Recursive sequential combustion using a discrete sector approach

F. Giuliani - A. Hofer - N. Paulitsch
Combustion Bay One e.U., advanced combustion management, Schuetzenhofgasse 22-7, Graz, Austria
Email: Fabrice.Giuliani@CBOne.at

ABSTRACT
Recursive sequential combustion (RSC) is a novel concept developed by CBOne that maximises the interaction of circulated burnt gases with the reactants in the combustor of a gas turbine to improve combustion performance. Compared to existing Exhaust Gas Recirculation (EGR) or flameless methods, it takes advantage of the dynamics of injection to activate and maintain the process. The idea is basically to place all the burners right behind each other in the closed-loop corresponding to the annular combustor. The reactants enter and the burnt gases exit at the side walls. From an engineering perspective, the challenge is to properly design the flow so that this principle can operate efficiently over the entire operating range without failure.

This article introduces a RSC combustor design called discrete sector concept. The RSC principle is summarised and discusses the benefits of this technology versus conventional. The flow dynamics are entertained by the elevated momentum flux at the inlets. The effect of the heat conservatism of the hot core on the lean combustion robustness is rated regarding the lean blowout limits. The elevated core heat inertia is due to the permanent circulation of constantly renewed hot burnt gases. The heat-up of the reactants turns the lean combustion more robust. Another benefit is the recursive reburning effect that improves the NOx performance.

An advanced discrete sector concept design, its related CFD study and basic experiments done using this approach are discussed. The concept is shown to be plausible, sound, and promising, and the steps for further development of this technology can be found at the end of this paper.

KEYWORDS
Recursive sequential combustion, low-emission combustion technology, burnt-gas recirculation

NOMENCLATURE
AM Additive manufacturing
CFD Computational fluid dynamics, using openFoam
$D_{ref}$ 20mm, reference diameter of the front plate
GHG Greenhouse gases, direct or indirect, with focus on CO2, water vapor, NOx, and particle matter
NOx Nitrogen oxides, mostly NO and mostly of thermal origin
SIMPLE Semi-Implicit Method for Pressure Linked Equations (CFD solver)
RSC Recursive sequential combustion
TRL Technology readiness level, currently 2 (Elaborated technological concept)
INTRODUCTION

The RSC is a new combustion concept that maximises the interaction between the burnt gases and the reactants, within a feasible framework for aviation. The incentive is the reduction of GHG in the aviation and energy sectors, as well as investigating new combustion concepts for future fuels. The idea is to perform a robust lean combustion process with excellent NOx and soot performance. This technology is developed in the frame of the project MOeBIUS (Momentum-Enhanced Blend of the Reactants With Recirculated Burnt Gases) introduced in Giuliani et al. (2021). The main features of this technology refer to flue gas recirculation concepts, sequential combustion, flameless concepts as well as annular combustion devices in which a tangential flow component is purposely generated (see Wilkes and Gerhold (1980); Pennell et al. (2017); Kruse et al. (2015); Savary and Taliercio (2016)).

The RSC implies that all the flames are arranged behind each other in a closed loop, while the inlets and outlets are situated by the sides. One of the objectives of this study is to find a way to recirculate at least 20% of burnt gases at the least possible effort. According to the previous literature, a recirculated quantity of 20% of the burnt gases could lead to a reduction by 50% of the NOx under some conditions due to the benefits of reburning (Yeh and Liang (2013)). This paper discusses a RSC concept where the burners are distinct from each other, called the discrete sector concept. This is an alternative to the constant section concept presented in Hofer et al. (2022). The geometry is produced in view of a demonstrator, where the closed loop performance will be compared to a single burner, and both function testing and operating range will be addressed. A geometry for this discrete sector is proposed and studied numerically.

Since the main subject treated here is flow design, the focus is put on the steps followed during the progress of the study. Eventually, it is shown that a burnt gas circulation, essential to the principle of RSC, is particularly effective when driven by a promising injection system whose key element is a double spiral vortex generator.

RECURSIVE SEQUENTIAL COMBUSTION

RSC Specifics

The recursive sequential combustion combines the features of exhaust gas recirculation and of sequential combustion as explained in details in Giuliani et al. (2021) and in Giuliani (2020).

Fig.1 shows a display of the technology by comparison to conventional. The idea is to literally place the burners one behind the other, their axis corresponding to the generatrix of the torus of the annular combustion chamber. Its main feature is a large circulation of the burnt gases in the tangential direction, along the annulus of the combustor. At the system analysis level, the same figure shows two diagrams where the main functions of the conventional and RSC burners are displayed for comparison. The main difference is the shape of the injection/mixer/burner stage, which shows two completely different projection directions of the fresh gases (in the direction of the machine axis in the conventional case, and perpendicular to the latter direction in the case of the RSC).

An analogy can be drawn between the principle of the RSC and a flywheel mounted on a rotating machine. While the flywheel maintains the kinetic energy of a rotor, the closed loop flue gas recirculation ring maintains the thermal core of the combustion chamber. The RSC is therefore very heat conservative and should be less sensitive or more robust to sudden flame changes than conventional systems.

This concept implies high injection velocities, or more precisely, higher momentum flux at the inlets than at the outlets that entertain the recursive sequential combustion. Attention is paid
Figure 1: Comparison between the burner arrangement in a state-of-the-art gas turbine annular combustor (left), and the one proposed using the recursive sequential combustion (right). Top: overview. Bottom: comparison at system level.

to the fine tuning of the flow design, to make high speed flows and fresh/burnt mixing effective, while the pressure losses remain bounded within state-of-the-art ranges not exceeding 5%. An underlying idea is to use additive manufacturing to design the well-profiled and optimised ducting, based on a CFD approach. The high-speed injection feature appears to be a promising candidate for fuels with elevated flame velocities, such as hydrogen (Han et al. (2020)).

The second difference is the flow splitter at the outlet, that returns a part of the burnt gases in the next burner. In the case of the constant section concept, all functions shown in Fig.1 happen simultaneously in any section normal to the combustor torus. What results is a closed ring of fire, in detail, it is a series of twisted flames, intertwined in the form of coils or placed one behind the other to sustain the recursive reburning phenomenon. In the case of the discrete sector concept developed in the present paper, the burners and the flames are clearly distinct, and the functions previously exposed in the diagram correspond to objects having the specific role.

Possible RSC designs

Fig.2 illustrates two possible RSC concepts. In a 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) while in a constant sector concept, all of these functions take place simultaneously in any radial cross-section of the annular combustor. While the constant section concept is more promising for aeronautical applications due to its high-level of function integration, the topic of this paper is related to the development of a discrete sector geometry, chosen for low TRL demonstration. A CFD approach of the constant-section concept is presented in Hofer et al. (2022).

**Early RSC demonstration, and technical challenges**

A basic experiment was conducted at CBOne to establish the RSC using a burner-flow separator assembly and a closed loop, as shown in Fig. 3. The mixture is air-butane injected as two jets, diametrically opposed in a convergent, projecting the flow in order to generate a spin combined to a circulation along the burner centerline. The flow separator is simply an expansion situated at the end of a liner made up of JGS2 silica quartz glass, forcing the major part of the burnt gases flow to reverse in direction. The rest enters the loop, keeping up its momentum and returning to the location where the injection is made.

One specific of the RSC burner is that it must be conceived to circulate a larger volume flow in the combustion primary zones than conventional. The reason for that is related to the heat-up of the reactants at injection. By returning about 20% of the burnt gases, the volume flow of the diluted reactant augments with a factor slightly greater than 2 when the heat exchange is excellent. This means that in absence of inlet adaption (hence reduction) the flow speed can double in the narrowest sections. This can lead to a flame destabilisation observed after ignition and closure of the RSC process, as shown in the same figure.
Using the shown hardware and without post-ignition flow adaption, the cycle is maintained about half a minute - long enough to conclude that RSC is viable and promising.

Figure 3: Early RSC feasibility demonstration. Top: flame destabilisation mechanism as soon as the recursion settles, and highlight of the need in combustor design able to sustain larger volume flow variations than conventional. Bottom: early demonstration. The flame pictures are a close-up of the glass as shown on the test set-up. The main flow moves from left to right.
GEOMETRY OF THE DISCRETE SECTOR CONCEPT

Early concept

Based on the previous observations, one needs an injection that drives the circulation motion, that allows a high degree of interaction between the burnt gases and the freshly injected one, and that allows an aerodynamic flame stabilisation in a large range of volume flow variation. Attention is paid to the advanced flow design in terms of aerodynamics, to combine high speed reactant injection with moderate pressure loss. An expanding cone is an ideal shape to contain strong variation in injection velocities. A novel vortex generator approach is therefore proposed. The design discussed in the following is a variation of previous works at CBOOne (see Moosbrugger et al. (2019); Giuliani (2019)). The vortex generator consists of two blades resembling a ploughshare that bring in the fresh mixture. The spiral shape of the latter brings a

Figure 4: Double-blade vortex generator principle with open lower side, using a double-spiral inlet to condition the flame dynamics (left), and drive the burnt gases aspiration in a recursive manner (right). Bottom: schema with the denomination of the elements of a recursive sequential sector.
spin to the flow while a widening allows the flow to be projected in the direction perpendicular to the feed. The expansion generates a depression in the middle, that in its turn generates an aspiration on the lower side, aspiring the burnt gases. This vortex generator extends a premixing length, followed immediately by a sudden expansion at the desired location of the vortex stabilized flame. Attention is paid that the pressure loss cascade from the inlet boundary condition to the combustion liner does not exceed 5%. The vortex generator model shares similarities with burners used in the stationary gas turbine sector (e.g. Jansohn et al. (1997); Subash et al. (2021)) with the difference that the hole on the lower side is used to aspirate the circulated exhaust gas and ease the flow split, while on the known burners a fuel and/or water lance is placed at this location.

The combination of several profiled foils (here two, as shown in Fig.4) is desired to tend as much as possible towards an axisymmetric flow. One proposal is to perform the premixing directly in the spires of this double spiral arrangement. The hypothesis is that a high speed of injection prevents the flame from touching the walls, which was observed eventually. However, the flame stabilises for the time being in the inner cone of the vortex generator, which is not suitable for long running times due to the high thermal stress caused by the radiation. Solutions to detach and keep away the flame from the wall by means of a premixing tube combine form factors and wall cooling are in progress. The advanced design is shown in Fig.5.

FLOW SIMULATION

Presentation of the model

The mesh shown in Fig.6 is based on a cast of the flow paths in the discrete sector discussed previously. Designed using CAD, it is imported as an STL file and converted into an unstructured mesh of 607000 points producing 584000 cells (hexahedra), using the snappyHexMesh utility.

The surfaces and sections of the model are organised in 19 patches defining the walls, the two inlets, the outlet and the periodic boundary condition. The flow inlets are the outer sides of the double-spiral vortex generator. The outlet is the outer ring situated between the flametube of inner diameter 40 mm and the exhaust tube of inner diameter 60 mm. The lower and upper sides along the main axis are the intake of the circulated gas, therefore upstream from the splitter.
Figure 6: Operating conditions (left) and mesh (right) of the discrete RSC sector where the boundary conditions are highlighted.

and downstream from the vortex generator. The same section is used as a periodic boundary condition, to make the flow recursive as intended.

At current model stage, transition parts such as the U-curved connectors from the non-reactive mock-up shown in Fig. 7 are not modeled, as well as the cooling air is not implemented yet.

**Results, non reactive case**

A numerical model of the sector is studied to address the flow. The aerodynamics are studied under non-reactive conditions at room conditions. The solver is simpleFoam, a steady-state solver for incompressible turbulent flow. The pressure-velocity coupling is realised with the SIMPLE algorithm. The solver is used together with the openFoam suite (see Moukalled et al. (2016)).

The calculation is performed in parallel on a six core processor. The inlet conditions are applied for different operating conditions as written in Fig. 6, while the atmospheric pressure is set as an outlet condition.

The double spiral vortex generator was tested in three flow configurations covering the desired operating range. Most of the plots displayed in this article correspond to the design point. One immediate result is the effective circulation for all three configurations. Not only the circulating stream is active in one direction perpendicular to the air feeds, but the ratio of circulated air divided by the inlet is nearly constant for the three points. Even though computing the swirl number is uncommon for this type of geometry (it usually applies to burners with radial or axial swirl designs, see Beér and Chigier (1972)), its value computed at a distance $D_{ref}/2$ from the front plate remains relatively alike.

Fig. 7 represents the streamlines, to illustrate the effectiveness of the flow design. The colour
Figure 7: Flow pattern in one sector using streamlines, and flow visualisation for plausibility check on the non-reactive mock-up highlighting the effectiveness of the RSC’s circulation.

of the streamlines represents the flow speed magnitude at a given location. On the lower side, burnt gases are aspired, these are the same that leave the splitter at the opposite side, to the top. The vortex generator does its job, and the spinning flow is contained over a short distance in the premixer. After that there is a sudden expansion, where the flame location is expected. The second upper half contains the splitter with the deviation of the major part of the flow towards the outer ring. The U-turn towards the exhaust is well visible. The analogy between the desired features is established: a trapped flow circulating in the loop while it rotates on itself could clearly be simulated, and confirms the observations made with flow visualisation despite the simplifications made.

This observation was confirmed by an experiment using incense smoke as seeding particles, where laser sheets through the flow highlight the effectiveness of the closed-loop circulation. The set-up is composed of two discrete sectors connected with U-bends to each other. For this experiment, the outer glass tube directing the exhaust was removed to avoid multiple reflection, although the same observations were made in their presence. Two laser beams creating two thin sheets allow to observe that the flow pattern behaves as planned through the flametubes, and in a well reproducible manner. The shots represented in Fig.7 highlight the flowing circulation (longitudinal sheet) and the effective rolling vortex in the flametube (slanted sheet). The three flow conditions were studied, and the design point is shown. Once the form factors of the vortex generator and premixing tube will be frozen (not the case yet), the same facility will be used for velocimetry measurements, real turbulence assessment and model validation.
Figure 8: Midplane concentrations of methane (left) and steam (right). The flame front corresponds to the transition between the two regions.

**Reactive test case, work in progress**

Reactive CFD is done under openFoam with the solver reactingFoam (Unsteady Reynolds-averaged Navier-Stokes models, reactive, compressible) with an air-CH4 mixture. The chemistry model is GRI-Mech 3.0 (Smith et al. (1999)). The turbulence model is the standard k-epsilon model, the turbulent combustion model is the eddy dissipation concept (EDC).

The fuel placement (CH4 concentration) and generation of hot gases (Fig.8) show that this configuration is promising for generating a swirl stabilised flame positioned after the sudden expansion. However, a few details must be corrected. The blockage observed at the flow separator is too great so that this part will be reprofiled to avoid flow detachment and strong discharge zone. The current study is about the ignition sequence that settles the flame first, followed by an adaption of the inlet flow while the short-cut of burnt gases is established. This is where most of the times, the flame is being pushed apart from the sudden expansion, which leads to extinction. Once the trade-off on the new dimensions is found acceptable and that the operating conditions are settled, one will move towards the prototyping of the RSC combustor.

**CONCLUSIONS**

The concept of RSC using discrete sectors has been validated by this study: although perfectible, the circulation is effective, and the double spiral introduction of the reactants is promising. Therefore the method is recommended for further development. The next steps will be the reactive flow simulation to set a steady-state recursive combustion at the desired location. The trends driving the definition of a form factor showing a sweet point will be supported by basic experiments for validation. These tests will also provide performance indications, by comparison to a single burner submitted to similar reacting conditions. Considerations such as manufacturing feasibility, flame monitoring or instrumentation have accompanied the project from the beginning. The demonstration of a better combustion performance of RSC compared to state-of-the-art gas turbine combustion is essential for the further development of this technology.

**ACKNOWLEDGEMENTS**

This applied research is supported financially since 2018 by the FFG (Austrian Research Promotion Agency) and by the BMK (Austrian Federal Ministry for Climate Action, Environment, Energy, Mobility, Innovation and Technology, 2018-2019 aka BMVIT). The industrial property aspects are supported by the FFG/PATENT.SCHECK programme: projects rePeaT
IP (contract 870672) and RingOfFire (contract 876669). The low-TRL exploratory research MOeBIUS (contract 881041) is supported by the programme on applied research in aeronautics called FFG/TAKE-OFF.

The authors gratefully acknowledge the computing time on the supercomputer JURECA (Jülich Supercomputing Centre (2018)) at Forschungszentrum Jülich.

REFERENCES
References


