Recursive sequential combustion: an innovative and high-performance combustion technology, aimed at the fuels of the future

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Abstract:

The Recursive Sequential Combustion (RSC) invented by Combustion Bay One e.U. aims to produce robust lean combustion with excellent performance in terms of combustion efficiency, NOx and soot emissions. It addresses the fuels of the future, among others hydrogen. The audience at EnInnov 2022 will benefit from the latest progress made in the MOeBIUS project.

This contribution presents the RSC technology and the early developments made at early Technology Readiness Level (TRL, currently TRL 2, meaning that the concept's plausibility was established). It is explained why trapping a permanent hot gases recirculation serves the combustion in a positive manner. The technical adaptions on the burner structure are discussed, and two concepts named discrete RSC sector and constant-section RSC are presented. It is shown why new materials and additive manufacturing are promising technologies that will help to produce the first demonstrators. The paper ends with a detailed CFD investigation of the constant-section concept.

Keywords: Combustion, low-emissions, fluidic-driven thermal inertia, flow-design, additive manufacturing, gas turbines, future fuels including Hydrogen

Introduction

A new combustion method called Sequential Recursive Combustion has been invented by Combustion Bay One e.U. and is presented and described herein. It aims to produce robust lean combustion with excellent performance in terms of combustion efficiency, NOx and soot emissions. It addresses the fuels of the future, among others hydrogen. The key feature is the maximisation of the interaction between the burnt gases and the fresh reactants, using a groundbreaking combustion chamber architecture.

The background of this study connects directly to the Paris Agreement's goal of limiting greenhouse gas emissions so that the average temperature increase remains well below 2

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degrees Celsius by the end of the century, and to the needs of the aviation sector to contribute positively to this effort.

Consumption of conventional resources is expected to plateau and begin to decline over the decade. While this change is urgent for environmental reasons, it must be borne in mind that fossil fuel resources are finite, that the long-forgotten concept of peak oil is another harsh reality, and that the legacy of natural resources for future generations is essential. This decrease will be linked to the effective transition mentioned above, combined with a better use of these "transitional fossil fuels", possibly blended with new fuels. In other words, the fuel of the future will be scarcer, and we must make the best use of it.

Industrialised countries have started their transition to a post-fossil fuel, carbon neutral economy. Many sectors that need heat and high temperatures rely on combustion and therefore need fuels. These include among others the energy sector, metallurgy, the concrete industry and aviation. The advantage of burning fuels is that it is an established, though improvable, technology that provides energy on demand in a well-controlled way. The fuels of the future will be whether carbon-free such as hydrogen, or synthetic hydrocarbons resulting from a process that ensures a neutral or negative atmospheric CO2 balance.

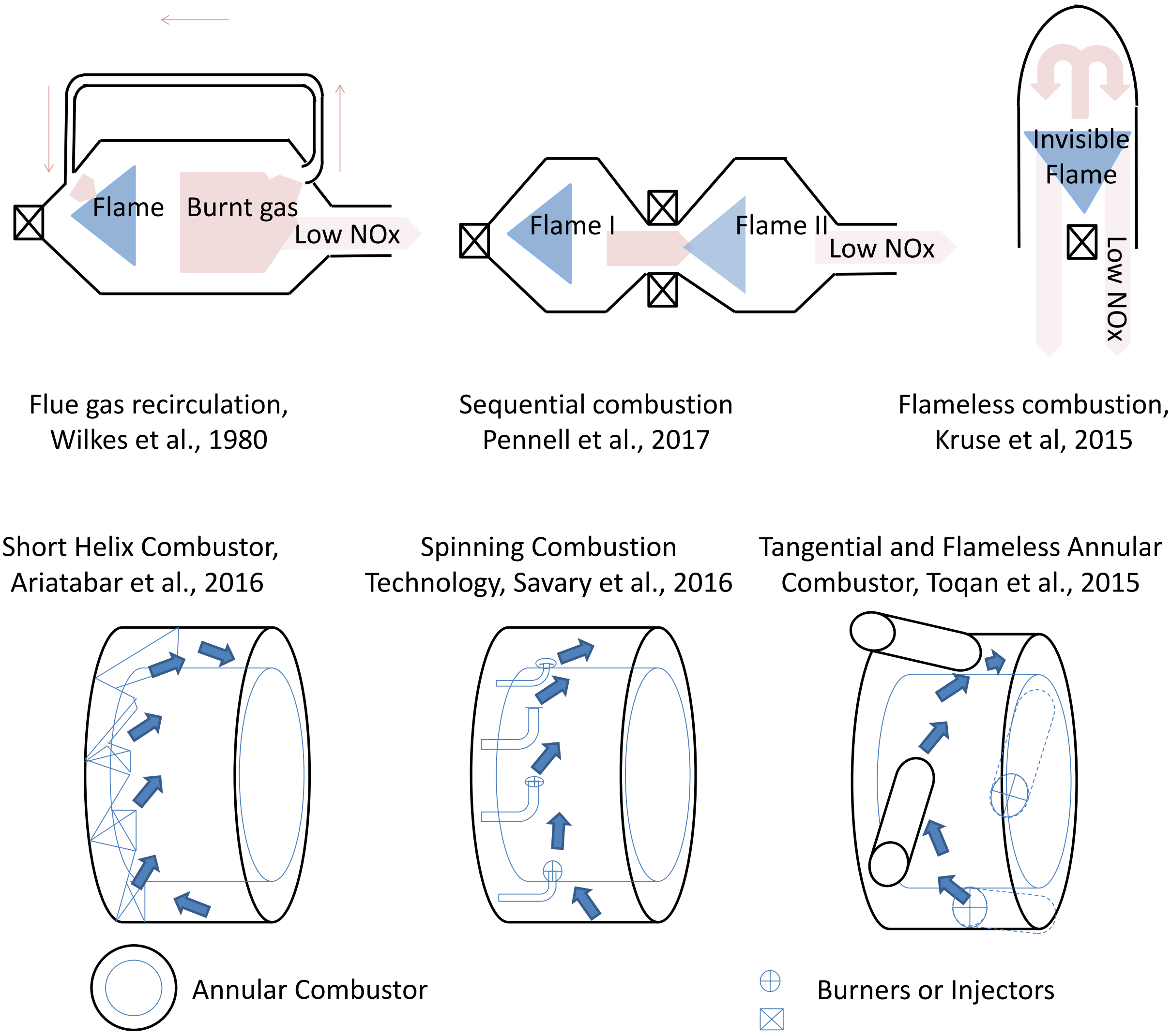
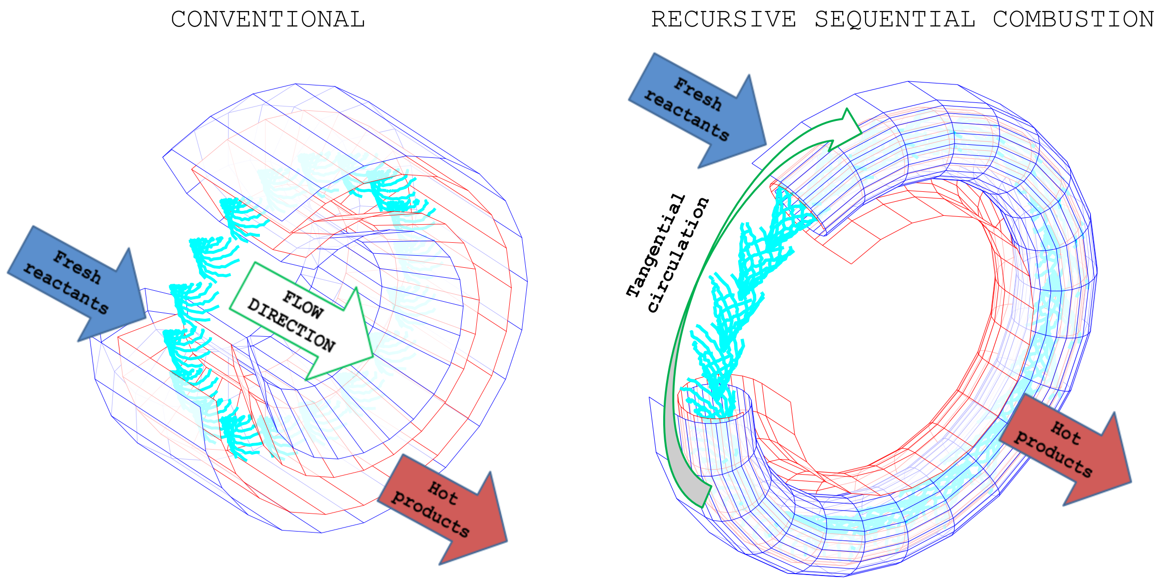


Figure 1: A review on combustion systems using the recirculation of burnt gases

The challenge with synthetic fuels is to limit NOx and particulate emissions. The challenge with the use of pure hydrogen is to withstand the extreme heat generated by combustion, and to limit the thermal NOx emissions associated with these high temperatures. In the particular case of hydrogen, which is promised to be widely deployed in civilian applications within 15 years including aviation, let's face it: the question of safety of installations and vehicles is a major issue, and burner technology is far from ready.

There is therefore an urgent need to improve combustion techniques. The latest advances in materials combined with production technologies, including additive manufacturing, make it possible to produce compact combustors with advanced thermal management, operating at high levels of power density in a safe, reliable and flexible manner. The work presented in this article is part of this effort.

The RSC concept is introduced, together with the low-TRL research project MOeBIUS (Momentum-Enhanced Blend of the Reactants With Recirculated Burnt Gases). Two RSC combustor approaches are proposed, and the plausibility is investigated by means of CFD. The paper ends with the future perspectives on the project, hoping that the Energy Innovation conferences will attract the interest of future partners. Together we could locally bring this technology to maturity, deploy it in large numbers, and generate economic success beneficial for all.



Combustor flow direction=Flame direction, in direction of the axis of symmetry of the annular chamber. The feed- and outflows are in line with the flames.

Combustor flow direction=toroidal direction. The flames follow each other and close the circle. The feeds and outflows are lateral to the flames.

Figure 2: Comparison of the arrangement and flow pattern between a conventional annular combustor and a Recursive Sequential Combustor.

1 The Recursive Sequential Combustion (RSC)

1.1 Maximising the interaction between burnt gases and fresh reactants

A typical industrial burner is designed to operate for several tens of thousands of hours under harsh operating conditions. Most of the time these burners rely on diffusion flames, which means that the reaction takes place where oxidant (the air) and the fuel meet. One typical feature is a long jet flame, extremely bright. The brightness connects directly to the formation of soot, while thermal NOx is generated in the hottest parts of the flame. Since 30 years most models include, where possible, a fuel-air premixer to generate a premixed flame, usually operated in the lean domain (excess of air) that generates much less soot and NOx than the previous. The limitations of lean premixed combustion are the extinction limit, also called lean-blow out (LBO) and the combustion stability, since the flame is prone to generate thermoacoustic instabilities at that regime. The technical challenge is to achieve complete combustion in a well-controlled and well-repeatable manner while keeping NOx and soot levels low. Of course the burner must be affordable, flexible in use and easy to maintain.

Several technologies have been proposed to lower the LBO limit and / or to generate less NOx at a given operation while ensuring complete and stable combustion. These are based on an interaction between the burnt gases and the fresh reactants. The benefits are that the reactants are preheated, so that the activation energy needed to achieve combustion is reduced, leading to a more robust combustion in the lean domain. In the meantime, since the exhaust gases have been cooled down in this process, the cooling effort on the hot end can be reduced. Additionally, the thermochemistry of combustion is impacted in a positive manner by the effect of reburning. The elevated steam contents of the burnt gases absorb a part of the heat generated by the flame, leading to a lower NOx generation, while the NOx contents of the burnt gases can recombine back into nitrogen. Concepts that exploit purposely the flue gases are called flue gas recirculation [1]-[2], sequential combustion [4] and flameless combustion [3]. In the particular case of annular combustors in gas turbines, lately, novel burner arrangements developed by [5]-[7] maximise the flame-flame interaction by tilting the burners. The review on these concept principles is sketched in Figure 1.

1.2 Placing the burners behind each other’s, in a loop.

The novelty of recursive sequential combustion is that the combustion chamber is arranged in a closed loop, where all burners are literally located one behind the other (Figure 2). They are supplied from the sides with premixed air and fuel. While the major part of the burnt gases exit from the sides, a portion of these gases is derived to meet and interact with the reactants in the next burner. At system level, this technology bring a unique thermal inertia, that is absent from conventional burners. Ultimately, the hot core generates a permanent hot gas circulation that sustains combustion, allowing robust, lean-burn operation showing a better flame stability near the lean blow out limit and a better combustion performance in terms of NOx and soot than on a conventional system operating at a similar equivalence ratio.

As in a rotary system equipped with a flywheel, this amount of trapped and circulating burnt gas ensures high thermal conservation. The heat promotes complete oxidation of the particles, and the reburn thermochemistry helps to reduce NOx [9][10].

The recursive sequential combustor is summarised in Figure 3. The flue gas recirculation has the following effect. The fresh gases are first heated-up by the recirculated gas quantity. This effect speaks for higher combustion stability under lean condition. Indeed, due to the pre-heat, the entry temperature of the reactants is higher therefore less activation energy is required to maintain combustion. After that, they mix together, so that the oxygen concentration is lowered and the steam concentration is higher. The combined effect of these tends to slow down the reaction, partly because the oxygen content becomes lower, and partly because the steam absorbs a lot of heat through the flame. The NOx reduction due to the reburn effect happens in the meantime. This concept is effected when about 20% of the burnt gases can be circulated and penetrate the next flame [1][4].

However, circulating a given quantity of burnt gases actually costs energy, mostly in terms of heat loss and turbulence. The design must therefore take as much as possible advantage of the flow dynamics in the combustor, and avoid sampling and redirecting the burnt gases. It must be compact. Last but not least, the design must be robust so that each burner withstands its gathering of hot gases.

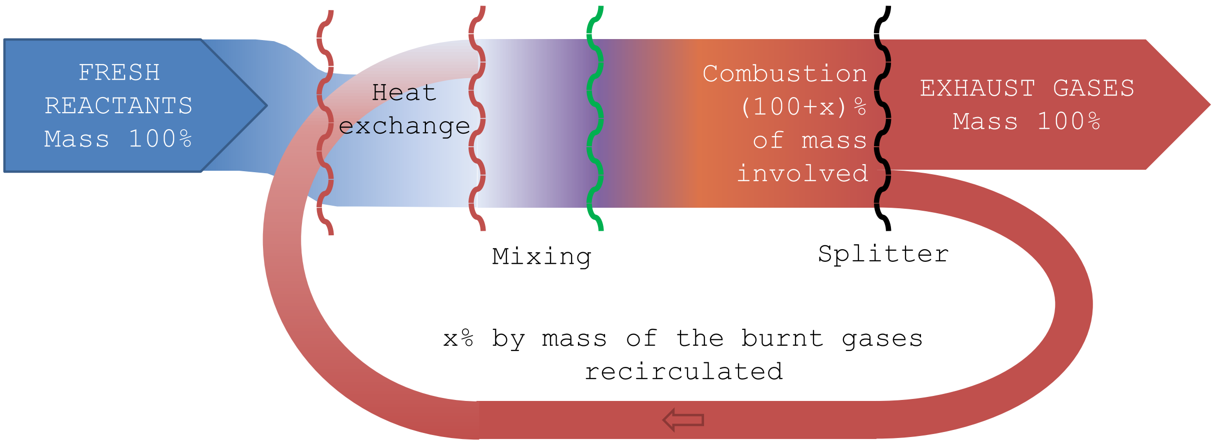


Figure 3: the recursive sequential combustor principle at system level

1.3 Possible RSC designs.

The effort necessary to circulate the burnt gases can be achieved with a novel flow design.

In a conventional gas turbine combustor all burners are placed near each other and the flame-flame interaction is minimal (Figure 4). The challenge is therefore to change the main direction of the burnt gases by comparison to the inlet and to the exhaust. One must therefore think a torus-like combustor where a flow of burnt gases circulates in closed loop, where the motor effect is the momentum brought by the fresh reactants introduced by the sides. The burnt gases should be given the possibility to split into a quantity that leaves by the side as well, and a quantity that contributes to the circulation of trapped burnt gas.

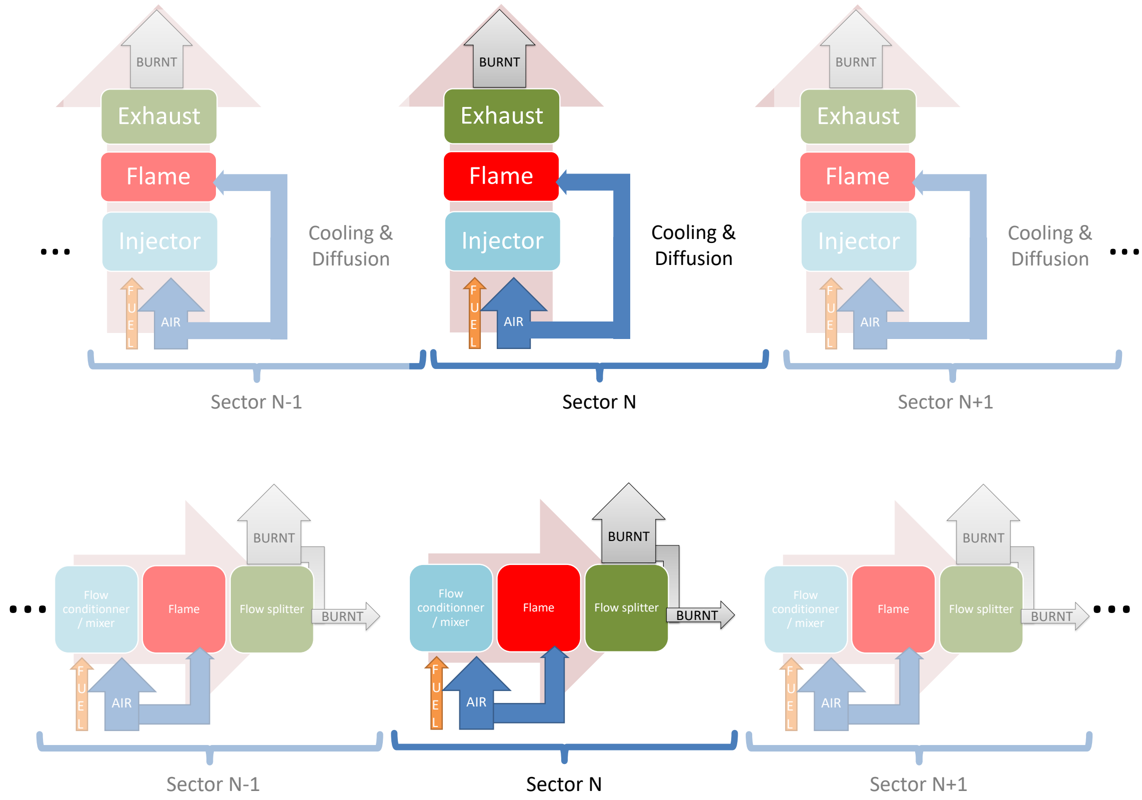


Figure 4: Flow process and directions at component level in a RSC combustor (bottom) by comparison to the conventional arrangement of neighbouring burners (top).

Figure 5 illustrates two possible RSC concepts called “discrete sector” and “constant section”. In discrete sector geometry, the flames are well-separated due to a clear distinction of all subsequent functions (intake of burnt gases, flow conditioning with fresh reactants, flame, hot gas relaxation, hot gas split and exhaust, derivation of a burnt gas quantity to the next intake and so on). All system level functions happen one after the next as shown in Figure 4, bottom.

This paper describes more into details the constant section concept, which is more likely to fit the frame of a propulsion gas turbine than previous. In a constant section RSC, each of the functions shown in Figure 4, bottom, take place simultaneously in any radial cross-section of the annular combustor.

The flow specifics are shown Figure 6. The left scheme shows the flow in a discrete sector configuration. This is a first draft, where each sector builds one side of a polygon-like RSC – in that case, a triangle. The hot gases circulate in the frame, and the three chimney evacuate the burnt gases after they passed the splitter. The right side is a constant-section RSC, inspired from a highly heat conservative burner concept called Swiss-Roll Combustor [11]. Here, the double-spiral shape is extruded in a circular manner as can be seen in Figure 5, bottom right. The spiral part serves as a heat exchanger between incoming reactants and outgoing burnt gases. The section in Figure 6 (with an exaggerated number of spires, to get the idea of pre-heat of the reactants) replaces the conventional combustor from the compressor outlet to the turbine inlet. The inner spires replace the conventional flametube.

The flame is placed away from the wall by combining high flow speeds at the walls with an adequate fuel placement. The interaction fresh/burnt gases happens shortly before the burnt gases leave, they are forced to cross a fast moving, thin air sheet of reactant coming along the wall. This interaction is combined to the induction of an out of plane flow, to improve the flame-flame interaction and generate the circulation. The motor effect of this circulation is a function of the ratio of momentum flux at the reactant entry (high) and at the burnt gases outlet (low).

The following focuses on the constant section burner geometry.

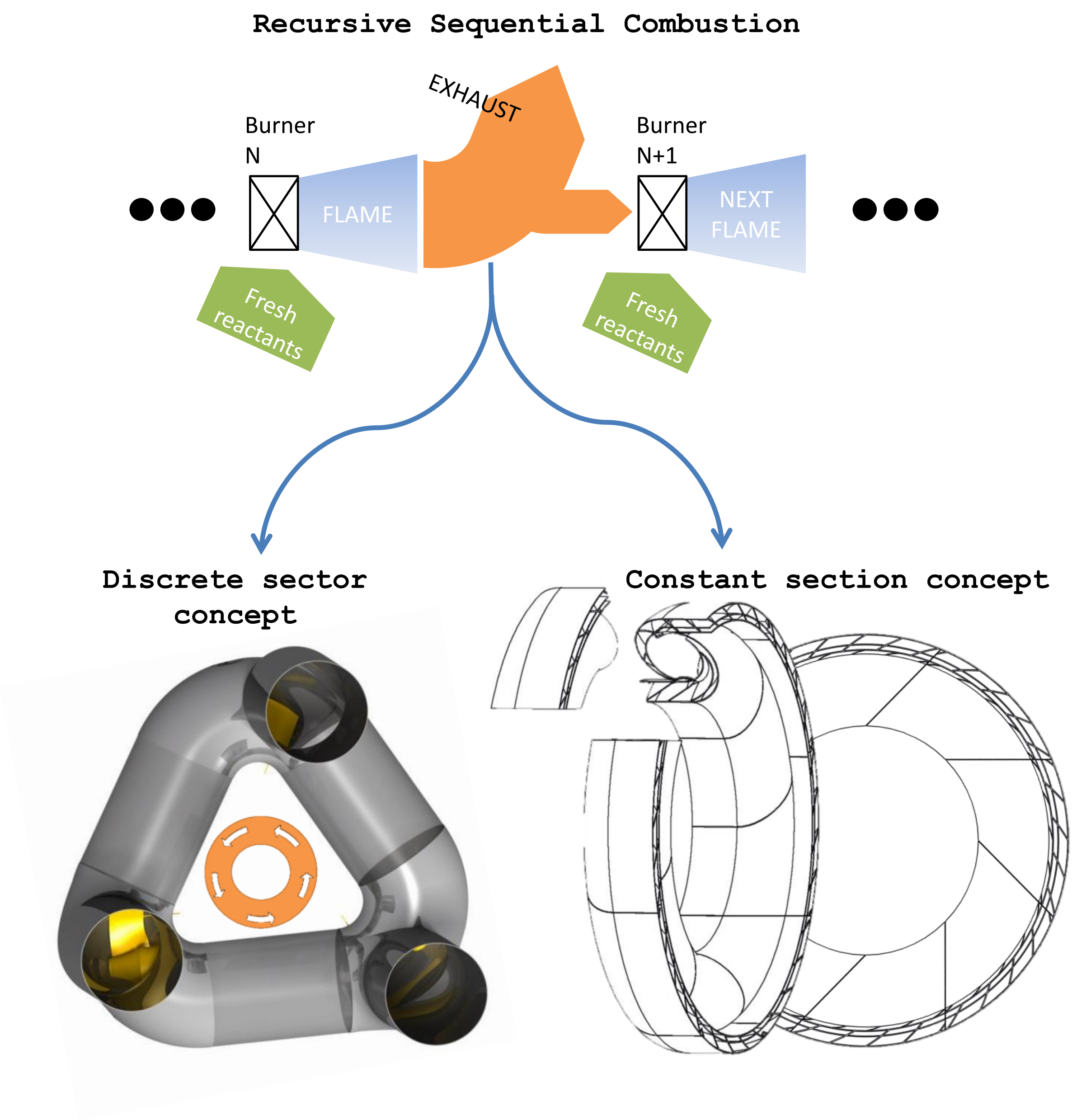


Figure 5: Possible RSC concepts

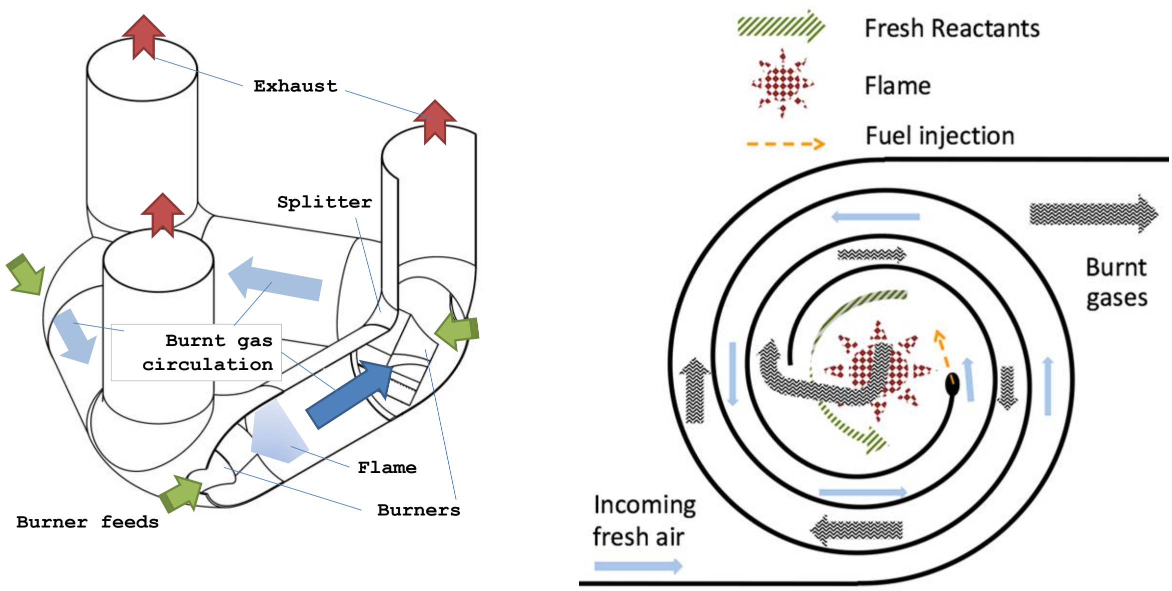


Figure 6: flow specifics in a discrete-sector RSC concept (left) and a constant section RSC (right)

2 Design of a constant-section RS combustor

An advanced design was created for a micro gas turbine in the 250 kW range. The inner volume of the chamber is constituted of a torus with generating line diameter 300mm and section diameter 60mm. Figure 7 reveals the construction details of this concept. The blades on the inlet and outlet generate the out of plane component necessary for the flow circulation along the torus. The air is injected in two regions, and the hot gases are gathered in one channel only. Here, the fuel injection is situated between the hot gas outlet and the air inlet.

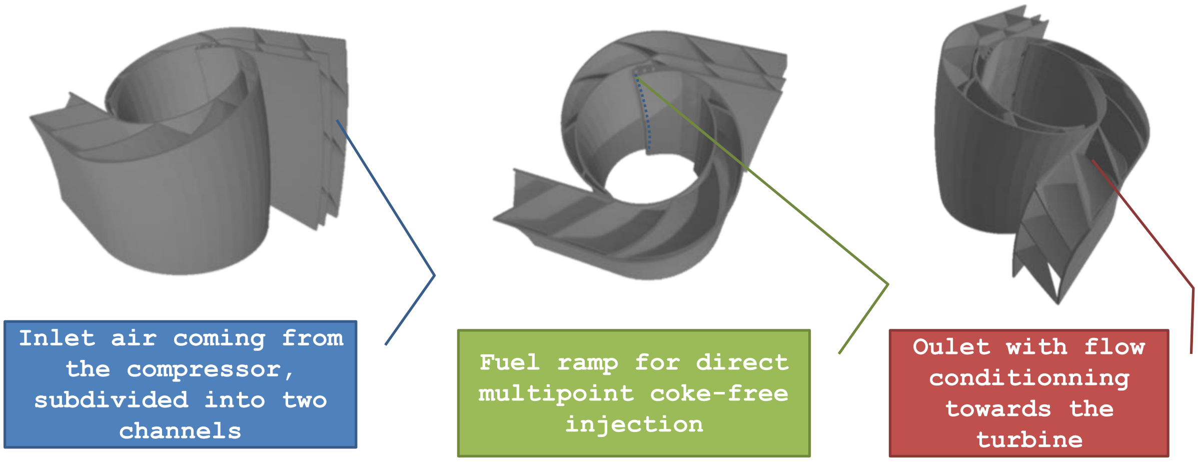


Figure 7 3D design of a RSC combustor

Once the parts of Figure 7are assembled together, and that the loop is closed, the MOeBIUS combustor appears, as shown in Figure 8. Although having a particular dynamic and being composed of many flamelets with a spiral form, this design produces a ring of fire trapped in the torus, which ensures a maximum flame-flame interaction and improves the thermal inertia of the hot core.

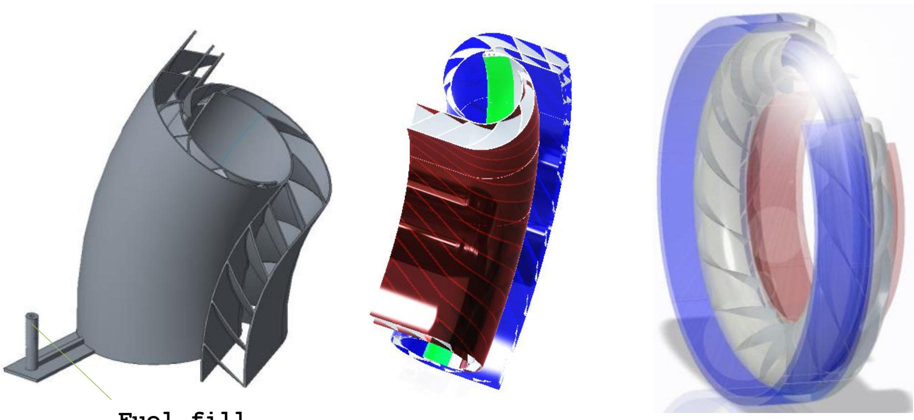


Figure 8 The MOeBIUS RS combustor

The question remains, how to build it? Three options are proposed in Figure 9. A conventional manufacturing is possible by using stamped and cut metal sheets and then welding them together. This is used e.g. for reverse-flow combustors for helicopter gas turbines. Given the complexity of the shapes, one might prefer to rely on additive manufacturing, produce the combustor piecewise end bring the parts together. This method was used with good success by Clemen et al. [12]. Some issues of inner seamless seals remain open though. One last proposal is to produce the nearest possible arc to a half-torus, and use binding elements that will assure the fuel distribution and ignition.

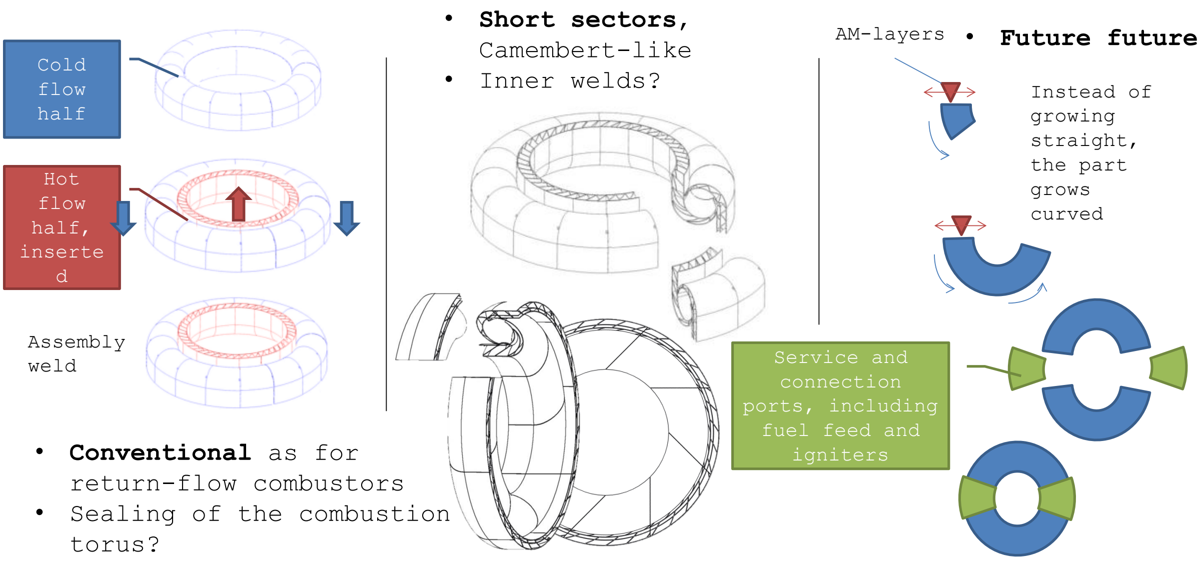


Figure 9 Production options, with focus on Additive Manufacturing

3 CFD simulation

A full 3D simulation of the reactive flow is done using openFoam [13]. The constant cross-section annular combustion chamber has been cut into 32 sectors, each representing 11.25° of angle, constituting a complete circular RSC combustion chamber when assembled. The upper and lower sides of the torus part constitute the periodic boundary conditions of this volume. The inlet and outlet canals are therefore fully defined.

The single element composing this volume (Figure 10) is made-up of 340,632 hexahedral cells. It consists of a round central combustion chamber with a small gas inlet splitting the wall. Air reaches the chamber from two inlets, an inner and the burnt gases leave through an outer one, via channels which enforce an out-of-plane velocity component.

In this simulation, the gas inlet is positioned shortly after the burnt gas outlet. There are two air inlets. Each part has inlet and outlet channels where the top wall is the guide blade to organise the tangential movement into the chamber, or condition the turbine inlet flow out. The slopes of the incoming and outgoing channels in relation to the generatrix of the torus are 12.5° angles. The toroidal flame tube is fed by air entering at high speed into two separate regions. The first channel provides combustion air and the second provides dilution air. The high velocity projection of the air along the wall is intended to protect the wall from the flame.

The reactingFoam solver (transient, compressible, k-epsilon turbulence model, detailed species) is used to simulate an air-methane mixture at a global equivalence ratio of 0,65. The expected exhaust temperature is therefore 1750K.

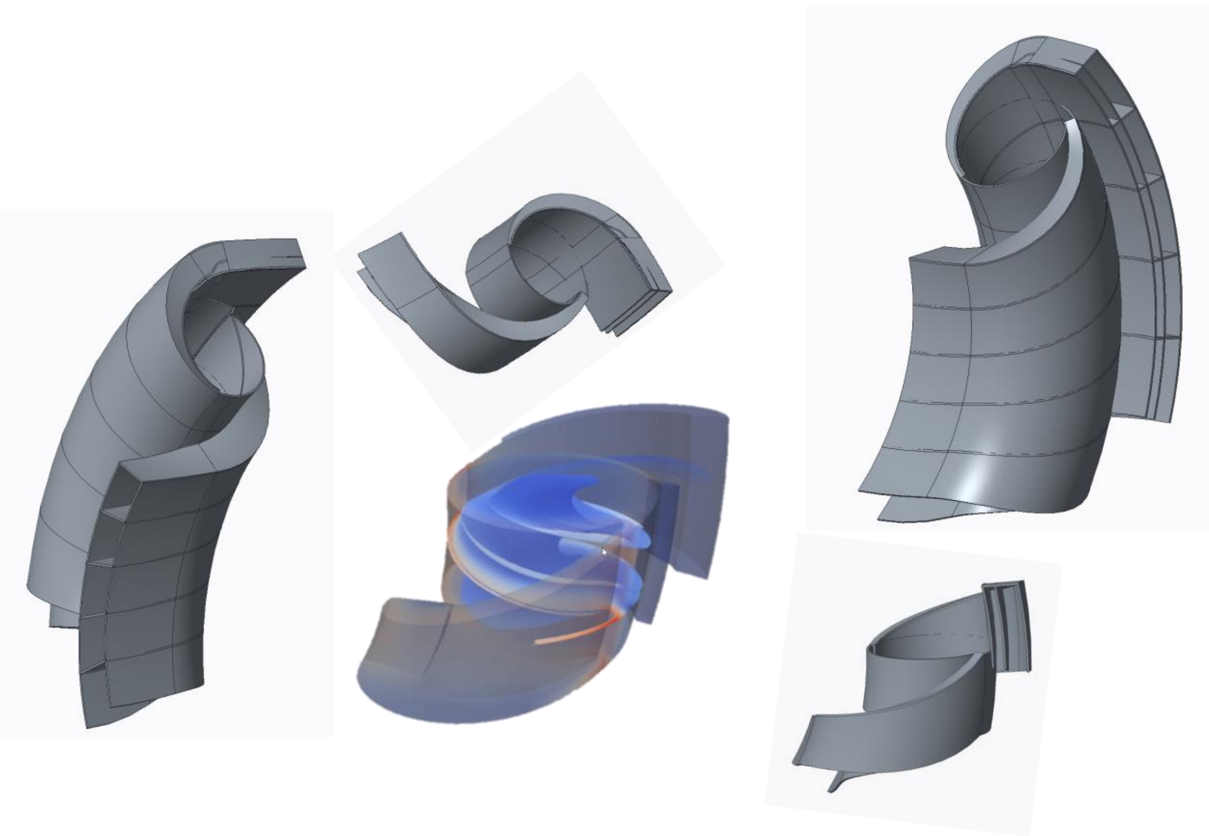


Figure 10 Recurrent model sector used for CFD calculation, including in full inlet and outlet canals, walls and guide vanes

By exporting the data and proceeding to a polar translation of the geometry and related variables, it is possible to reconstitute the flow in larger sections and compute the streamlines emitted from the inlet. The result is shown in Figure 11. While most of the introduced flow leaves up to the second sector, most of the circulated burnt gas will progress on one quarter of a round. The circulation of hot gases along the annulus is therefore effective.

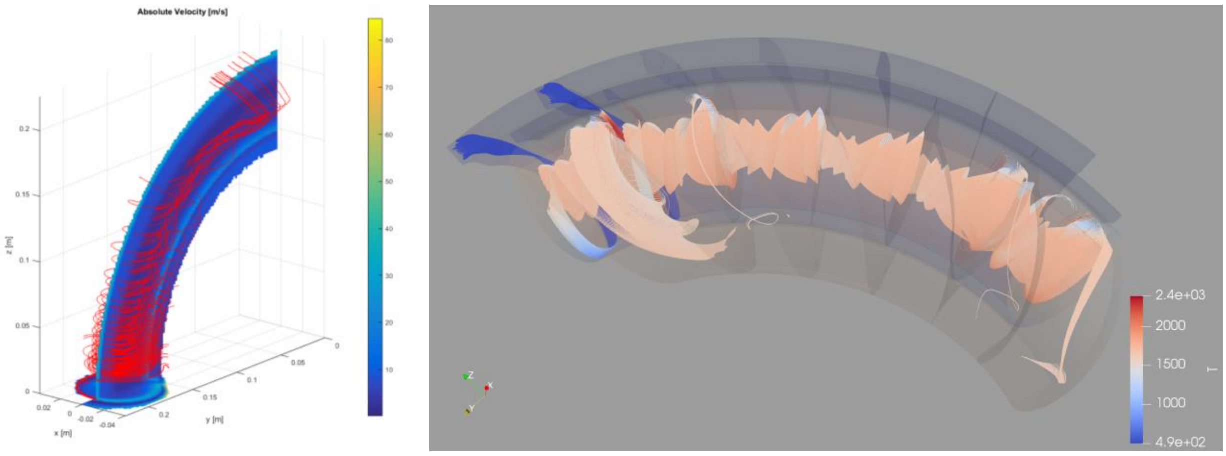


Figure 11 Calculation of streamlines on the RSC sector.

The computation is done for a situation corresponding to full load, where the maximum speeds are met at the limit of the compressibility limit Mach 0,3. The results are shown in Figure 12. The pressure loss has 5% and is therefore quite great, due to the narrow inlet passages to increase the inlet momentum flux, and the U-turn forcing the burnt gases to meet the fresh ones. Nevertheless, when considering the total pressure loss between compressor outlet and the turbine inlet in a real machine, this pressure drop is acceptable. It could be improved by fine-tuning the outlet canal, indeed a flow detachment is visible on the velocity map. The flame runs along the circumference at an acceptable distance to the wall, with exception of the direct vicinity of the fuel injection that requests extra cooling. The burnt gas temperature corresponds to the expected one (1750K with an assumption of adiabatic conditions). This early development therefore validates the plausibility check of this study.

4 Conclusions and perspectives

4.1 The recursive sequential combustion is very promising

The constant section RSC concept was validated by this study. The geometry has the ability to organise the flow to maximise the interaction between the reactants and the burnt gases as hoped. While the geometry of the paper is still subject to modification to better establish the chances of a successful demonstration, a milestone has been reached.

Although showing a complex flow design, the RSC actually simplifies the flame back to a “ring of fire”, well bounded in its torus. That should make the hot core more heat-conservative and therefore more robust versus small perturbation, or near the extinction limit.

The technical challenges are the choice of materials and the feasibility of the designs. High temperature alloys and additive manufacturing seem to offer the best chance of success. The technology is now moving towards experimental demonstration, which is the next step.

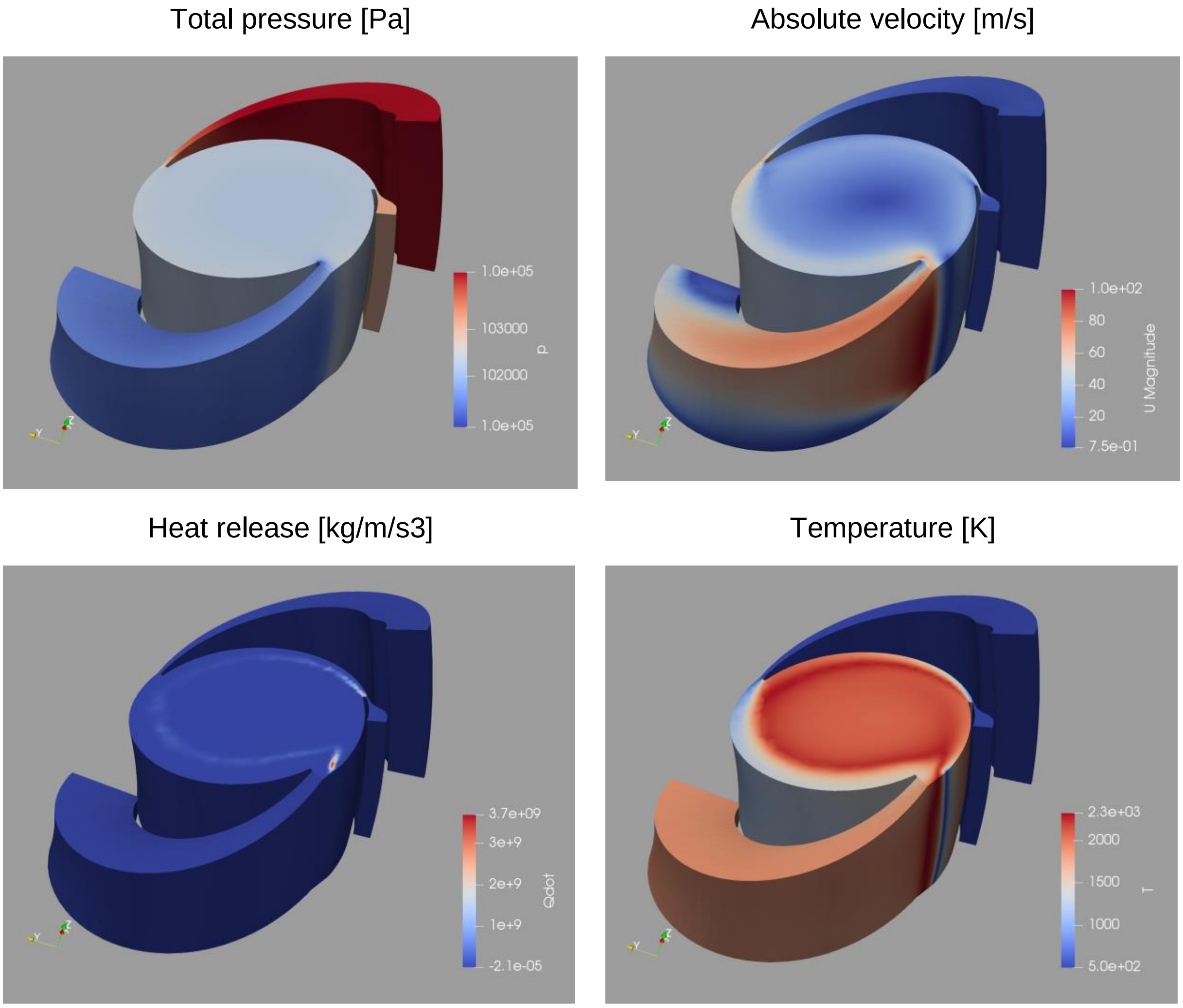


Figure 12: Pressure loss, velocity maps, heat release location (flame) and flow temperature.

4.2 Towards a safe and reliable combustion of hydrogen

A specific feature of RSC technology is the need for fine-tuning of the momentum flow of the combustion chamber inlets (high) and outlets (low), combined with an advanced flow design. Reactants are introduced at high velocity (up to Mach 0.3 - i.e. at the limit of incompressibility) to stabilise aerodynamically the flame along a vortex, at a safe distance from the walls.

This same characteristic is important for the use of hydrogen as a fuel, as it prevents the phenomenon of flashback. Due to the high reactivity of hydrogen, the premixed flame tends to return to the injection point inside the injector and settle there as a diffusion flame capable of irreparably damaging the combustor in a very short time. This flashback problem when using hydrogen or hydrogen-rich mixtures is the major concern of current combustor designers. We believe that the MOeBIUS paradigm can remedy this, and therefore represents a promising option for the safe, reliable and low-NOx combustion of hydrogen.

The motivations and principles of RSC will be explained, and two possible designs called the discrete sector and constant section concepts will be presented. At present, effective designs produce the desired circulation in both concepts. The audience will benefit from the latest progress made in the MOeBIUS project.

5 ACKNOWLEDGMENT

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