Numerical Investigations of the Response of a Simplified Burner-heat exchanger System to Inlet Velocity Excitations

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- Thermoacoustics
- Challenges
  
  - Thermoacoustic noise is currently an issue in domestic heating systems
  - Closer burner and heat exchanger in compact condensing boilers
  - The industry’s need for design rules to make thermoacoustically stable systems
- **Goal**

  - The physics of the interactions between a burner and a heat exchanger from a hydrodynamic and thermoacoustic point of view

  - In this presentation the method of modelling, implementation of CFD setup, validation of the simulations and first illustrative results will be discussed
- Numerical domain
  - Flat multi-slit burner
  - Plane 2D symmetric
  - Dimensions in mm
- The model

  - ANSYS Fluent CFD code
  
  - Laminar flow with energy equation
  
  - Species conservation

\[
\frac{\partial}{\partial t}(\rho Y_i) + \nabla \cdot (\rho \vec{v} Y_i) = -\nabla \cdot \vec{J}_i + R_i + S_i
\]

  - Single step reaction

\[CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2\]

  - Arrhenius formulation

\[k_r = A_T \beta e^{-E_r/RT}\]

  - Modified to get the correct laminar flame speed
- Verifications

- Pseudo-1D model (0.02 × 35mm)
- Grid independency
- Verifications

  - Pseudo-1D model (0.02 × 35mm)
  - Grid independency
  - Equivalence ratio sensitivity

![Graph showing equivalence ratio and SI values across various studies.](image)
- Verifications

  • Pseudo-1D model \((0.02 \times 35\text{mm})\)
  
  • Grid independency
  
  • Equivalence ratio sensitivity
  
  • Unburnt temperature sensitivity

![Graph showing comparison of different studies](image)
- 2D grid, using 1D conclusions, 165,000 elements
- Flame transfer function

  - Velocity perturbation as input and heat release rate as output
  - Step increase of 5% with assumed linearity, 40ms relaxation time
  - The (complex) flame transfer function defined as relative flame response divided by the relative upstream velocity perturbation, in frequency domain

\[
TF(f) = \frac{q'(f)/\bar{q}}{u'(f)/\bar{u}}
\]
### - Case studies

<table>
<thead>
<tr>
<th>Distance between Burner Deck and Heat Exchanger (mm)</th>
<th>Inlet Velocity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Hex05-V25 Hex05-V50</td>
</tr>
<tr>
<td>10</td>
<td>Hex10-V25 Hex10-V50</td>
</tr>
<tr>
<td>15</td>
<td>Hex15-V25 Hex15-V50</td>
</tr>
<tr>
<td>N/A</td>
<td>NoHex-V25 NoHex-V50</td>
</tr>
</tbody>
</table>

- P = 1atm
- Symmetry
- T = 350K
- T = 500K
- V = 25-50cm/s
- T = 300K
- Left: inlet velocity 25 cm/s

  • Reaction rate (kmol/m³s)

- Right: inlet velocity 50 cm/s

  • Temperature (K)
- Flow field through flame and around heat exchanger
- Offset for Hex05V50
- Response to square excitation
Case Studies with Heat Exchanger
Acknowledgement

Conclusions

Results

Numerical Model

Introduction

ReacTF - V50

NoHex Hex15 Hex10 Hex05

Gain

Phase

Frequency (Hz)

0 100 200 300 400 500 600 700 800 900 1000

Gain

0.0 1.0 1.2 1.4 1.6

0.0 0.2 0.4 0.6 0.8

0.0 0.1 0.2 0.3

0.0 0.1 0.2 0.3

Phase / \pi \text{ (rad)}

Frequency (Hz)

0 100 200 300 400 500 600 700 800 900 1000

Gain

Frequency (Hz)

0 100 200 300 400 500 600 700 800 900 1000

Phase / \pi \text{ (rad)}

Frequency (Hz)

0 100 200 300 400 500 600 700 800 900 1000

Gain

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0 100 200 300 400 500 600 700 800 900 1000

Phase / \pi \text{ (rad)}

Frequency (Hz)
**Introduction**

**Numerical Model**

**Results**

**Conclusions**

**Acknowledgement**

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**Gain**

- Hex15
- Hex10
- Hex05

---

**Phase**

- Hex15
- Hex10
- Hex05

---

**HexTF - V50**

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**Time**

**Normalized Heat Exchanger Heat Flux**

- Hex15
- Hex10
- Hex05

---

**Frequency (Hz)**

0, 100, 200, 300, 400, 500, 600, 700, 800, 900, 1000

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**Normalized Heat Exchanger Heat Flux**

0, 5, 10, 15, 20, 25, 30, 35, 40

---

**Phase/π (rad)**

- Hex15
- Hex10
- Hex05

---

**Normalized Heat Exchanger Heat Flux**

0.96, 0.97, 0.98, 0.99, 1.00, 1.01, 1.02, 1.03, 1.04

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**Time (ms)**

0, 5, 10, 15, 20, 25, 30, 35, 40

---

**HEX TF-V50**

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**Normalized Heat Exchanger Heat Flux**

- Hex15
- Hex10
- Hex05

---

**Time (ms)**

0, 5, 10, 15, 20, 25, 30, 35, 40
Results

**DeckTF - V50**

- **Gain**
  - Frequency (Hz)
  - Gain
  - NoHex, Hex15, Hex10, Hex05

- **Phase**
  - Phase/\(\pi\) (rad)
  - Frequency (Hz)
  - NoHex, Hex15, Hex10, Hex05

- **Time**
  - Normalized Burner Deck Heat Flux
  - Flow Time (ms)
  - NoHex, Hex15, Hex10, Hex05
- The possibility of calculating a total transfer function

\[
\frac{Q_{\text{flame}}}{Q_{\text{input}}} TF_{\text{flame}} + \frac{Q_{\text{hex}}}{Q_{\text{input}}} TF_{\text{hex}} + \frac{Q_{\text{deck}}}{Q_{\text{input}}} TF_{\text{deck}}
\]

\[
TF_{\text{flame}} + \frac{Q_{\text{hex}}}{Q_{\text{flame}}} TF_{\text{hex}}
\]

\[
TF_{\text{total}} = TF_{\text{flame}} - \left| \frac{Q_{\text{hex}}}{Q_{\text{flame}}} \right| TF_{\text{hex}}
\]

Transfer Function

- Comparison with transfer matrix
- The possibility of calculating a total transfer function
- Experimental setup
- The model accurately predicts combustion properties

- Absolute heat release changes with approaching hex, but normalized values and flame transfer function don’t

- Impingement causes intense flame cooling, counter phase behavior, and in special cases some degree of offset

- Decoupling elements transfer function in order to construct a total transfer function enables better system identification and thermoacoustic design possibilities
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