"Flameless Oxidation Combustor Development for a Sequential Combustion Hybrid Turbofan Engine"

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Gas Turbine Pollutants

There is a global need to reduce emission and GHG from aircraft. This can be achieved by:
• Drag reduction
• Use of low carbon fuel (LH2 & CNG)
• Improved engine design

AHEAD MF-BWB

Sketch of the AHEAD engine with two combustion chambers; primary for cryogenic fuel (H2/LNG) and secondary for jet/ bio jet fuel (kerosene) combustion

Combustion technique for secondary combustor: Flameless Oxidation.
The Concept of Flameless Gas Turbine Combustor

NOx FORMATION REGION

Flame stabilizing and general airflow pattern.

Conventional

Flameless

Low NOx production

2200°C

1500°C

1300°C

400°C

T

X
Flameless Oxidation Method for NOx Reduction

Different Combustion Regimes

Ref.: Prof. Arvind G. Rao, TU Delft
Suggested combustor configuration

Split ratio: 1 : 4.7
1. Select a reduced chemical kinetic mechanism for CFD simulations for specific fuel (using surrogate fuel instead if JP-8).

2. Verify the flame characteristics and emissions using the reduced mechanism with respect to the detailed mechanism and with experimental results.

3. “Surrogate A” was selected as an alternative to represent the JP-8.

<table>
<thead>
<tr>
<th>Surrogate A compounds</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal alkanes</td>
<td>60</td>
</tr>
<tr>
<td>n-Decane, <strong>C10H22</strong></td>
<td></td>
</tr>
<tr>
<td>Cyclo alkanes</td>
<td>20</td>
</tr>
<tr>
<td>Methyl-cyclo-hexane, <strong>C7H14</strong></td>
<td></td>
</tr>
<tr>
<td>Aromatics</td>
<td>20</td>
</tr>
<tr>
<td>Toluene, <strong>C7H8</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100%</td>
</tr>
</tbody>
</table>

Chemical Kinetic Scheme for CFD Simulations
Comparison between detailed and reduced (“Kundu – Creck’) mechanism for “Surrogate A” and an experimentally based 2-step mechanism by Meredith and Black (2006) was performed using CHEMKIN.

Evaluation of different reduced model using CHEMKIN simulations

Temperature vs. residence time

CO mole fraction vs. residence time

In GT and Jet Engine, the relevant residence time range is 1~10ms & the temperature is the important parameter. Hence, the Meredith 2-step mechanism was selected!

Take Off. Inlet condition: Input mass gas fraction: gH2O=0.0656, gO2=0.1731, gN2=0.7613, mixture flow rate= 21.73 kg/s, T=1185K. 
P=8.56 bar.
Comparison between model Surrogate A and experimental data for Jet A at two initial temperatures

Reduction of the ignition delay time due to air vitiation.

Air vitiation slows combustion process.

In practice, the reactance increases their temperature above inlet temperature by mixing, thus reducing the actual ignition delay time.

Effect of vitiation on ignition time for $T_{in} = 1185K$ and $T_{exit} = 1800 K$.

Sample Results: Effect of air vitiation on ignition time

Laboratory test conditions for AHEAD, $T=973K$

$t_{ignition} = 35 \text{ ms}$

$t_{\text{Fresh air.}} = 2.4 \text{ ms}$,

$t_{\text{Vitiated air}} = 2.9 \text{ ms}$

Reduced Kundu – Creck (C12H23)
Sample Results: Effect of air vitiation on combustion temperature

Vitiation reduces combustion temperature
Computational mesh & Velocity vectors indicating the large internal circulation

- Mesh;
  - green arrows - fuel inlets, blue ones - air inlets,
  - white - outlet

**CFD Simulations**

- Fluent Code
  - Discretization - 2-nd order
  - Turbulent model - K - ε
  - Combustion - EDC (Eddy Dissipation Concept) model.
  - 2- Meredith & Black reaction mechanism

\[ \rightarrow \text{Recirculation Ratio } ~ 1.5 \]
Static temperature distribution

Mass averaged static temperature at the exit 1299K

→ Almost uniform temperature distribution
CO mass-fraction at the exit - 30.7 ppm

→ Very little CO emission → \( \eta_b \) high

CO distribution
NOx mass-fraction at the exit - 0.45ppm

→ Very Low NOx emission

NO distribution
Experimental verification of CFD simulations

- Operating pressure 1bar (atmospheric), maximum air supply of 10 gr/sec
- Size limitation of the test chamber (300 mm in diameter) determined the need to limit the model to 1/3 linear geometrical scale
- similar residence time - Velocities reduced to 1/3
- similar temperature values at combustion zone and at the exit of the combustor.
The reduced experimental model

Schematic

Metal SS 310

Design
Experimental facility (IST, Lisbon, Portugal)
Variation of CO with $\Phi_{\text{global}}$

air flow rate 230, 370 and 420 L/min, no water and no N2 addition

$\rightarrow$ CO emission is reduced with increasing $\Phi_{\text{global}}$
Variation of NOx with $\Phi_{\text{global}}$, air flow rate 230, 370 and 420 L/min, no water and no N2 addition

$\rightarrow$ NOx emission is increase with increasing $\Phi_{\text{global}}$
Variation of CO with nitrogen addition,
air flow rate 230 L/min, no water addition
Power: 2.8 kW - φ Global : 0.19 – Air : 230 L/min

→ CO emission is not sensitive to N2 addition
Variation of NOx with nitrogen addition, air flow rate 230 L/min, no water addition.
Power: 2.8 kW -- $\phi_{\text{Global}}$ = 0.19, Water: 0 g/h

$\rightarrow$ NOx emission is reduced by N2 addition
The flame while increasing N2 flow rates, airflow 230 L/min, power: 2.8 kW – φ Global : 0.19
Variation of CO with H2O,
$\phi_{global} = 0.18$; blue: Air = 420 L/min, N2 = 40 L/min; red: Air = 220 L/min, N2 = 20 L/min

→ CO emission is not sensitive to H2O addition
Variation of NOx with % H2O,

Φ_{global} = 0.18; Blue: Air = 420 L/min, N2 = 40 L/min, red: Air = 220 L/min, N2 = 20 L/min

→ NOx emission is reduced by H2O addition
CFD study of the experimental model

The numerical mesh of the experimental combustor

Split ratio: 1 : 2.7

O₂+N₂+H₂O

O₂+N₂+H₂O + CH₄
Static temperature distribution:
average temperature at the exit is 825K and maximum temperature is 1770 K

→ Less uniform temperature distribution, probably due to lower mixing
Velocity field (m/s)
[CO] at the exit ~ 41 ppm

→ Comparable low level of CO emission as in full scale → high

CO mass-fraction
[NO] at the exit \(\sim 0.016\) ppm

→ Comparable very low NOx level of NOx emission as in full scale

NO mass-fraction
→ Shallow gradient of OH → Distributed reaction → Flameless Oxidation
→ Similar pattern of CH* emission between CFD and experiment

CH* mass fraction
The development of the Flameless Oxidation regime
### Verification of CFD results

<table>
<thead>
<tr>
<th>Oxidant characteristics</th>
<th>Combustor performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2</td>
<td>N2</td>
</tr>
<tr>
<td>CFD simulation</td>
<td>0.190</td>
</tr>
<tr>
<td>Experimental results</td>
<td>0.193</td>
</tr>
</tbody>
</table>
The AHEAD Engine
Summary & Conclusions

• A generic combustor design applying the Flameless Oxidation combustion regime, while using vitiated air was developed and its characteristic were realized using CFD modelling.

• An experimental model of the combustor was built, however with reduced dimensions and for lower operating pressures.

• CFD modelling of the experimental model presented similar results as during experiments, thus validating the ability of the CFD to model such combustor’s configuration and combustion regime.

• This confirm the feasibility of the suggested combustion configuration for the AHEAD hybrid engine.
Thank You.....!
COMBUSTOR DESIGN BASED ON CHEMKIN AND CFD SIMULATIONS (contd..)

- Performance requirements and emission limitations
- Combustor preliminary shape based on operational parameters and geometrical design limitations
  - Fuel and Oxidizer distribution for primary and dilution zones
    - Geometry
    - CFD simulations
      - Select model for Turbulence, Atomization, Combustion and Heat transfer
        - Build grid and perform Grid verification
          - Run calculation
            - Comparison results
              - Satisfactory agreement

- Developed combustor model
- LNG/LH2 Main Combustor
- Kerosene/Biofuel Secondary Flameless Combustor
- Bleed air cooled by LH2
- Shrouded fans
- Higher Specific Thrust
- Low Installation Penalty
Emissions under FLAMELESS conditions

\[ \eta_{b,ch} = 1 - \frac{m_{CO} Q_{R,CO} + m_{UHC} Q_{R,UHC}}{m_f Q_{R,F}} \geq 99.9\% \]

CO vs Air_2

Secondary Air

NOx vs Air_2

Secondary Air
Towards complete Flameless combustion