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THE SAFRAN HELICOPTER ENGINE SPINNING FLAME COMBUSTOR CONCEPT TO MEET CUSTOMER NEEDS

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ABSTRACT

The main concern to achieve ongoing rotorcraft challenges is to provide an efficient and operational needs oriented engine concept. Significant progress towards development and validation of the last generation of SAFRAN Helicopter Engines combustion chamber is presented in this article : the spinning flame combustor.

This new combustion chamber concept will enter in service for the first time on the Airbus H160 helicopter, early 2018.

This entry in service is the outcome of 40 years of research and development performed at SAFRAN Helicopter Engines, focused on the global optimization of a widened combustion perimeter, considering all parts from the low pressure fuel pump to the combustion chamber exhaust, including valves, fuel pipes, injectors and actuators, and all components involved in the fuel management of the combustor and the combustor itself.

The rotorcrafts operational needs, applied to the combustor have not drastically evolved during these last 40 years: in the 80’s, the combustor efficiency was already close to 97% and the cold-soaked lighting envelope reaching 6000m and -50°C. Since then, the engine efficiency gains could not be reached through combustor modification (already topping 97% efficiency) and the lighting envelope has not evolved, considering the rare opportunities to soak a helicopter at 6000m and -50°C.

Thus, two ideas have driven the research and development of the spinning flame combustor :

- Simplification providing reduction of mass, cost and unavailability of the engine, with the same operational needs as exposed above
- Improvement of operational needs, anticipating future applications including hybrid propulsion systems and new power management strategies.

To achieve these goals, this technology has been inspired by two existing ones, the benefits of which have been combined :

- The sling combustor technology invented by TURBOMECA in the early 50’s, and still existing in state of the art applications like ARRIEL and MAKILA Turbomeca turboshaft engines, but as well in Williams FJ44 turbojet engines for example. Due to its original rotating fuel injection wheel, the fuel system of such engines is very simple and the resulting combustor and casing are cheap and light.
- The localization of fuel swirlers and injectors around the combustor, rather at its end, allowing easy maintenance and reducing coking. Such a technology exists on many applications like Pratt and Whitney 206 family engines, as well as APS2000/3000 APU family, etc.... This technology will be called tangential injection in the following chapters.

The spinning flame combustor technology combines the simplicity of the fuel system, the low mass and cost of the combustor and casing of the sling combustor, with the maintainability of the tangential injection. To achieve this, the whole airflow will be injected tangentially into the combustor, as well as the fuel through the injectors. Thus, the combustion generated by a fuel injector will be directed toward the next one and so one, creating a unique flame ring spinning into the annular combustor, being beneficial for ignition, compacity and homogeneity.

In order to develop and bring into service such a new technology, the most advanced innovative concepts regarding design, technologies and manufacturing process have been used in order to reach a very high level of optimization. In particular, it requires a deep knowledge of several complex phenomena. Combining advanced CFD simulation and experiments provide a clear understanding of the way to optimize the integrated concept.

As a result, the presented technological breakthrough brings an extended operational range of use thanks to an improved flame stability combined with an optimized gas temperature homogeneity at the

combustor exit. Moreover, additive laser manufacturing and components combination induces drastic weigh reduction of more than 30% compared to previous turboshaft generation combustion chamber.

Customer will take immediately advantage of the spinning combustor technology in term of mass, reliability, security and cost of operation. Due to the design choices, easy repair solutions for inspections accessibility are provided.

The improvement of stability performances achieved will be used in future rotorcrafts applications in order to develop new hybrid or innovative propulsion strategies that may generate new engine operational needs like fast restart or automatic inflight relight for example.

1. INTRODUCTION

The main concern to achieve ongoing rotorcraft challenges is to provide an efficient and operational needs oriented engine concept. Significant progress towards development and validation of the last generation of SAFRAN Helicopter Engines combustion chamber is presented in this article: the spinning flame combustor.
This new combustion chamber technology will enter in service for the first time on the Airbus H160 helicopter in 2018.

2. PRINCIPLE

The spinning flame combustor is a new combustion chamber technology that fits in typical turboshaft engine designs.
Turboshaft engines deliver power thanks to a reduced speed rotating shaft. Ambiant air is compressed as close as possible to an isentropic process until its delivery to the combustion chamber casing. Then, fuel and air react together in an isobaric process to produce hot burnt gases. High pressure turbine and power turbine expand gas to transform enthalpy energy into torque on the shafts.
Modern turboshafts combine high performance, low mass, compacity, and low emission levels. To achieve these challenging improvements combustion chamber optimization is a key issue.
In a modern combustion chamber, air system management is of prime importance. Indeed, engine air flow is used as oxidizer to react during the chemical reaction in the primary air zone ensuring efficiency and combustion stability. Close to the fuel injector, aerodynamics is optimized to atomize fuel droplets ensuring flame stability and control. Over the whole combustor liner, air introduction is structured on one hand as a coolant fluid to maintain the walls under 1000 K but also to structure the mixing process to guarantee an optimal temperature profile at the turbine entry for thermodynamic and life optimization.
The spinning flame combustor will be presented in this article in its most widespread turboshaft configuration: the reverse flow combustor, see Figure 1. In this configuration, the combustor is situated around the high pressure turbine (HPT), the air and fuel are flowing in the direction opposite to the flow in other parts of the engine. At the combustor end, two bends reverse the flow to feed the high pressure nozzle guide vane (NGV). This classical design allows a short distance between compressor ant turbines parts, resulting in a shorter and lighter engine.

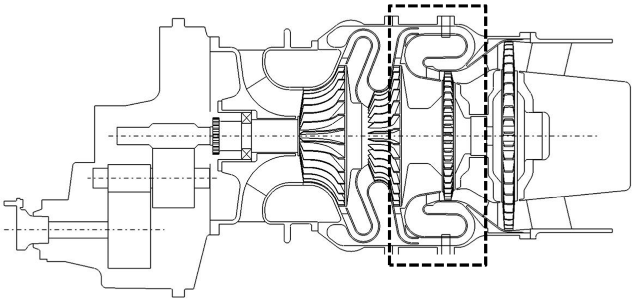

Figure 1 : Typical turboshaft engine and reverse flow combustor

The spinning flame combustor concept is based on the assembly of 3 design features:

- Radial/Tangential fuel injection
- Tangential airflow injection
- Compactness

Each one of these specificity already exists in traditional combustor designs, but their combination results in the spinning flame combustor, as shown in Figure 2: a global spinning flow is generated into the combustor, relating each injector to the others through an annular flame. This spinning flame allows reaching better performances of the combustion:

- Better stability
- Better lighting propagation
- Better gas temperature homogeneity

All these points will be detailed in the following chapters.

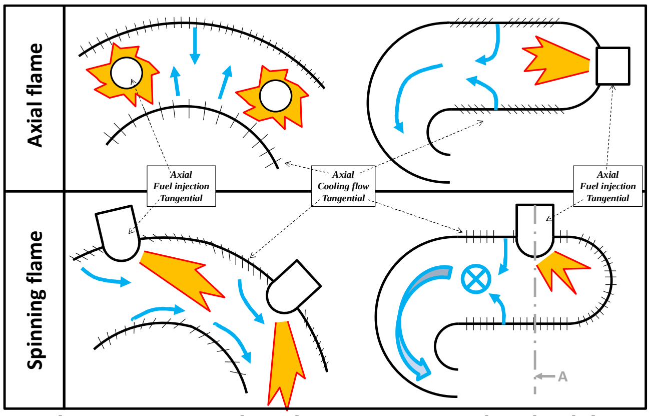

Figure 2 : comparison between conventional axial combustion and spinning flame combustion

3. DEVELOPMENT HISTORY

As mentioned earlier, the development of the spinning flame combustor is the combination of 3 technological concepts that have been developed and joined during the last 35 years.

3.1. Radial/tangential fuel injection :

The first one of these concepts is the tangential injection of kerosene into the combustor. This technology has been widely used during the past decades and has been the first of the 3 mentionned above to enter in service on a wide variety of applications. It appeared in the 80's on Auxiliary Power Units (APU) : GTCP 131 from Garett/Honeywell or APS2000 from Hamilton Sunstrand/Turbomeca, among others. It continued in the 90's on turboshaft engines with Pratt and Whitney PW206/207 family, or Rolls Royce/Turbomeca RTM322.

3.2. Tangential effusion cooling

The next step toward spinning flame combustion was the implementation of tangential effusion cooling. Early in Turbomeca history, effusion cooling has been at the heart of combustor cooling design, initially with electron beam drillings on the first ARRIEL engines combustors in the 70's, followed by laser drillings from 2000's on all combustors.

Effusion cooling consists in drilling thousands of submillimetric holes in the combustor liner in order to mimic a porous wall. This has two beneficial effects on the wall cooling :

- Convection into the holes which enhances thermal exchanges between the cooling air and the wall
- Protection of the combustor wall from the hot combustion gases by the creation of a cold film of air on the hot side of the wall

In addition to these beneficial thermal effects, this design reduces the mass by 2% to 5% and is relatively cheap to manufacture thanks to the drilling frequency of laser or electron beam drilling (typically 10 to 20 Hz).

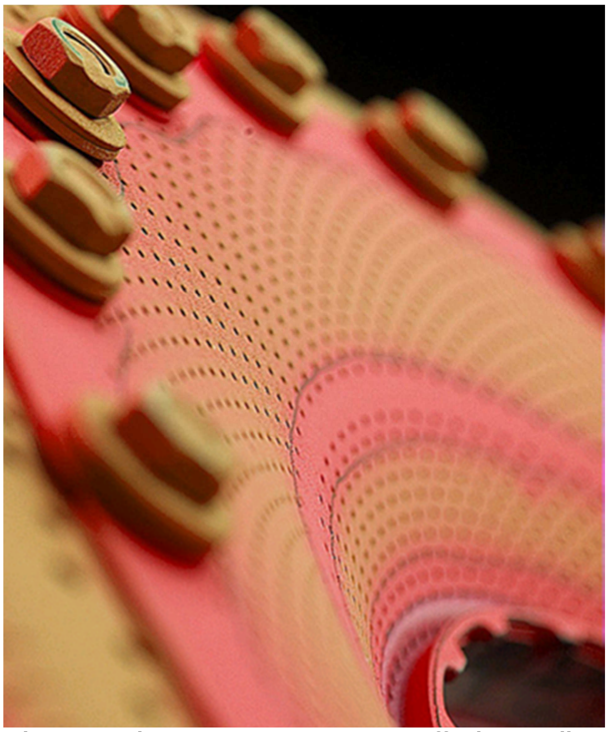

Figure 3 : Close-up on TURBOMECA effusion cooling drillings

This cooling device has spread very rapidly on worldwide combustors, as there is a relative consensus on the fact that it has a very good efficiency/mass/cost compromise. This vast majority of nowadays combustors equipped with effusion cooling use what is called "axial" effusion cooling: the axis of the effusion hole is secant with the combustor axis. A less widespread evolution in effusion cooling design consists in modifying the orientation of effusion holes, in order to make them create a swirling flow inside the combustor. The hole axis is no longer secant to the engine axis, but has a tangential compound. This effusion cooling technique is described for example in patents FR2955374 or FR3021097.

The combination of tangential fuel injection and the massive use of tangential effusion cooling is the second key element of the spinning flame combustion technology : it creates a global swirling flow inside the combustor which is typical of this new technology.

3.3. Compact combustor for turboshaft engines

The last but not least step towards spinning flame combustion within turboshaft engines has been to reduce the size of the combustor.

Indeed, aircraft turboshaft engines have two major contradictory constraints from the combustor point of view:

- They must be very light and compact
- They must handle a very large range of transient operation, generating a very wide range of aerodynamic conditions in which the combustor must operate

In particular, the applications close to spinning flame combustion in the field of APUs as mentioned earlier do not have such constraints because APUs often run at steady operating conditions, and have less drastic transient operating specifications.

This final challenge has been fulfilled thanks to a succession of combustor demonstrators tests, as well as academic and applied research work on combustion and its modelization. This point will be further developed in a dedicated chapter.

3.4. Engine demonstrator : Tech800

The main step leading to the entry in service of the spinning flame combustor has been its introduction on the engine demonstrator Tech800. Tech 800 was the result of a research study financed by the European Commission's Clean Sky program, a public-private partnership with the European aerospace industry.
This 1,100 shp turboshaft demonstrator has been developed in collaboration with 34 partners (18 of which were SMEs) plus 12 universities and research centers from 10 European countries [1].
This strong effort allowed to bring to maturity the spinning flame combustion technology : the first bench test of the Tech 800 took place in April 2013. This demonstrator offers a double digit benefit in terms of fuel consumption and CO_2 emissions compared to the year 2000 state of the art.

3.5. Engine Entry in service : ARRANO

With the technology validation on the Tech800 demonstrator, the spinning flame combustor could be deployed on next SAFRAN Helicopter Engines engine development: the ARRANO engine.
The Arrano represents a perfect synthesis of new-generation and proven technologies. It incorporates a two-stage centrifugal compressor, the aerodynamics of which are designed to deliver performance and reliability. It also features a single-stage power turbine that contributes to its reduced fuel consumption.
The ARRANO combustor uses the spinning flame combustion technology. Moreover, the ARRANO combustion system uses components manufactured using the additive manufacturing process. The injectors in the combustion chambers of series production models are produced using lasers to fuse a metal powder compound. This process enables complex-shape parts to be obtained much faster, and using fewer parts. The use of such a process contributed strongly to the success of the spinning flame combustion technology.

First tests of the Arrano engine took place in February 2014 at Turbomeca's Bordes factory; its performance levels in terms of fuel consumption were soon validated.
First flight occurred in January 2016, see Figure 4.

Figure 4 : First flight of the ARRANO 1A engine on H160 helicopter, 2016 january 27th

The Arrano is the most innovative and high-performance engine in its class. It embodies the technological know-how and expertise that has lain at the heart of Turbomeca's reputation for nearly 75 years.

4. DESIGN AND MANUFACTURING CHALLENGES

4.1. Advanced numerical simulations and experimental optimization

During the 35 years of development of the spinning flame combustion, engineers took advantage of both experimental and numerical activities. Both of it are complementary and in recent years, numerical tools and High performance computing have emerged and becomen essential.
Due to the high complexity of the phenomena involved in combustion chambers, the 15 last years of development of new combustion technologies have always used the latest developments in combustion

modelization. Indeed, the place in a turboshaft engine where the higher number of physical phenomena are involved and coupled is combustion chamber:

- Subsonic fluid mechanics around the combustor
- Liquid fuel and coking into the fuel system
- Primary atomization of fuel in the injectors
- Fuel evaporation close to the injection systems
- Gaseous fuel combustion into the combustor
- High turbulence modelization into the combustor
- Airflow mixing in the dilution zone
- Heat transfers at the wall including conduction, convection and radiation

This trend is very well shown by both Figure 5 and Figure 6 which show respectively the evolution of computational capacities worldwide and the computational effort used to setup combustion systems at SAFRAN Helicopter Engines on the same period.

Figure 5 : worldwide computational performances evolution [3]

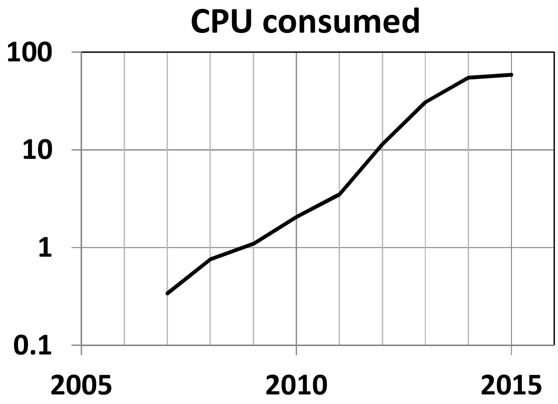

Figure 6 : SAFRAN Helicopter Engines computationnal resources consumption

In particular, the developments in unsteady simulations have been very much linked with combustion due to the high level of unsteadiness of the physical phenomena listed above. To achieve these developments, SAFRAN Helicopter Engines has established a partnership with numerous research laboratories and institutes to ensure the availability of state of the art modelization tools. The main partner for this last decade has been CERFACS (Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique) which has developped the AVBP software.

AVBP is a Large Eddy Simulation (LES) code dedicated to complex geometries. It uses a high-order Taylor Galerkin scheme on hybrid meshes for multi species perfect of real gases. It is a world standard for LES of combustion in engines and gas turbines, owned by CERFACS and IFP Energies Nouvelles. It is used by multiple laboratories (IMFT, EM2C, TU Munich, Von Karmann Institute, ETH Zurich, etc) and companies (Safran group, etc).

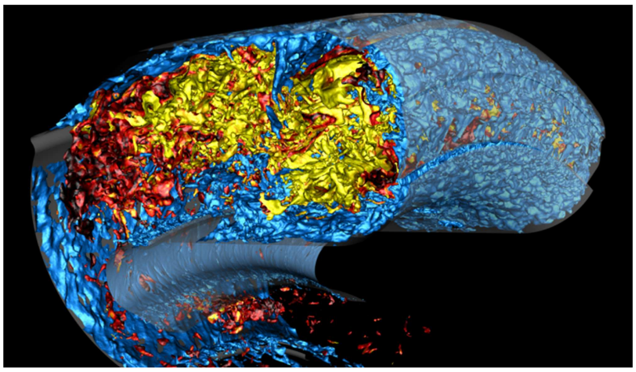

Figure 7 : Example of unsteady simulation of a spinning flame combustor

This high fidelity simulation makes engineering approach evolving. Experimental set-up is dedicated to data base generation and final design validation while numerical approach is preferred for intermediate loop of design optimization.
During the development of the spinning flame combustion technology, the AVBP software has intensively been used in order to handle lean blow off, lighting, emissions as well as exhaust gas temperature profiles.
Figure 8 and Figure 9 show the AVBP software typical prediction capabilities on SAFRAN applications for exhaust gas temperature profiles and lean blow off performances [2].

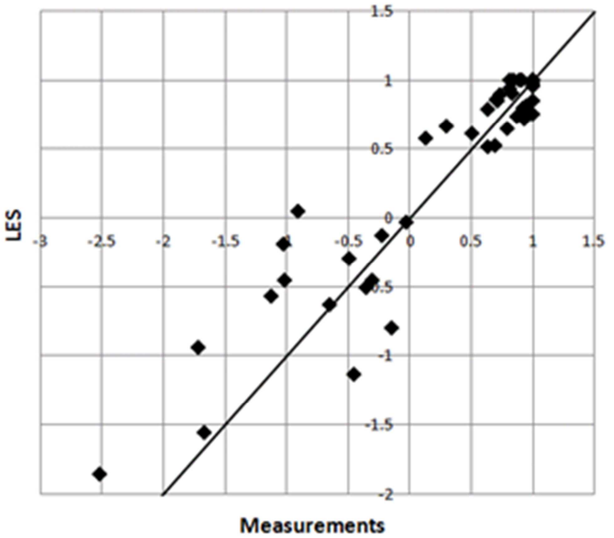

Figure 8 : Dimensionless temperature (RTDF) at different radii for a set of SAFRAN combustors. RTFD values are normalized by the maximum of the 1D profile

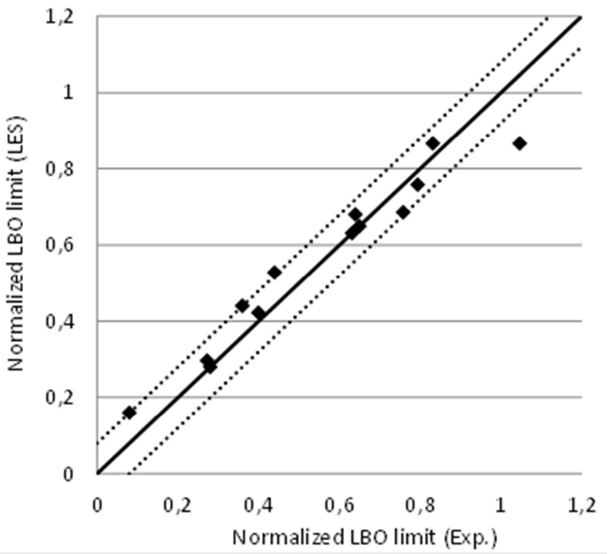

Figure 9 : LBO limit prediction (LES) vs experimental data for a set of SAFRAN combustors in various operating conditions. Values are normalized by the fuel-air ratio at take-off power. Dotted lines correspond to the error zone of +/-2 ‰.

4.2. Additive manufacturing

Another key evolution that made the spinning flame combustion possible has occurred in the production sector with the emergence and maturation of additive manufacturing.
This new production technology allowed the production of very complex designs that were usually non possible to manufacture or at costs beyond what is acceptable for mass production.
Injection systems, that are the key elements of the spinning flame combustion technology, could simply not have existed with conventional manufacturing. Indeed, they collocate the highest share the combustion system complexity, and are at the heart of key combustion performances:

- Blow off
- Lighting
- Fuel vaporization and mixing
- Flame stability

As a result, other components of the combustion system such as liners, dome, external and inner elbows could be freed from some complex functionalities. This allows reducing the production costs of these components resulting in a global reduction of manufacturing cost and cycles that will be detailed below.

Figure 10 : Additive manufacturing of conventional (left) and spinning flame (right) combustor fuel injectors

4.3. Collocated design, manufacturing and test teams

Both, at the beginning of its development in the 1980's when high performance computing was not mature enough, and at the end of the development in the 2010's, to build numerical simulation data base and to validate final concept version, experiments have been used with advanced post-processing.

For a given performance of the combustor, experiments are prefered when :

- Numerical methods do not exist or are note mature enough (fine tuning of wall temperature),
- Numerical methods are more expensive than experimental ones, mainly regarding start procedure simulations,

Despite the dramatic rise of computing power, knowledge remains relatively poor considering combustion coupled phenomena in a combustor. At least, these phenomena are not known enough to rely completely on numerical tools. Thus the final validation of any combustor performance is still made by experiments.

An example of Lean Blow off experiments at SAFRAN Helicopter Engines testbench on a spinning flame combustor is shown on Figure 11 (left).

Figure 11 (right) presents a typical result gas temperature field analysis based on gas analyzer measurement at the combustor exit for high pressure parts thermal loads validation.

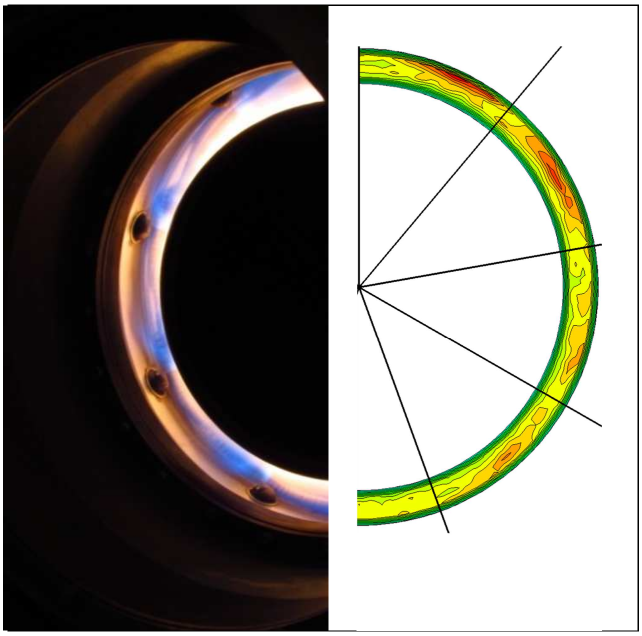

Figure 11 : Example of Lean Blow Off (left) and exhaust temperature distribution (right) tests at SAFRAN Helicopter Engines facility

This extensive use of experimental tools for combustion design was possible thanks to the availability at SAFRAN Helicopter Engines Bordes facility of 3 teams:

- Design department
- Manufacturing worshop
- Experiments and test benches teams

With those 3 teams collocated in the same place, design/manufacturing/testing cycles have been drastically reduced. The time between a test on the combustion test bench, and the next one with a modified hardware could sometimes be dropped to 1 ½ day.

Moreover, these modification cycle times have only be possible thanks to the use of design and manufacture organizations different from the mass production ones: taskforce teams have been formed in order to shorten all the delay times that are inherent to 'big companies' organization. This specific project management method allowed optimizing both time and money spent to bring the spinning flame combustion technology to maturity.

At the end, 39 versions of flame tube combined with 11 versions of injectors combined with 10 versions of external elbow have been studied and/or manufactured and/or tested to bring the spinning flame combustion to fly on the ARRANO engine, on 2016 January 27th.

5. BENEFITS

All these developments and efforts spent to bring this new combustion technology to maturity for turboshaft engines had one goal: reduce mass and cost and in the same time improve performances of the combustor system.
Indeed, the spinning flame combustion technology is the result of a global functional analysis on the whole combustion perimeter: from the fuel pump to the combustor exhaust. This perimeter includes most of the fuel system which gives a very different perspective than standard "components oriented" optimizations. We will discuss further the gains obtained with this technology that result from this global approach.

5.1. Gas temperature homogeneity at combustor exit

One of the more straightforward benefits of spinning flame combustion is the improvement of mixing within the combustor, enhancing dilution of hot gases generated by the fuel combustion.
This improvement allowed reducing the primary zone volume and the number of fuel injection points into the combustor, for a given specification of temperature homogeneity at combustor exit, usually characterized through the Overall Temperature Distribution Factor (OTDF).
In the end, this allowed a mass and cost reduction for a constant homogeneity performance enhancing the use of conventional turbine cooling system.

5.2. Lightening

Another major improvement in combustion performances is the ability to ignite the whole combustor in a very short period of time.
Typical combustors used to ignite specific start injectors, before the flame propagates itself from one main injector to its neighbor, until the whole combustor is ignited. As the main flow in conventional combustors is mostly axial, the tangential propagation from one injector to another is relatively long so that the full ignition of the combustor can last several seconds at ground standard conditions.

With spinning flame combustion, the start injectors are integrated into the main injectors, resulting in dual fuel circuits injectors. Thus, ignition of the combustor is realized in a dual injector, and the global tangential movement of the flow inside the combustor enhances the flame propagation from one injector to next one which results in a quasi-instant full ignition of the combustor. The full ignition process captured with high speed cameras at SAFRAN Helicopter Engines test facility is presented in Figure 12 and takes only 60ms to complete.

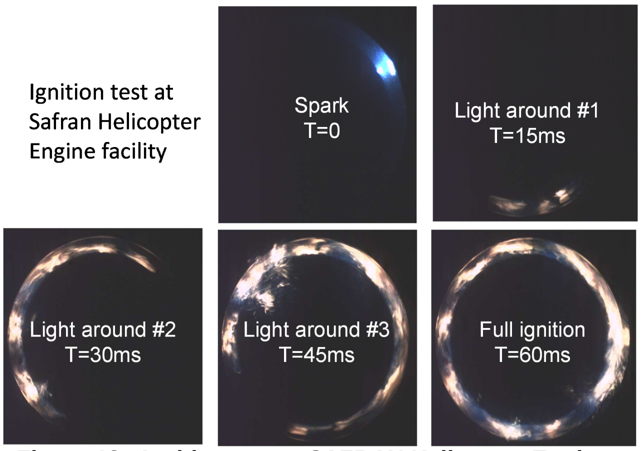

Figure 12 : Ignition test at SAFRAN Helicopter Engines facility with 1000fps camera

This ignition improvement reinforces engine robustness for standard helicopter applications, even if their starting envelopes have little evolved since 70's with usually 6000m -40°C operational needs. But, fast combustor full ignition is a key performance when developing next generation propulsion strategies. These strategies often involve to shut off one of the aircraft engines, in order to optimize the system efficiency. At the pilot demand, it could be then mandatory to be able to start-up the shut off engine as fast as possible. The delay to recover the full engine performances is drastically shortened in safe condition with the use of the spinning flame combustion.

5.3. Mass

By thinking the combustion system globaly, major simplifications of the system have been achieved.
As mentioned earlier, most of the system complexity has been concentrated in injectors, obtained by additive manufacturing. At the end, some fuel system equipments could be suppressed, gaining mass and reliability of the system. On the combustor parts themselves, the injector number reduction mentioned in the "temperature homogeneity" paragraph, as well as simplified combustor parts mentioned in the "additive manufacturing" paragraph lead to a mass reduction of combustor parts of 50% compared to 1980's technology and 30% compared to 2010's technology.

5.4. Cost

For conventional helicopter applications, the main improvement of this new technology is the production cost. As mentioned earlier, the combustor operational needs for conventional helicopter applications have little evolved in the past 35 years :

- Startup envelope up to 6000m -50°C
- Lean Blow Off limits allowing quick decelerations
- 95% to 97% thermodynamic efficiency
- 4000h to 6000h life

Thus, for such applications, the major gain of spinning flame combustion has been the production cost reduction that has been made possible by the global system optimization mentioned in earlier paragraphs. Figure 13 show the gains in mass and cost compared to earlier conventional combustor technology. Both are divided by nearly 2 since 1981 conventionnal combustor design.

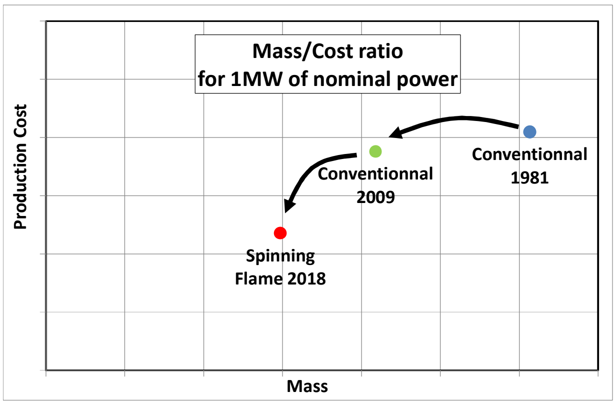

Figure 13 : Mass and Cost reductions of the spinning flame combustor

6. CONCLUSION

The presented technological breakthrough presented here brings an extended operational range of use thanks to an improved flame stability combined with an optimized gas temperature homogeneity at the combustor exit. Moreover, additive laser manufacturing and components combination induces drastic weigh reduction of more than 30% compared to previous turboshaft generation combustion chamber.
Customer will take immediately advantage of the spinning combustor technology in term of mass, reliability, security and cost of operation. Due to the design choices, easy repair solutions for inspections accessibility are provided.
The improvement of stability performances achieved will be used in future rotorcrafts applications in order to develop new hybrid or innovative propulsion strategies that may generate new engine operational needs like fast restart or automatic inflight relight for example.

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