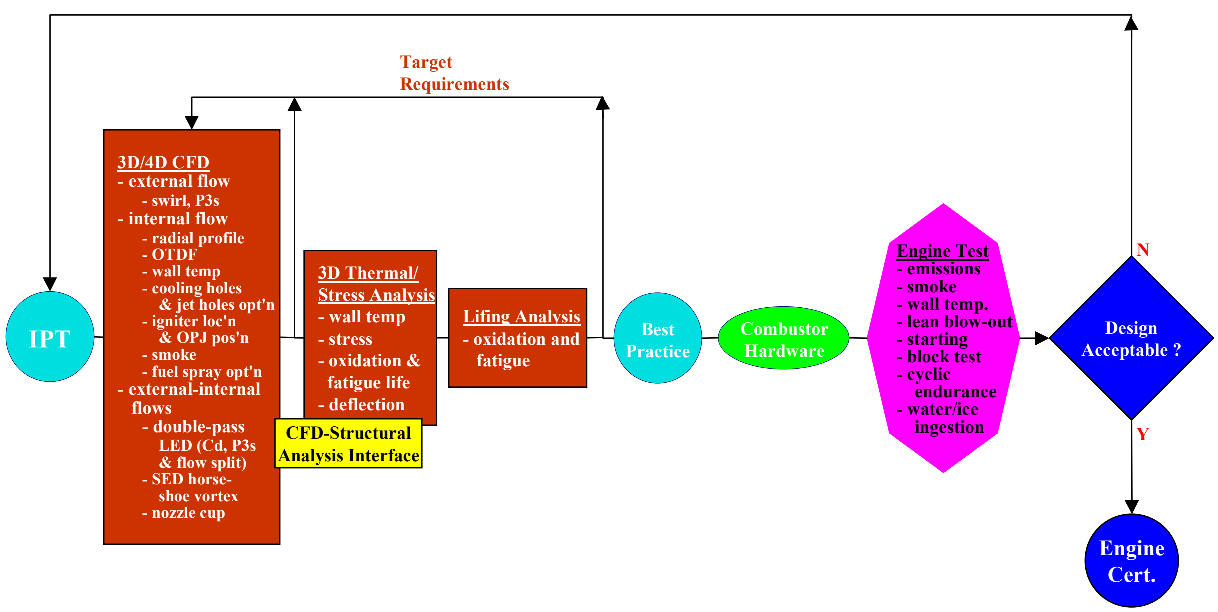

Figure 10: Improved Combustor Design Process

The more recently evolved design system, as illustrated in Figure 10, has relied more heavily on 3D modelling tools validated by past rig and engine data; best practices are rigorously followed to ensure full analysis and engine validation of design are followed by further hardware changes where required. Although this requires upfront commitment of engine tests for combustors, a more rapid development of the final product results, with fewer design changes. Application of these design process in engine programs have been previously presented by Hu et al (1998), Sampath et al (2001).

Advancements in computer hardware, parallelized CFD codes and arbitrary grid-to-grid interface have enabled grid meshing of the entire combustion system and more detailed flow analysis. The advantage of solving the entire combustor domain has been reported by McGuirk et al. (2000) and Malecki et al. (2001). The present design process is evolving toward this 3D combustion system modelling approach where all the details of the combustion system are taken into account.

Computational-Based Design Tools

Combustor 3D CFD based methods have been applied extensively to design the primary zone, optimize the radial profile, design fuel nozzles, predict NOx, smoke, and wall temperatures. Local component models have also been used in detailed optimization such as mixers for industrial engines. Examples of the roles of computational-based design process are discussed in the following section. The multi-dimensional CFD code used to perform combustion system analyses was CFX-TASCflow Navier-Stokes code.

Combustor External Flow

External geometries in a combustion system include diffuser pipes, fuel nozzles, fuel nozzle bosses, ignitors, support pins, ignitor and support pin bosses, combustor outer casing, diffuser casing and turbine support casing. Compressed air leaving the 3D diffuser gives a highly biased outflow due to the vortices formed at the bend of the diffuser pipe. The outflow diffuses rapidly into the outer annulus, some flows move forward and some move rearward of the annulus. Without analytical tools, such local 3D flow structures are impossible to predict. To predict flow split of a combustor requires information on the local static pressure and annulus flow velocity. Static pressure normally recovers in the forward branch of the outer annulus. As the flow turns around to feed the reverse branch, static pressure decreases near the exit of the diffuser due to dump loss and turning loss. More pressure losses can also be found at the dome flange and fuel nozzle region. The 3D CFD model provides the understanding of the flow structures and pressure distributions in the annulus. The predicted local static pressures can be used to update the flow split analysis. The analyst can iterate between 3D CFD pressure prediction and 1D flow split analysis to achieve proper flow split calculation.

Combustor Internal Flow Structures & Flowfield Temperatures

3D CFD is a valuable tool in the aerodynamic design of a combustor. The combustor primary zone aerodynamic designed and optimized using CFD tool is shown in Figure 11. The axial, circumferential jet positions and sizes of the primary jets, as well as how they are staggered with the opposing rows are crucial in creating a stable recirculation region that also enhances fuel-air mixing. Optimization of the primary recirculation zone involves detail and careful modelling of the fuel nozzle aerodynamics and spray. Prediction of hot spots and overcooled liners can be very helpful to improve liner durability and reduce emissions due to wall quenching. The nozzle-to-nozzle interactions in the primary zone due to engine swirl are also highly beneficial to flame propagation during transient operations. The structures of cross-feeding flowfields in the combustor can be seen in Figure 12.

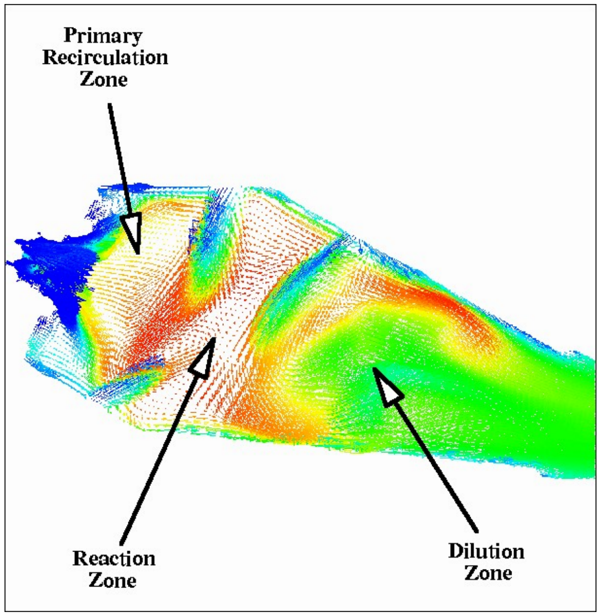

Figure 11: Predicted Combustor Flow Characteristics and Temperatures

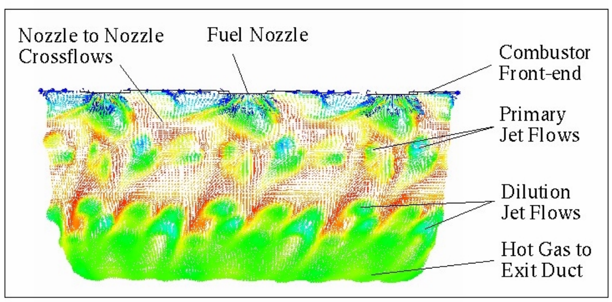

Figure 12: Circumferential Flow Characteristics and Temperature Field

Radial Profiles and Pattern Factors

3D CFD is used extensively to predict thermal mixing problems. One of the major application is in the optimization of the dilution jets to achieve target combustor exit temperature profile and pattern factor. The optimization of the radial profile is generally time consuming because of the multiple parameters involved (number of rows, number jets per row, staggered or in-line, axial positions, circumferential positions and hole sizes). Mixing efficiency of dilution jets in confined crossflow is affected mainly by the momentum ratio of the main crossflow and the dilution jets, the strength of swirl in the crossflow relative to the incoming dilution jet flow, annular height, pitching and hole diameter of the dilution jets. Mixing of multiple jets in a crossflow has been investigated by Holdeman (1991), Blomeyer et a. (1996), Liscinsky et al. (1996), Holdeman et al. (1996) and Holdeman et al. (1997). The benefits of using CFD to perform parametric studies on these control parameters are time saving, cost saving and analyst's ability to visualize the formation of the exit temperature pattern.

Example of successful CFD application to radial profile development is shown in Figure 13. Numerical dyes were injected into each inflow boundaries of the combustor internal CFD model and scalar distribution of each flow device at the combustor exit plane were plotted. The peak of the temperature radial profile at the combustor exit could be lowered by adding more air flow through either the fuel nozzle, the two rows of the dilution jets on the outer liner or the inner dilution jets, according to this map. Another example is shown in Figure 14 which confirms predicted exit temperature distribution with measurements. A full 360 CFD model of the combustor was used to solve this particular problem.

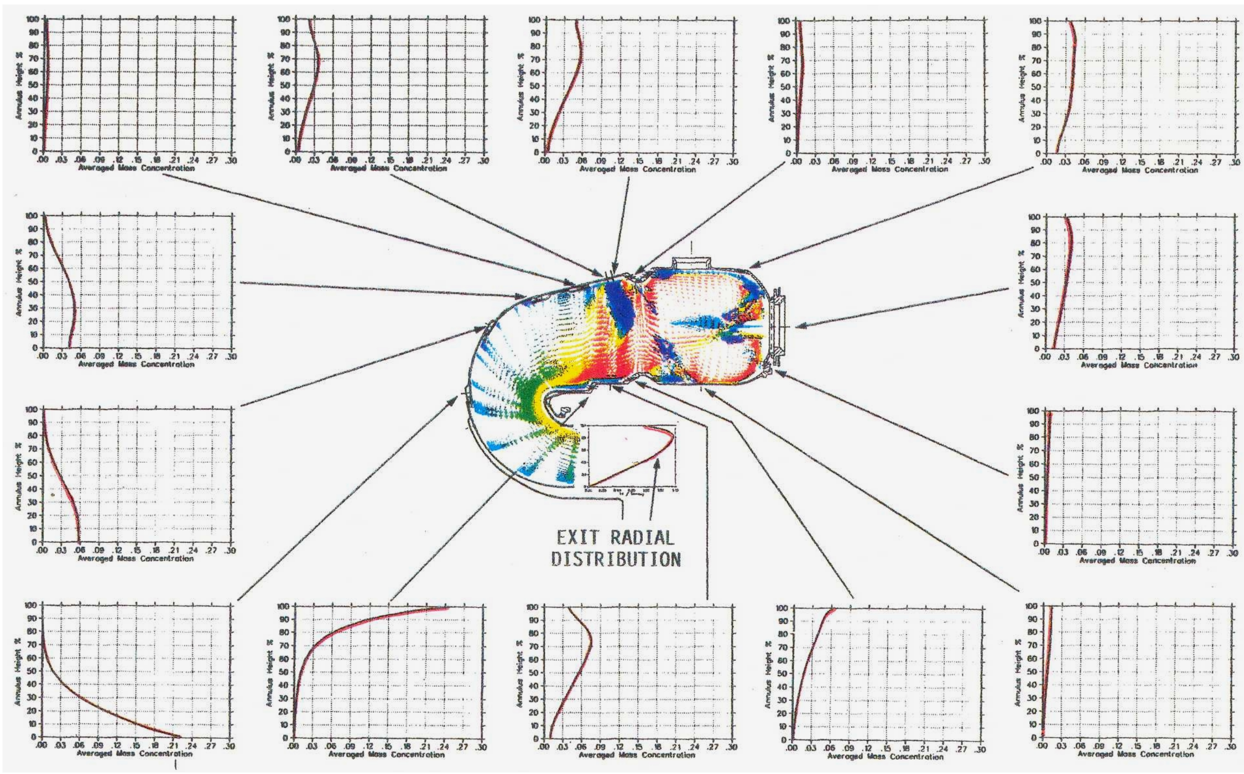

Figure 13: Contribution of Air Inlet Stations to Radial Profile

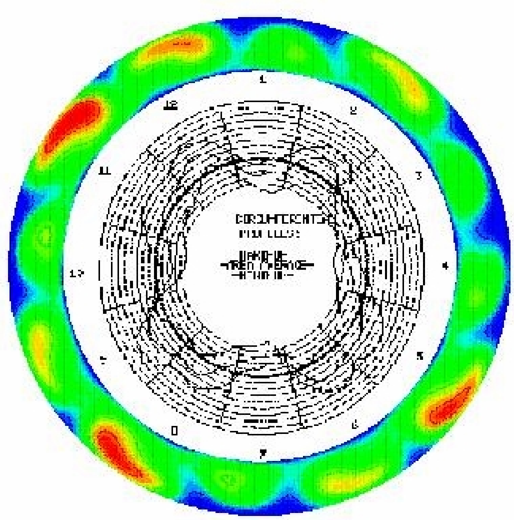

Figure 14: Comparison of Predicted and Measured Temperature Distributions

NOx Emissions

Once the reactive flowfield has been predicted by CFD, post-processing of NOx using extended Zeldovich mechanism can be use to predict thermal NOx. Since NOx is an exponential function of combustor gas temperature, minimizing the residence time of the hot gas and lowering the gas temperature of the hot streaks can reduce the amount of NOx emissions. Analysing the solution of CFD runs can provide much better understanding of the NOx formation regions and indication of where to tackle NOx. The NOx production region of the PW308A combustor is shown in Figure 15. An iso-surface of NOx is seen located in the high temperature region of the combustor in the primary zone. NOx continues to form as the hot streak escapes between the dilution jets into the dilution zone. NOx emissions can be predicted along the engine running line at the four engine settings according to ICAO emissions certification procedures. A typical example of NOx prediction is shown in Figure 16. The agreement of the predicted NOx with engine measurement is fairly good, except at one data point which is about 15% under-predicted. The NOx formation region in the this combustor case is immediately around and downstream of the primary jet where NOx is formed by the addition of fresh oxygen aiding combustion. Most of the NOx forming region is seen quenched downstream by the opposing inner and outer dilution jets. Some of the NOx forming regions streak out between dilution jets and contributing to the NOx measured at the exit plane.

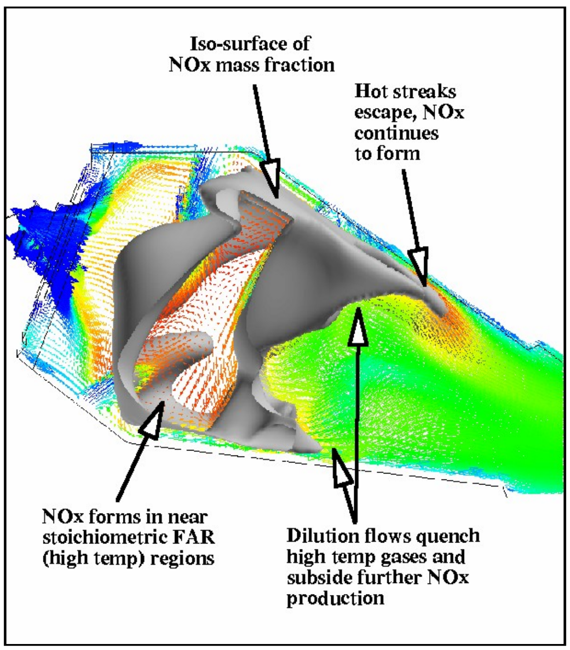

Figure 15: Prediction of NOx Formation Regions in a Combustor

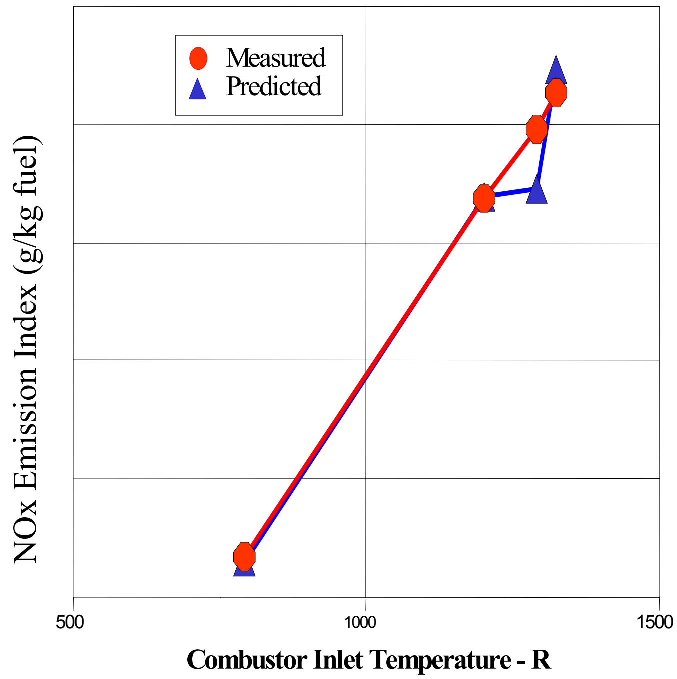

Figure 16: Combustor Modelling for NOx Emissions

Smoke Emissions

Semi-empirical smoke post-processing algorithm has been developed to predict SAE smoke number from converged CFD solution. This smoke model has been successfully applied to several P&WC combustors. Graphical presentation of high smoke generation region from CFD solution provides insight into approaches for rapid resolution of smoke issues. Figure 17 showed a baseline combustor that had a measured SAE smoke number of 60 at maximum power. 3D CFD solution indicated that most of the unmixed rich fuel was found in the primary zone nearby the fuel nozzle. The smoke generation picture allowed the analyst to pinpoint the location where additional combustion air should be injected to improve the fuel-air mixing and reduce the smoke generation region. As seen in Figure 17, the correlation between predicted versus measured smoke number is extremely good. Such active CFD modelling activities have saved significant number of engine hardware changes and test iterations.

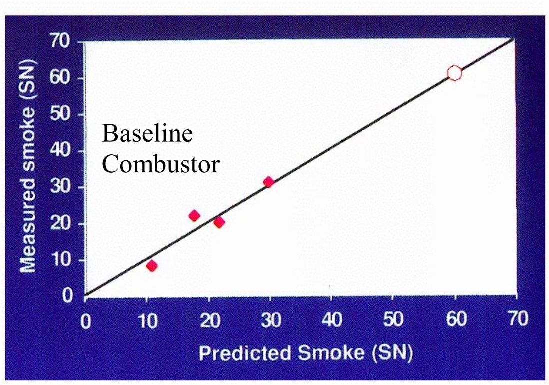

Figure 17: Use of Modelling for Smoke Reduction

Metal Temperatures and Stresses
The computational-based design system integrates the aerodynamic analysis tool with the heat transfer and structural analytical tools currently through soft links. The CFD predicted gas temperatures near the walls and the heat transfer coefficients are mapped onto the unstructured mesh for heat transfer analysis. The predicted wall temperatures are then used to update the cooling fluxes used in the CFD model. Several iterations between CFD & heat transfer analysis are typically performed to arrive at converged metal temperatures. Stress and lifing analysis are then performed to provide prediction of the life of the combustor. Comparison of the predicted metal temperatures with the thermal paint on combustor are shown in Figure 18. Despite the normal uncertainties of the thermal paint test data, agreement of the test results with analysis was quite good. CFD tools are being successfully used in combustor development. Similar practices of thermal and structural analyses are followed for fuel nozzles as well.

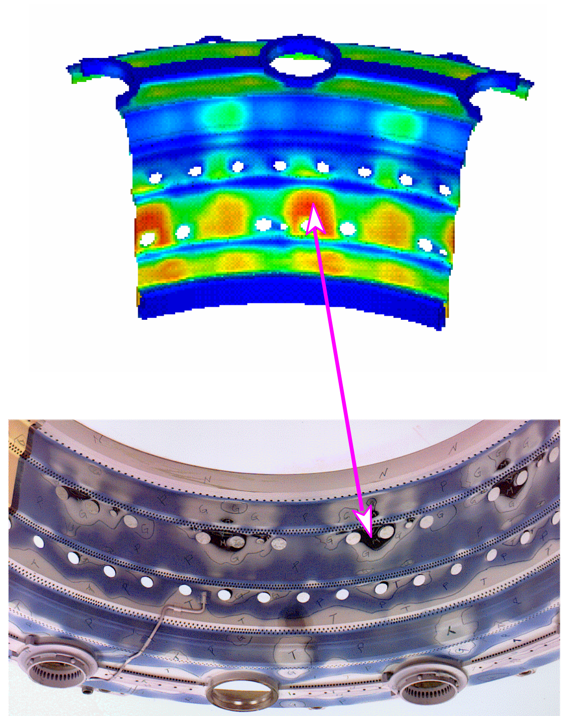

Figure 18: Comparison of Predicted Metal Temperatures with Thermal Paint Results

Full External-Internal Combustion System Modelling
With advancement of parallel processing, memory size and power of computing, the dream of solving the entire combustion system is now possible. An example of a complete 3D CFD model is shown in Figure 19. A 3.5 million node model of a combustion system from diffuser exit to turbine inlet comprises of multi-block structured meshing of louvre holes, jet holes, backside impingement holes and fuel nozzle air passages. The predicted static pressure field shows that pressure is quite uniform in the forward region from about the diffuser exit to the small exit duct cold-side. However, a significant decrease in pressure is seen in the region below the diffuser. Effects of local geometries in the flow field can be assessed. This full external-internal model eliminated many uncertainties in the boundary conditions that go into the internal hot flow analysis. Some more validation work is still required to establish optimum grid density, transition from one zone to another, and the effect of diffuser inlet or exit profile on wall temperatures, exit radial profile and pattern factor.

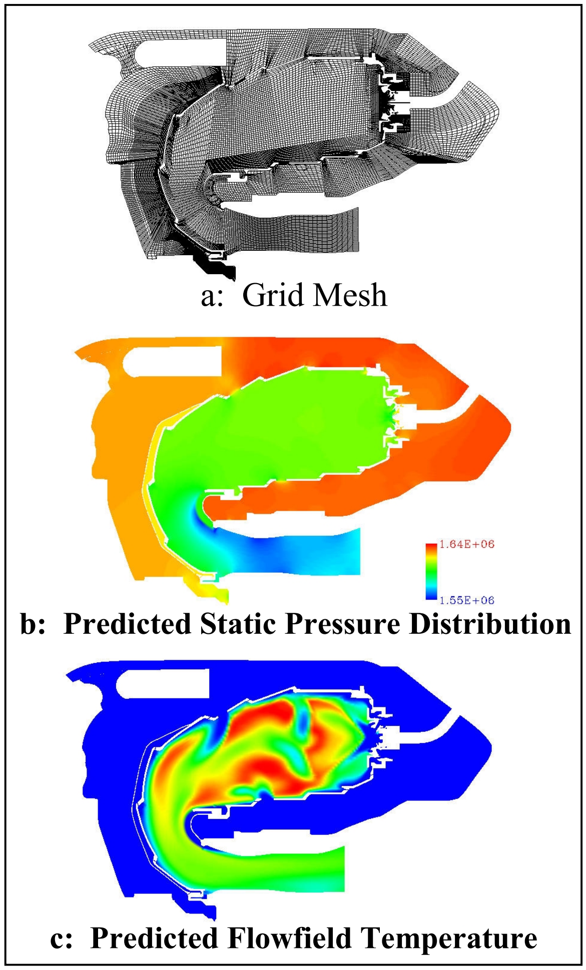

Figure 19: Full External-Internal 3D CFD Analysis

Preliminary Multi-Disciplinary Design Optimization For Combustor

The preliminary design of a combustor involves much information and knowledge from many disciplines in order to conceptualise a new combustor design. As the design cycle is 12 months or shorter, the 2D cross-section of the combustor needs to be defined and fixed by the end of the preliminary design stage. Once the program enters into detail design phase, the combustor cross-section should not be modified to enable planning, tooling and manufacturing groups to start working toward the first piece of engine hardware.

An optimized design of a combustor depends on its aerodynamics, structural integrity, cooling features, manufacturing techniques, materials, weight, cost, mechanical construction, and repairing scheme. A preliminary design tool that collects lessons learnt of previous combustors through market feedback analysis, design rules based on empirical correlations, 1D physical models, cost model and experimental database becomes extremely attractive to combustion designers and engineers. An optimization algorithm can be linked to this tool to optimize all the critical combustor parameters.

A preliminary design tool that include an interface with the CAD system to obtain the combustor outer casing, diffuser casing, and turbine support case envelope is required. The preliminary combustor volume and primary zone volume will then be calculated by the preliminary design tool. The designer can specify the type of cooling schemes for each panel and the type of fuel nozzle to be selected. The construction and manufacturing processes, the weight and cost of the system will be calculated upon the completion of the input data. The combustor designer can have an interactive session on the tool that gives instant response to the combustor sketched, on preliminary estimation of emissions, combustion efficiency, pattern factor, life, cost and weight.

Design Optimization For Combustion Sub-Components

Current combustor design in the detail phase depends heavily on engineers utilizing and interacting with computational-based design tools, and making judgements of directions to take and decisions along the design processes. The final design normally is the product of what the design team has experienced and boundaries they have ventured out to. There are many parameters in each sub-component that contribute to the success of its performance and life. In most cases, the design engineers do not know the amount of impact of each parameter to the design. Many iterations and configurations have to be performed to arrive at a design that is workable. However, there is a significant amount of design space that the team have not yet explored and that the team design may not have yet been optimized. The common constraint of the optimization process is the tight schedule of the design project and length of time to conduct optimization experiments. Also, the test matrix may be limited or incomplete. Recent research effort and resources have been devoted to artificial intelligence. Design optimization tools such as automated design of experiment, neural network, genetic algorithms and automated integrated system software become practical for industrial use.

Optimization process is needed in every aspect of a combustor design. Aerodynamics inside a combustor requires optimization of combustor volume for low emissions, low smoke, good flame stability at lean-blow out conditions, cold start and altitude relight capability, high combustion efficiency, low pattern factor and acceptable temperature radial profile. Aerodynamics and hydrodynamics of a fuel nozzle requires good atomization, droplet size and mass distribution, spray cone angle, fuel-air mixing rate, flow recirculation, coking and carbon free components and no aero-acoustic issue. Parameters that affect these combustor performance may include liner pressure drop, outer annulus geometry and blockage, diffuser flow exit swirl and mass distribution, length and height of primary, secondary and dilution zones, hole pattern, hole size, hole position, number of hole, orientation of hole and cooling scheme geometry. Thermal and structural issues of the combustor liners and fuel nozzles are oxidation, low cycle fatigue, temperature gradient, high temperatures, crack initiation, pressure and mechanical loadings and fretting due to dynamic issues. Parameters that may affect the mechanical behaviour and life of these components are wall thickness, material properties, cooling effectiveness, heat protection scheme, contact surface geometry, coating applied, leakage, type and dimensions of weld and braze and proximity of features to one another (e.g. flange, boss, hole, bolt, joint). Each sub-component of the combustion system can easily utilize an optimization tool that interfaces with the computational-based design process to achieve optimum design with leadtime reduction , on-time delivery, less human interaction and decision making, reduce design cost, reduce time-to-market, improve productivity, improve profit margins and provide more time for engineers to think, improve and innovate.

Role of Academia

There are many areas in combustor design that requires good understanding of the fundamentals and phenomena of flows and structures. Other areas that academia can contribute is database establishment, physical modelling and model validations. As CFD, thermal and structural codes become the main design tools for combustor today, the multiple physical submodels and assumptions used in these analyses must be validated with close form solution, experiments or actual engine data. Their accuracy, applicability and limitations should be properly defined and documented for users. When these tools are properly calibrated, validated and verified, they become very powerful design tools that can significantly improve the quality of first design, largely reduce the amount of risks in new designs, reduce leadtime in design, reduce company's investment on new products, reduce time to market. The university academia and national research institutions have been working closely with P&WC research team to address various practical combustor issues. P&WC also started a program where university undergraduates, graduates with Master's degree and post-doctorate can have one year working experience in the Combustion Module Centre. Such university personnel will be mentored by a combustion engineer and worked closely in one of the engine program with the IPT. His university sponsoring professor visits the Combustion Module Centre on a regular basis to monitor his progress and gain insight into the design process and design tools used at P&WC. The Combustion research team welcomes the professors to make proposals for research collaboration. P&WC also encourages employees to choose a practical gas turbine engine design problem as their thesis problem for Master's or Doctorate degree.

Some of the collaborative research with academia and research institutions include practical combustor flowfield characterization, fuel spray characterization, emissions modelling, combustion modelling, aviation fuel evaporation modelling, two-phase flow modelling, fuel droplet atomization modelling, soot modelling, conjugate heat transfer computation, alternative ignition system development, high temperature materials characterisation, thermal barrier coating characterisation, advanced cooling scheme development and database establishment, fuel nozzle coking studies, and alternative fuel spray development.

Areas of research topics to explore in the near future will be carbon formation and oxidation, combustion dynamics, combustion noise reduction, innovative low emissions concepts, large eddy simulation of combustor flows, flame instability, preliminary multi-disciplinary design optimization tool, advanced material characterisation and applications, low emissions fuel nozzles, advanced manufacturing techniques, optical patternation of production fuel nozzles, pulse-detonation combustion system and fuel cells power generation.

Conclusions

The small aviation turbine is changing rapidly in all its market segments and this has resulted in paradigm shifts in the design methodologies of the engine system as well as its components. Point designs are becoming a necessity in order to meet conflicting requirements from the new products. Design and development processes are being refined to achieve major reductions in design elapse times as well as improving quality of first design.

New challenges to combustor designs include continuous process improvements and technology developments for low emissions , without incurring performance or cost penalties. Good feedback of MFA data, is critical to maintaining a validated design system. Continued focus on quality and ownership costs are also essential to proactively respond to changing market demands

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