Proceedings of ASME Turbo Expo 2021
Turbomachinery Technical Conference and Exposition
GT2021
June 7-11, 2021, Virtual, Online

GT2021-59286

NUMERICAL INVESTIGATION OF THE LOW-SWIRL FLOW IN AN AERONAUTICAL COMBUSTOR WITH ANGULAR AIR SUPPLY

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ABSTRACT

Civil air traffic is predicted to further grow in the near future. Hence, the development of aeronautical combustors will face major challenges to meet future stringent environmental regulations. In the present study, an innovative gas turbine combustor with angular air supply called Short Helical Combustor (SHC) is investigated. The main feature of this concept is the helical arrangement of the fuel injectors around the turbine shaft. Aiming at the implementation of a lean-burn concept, a low-swirl lifted flame is adopted. This flame is lifted off and not anchored to the injector which opens the potential of low NO_x emissions due to a high degree of premixing within the combustor.

In this work, isothermal flow characteristics of such a generic SHC combustor are studied by use of RANS predictions with special emphasis on the interaction of adjacent low-swirl flows. For evaluating the influence of injector parameters on the flow field, a parametric study based on single sector simulations is performed. It is shown that the asymmetrically confined swirling jet flow is strongly deflected towards the sidewall of the staggered SHC dome. The deflection of the flow is associated with an asymmetric pressure field in the vicinity of the burner which is generally known as Coandă effect. As a consequence of the deflected flow, the angular momentum flux at combustor outlet is increased.

The interaction of the low-swirl jet and the SHC sidewall is investigated with regards to backflow momentum and residence time in the recirculation zone. It is concluded that by modifying the momentum of the air flow through the injector, the amount of recirculating air flowing back along combustor walls is strongly affected. The present work establishes an understanding of the underlying aerodynamics of the SHC concept which is essential for matching the requirements of lean lifted flames.

NOMENCLATURE

Symbols

α	Outflow angle
β	Burner tilting angle
d	Nozzle diameter
$\dot{D}$	Axial flux of angular momentum
Da	Damköhler number
H	Flame tube height
$\dot{I}$	Axial momentum flux
$\ell_{\mathcal{K}}$	Kolmogorov length scale
μ	Mass flux ratio
$\dot{m}$	Mass flux
M	Momentum of backflow
ρ	Density
p	Pressure
P	Nozzle position
R_0	Nozzle radius
R_{C}	Confinement ratio

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Re	Reynolds number
S	Swirl number
τ_{res}	Residence time
$t_{\mathcal{I}}$	Integral flow time scale
$t_{\mathcal{R}}$	Chemical reactions time scale
T	Temperature
u	Velocity
V_{rec}	Volume of recirculation zone
$\dot{V}_{rec}$	Volumetric flow rate of recirculation
x, y, z	Cartesian coordinates of the SHC sector
$\hat{x}, \hat{y}, \hat{z}$	Global Cartesian coordinates

Acronyms

CFD	Computational fluid dynamics
CTRZ	Central toroidal recirculation zone
LDI	Lean direct injection
LES	Large eddy simulation
LPP	Lean premixed prevaporized
NGV	Nozzle guide vanes
OGV	Outlet guide vanes
OPR	Overall pressure ratio
PVC	Precessing vortex core
RANS	Reynolds-averaged Navier-Stokes
SHC	Short Helical Combustor

INTRODUCTION

Along with efficient and stable performance over a wide range of operating conditions, low pollutant emissions are essential requirements for modern gas turbine combustors. In recent decades, advancements in materials and cooling technology have enabled aero engines to operate at very high overall pressure ratios (OPR) and turbine inlet temperatures. Consequently, the thermal efficiency of the engine is increased which in turn reduces the specific fuel consumption. This leads to environmental benefits in particular regarding to the emissions of CO and unburned hydrocarbons [1, 2]. However, high combustion temperatures cause an increase of the NO_x emission, since the formation mechanism of thermal nitrogen oxide does exponentially rise with the flame temperature [3]. In order to comply with the regulatory requirements for future civil aviation, low-emission combustor concepts for aircraft jet engines have to be developed ensuring environmental sustainability.

Lean-burn gas turbine combustors feature a great potential to significantly reduce NO_x emissions by operating the combustion zone under fuel-lean conditions using excess air. Furthermore, with effective fuel-air mixing, local temperature peaks yielding undesirable NO_x and smoke emissions can be eliminated [1, 4]. Lefebvre [5] states that the Lean-Premixed-Prevaporized (LPP) concept is capable of drastically reducing NO_x emissions due to low flame temperature and the elimination of 'hot spots'. The key feature of this concept is attainment of complete evaporation of the fuel and thorough mixing with air prior to combustion. However, the low-NO_x potential of LPP is offset by operational risks due to degraded combustion stability and its susceptibility to auto-ignition and flashback limiting the application in future high-OPR aero engines [6].

One remedy is the Lean-Direct-Injection (LDI) combustor, where the fuel is injected directly into the combustion zone and, hence, the risk of flame flashback is mitigated. Low NO_x levels are achieved because of lower reaction temperatures associated with lean combustion. The main design challenge arises from the use of liquid fuels, since fine atomization and rapid mixing before reaction is required in order to reach the same emission limits as with gaseous fuels [1, 6]. Therefore, the swirl configuration of fuel injectors affecting the flow field and combustion performance is critical in low-emission LDI systems as reported by Archer and Gupta [7].

In modern gas turbine combustors, the usage of high-swirl type of fuel nozzles is well-established. These swirl nozzles induce an airflow pattern which is characterized by a central toroidal recirculation zone (CTRZ) associated with high shear stresses and strong turbulence intensities. The CTRZ is caused by the vortex breakdown phenomenon. Recirculating hot combustion products are mixed with the incoming air and fuel, ensuring the sustaining and re-igniting of the flame in the primary zone [3, 8].

In recent years, low-swirl combustion based on premixed flames has been subject to extended research. In this context, the swirl intensity of the divergent flow downstream the nozzle is significantly low, with the result that vortex breakdown and flow reversal do not occur [9]. At the Engler-Bunte-Institute (EBI) of the Karlsruhe Institute of Technology (KIT), a low-swirl lifted flame has been investigated extensively in several experimental studies [10–13]. The test rig of the lifted flame burner is shown in Fig. 1 (left). In these investigations, the effect of gaseous and liquid fuels is studied at different operating conditions. Additionally, numerical predictions of the flame characteristics have been performed to support experimental findings [14–16]. In the studies of the lifted flame, a specific design of the fuel injection nozzle is applied [17]. The distinctive feature of this type of nozzle is that the flame burns in a lift-off regime and is noticeably detached from the injector establishing a premixing zone. This so-called lift-off zone is located between the nozzle outlet and the reaction zone, and promotes fuel evaporation and mixing of the reactants. Therefore, the flame can be regarded as partially premixed offering benefits of low NO_x emissions. At the same time, inherent risks of flashback and combustion noise related to premixed flames are strongly reduced. In a confined arrangement, outer recirculation zones are established due to entrainment of surrounding fluid by the low-swirl, but high-velocity flow. These vortices are established in the combustor edge cavities, and give improved flame stability by an upstream transport of reactive species back to the nozzle. Hence, the outer recir-

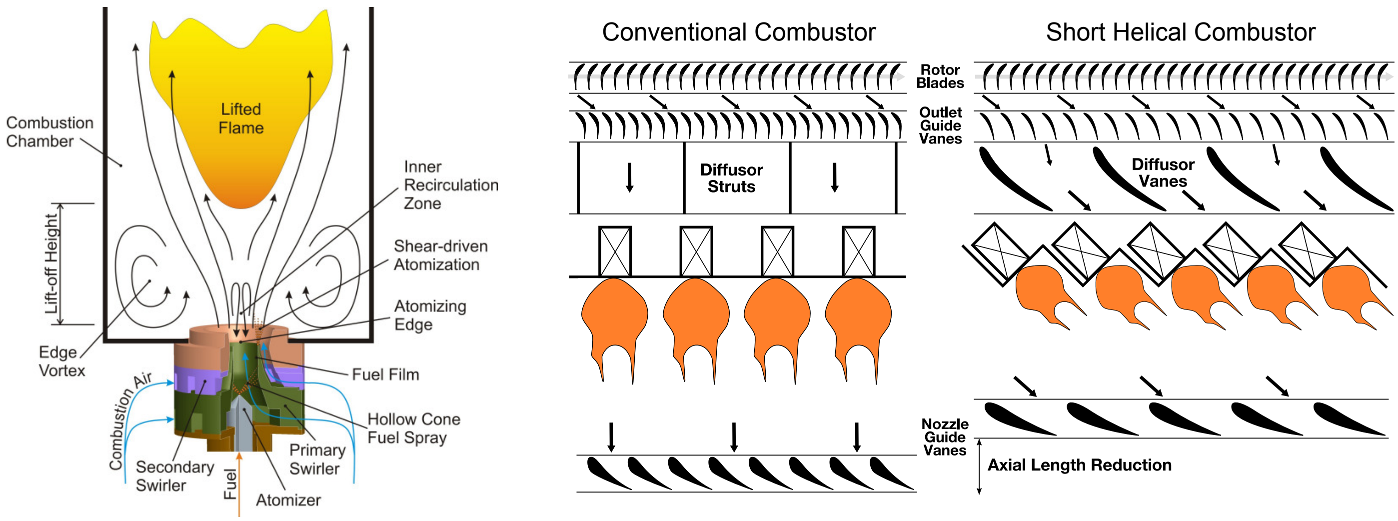

FIGURE 1. SCHEMATIC OF THE FUEL NOZZLE AND LIFTED FLAME FROM [12] (LEFT) AND COMPARISON OF THE SHC AND CONVENTIONAL COMBUSTOR REPRODUCED FROM [18] (RIGHT).

culation is the dominant stabilization mechanism. For fuel-lean mixtures, low-swirl lifted flames feature a significant reduction potential of NO_x emissions [12, 19]. However, to address the susceptibility to lean blowout which may be disastrous in aero engine combustors, piloting of the flames is required to ensure operational safety.

Instead of the conventional stabilization by a diffusion pilot burner, an innovative combustor concept for aero engines is proposed in this study. This novel combustor concept research is part of the European research program Clean Sky 2 Joint Undertaking. The unique concept is to integrate the low-swirl lifted flame in an annular combustor with angular air supply. The main feature of this combustor is the tilting of the burners in circumferential direction relative to the rotational axis of the engine. This particular arrangement may lead to an increased combustion stability, since flame piloting is achieved through interaction of adjacent burners. Therefore, safe and stable operation of the combustor can be ensured. The basic idea of tilting the fuel injectors in circumferential direction has led to several patents for different configurations in the past [18, 20, 21], among others. However, Ariatabar et al. [22–24] were the first to perform a fundamental analysis of aerothermal characteristics of high-swirl flames within the so-called Short Helical Combustor (SHC). A comparison of the SHC with a conventional combustor is shown in Fig. 1 (right). The flow coming from the compressor is supplied to the SHC with a tangential velocity component. For an annular combustor, the helical flow pattern enables the reduction of axial length. Consequently, weight can be saved and the mechanical integrity of the engine core may be increased. Furthermore, the number of outlet guide vanes (OGV) and nozzle guide vanes (NGV) is reduced, since a lower deflection is required in the vane stages by exploiting the angular momentum of the helical flow. This leads to a reduction of aerodynamic losses and cooling air demand. In the studies of Ariatabar et al., it is demonstrated that a double annular configuration with a tilting angle of 45°, in which radially adjacent swirls are counter-rotating and circumferentially are co-rotating, is most beneficial in terms of

1. maintaining relevant similarity and scaling rules,
2. homogeneity of recirculation zones and swirl flames and
3. uniformity of flow pattern at the combustor exit.

In this regard, the axial combustor length could be reduced by approximately 30 %. In similar studies, the tilting angle for a single annular configuration is varied [25]. It is found that the flow field exhibits four different vortex modes depending on the axial distance between adjacent swirlers. These vortex modes affect the recirculation and the temperature field of the isothermal and the reacting flow. When increasing the tilting angle, the exchange of mass and energy between the recirculation zones is reduced due to an aerodynamic boundary.

Since the SHC concept is rather new, little knowledge about dominant flow phenomena and their interactions is presently available through publications and up to now no study of low-swirl flame characteristics in SHC configurations is available. In this work, isothermal predictions of such a low-swirl flow in the helical burner arrangement of the SHC are performed for the first time. The preliminary results to be presented here serve as a starting point for the development of an aero engine combustor that is based on the combination of the SHC concept and the lean lifted flame. This pioneering lean-burn combustor enables the adoption of the LPP concept and enforces safe operation. Thus, it can be considered as a breakthrough with the capability of matching long-term targets of ACARE Flightpath 2050 regarding ultra-low NO_x emissions [26].

The objective of the present study is to gain insights into the SHC underlying aerodynamics in case of low-swirl flow to be capable of meeting the particular flame requirements. In the first section of the paper, the numerical model of the generic combustor sector is introduced. In this context, computational fluid dynamics (CFD) results of the reference configuration describing the baseline design are presented. Special emphasis is put on the aerodynamics, especially on the interaction of the low-swirl jet and the sidewall of the staggered SHC combustor dome. Subsequently, the parameter matrix of characteristic injector properties which are varied by means of a parametric study is reported. The comparison and assessment of different injector setups is supported by the description of flow kinematics based on contour plots of the flow velocity as well as the mean flow angle at combustor exit, the linear momentum of backflow and the residence time inside the recirculation zone. Finally, conclusions of the impact of injector parameters on flow deflection and recirculation are given.

NUMERICAL MODEL

In this section, the numerical model of the generic SHC sector is presented. The focus is on the definition of the computational domain and the simulation setup including mesh and boundary conditions employed in this work.

Computational Domain

A simplified aero engine combustor is used for the investigations. The generic geometry of two adjacent SHC sectors representing the baseline design is shown in Fig. 2. For all flow predictions to be presented, the tilting angle β of the burner axes with respect to the machine axis is 45°. The specific tilting angle features the maximum deflection angle of the flow leaving the last compressor stage. Consequently, the resulting SHC embodiment is regarded as the optimal design, because the potential of the concept can be greatly exploited. In contrast, a higher tilting angle would require a complicated design of the OGV and prediffuser vanes which will induce the helical flow pattern. Furthermore, the size of the sidewall would increase leading to an increased cooling air requirement [22].

Investigations of the scaling of the combustor by Ariatabar et al. [22] based on a constant volume scaling of a reference burner revealed that a double annular design is favorable. This implies compact internal recirculation zones and circumferential uniformity of the high-swirl flames. However, in the present work, the single annular design is chosen, since the flame stabilization mechanism of the low-swirl type of flow is inherently different and needs to be investigated fundamentally in the nonsymmetrical flow confinement of the SHC.

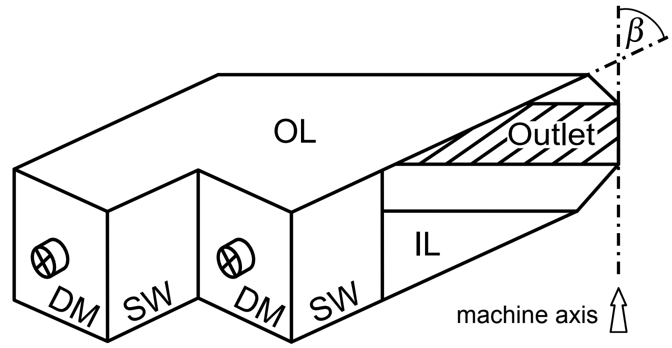

FIGURE 2. GEOMETRY OF ADJACENT GENERIC SHC SECTORS. DM: DOME, SW: SIDEWALL, OL: OUTER LINER, IL: INNER LINER.

The swirl nozzle representing the reference geometry of this study was used in experiments by Kasabov and Zarzalis [12] (see Fig. 1). It is characterized by an effective area of 319 mm^2. The swirl imposed by the nozzle can be quantified by the nondimensional swirl number $S = \dot{D}/(R_0 \dot{I})$, where $\dot{D}$ and $\dot{I}$ are the axial flux of angular momentum with respect to the burner axis and the axial momentum flux of the swirl flow, and R_0 is the nozzle radius, following the definition of Gupta et al. [27]. In this particular nozzle, only the inner primary flow is swirled and quantified by the nominal value of $S_\mathrm{i} = 0.76$, whereas the outer secondary flow is not swirling ($S_\mathrm{o} \approx 0$). This arrangement leads to the flame being lifted off and stabilized in the low-swirl flow field [10]. For the present numerical investigations, the nozzle is approximated by a cylindrically shaped inlet section. Hence, parameter variations of the nozzle characteristics can be performed.

To prevent undesired backflow effects at the outlet of the computational domain, a convergent duct is attached to the flame tube. Moreover, the overall combustor dimensions are defined to reflect the test rig of experimental studies performed in parallel within the same EU funded research project [28].

Based on the generic SHC geometry presented in this section, the numerical predictions comprise a single periodic sector. The setup of the flow simulation is explained subsequently.

Simulation Setup

The non-reacting simulations are performed using the CFD numerical toolbox OpenFOAM 7. The governing equations are solved by a pressure based solver based on a low Mach number approach. To account for possible transient behavior of the swirl flow interacting with the confinements, the unsteady Reynolds-averaged Navier-Stokes (RANS) method is used starting from the steady-state solution. The numerical time step of the transient

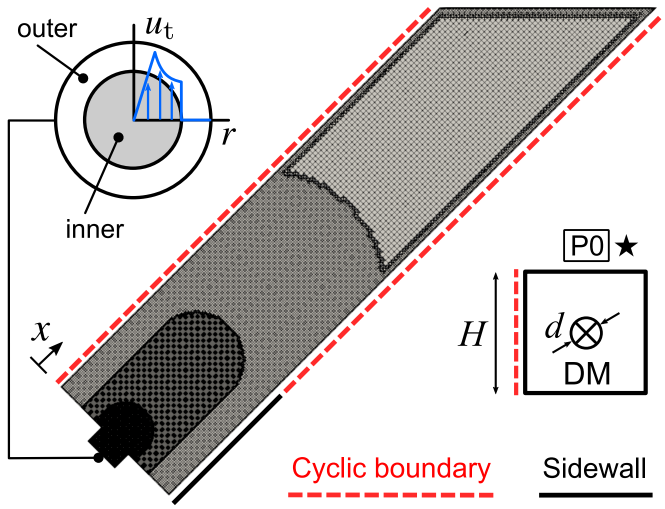

FIGURE 3. REFERENCE CONFIGURATION (★). COMPUTATIONAL GRID WITH BOUNDARIES (MIDDLE), ILLUSTRATION OF THE INLET PATCH WITH SWIRL PROFILE (LEFT) AND NOZZLE POSITION ON THE COMBUSTOR DOME (RIGHT).

predictions is 2.5×10^{-6} s with a total simulation time of 100 ms. Spatial derivatives are discretized by second order schemes. For the temporal discretization, a second order time implicit scheme is employed. In this RANS framework, turbulence is accounted for by the renormalization group (RNG) theory k-ε model [29].

In Fig. 3 (middle), the computational grid of the reference configuration is depicted exemplary. It consists of approximately 3 million elements, mostly hexahedral cells which reduce adverse numerical diffusion due to the low skewness of the cells. To this end, an efficient octree algorithm for the mesh generation is applied. High velocity gradients in the flow field located close downstream of the inlet section are resolved by adequate cell refinement zones. The overall mesh resolution is sufficient as indicated by a mesh independence study, not shown here.

In order to mimic the flow pattern and the shear layers of the real nozzle by using a simplified coaxial two-stage swirl nozzle, the circular inlet patch of the injector model is divided into a circular inner part and an outer annulus as shown in Fig. 3 (left). Thereby, different swirl intensities of the rotating flow can be imposed at the inlet by modifying the tangential velocity profiles of Rankine vortex type. The nature of the Rankine vortex can be regarded as representative for the tangential component of the flow emerging from the real swirl nozzle. This approach was confirmed by numerical predictions in a preliminary study. The tangential velocity profiles at the nozzle outlet were compared to profiles obtained from LES predictions of the flow through the swirl nozzle as reported in Refs. [15, 16].

The operating pressure of $p = 1$ bar is prescribed at the outlet and the temperature of inflowing air is $T_0 = 323$ K. The adopted relative pressure drop of the swirl nozzle is $\Delta p / p_0 = 3\,\%$ yielding a total air mass flux of $\dot{m}_{\mathrm{air}} = 25.3\,\mathrm{g/s}$ for the size of the nozzle effective area. A turbulence intensity of 12 % of the bulk velocity is imposed at the inlet. These operating conditions represent the non-reacting case as investigated by Sedlmaier [15] and Langone et al. [16] using the same, but downscaled type of nozzle.

By using translational cyclic boundary conditions as indicated by the dashed lines in Fig. 3 and the following Figures, the interaction of the low-swirl flows with adjacent combustor sectors is taken into account. At solid walls, adiabatic no-slip conditions are enforced. Furthermore, adaptive wall functions are employed accounting for both regimes in the turbulent boundary layer. The average y^+ values in the swirl injector model are approximately 10.

The simulation setup including boundary conditions presented in this section is used for all CFD simulations in the present work. In particular, the adopted relative pressure drop is kept constant ensuring Mach number similarity for all variations of the setup.

Reference Configuration

Finally, the reference configuration for the subsequent analysis of the low-swirl flow is presented. It features a nozzle position which is located at the center of the square SHC dome indicated with P0 as illustrated in Fig. 3 (right). The confinement ratio between the flame tube height H and nozzle diameter d is $R_{\mathrm{C}}^{\mathrm{REF}} = H/d = 4$. Regarding the angular momentum of the swirl flow, the outer flow is not swirling ($S_{\mathrm{o}}^{\mathrm{REF}} = 0$), whereas the swirl number of the inner flow is set to $S_{\mathrm{i}}^{\mathrm{REF}} = 0.6$ by adjusting the Rankine vortex profile (see Fig. 3, left). The latter value is lower compared to the theoretical value of the real swirl nozzle which reflects the dissipation due to friction losses in the nozzle air channels. The total air mass flux $\dot{m}_{\mathrm{air}}$ is split with a mass flux ratio of $\mu^{\mathrm{REF}} = \dot{m}_{\mathrm{i}} / \dot{m}_{\mathrm{o}} = 0.6$ which defines the values of axial velocity at the inlet patches. After the numerical model was introduced, in the following section of the paper, the results of the flow analysis of the reference configuration are presented focusing on the fundamental mechanism leading to the deflection of the low-swirl jet.

FLOW ANALYSIS OF BASELINE DESIGN

The structure of swirling flows in symmetric confinements including vortex breakdown and the precessing vortex core is addressed in a variety of researches. However, there are only a few studies available in literature explicitly elucidating asymmetric effects as pointed out by Ariatabar [30]. In this context, the substantial sensitivity of swirling flows to the geometric boundary conditions is emphasized.

In contrast to the previous studies of the low-swirl lifted flame enclosed in a single combustor tube, the present arrange-

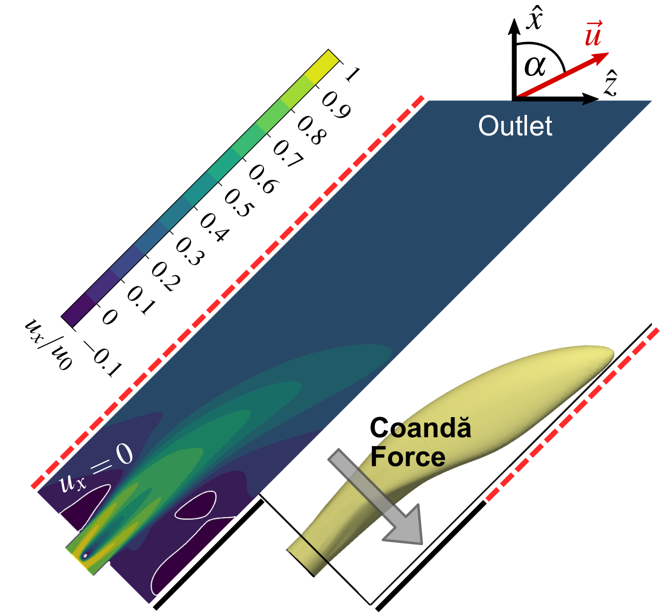

FIGURE 4. TIME-AVERAGED FIELD OF AXIAL VELOCITY IN CIRCUMFERENTIAL MID-PLANE (LEFT) AND ISO-SURFACE OF CONSTANT AXIAL VELOCITY (RIGHT). ARROW HIGHLIGHTS THE DIRECTION OF THE DEFLECTING FORCE.

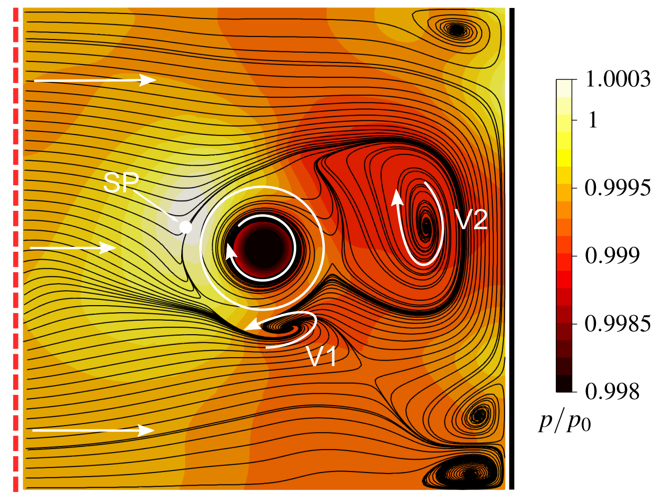

FIGURE 5. TIME-AVERAGED PRESSURE FIELD AND STREAMLINES IN A PLANE NORMAL TO THE NOZZLE AXIS LOCATED AT A DISTANCE OF 50 % LENGTH OF SIDEWALL. ARROWS INDICATE THE FLOW DIRECTION.

ment of tilted burners exhibits asymmetrically confined swirling flows. In this context, the focus will be on the aerodynamic characteristics of the low-swirl jet, because it might be strongly affected by the presence of non-symmetric sidewalls of the staggered SHC geometry.

Flow Field

In Fig. 4 (left), the structure of the flow field in the circumferential mid-plane of one SHC sector is depicted. The contour plot shows the velocity component u_x parallel to the x-axis of the tilted burner. The selected swirl configuration and mass flux distribution at the inlet of the reference case induces a high axial momentum jet penetrating deeply into the combustor. Since the total swirl number of the flow is well below the critical value of about 0.6, no vortex breakdown occurs [27] which is distinctive for the low-swirl flame (see Fig. 1, left). Furthermore, the non-swirling annular flow through the outer part of the nozzle encloses the inner swirling flow and prevents radial expansion which establishes a stable jet. In the experiments of Sedlmaier [15] it was observed that the jet flow features a precessing motion around the center line of the flame tube with low frequency of 3 – 4 Hz. In comparison to the precessing vortex core (PVC) which occurs in high-swirl flows, jet precession is a different phenomenon related to very low swirl numbers [31]. This complex precessing flow field could be reproduced for the enclosed flow situation of the single burner [15] with a similar numerical model validating the RANS method [28]. However, such a transient behavior cannot be found in the present numerical predictions which is attributed to the non-symmetrical confinement of the staggered combustor. Apart from the non-precessing motion in this study, the characteristics of the low-swirl jet is in good agreement with experimental investigations of Sedlmaier [15]. In particular the small internal recirculation zone inside the nozzle and the axial velocity field is well reproduced.

In the staggered arrangement, the flow is significantly deflected towards the combustor sidewall which is highlighted in Fig. 4 (right) by an iso-surface of constant axial velocity. This deflection from the straight direction is related to the Coandă effect [32, 33]. The jet flow does entrain some surrounding gas causing a pressure decrease in the vicinity of the jet. Due to the presence of the sidewall, the entrainment of adjacent gas is enforced on this side of the jet. As a result, the pressure drops near the sidewall leading to a pressure difference across the jet. This imbalance exerts a force on the flow, which finally bends the jet towards the sidewall.

Since the pressure is the driving force of the Coandă effect, the pressure field in a plane normal to the nozzle axis is shown in Fig. 5. The plane is located at a distance from the nozzle which is 50 % of the length of the sidewall in burner axial direction. Furthermore, streamlines of the flow field are shown. The low-swirl jet situated at the center of the sector is indicated by a circular line. Through the cyclic boundary, the entrained fluid of the adjacent burner enters this sector. The high-velocity jet can be imagined as a cylindrical obstacle which forces the crossflow

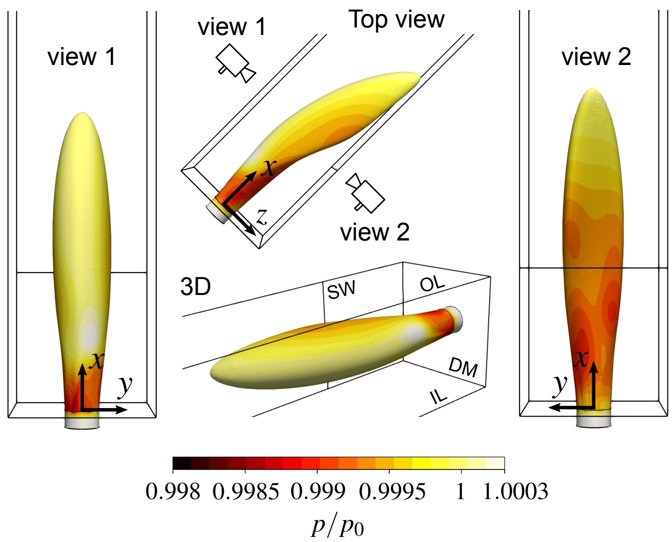

FIGURE 6. ISO-SURFACE OF CONSTANT AXIAL VELOCITY COLORED BY THE TIME-AVERAGED PRESSURE FIELD.

of the adjacent sector to flow around. When impinging on the jet, the crossflow stagnates which forms a high pressure zone at the stagnation point SP. Additionally, in the wake between the jet and the sidewall, two vortices, V1 and V2, can be identified. The static pressure in the wake region is lower compared to its surroundings. The resulting pressure gradient normal to the sidewall establishes the Coandă force which causes the jet to be deflected towards the wall.

To investigate the three-dimensional characteristics, an iso-surface of constant axial velocity colored by the static pressure is shown in Fig. 6. The contour plot is viewed from different camera positions. As it can be seen, the pressure difference across the jet prevails over a long axial distance starting from the nozzle. Hence, the flow can strongly interact with the flow in the adjacent sector. This interaction can be advantageous, since combustion products will be advected in circumferential direction to the adjacent flame and, thus, ensure ignition and enhance stability of the flames in the annular combustor.

In order to quantify the strength of flow deflection and to compare different nozzle parameter scenarios, the angle α between the flow and the machine axis $\hat{x}$ at the combustor outlet is evaluated (see Fig. 4). It is written as follows:

$$\tan(\alpha) = \frac{u_{\hat{z}}}{u_{\hat{x}}} \quad . \tag{1}$$

The mean exit flow angle of the reference configuration is $\overline{\alpha}^{\mathrm{REF}} = 79°$ which reflects the mass flux weighted average. This value is considerably higher than the geometrical tilting angle of the burners of $\beta = 45°$. The difference is related to the intense flow deflection. Hence, the angular momentum flux of the helical flow with respect to the machine axis at the combustor outlet is increased compared to the initial angular momentum at the inlet of the annular combustor.

By comparing the underlying physics of the low-swirl flow within the SHC framework with the studies of high-swirl flames carried out by Ariatabar et al. [22–24], it can be concluded that the relevant mechanisms causing an alteration of initial angular momentum of the helical flow are essentially different. The results of Ariatabar et al. reveal that the high-swirling jets impinge on the sidewall which establishes an asymmetric distribution of stagnation pressure on the staggered wall. Consequently, a resulting pressure force is induced in adverse circumferential direction. On that account, an unwanted decay of the high initial angular momentum compromising the SHC benefits does occur. This effect underlines the relevance of investigating the complex interaction of low-swirl flow with the sidewall of such a tilted combustor arrangement.

Recirculation Zone

In this section, the recirculation zone of the reference configuration formed in the vicinity of the SHC dome is studied. In the absence of a vortex breakdown, the stabilization mechanism of the lifted flame strongly relies on outer recirculation zones (see Fig. 1, left). Hot gases flowing back along the combustor walls and feeding the flame base is an essential requirement of the flow field. Making sure that the flow field provides proper flame stabilization is one of the first steps in combustion chamber engineering [34].

In Fig. 7, the iso-surface indicating a value of zero velocity in burner axis direction is shown. The volume defined by this surface is considered to be the recirculation zone, because the axial velocity is negative inside. The shape of the recirculation zone can be described as a complex three-dimensional structure. On one hand, the short sidewall, which is the only lateral confinement of the low-swirl jet flow, is almost entirely covered by the flow recirculation zone. On the other hand, the combustor outer and inner liners feature barely fluid flowing back. This may be attributed to the asymmetric confinements combined with the non-axisymmetric velocity profiles at the inlet of the nozzle. Compared to the single burner arrangement, where recirculation zones are established entirely around the jet flow, within the SHC configuration, the recirculation zone is characterized by irregular dimensions and possibly less intense backflow which may challenge the stabilization of the lifted flame.

In the following, two characteristic quantities are defined in order to quantify recirculation effects and to compare different setups subsequently. Using the volume V_{rec} and the volumetric

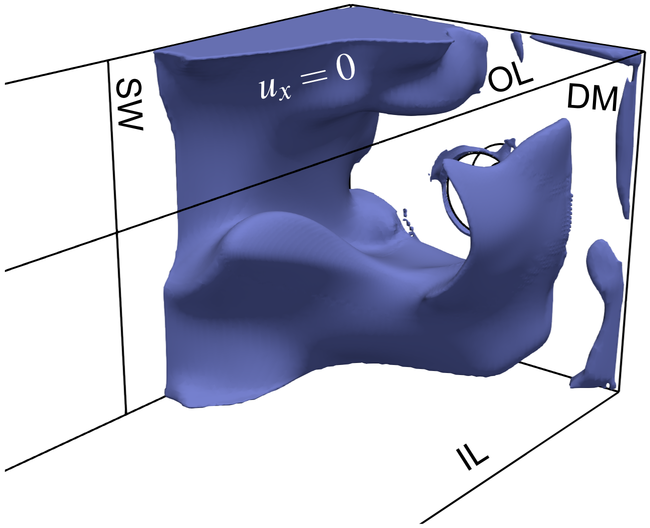

FIGURE 7. ISO-SURFACE OF ZERO AXIAL VELOCITY INDICATING THE RECIRCULATION ZONE IN THE VICINITY OF THE COMBUSTOR DOME.

flow rate $\dot{V}_{\mathrm{rec}}$ of the flow entering the recirculation zone, the residence time τ_{res} of the flow within this zone is calculated by

$$\tau_{\mathrm{res}} = \frac{V_{\mathrm{rec}}}{\dot{V}_{\mathrm{rec}}} \quad . \tag{2}$$

Furthermore, beside the residence time, the absolute amount of recirculating fluid is essential, as it determines the thermal energy flux of hot backflow which serves to ignite the flame. Consequently, the linear momentum M of the backflow is evaluated by integrating the axial mass flux density over the volume of the recirculation zone:

$$M = \iiint\limits_{V_{\mathrm{rec}}} \rho u_x \,\mathrm{d}V \quad . \tag{3}$$

For the reference configuration, the residence time in the recirculation zone is $\tau_{\mathrm{res}}^{\mathrm{REF}} = 10.4\,\mathrm{ms}$ and the backflow momentum is $M^{\mathrm{REF}} = 0.73 \times 10^{-3}\,\mathrm{N\,s}$. These reference values are used for normalization of the results of the parametric study.

As elucidated in this section, the flow field of the low-swirl flow of the SHC arrangement features unique characteristics regarding flow deflection and recirculation. Hence, to further understand the aerodynamics and to have a better insight into the complex 3D flow structure, in the subsequent section a parametric study is performed by varying the nozzle parameters. Thereby, the impact of each parameter on the flow field is assessed.

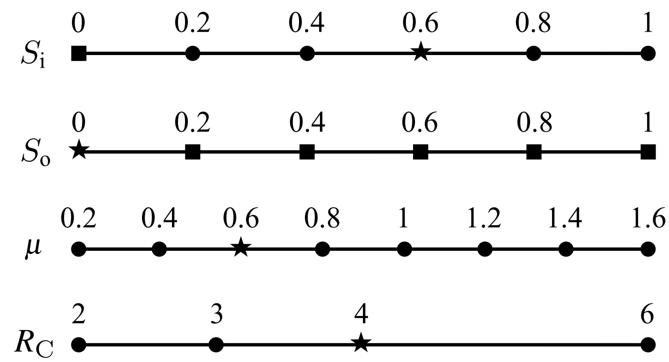

FIGURE 8. PARAMETER MATRIX INCLUDING THE REFERENCE CONFIGURATION (★). FOR VARIATION OF OUTER SWIRL NUMBER (■): $S_\mathrm{i} = 0$.

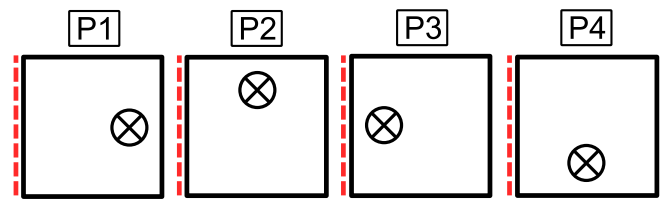

FIGURE 9. VARIATIONS OF NOZZLE POSITION ON THE COMBUSTOR DOME.

PARAMETRIC STUDY

Up to this point, a robust and efficient numerical framework for the prediction of the low-swirl flow interacting with adjacent sectors in the SHC was developed. Furthermore, the governing mechanism driving the flow is identified and can be quantified. Aiming at the implementation of the lean lifted flame in the SHC, it is crucial to know how to control the flow to meet the particular flame stability requirements.

Parameter Matrix

The impact of five parameters affecting the pattern of the flow field downstream the swirl nozzle is studied. To this end, in Fig. 8, the parameter matrix is shown. The parameters are the inner and outer swirl number, S_i and S_o, the mass flux ratio μ and the combustor confinement ratio R_C. Furthermore, the position of the nozzle on the SHC dome indicated by P is varied. The different nozzle positions are shown in Fig. 9. The reference position is reported in Fig. 3 (right). Each scenario investigated in the present work features the variation of one single parameter starting from the reference configuration as baseline design.

The only exception is the variation of the outer swirl number. In this context, the inner swirl number is set to $S_\mathrm{i} = 0$. Thereby, the total swirl number at the outlet section of the nozzle is kept below the critical value of 0.6 ensuring that no vortex breakdown does occur. Please note that the total swirl number is more sensitive to the outer flow, since the mass flux for $\mu = 0.6$ is approximately twice as much as of the inner flow. The configuration with a non-swirling inner flow, where only the outer flow is swirled by the nozzle is also generating a lifted flame. The technical relevance of this type of low-swirl injector was investigated by Cheng [9]. The configuration of a zero-swirl flow is not investigated in the present study.

By modifying the mass flux ratio μ at the inlet, the axial momentum ratio of the inner and outer flow is affected. It is worth mentioning that by increasing the mass flux ratio and keeping the swirl numbers constant, the total swirl number will rise.

The confinement ratio is an important parameter of technical combustion applications. It determines the expansion of the swirl flow emerging from the nozzle. Hence, the structure of recirculation zones is strongly affected, either the internal zone in high-swirl configurations due to vortex breakdown or outer recirculation zones along combustor walls of low-swirl flows. The impact of the confinement of the flame and its effect on emission characteristics was extensively investigated, e.g. [35, 36]. However, for the asymmetric and tilted SHC arrangement, the conditions are different.

The position of the nozzle is shifted in counter-clockwise direction starting from P1 closer to the sidewall (see Fig. 9). By varying the nozzle position, the distance to the sidewall and combustor liners changes. This might affect the recirculation zone, in other words the backflow momentum and the residence time.

Impact on Outflow Angle

The outflow angle α as calculated by Eq. 1 reflects the flow angle relative to the machine axis at combustor exit. It is a measure of the flow deflection due to interaction of the low-swirl jet with the sidewall. By comparing the outflow angle with the tilting angle of the SHC burners, it can be concluded whether the initial angular momentum at combustor inlet is increased or partially reduced. Furthermore, it determines the angle of attack of the turbine NGV and, hence, it is essential for turbine efficiency and combustor-turbine interactions.

Plots of the axial velocity for the variation of the outer swirl number S_o are shown in Fig. 10. For low outer swirl ($S_o = 0.2$), no significant differences are obtained compared to the reference configuration (see Fig. 4). It is apparent that the low-swirl jet remains stable in axial direction and features a high axial momentum which is the premise for the Coandă effect along the sidewall resulting in a high outflow angle. The impact of the interaction of the non-swirling inner part and the outer flow rises when increasing the outer swirl number. Despite high values of S_o ($S_o = 0.6$ and $S_o = 1$), vortex breakdown and inner recirculation do not occur, but the swirl flow expands radially. This is attributed to the non-swirling inner flow preventing a reverse flow on the burner

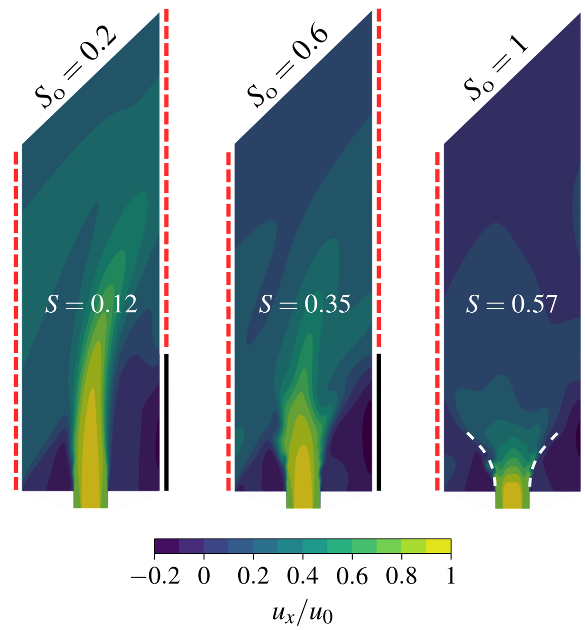

FIGURE 10. TIME-AVERAGED FIELDS OF AXIAL VELOCITY AND TOTAL SWIRL NUMBERS FOR VARIATION OF OUTER SWIRL NUMBER ($S_i = 0$).

axis. As a result, the axial momentum is dissipated promoting flow instabilities and, finally, the jet breaks up. Hence, the flow deflection is reduced for high outer swirl numbers. Furthermore, due to less intense entrainment, the interaction with the adjacent sector flow is limited. In Fig. 10 (right), the radial expansion of the divergent flow downstream the nozzle is indicated by white dashed lines. This configuration features a total swirl number of $S = 0.57$ with only the outer flow swirling. It is comparable to the low-swirl injector with swirl numbers between 0.4 and 0.5 investigated by Cheng [9]. Qualitatively, the flow field characteristics are similar, apart from the impact of the non-symmetric confinement on the aerodynamics in this study.

To study the flow deflection caused by varying the outer swirl number quantitatively, in Fig. 11 (left), the mean outflow angle at the combustor exit is shown as a function of the outer swirl number S_o, for a non-swirling inner part of the flow. The outflow angle decreases rapidly once the outer swirl number exceeds a value of 0.6 which is associated with the onset of jet break-up. However, even for the largest outer swirl, the outflow angle is greater than 45° which is the SHC tilting angle. Thus, all investigated variations of the outer swirl number exhibit an increase of angular momentum with respect to the machine axis caused by deflection towards the lateral sidewall.

The influence of the confinement ratio R_C on the outflow angle α is shown in Fig. 11 (right). Increasing the confinement ratio and keeping the burner diameter d constant, requires the

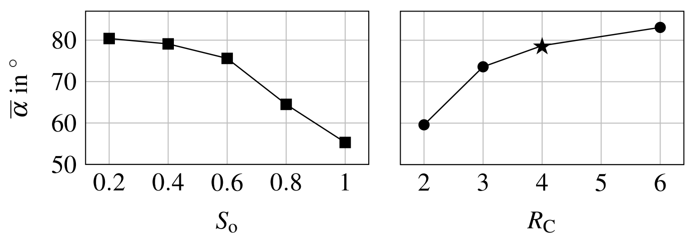

FIGURE 11. IMPACT ON OUTFLOW ANGLE.

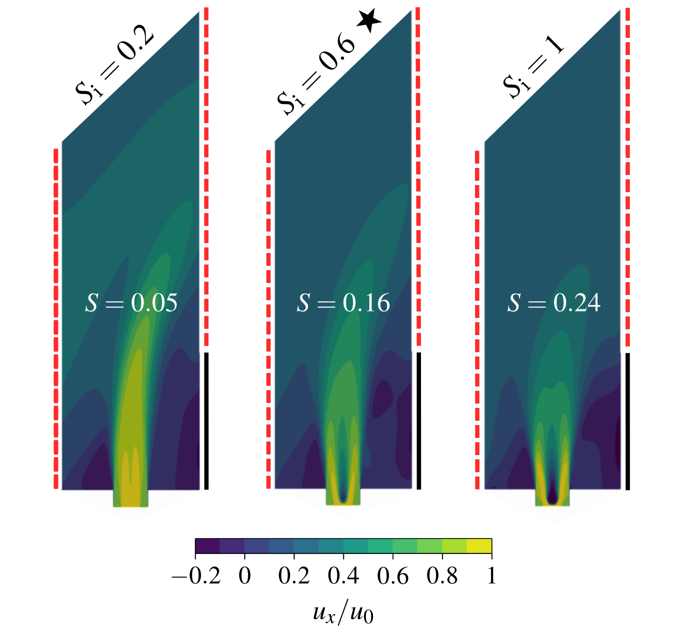

FIGURE 12. TIME-AVERAGED FIELDS OF AXIAL VELOCITY AND TOTAL SWIRL NUMBERS FOR VARIATION OF INNER SWIRL NUMBER ($S_o = 0$).

increase of flame tube height H. Note that also the flame tube width increases, since the sector cross section is square for all scenarios. For compact configurations of small confinement ratios, the impact of the confinement is more distinctive. This is related to a reduced pressure difference across the jet flow, since the distance between the jet and the combustor liners decreases as the flame tube volume decreases. Consequently, the circumferential momentum of the crossflow around the circular jet is alleviated leading to small outflow angles.

For the other scenarios investigated in this study, the mean flow angle at the SHC outlet is greater than 75°. Hence, no significant impact of the other parameters on flow deflection was observed. For illustration of this observation, the axial velocity fields for the variation of the inner swirl number S_i are shown in Fig. 12. Due to the high axial momentum of the non-swirling outer flow enclosing the inner nozzle flow, the jet entering the

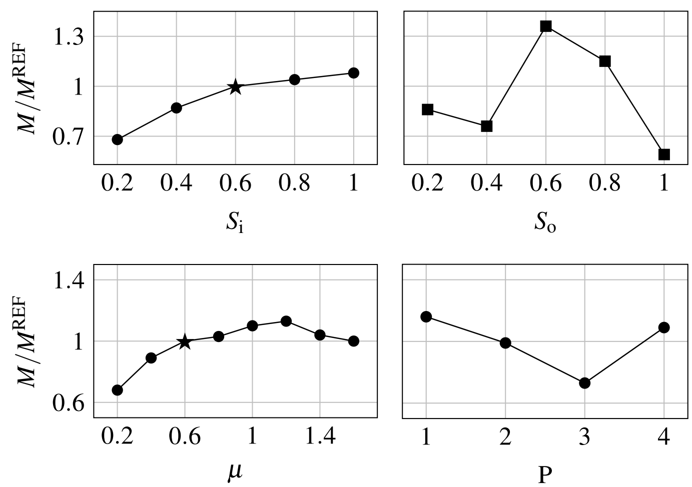

FIGURE 13. IMPACT ON BACKFLOW MOMENTUM.

combustor persists in axial direction without breaking up when increasing the inner swirl number. This is the basis of the Coandă force which causes strong deflection and, hence, high outflow angles at the combustor exit. For high inner swirl ($S_i > 0.6$), a small internal recirculation zone is established inside the nozzle, but not affecting the jet flow significantly.

By the variation of the inner and outer swirl number, it could be demonstrated that at higher total swirl number the jet flow will be less deflected leading to smaller outflow angles (see Fig. 10 and 12). By analyzing the jet flow patterns of these configurations, it can be concluded that beside the total swirl number the combination of the inner and outer swirl is to be taken into account equally when designing such a burner concept.

Impact on Momentum of Backflow

The momentum of the recirculating gas as evaluated by Eq. 3 is investigated in this section. Since the lean lifted flame is mainly stabilized by outer recirculation zones, the total enthalpy flux in the corner vortices back towards the flame determines flame stability.

In Fig. 13, the impact of the swirl nozzle parameters on the backflow momentum M is illustrated. Raising the inner swirl number S_i beyond the reference value of 0.6 may lead to a slight increase of M. On the contrary, a smaller inner swirl will reduce the amount of recirculation.

The variation of the outer swirl number S_o reveals that in between values of $S_o = 0.5$ and $S_o = 0.8$ a high backflow momentum can be achieved. As outlined previously, the outer swirl number strongly affects the axial momentum of the swirl jet. In combination with the length of the lateral sidewall where recirculation largely occurs, the reported values of S_o seem to enhance recirculation effects.

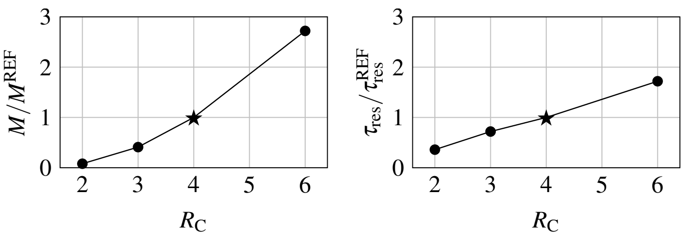

FIGURE 14. BACKFLOW MOMENTUM (LEFT) AND RESIDENCE TIME (RIGHT) OVER CONFINEMENT RATIO.

The impact of the mass flux ratio μ on the momentum of backflow is rather small, with slightly higher values compared to the reference case at the optimum around $\mu = 1.2$. However, for small mass flux ratios resulting in high axial velocities of the outer non-swirling flow, the effectiveness of recirculation decreases. This may be attributed to the extremely high axial momentum flux of the stable jet flow passing the sidewall.

By shifting the nozzle in radial direction to positions P2 and P4 close to the combustor liners, the backflow momentum is not affected. In contrast, reducing the distance to the sidewall characterized by P1 yields increased interaction of the low-swirl flow with the sidewall resulting in a stronger recirculation. For P3, the contrasting impact is observed.

By increasing the confinement ratio R_C for constant nozzle diameter, the volume and the cross sectional area of the combustion chamber increases. Consequently, the amount of recirculating hot reaction products increases which leads to more intense preheating of the reactants and, hence, induces positive effects on turbulent flame speed and flame stability [37]. This interrelation can be endorsed by the present results, as the momentum of backflow steeply increases with increasing confinement ratio which is shown in Fig. 14 (left).

Impact on Residence Time

The impacts on the flow residence time inside the recirculation zone (see Eq. 2) is assessed subsequently. In ultra-lean combustion systems of equivalence ratios of $\phi < 0.5$, the formation of NO_x pollutants does marginally correlate with the residence time in the reaction zone which is associated with moderate flame temperatures [3]. Furthermore, premixing of air and fuel in the premixing zone of the lifted flame downstream the swirl nozzle, but upstream of the flame zone, is the prerequisite for low NO_x emissions of this type of flame. The turbulent Damköhler number, $Da_t = t_{\mathcal{I}}/t_{\mathcal{R}}$, is the ratio of the integral flow time scale $t_{\mathcal{I}}$ of large turbulent eddies to the time scale of chemical reactions $t_{\mathcal{R}}$. To quantify the mixing phenomenon, the integral time scale $t_{\mathcal{I}}$ of

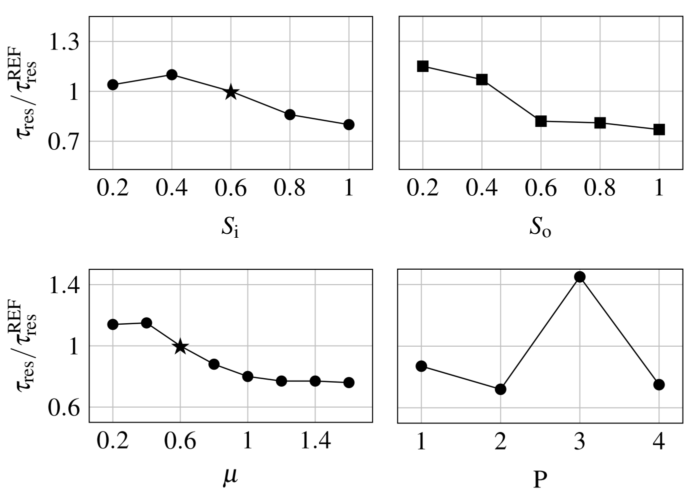

FIGURE 15. IMPACT ON RESIDENCE TIME.

the flow to be trapped in the recirculation zone can be estimated by the residence time τ_{res}, so that

$$t_{\mathcal{I}} \sim \tau_{res} = V_{rec}/\dot{V}_{rec} \quad . \tag{4}$$

Hence, to promote turbulent mixing processes, the residence time is to be increased.

The turbulent Damköhler number of the lean lifted flame is of $\mathcal{O}(1)$ as indicated by Sedlmaier [15] and Kasabov [37]. Thus, beside the effect of turbulence, the impact of the speed of chemical reactions $t_{\mathcal{R}}$ on the combustion regime and combustion performance has also to be accounted for. However, this is not an issue of the present paper which focuses on flow aerodynamics. The effect of chemical time scale could be investigated in more advanced studies.

In Fig. 15, the impact of the swirl nozzle parameters on the flow residence time is shown. Regarding the inner and outer swirl numbers, S_i and S_o, a decrease of residence time is observable by increasing the swirl. For small swirl numbers, higher residence time can be achieved compared to the reference configuration.

The mass flux ratio μ causes a decreasing residence time for higher values. Assuming a constant volume of the recirculation zone V_{rec}, the volumetric flow rate $\dot{V}_{rec}$ must increase. This can be attributed to the smaller axial momentum of the outer annular jet which enhances recirculation. However, this leads to a negative impact regarding the macro-mixing process.

An increase of the mass flux of the inner swirling flow yields higher axial and tangential velocities. Hence, the Reynolds number Re of the inner nozzle flow increases which results in a smaller Kolmogorov length scale $\ell_{\mathcal{K}}$ of the viscous eddies, since $\ell_{\mathcal{K}} \sim Re^{-3/4}$. Since the fuel is injected into the shear layers of the inner and outer flow of the nozzle, an increase of small scale turbulence yields better micro-mixing effects.

Increasing the distance of the nozzle to the SHC sidewall (P3) strongly increases the residence time. This effect is related to a small volumetric flow rate in the recirculation zone resulting in the lower backflow momentum. However, this configuration might be beneficial regarding the mixing performance. The other nozzle positions exhibit smaller residence time.

For the confinement ratio R_C (see Fig. 14, right), the residence time increases linearly with increasing combustor volume. As elucidated before, the volume of the recirculation zone and the amount of fluid flowing back will increase.

CONCLUSION

A novel combustor concept for aero engines based on the staggered arrangement of the combustors is introduced. This Short Helical Combustor (SHC) features a helical arrangement of the burners around the turbine axis requiring an angular air supply. The integration of a lean lifted flame in the SHC promises the significant reduction of the NO_x emissions while ensuring safe and stable operation.

The characteristics of the isothermal low-swirl flow of the lifted flame is studied in the tilted burner arrangement of the SHC concept. To this end, the aerodynamics of the low-swirl flow in a generic combustor geometry are predicted using a periodic single sector. It is observed that the low-swirl flow strongly interacts with the sidewall of the staggered SHC dome. In this context, the flow is deflected towards the sidewall due to an asymmetric pressure field. This phenomenon is explained by the Coandă effect. Consequently, the angular momentum flux of the helical flow at the combustor outlet is increased compared to the nominal tilting angle of the burners.

A systematic parametric study is performed to elaborate the impact of characteristic parameters of the swirl nozzle on the flow in the SHC by using a simplified coaxial swirler. It is shown that the flow field is highly sensitive to the swirl number of the outer flow through the injector which mainly determines the axial momentum of the low-swirl jet interacting with the adjacent burner.

Since the lifted flame is stabilized by outer recirculation vortices, the momentum of backflow and the residence time inside the recirculation zone are evaluated. It is found that, beside the distance of the jet to the sidewall, the position of the inner and outer liners are crucial. Hence, the ratio of nozzle diameter to combustor diameter is crucial for the recirculation characteristics. In general, a high confinement ratio between the flame tube and the swirl nozzle is advantageous regarding the stabilization of the flame, and prevaporation and fuel-air mixing may be promoted.

The present work demonstrates that it may be in reach to develop a lean-burn combustor by stabilizing a lifted low-swirl flame in the tilted SHC burner arrangement. Thus, inherent drawbacks of the LPP concept may be overcome. Based on the fundamental insights gained in this study, the reacting flow field will be investigated in future work to take the heat release of the flame into account. It is expected that the deflection of the jet flow will be reduced due to thermal expansion causing an acceleration of the flow in the burner axis direction. The study of recirculation ensuring flame stability for the reactive case will enable the evaluation of the feasibility of the innovative combustor concept. Furthermore, similarity parameters will be derived to globally describe the effects observed in this study.

ACKNOWLEDGMENT

This project has received funding from the Clean Sky 2 Joint Undertaking (JU) under grant agreement No 831881 (CHAiR-LIFT). The JU receives support from the European Union's Horizon 2020 research and innovation programme and the Clean Sky 2 JU members other than the Union.

The numerical computations were performed on the high performance computing cluster bwUni-Cluster at the Karlsruhe Institute of Technology. The HPC resource bwUniCluster is funded by the Ministry of Science, Research and the Arts Baden Württemberg and the DFG ("Deutsche Forschungsgemeinschaft"). The authors acknowledge support by the state of Baden-Württemberg through bwHPC.

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