Toward LES of an ignition sequence in a full helicopter combustor

M. Boileau[†,*] J.B. Mossa[†], B. Cuenot[†], T. Poinsot[‡], D. Bissières[◇] and C. Bérat[◇]

[†]*CERFACS, Toulouse, France* [‡]*IMFT - CNRS, Toulouse, France* [◇]*Turbomeca (SAFRAN group), Bordes, France*

Being able to ignite or reignite a gas turbine engine in a cold and rarified atmosphere is a critical issue for many manufacturers. In the Vesta combustor of Turbomeca, 18 main burners are ignited by two pilot flames. The success of an ignition attempt depends on the completion of three steps. In a first step, a spark plug must ignite the fuel spray produced by each starting burner to generate the pilot flames. In a second step, these two flames must provide a sufficient amount of energy to initiate a stable combustion in the main burners located in their vicinity. Finally, the reactive zone must propagate from one main burner to its nearest neighbour until the whole chamber is ignited.

These three steps are strongly influenced by the topology of the flow as well as the two-phase turbulent combustion phenomena. To represent properly the physics involved in such a complex and unsteady process, Large Eddy Simulation (LES) seems to be a powerful tool. This technique has been successfully applied to turbulent reactive flows (Selle *et al.*[1]) and recently extended to two-phase combustion in gas turbines (Pascaud *et al.*[2]). The numerical tool used in the present study couples an eulerian solver for the liquid spray with a LES solver for the gas flow. Thanks to the use of unstructured grids, it can be applied to complex geometries.

This work focuses on the propagation of the flame from the starting burners to the whole chamber but not on the ignition of the starting burners themselves: the spray flame produced by the starting injector is simply replaced by a hot gases jet. First, two-phase flow calculations will be presented in which this jet ignites one isolated burner. Then, some results will be shown from a single-phase flow calculation done on the IBM supercomputer BlueGene/L - cited by TOP500 as the world's fastest machine - where the use of 2048 parallel processors have enabled to start computing on the full combustor domain (i.e. 18 main injectors + 2 pilot flames).

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Introduction

In the performance of an aeronautical gas turbine, the capability of ignition is a crucial criteria. For an helicopter engine, a fast and reliable lightup is needed for various altitudes i.e. different atmospherical conditions of pressure and temperature. In that context, a comprehensive understanding of the physics involved in the ignition process would be a useful gain for combustor designers. As described in Lefebvre,[3] many igniter concepts can be used by manufacturers as an initial input of energy in the combustor. In the annular combustor Vesta, Turbomeca uses two torch flames produced by separated injectors in order to ignite the 18 main injectors. This technology implies an ignition process which can be divided in three steps. In a first step, a classical spark plug produces a spark which ignites the fuel spray provided by the pressurized starting injectors. These two injectors are located in opposite quadrants of the combustor, between two main injectors in the case of Vesta. The torch flame thus created must transfer sufficient energy to the air-liquid fuel mixture coming from the closest main burners in order to initiate a stable combustion. Finally, the reactive zone propagates to their neighbours and light-up the whole chamber in an iterative process.
As a powerful computational tool for transient flows, large eddy simulation is a promising method to simulate such an ignition sequence. Some recent applications by Selle *et al.*[1] has shown very good predictivity for turbulent reactive flows in gas turbines. Since the role of the dispersed phase of fuel is of prime importance in the ignition process, a solver for this liquid phase is required. The calculation of a turbulent, compressible and reactive two-phase flow in a realistic combustor geometry has been successfully performed by Pascaud *et al.*[2] thanks to the LES code AVBP. The present article describes how AVBP has been applied to the case of an ignition sequence in the Vesta combustor.
The first part describes the computing method used to handle the LES calculation. First, a brief description of the numerical tool is provided. Then, details are given for the technique to model the effects of the starting burner using the analogy with a hot jet. Finally, two studied cases of the Vesta combustor are presented: a two-phase flow calculation in a single sector and a single-phase calculation in the whole 18 sectors with the IBM supercomputer BlueGene/L. In the second part, results for the two-phase ignition are discussed and a snapshot is shown for a first calculation in the full combustor.

*boileau@cerfacs.fr

Computing method

Numerical Tool

The calculations presented in the present article have been performed using the solver AVBP, a research CFD code devoted to compressible and reactive flows in LES. It can be used on both structured and unstructured grids which makes it easily applicable to the complex geometry of a combustor. Turbulent combustion is taken into account by a Dynamic Thickened Flame model[4] while turbulence itself is treated with a LES Smagorinsky model for the subgrid scale effects. The liquid dispersed phase is described with an eulerian point of view and coupled with the gaseous carrier phase to account for drag and evaporation. Details about this two-phase flow model can be found in Pascaud *et al.*[2] A specificity of AVBP is its ability to run with a very good efficiency on a high number of parallel processors. One aim of this work is to evaluate the performance of AVBP in a heavy calculation requiring the use of thousands of processors.

Modelling of the starting burner

This work focuses on the problem of how combustion is initiated in the main burners thanks to the energy released by the starting burner. The starting burner themselves are supposed already ignited and are modelled by hot jets.
Figure 1 shows an ensemble view of the Vesta combustor. It is an annular combustor which can be divided into 18 identical sectors. For each sector, the kerosene spray is provided by an aerodynamic main injector which creates a swirled jet. Figure 2 makes a zoom on two sectors to exhibit the limit of the computing domain as a well as the cutting surface C, later used to show certain results.

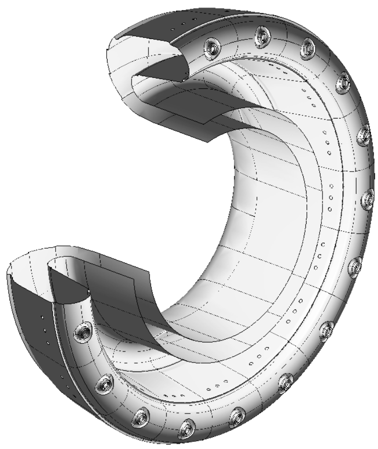

Fig. 1 Global view of the Vesta combustor (14 of the 18 sectors are represented).

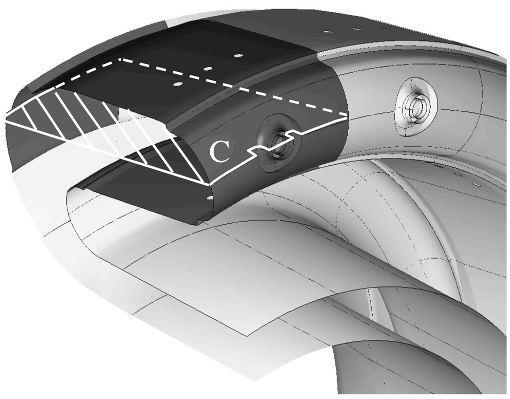

Fig. 2 Zoom on two sectors: limit of the computational domain (in dark) and cutting surface C (in white).

Figure 3 is a sketch in the C surface that shows how the ignition injector is located between two main injectors. The kerosene injected by such a pressurised injector forms a spray burning with the air coming from the multiple combustor inlets and creating a torch flame. Figure 4 describes how the burning spray has been replaced by a simple jet of hot gas. This gas is the combustion product of a stoichiometric kerosene/air mixture in terms of species composition (CO_2, H_2O and N_2) and temperature (adiabatic flame temperature). Injecting an inert and hot gas enables to provide some of the burner power, in the form of an enthalpy flux, without adding the complexity of the spark ignition of a fuel spray. In order to stay as realistic as possible, the axis position of the starting injector has been kept and the jet parameters have been calibrated. First, the jet mass flow has been chosen to provide a power corresponding to the combustion of the fuel mass flux. Then, in absence of quantitative experimental data for the real spray, some ”good sense” assumptions have been made concerning the jet geometry. So, both diameter and bulk velocity have been calibrated to give a reasonable jet length. It is noticeable that the dynamic effect of this hot jet on the surrounding flow is rather low due the high density ratio between the hot gases and the fresh air. Thud, in order to take into account the spread of the original flame coming from an open spray cone (Fig. 3), a swirling component has been added.
Such simplifications cannot lead to predictable results. Nevertheless, some interesting analysis can be made concerning the processus of ignition and flame propagation in this kind of configuration.

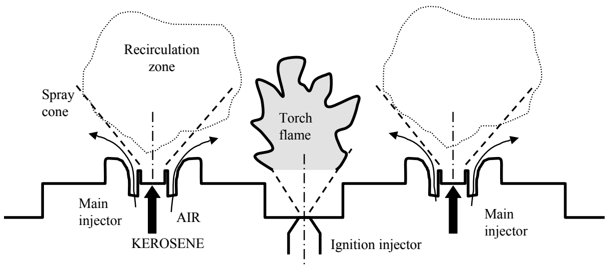

Fig. 3   Real configuration

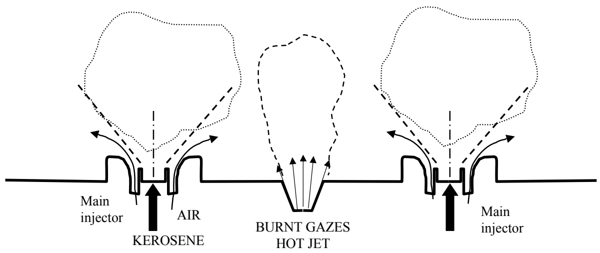

Fig. 4   Calculated configuration

Description of the configuration

Among the different calculations performed with AVBP on the ignition of the Vesta combustor, two are retained to be presented in the present article:

1. a two-phase calculation in a single periodic 20 deg. sector including one main burner and one hot jet for the starting burner (later called Case S)
2. a single-phase calculation in the full 360 deg. combustor including 18 main burners and 2 hot jets (later called Case F)

Case S: Ignition of a single sector in two-phase flow

Figure 5 describes the boundary surfaces of the computing domain.

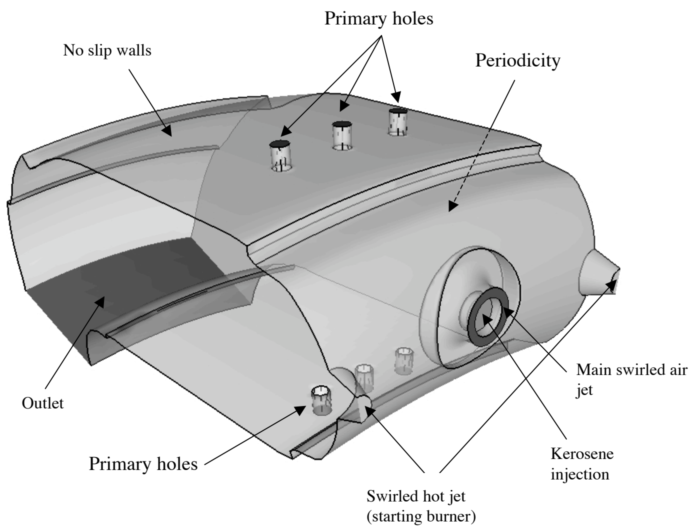

Fig. 5   Computing domain of the single sector calculation (Case S)

The parameters for the boundary conditions are listed in Table 1. The lateral surfaces are set as axi-periodic conditions to be as less restrictive as possible. All the inlets and the outlet are NSCBC boundaries[5] which are non reflecting for acoustic waves. The computing domain does not include the full swirler geometry of the main injector. So, the imposed velocity profile has been calibrated using a previous non reactive LES calculation in an extended domain taking into account the complexity of the whole swirler geometry. The real combustor also has cooling films and multi-perforated walls which are not included here because they would add useless complexity in relation to the objectives of this work. Finally, one can notice that the physical boundary parameters are not favourable for ignition in terms of air and fuel jets temperature and droplets size. However, these values correspond to real starting conditions for a typical helicopter gas turbine.

The entire domain has been meshed using tetrahedral cells with a good refinement around the inlets and in the combustion zone (Fig. 6). The obtained grid has 1.03 million cells and 178 thousand nodes.

Name	Boundary type	Physical parameters
Primary holes	inlet (jet in cross flow)	Air at $T = 273\ K$
Main injector	Inlet (2 swirled contrarotating jets)	Air at $T = 273\ K$, Monodisperse spray of kerosene droplets: size $d = 100\ \mu m$ $T = 273\ K$
Hot jet	Inlet (swirled jet)	Burnt gas mixture at $T = 2400\ K$
Combustor walls	Wall	No slip, Adiabatic
Outlet	Pressure imposed	$p = 1.18\ bar$

Table 1 Boundary conditions for Case S

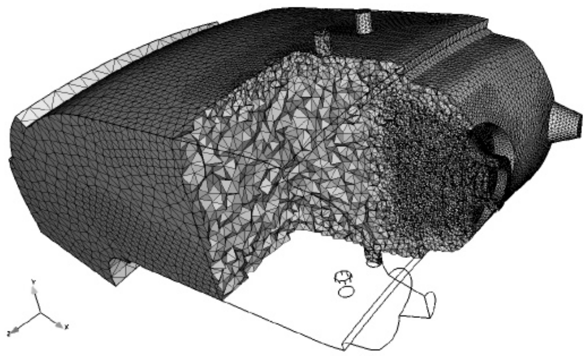

Fig. 6 View of the computing tetrahedral grid

In order to be as close as possible to the real ignition conditions, the initial condition of the run is the one of a steady non reactive flow where liquid kerosene is injected but weakly prevaporized. At the beginning of the calculation, the hot jet flux is applied with a relaxation time avoiding introduction of excessive acoustic perturbation.
A 52.6 ms ignition sequence was calculated on a SGI Origin 3800 using 64 parallel processors and took around 100 hours of execution time.

Case F: Ignition of the full combustor in single-phase flow

The parameters for the calculation in the entire Vesta combustor are the same as in case S with the following differences:

1. Due to technical and timing constraints, the liquid kerosene spray has been replaced by an equivalent injection of gaseous kerosene. This new injection has the same mass flux and the same profiles for concentration and velocity than the previous liquid one.

2. Periodicity condition is removed since 360 deg. are computed.

3. Among the 18 sector, two hot jets are used to represent the two real starting burners (Fig. 7).

The 360 deg. grid has been produced by replicating periodically the original 20 deg. grid. This final grid is composed of 3.14 million nodes and 18.6 million tetrahedral cells.
To handle such a large calculation, the present fastest supercomputer BlueGene/L has been used. BlueGene is an IBM parallel computer equipped with a powerful network which enables efficient runs on thousands of processors. Case F has been run on a rack of 2048 processors for 10 ms of physical time which corresponds to the beginning of the ignition sequence. Further times have not been reached because of computing problems that could not be solved while access to the machine was open. These problems are currently investigated by a collaborative team including IBM and CERFACS. Up to now, about 60,000 iterations have been performed within an execution time of around 17 hours.

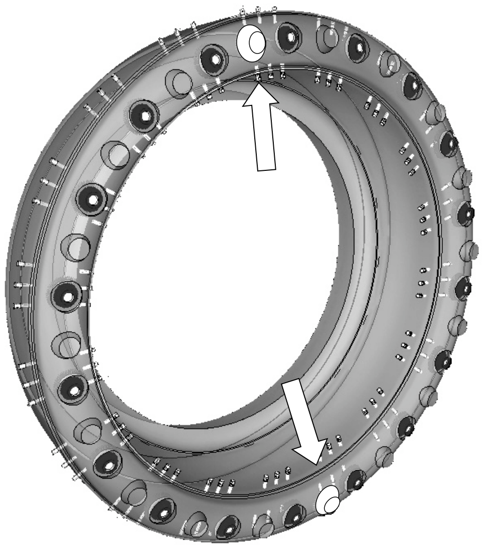

Fig. 7 Computing domain and boundary conditions of the full combustor (Case F). White arrows point the hot jets location.

Results and Discussion

Case S: Ignition of a single sector in two-phase flow

Figure 8 illustrates the temporal variation of relevant quantities through the ignition sequence. During the first ten milliseconds, the hot jet increases the gas mean temperature. The fuel droplets carried in the hot environment of the jet evaporate faster producing fuel vapor and inducing two phenomena:

1. A reaction zone takes place around the hot jet where the high temperature enables to maintain a sufficient evaporation rate. During the first 15 ms, this reaction only consumes a low part of the liquid fuel as shown by the reaction and evaporation rates plots (Fig. 8, right graph).

2. The unburnt fuel is blown downstream and its vaporisation creates an accumulation of gaseous fuel downstream the primary zone. Once mixed with air and heated by the hot jets, this fuel vapor burns fast releasing a great amount of heat (Fig. 8, left graph).

3. This heat release induces a strong pressure wave which disturbs the inlet fluxes as shown by the hot jet curve on the left graph of Fig. 8. At this time, the reactive zone coming from the hot jet is entering the central recirculating zone created by the vortex breakdown of the main injector inlet.

4. Once the recirculating zone fulled by hot gases, the flame is stabilising in front of the swirled jet. Even after the hot jet has been cut off (at 38.7 ms), the combustion stays stable with an equilibrium between the evaporation rate and the burning rate (Fig. 8, right graph) as well as an almost steady mean gas temperature (Fig. 8, left graph).

To better understand what happens in the primary zone, Fig. 9 exhibits some key variables of the flow on the cutting surface C (Fig. 2) for different times of the ignition process. Although this two-dimension view stays restrictive for a three-dimension flow, it gives a good idea about how combustion propagates from the ignitor region to the main injection zone.

First, the 8.21 ms snapshot illustrates how the main swirl jet induces a vortex breakdown with an intense recirculating zone. This phenomenon has been described by Lucca-Negro[6] and is known to be a stabilising mechanism for jet combustion. This snapshot also shows that the recirculating zone stays poorly influenced by the surrounding hot jet as the reactive zone is kept outside the back flow line. Nevertheless, some hot gases are sporadically captured leading to an increasing mean temperature inside the back flow line, as shown on the 23.59 ms snapshot. At 24.75 ms, a part of the hot jet flame is entering the back flow zone and seems to be extinguished before propagating up to the main injection (time 24.96 ms and 25.33 ms). Thanks to the heat released by the passage of this flame, gaseous fuel becomes more present in the region close to the vortex breakdown. This enables a strong flame to propagate to that place at around 27.52 ms. However, until the whole recirculating zone is not fulled by hot gases, this flame is not stable yet

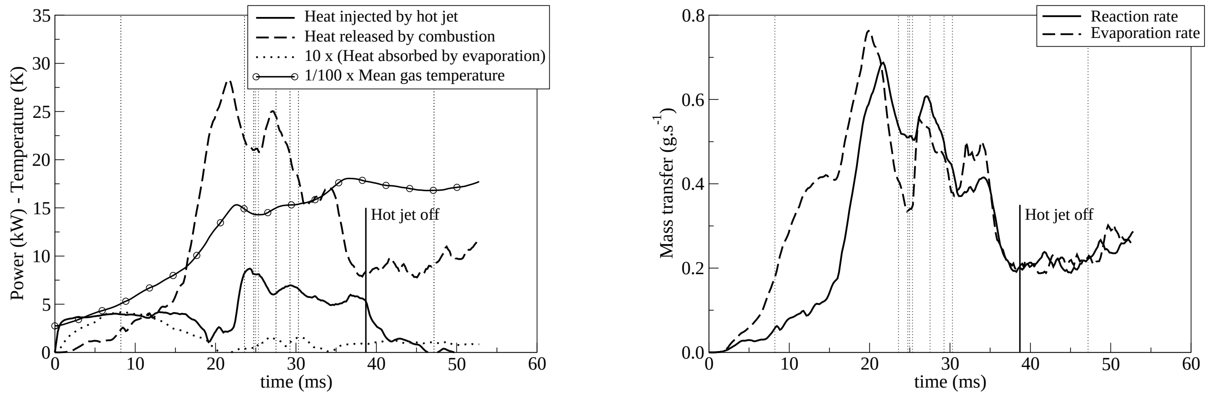

Fig. 8 Temporal evolution of various total quantities in the domain. Left: energy transfers and gas temperature. Right: mass transfers. The vertical lines indicate the instants of the 9 snapshots featured in Fig. 9.

(29.26 ms snapshot). Finally, from 30.30 ms, where a high temperature can be found almost everywhere in the primary zone, until the end of the simulation, a stable combustion is observed in the main burner.
The 47.18 ms illustrates the steady configuration of the reactive flow, featuring:

- A primary reactive zone anchored to the main injector. It corresponds to a diffusion flame fed by the air coming from the external swirler of the main injector and the vaporisation of the liquid kerosene spray injected by the internal swirler.
- A secondary and downstream flame burning the excess of fuel with the air injected by the transversal primary holes.
- The tracks of a row of these primary jets appears through three cold spots that one can distinguish in the temperature field.

Case F: Ignition of the full combustor in single-phase flow

Figure 10 provides a view of the ignition in the full combustor geometry. At the time reached in this simulation i.e. 10.8 ms, 4 burners among 18 are ignited. Further calculations of this case should exhibit the propagation from one main burner to its neighbour, already observed in a previous three-sector calculation (not presented in this article).

Conclusions

A computational method has been presented for the large eddy simulation of the ignition sequence inside an helicopter combustor. A complete ignition process has been investigated through the case of two-phase reactive flow in a realistic geometry for a single sector of the combustor. Due to the various approximations including the starting burner modelling, this calculation does not claim to be predictive. However, some key mechanisms of the ignition, such as the interaction between the hot gas jets and the main back flow zone, have been brought to the fore. In particular, it has been shown that a full stabilisation of the flame is obtained when the back flow region temperature is sufficiently high to maintain a strong evaporation of the liquid fuel. Morever, the feasibility of calculating a complete combustor ignition has been demonstrated through a run on 2048 parallel processors with the supercomputer BlueGene/L. Even if this technique requires some added developments in the present code, it seems very promising for the future of LES computations in turbulent combustion.

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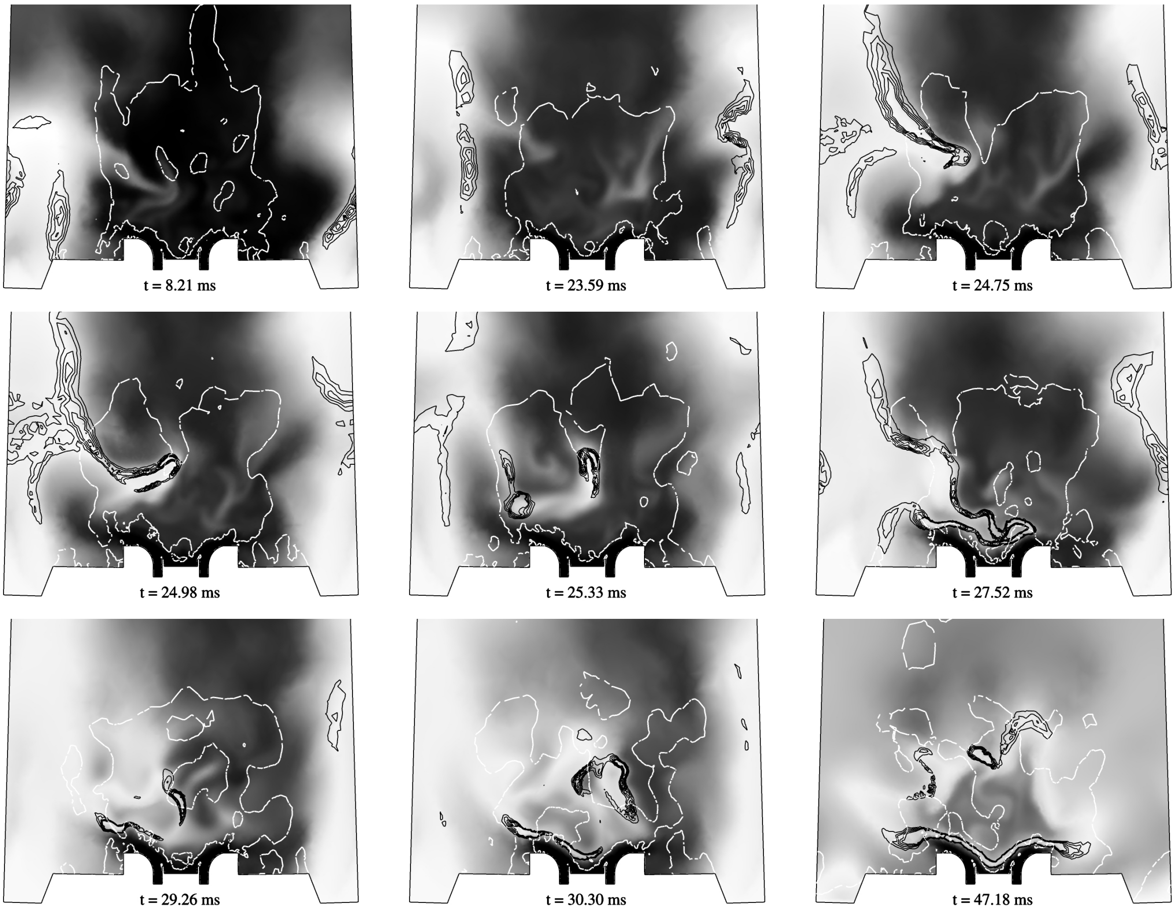

Fig. 9 Propagation of the reactive zone from the hot jet to the main injector on cutting surface C. Grey scale: gas temperature (black: 273 K → white: 2400 K). Black lines: reaction rate isolines. White lines: back flow lines.

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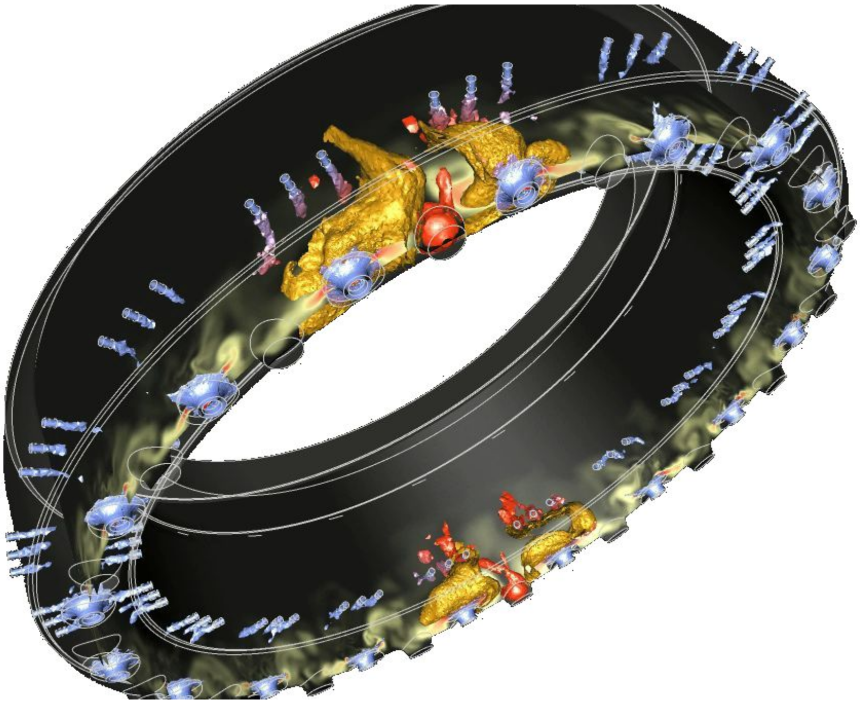

Fig. 10 Ignition of the full Vesta combustor. Color scale on clipping surface: fuel mass fraction. Bleu surfaces: cold air inlets. Red surfaces: hot jets. Golden surfaces: flame.