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Effect of dilution in an inter-turbine Flameless combustor

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Alternatives to combustion in aircraft engines are not expected to become feasible in the decades to come. As the aviation traffic increases and regulations become more stringent, reduction in pollutant emissions are needed. The Flameless Combustion (FC) regime has been one of the promising candidates to achieve lower emissions in gas turbine engines. This combustion regime is characterized by well-distributed reactions, with low peak temperatures, resulting in lower emissions and acoustic oscillations. However, the attainment of the FC regime is not straight forward considering the conditions and requirements of gas turbines. Most of the previous combustor design attempts failed to provide broad operational range, high combustion efficiency, or were difficult to integrate in an engine.

Along with a novel aircraft concept, the European project AHEAD (Advanced Hybrid Engines for Aircraft Development) resulted in the conceptual design of a gas turbine engine with two sequential combustion chambers[1]. As the aircraft concept allows the use of cryogenic fuels, the first combustion chamber was designed to operate with hydrogen or natural gas. The second is the inter-turbine combustor herein studied, which would operate under the FC regime burning conventional fuels.

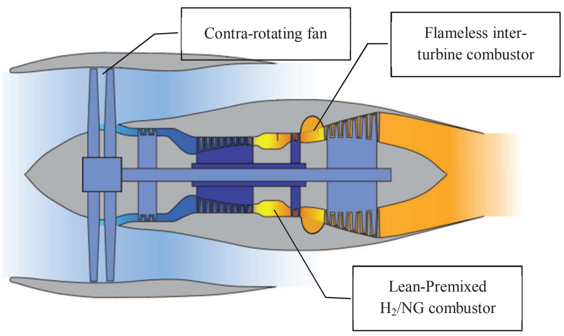

Figure 1 – Engine concept proposed along the AHEAD project[1].

As the incoming oxidizer in the inter-turbine combustor is the exhaust of the first combustor, temperatures would be high and oxygen concentration lower, helping the attainment of the FC regime. Furthermore, the power split between the two combustors would enhance the operational range.

After the conceptual design was accomplished[2], a scaled and simplified experimental combustor was built to assess the design and allow improvements. Instead of the full annular combustor, a 18 degree wedge was adopted, containing three fuel ports (Fig. 2). The fuel employed was methane, to simplify operation and subsequent computational simulations. Data on emissions was acquired for several levels of oxidizer dilution with nitrogen. Air and nitrogen were mixed and preheated to temperatures around 580 K.

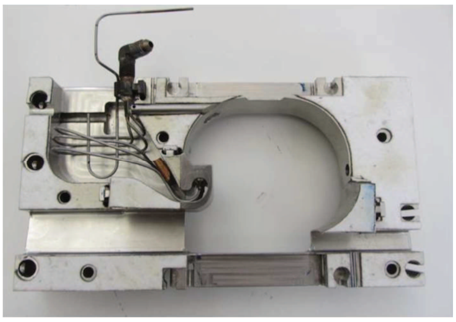

Figure 2 – Section of the proposed annular combustor used during the experiments.

The simulations here presented were performed in order to assess the use of CFD to improve the design of the combustor in relation to pollutant emissions. More specifically, the use of FGM (Flamelet Generate Manifolds)[3] along with RANS was investigated, since its computational cost is considerably lower than other models (as the Eddy Dissipation Concept and the Conditional Source Term Estimation). ANSYS Fluent® was employed while combustion was modelled using both adiabatic and non-adiabatic FGM. The manifolds were generated using the GRI 3.0 mechanism. FGM's progress variable was defined in function of CO_2 and CO mass fractions. Attempts using H_2O did not provide better results. The *k-ε* turbulence model was employed as tests using *k-ω* SST and Reynolds Stress turbulence models did not significantly change the results in terms of emissions. Along with the non-adiabatic approach, radiation was taken into account using the Discrete Ordinates model. In some simulations, heat conduction through the walls was included by imposing an estimated outer wall temperature, as well as their thicknesses and thermal properties. The NOx emissions were predicted using transport equations for the mass fraction of NO, N_2O, NH_3 and HCN, with their source terms calculated via Thermal and Prompt NOx mechanisms.

Figure 3 – Damköhler number contours in the mid-plane of the combustor for two different oxidizer compositions. Simulations including radiation modelling.

The computational mesh was refined until no relevant difference was spotted in the emissions and mid-plane fields results. The employed mesh was fully hexahedral and had 5.6 million nodes.

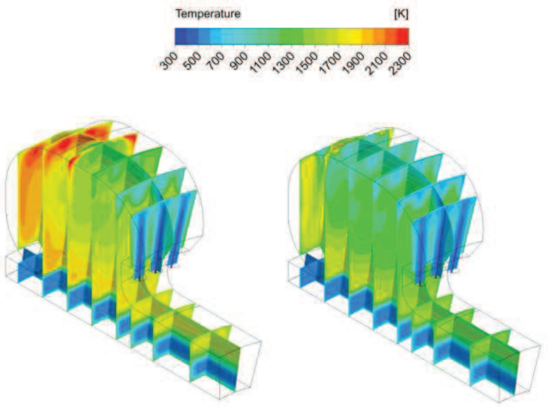

Figure 4 – Temperature contours for the case without nitrogen dilution (left) and with 100 l/min nitrogen addition to the oxidizer stream (right). Simulations including radiation modelling.

The cases simulated had different levels of N_2 dilution. The air (230 l_n/min) and fuel flows were constant. The case with no N_2 addition had global equivalence ratio of 0.2, taking into account both the dilution air and the combustion air that enters the chamber along with the fuel (in coflows).

Analysing Figs. 3 and 4, it is noticeable that dilution possibly shifts combustion to the FC regime, as temperature and Damköhler number drop. Interestingly, 60 l_n/min of N_2 addition (right hand side of Fig. 3) results in very low NOx emissions and further dilution is not advantageous (Fig. 5).

The computational modelling was able to predict the trend in both NOx and CO emissions with increasing amount of N_2 in the oxidizer stream. NOx emissions were very sensitive to the inclusion of radiation, especially for cases without N_2 or with little dilution. The peak temperatures in the combustor drop significantly with radiation.

Although the trend was captured, CO emissions were overpredicted. Possibly, such limitation could be overcome using a multi-stage FGM approach, as suggested by Göktolga et al.[4]. Using more than one progress variable could be the solution to have more accurate predictions.

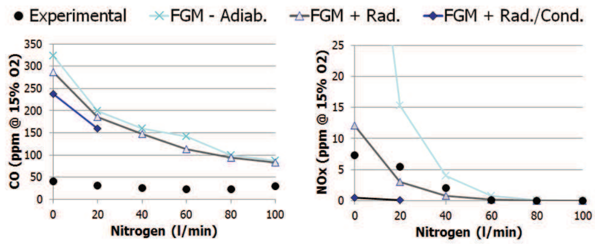

Figure 5 –CO and NOx emissions as function of nitrogen addition in the oxidizer stream.

When heat conduction through the walls was included, the predicted NOx emissions were too low. The discrepancy is attributed to the uncertainty in the estimated wall temperatures. No measurements were performed and the chosen values could be wrong.

Analysing the overall results, one can conclude that the set of models can be used to evaluate modifications and possible improvements in the inter-turbine combustion. However, this should be done carefully, as only the qualitative behaviour is replicated. The flow field analysis shows most of the reactions happen close to the combustor walls. Therefore, the large recirculation region designed to accommodate the highly distributed reactions is not performing as expected. Different fuel injection positions and directions shall be tested, as well as modified cavity geometries.

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