NUMERICAL VALIDATION OF PRIMARY MEASURES FOR EMISSIONS REDUCTION OF SMALL-SCALE BIOMASS COMBUSTION

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ASCI mini-symposium: “Combustion in energy transition”, February 2022
Small scale biomass boilers – design challenges

• Small scale wood pellet boiler design considerations:
  – Design of such appliances is limited by the end cost to the customer/user of the heating system.
  – Low operating costs are important - only fuel and maintenance costs are expected.
  – Strict emission and efficiency regulation norms must be always met.

• Secondary emission reduction and efficiency elevation measures:
  – Aimed at the post combustion zone after the combustion process.
  – Selective non-catalytic reduction (SNCR), selective catalytic reduction (SCR), electrostatic filtering, etc.
  – Most common to large scale biomass firings for combined heat and power production (CHP).
  – Too expensive and simply not feasible for the application in small-scale boilers.

• Primary emission reduction and efficiency elevation measures:
  – Modification of the combustion process: geometric and process parameters of the reaction zone.
  – Primary measures are viable for small scale systems and are implemented in many different forms.
Air staging – basic principle

What is „Air staging“?

- A primary emission reduction measure for solid fuel combustion (e.g., wood pellets).
- Air staging (also: „air staged combustion“) is achieved by the spatially separation of the combustion air supply into two or more streams in order to create different reaction zones.
- Common to wood fuel combustion systems especially modern small-scale wood pellet boilers.
Air staging – influencing parameters

• The thermal and combustion effectiveness is essentially governed by the geometric and process parameters of the air-staged small-scale boiler.

• Geometric parameters:
  – Position, shape and orientation of air supply nozzles,
  – size of primary and secondary combustion zone,
  – size and shape of the combustion chamber,
  – geometry of the combustion chamber, etc.

• Process parameters:
  – Primary to secondary air ratio,
  – total amount of combustion air,
  – temperature of combustion air,
  – fuel supply stability, feeding principle, etc.

Air staged wood combustion system

The balance of Parameters is CRUCIAL

Geometry (size, shape)

Combustion air supply

Fuel feeding

SA

PA

CFD
Wood pellet boiler under study

- Fuel
- Secondary air
- Fuel rich zone
- Fuel bed
- Internal recirculation
- Primary air
- Homogeneous oxidation

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The experimental boiler

- Port 1
- Port 2
- Port 3
- Port 4
- Port 5
- Port 6
- Port 7
- Port 8
- Port 9
- Water mantle
- SA air supply assembly
- Port 10
- Port 11
- Port 12
- Fixed grate
- Underfed Burner
- Combustion chamber
- Cleaning lid
- Flue gas passage
- Baffle plate
- Second pass tube heat exchanger
- Steel sheet lining
- First pass tube heat exchanger
- Flue gas passage
The computational mesh

- Inner wall extension: W1
- Upper SA nozzle tubes (x 16): W2
- Outer wall of the channel: W3
- Inner wall of the channel with bottom extension: W4

- Baffle plate: Solid domain
- Boiler inner volume: Fluid domain
- SA nozzles: Fluid domain for case C0B or mass flow inlets for other cases
- SA diffuser: Fluid domain for case C8B or void domain for other cases
- Reactor: Fluid domain
- Fixed grate: Mass flow inlet Zones Z1-Z6
- SA channel: Mass flow inlet
- Water mantle: Heat transfer coeff.
- Chimney: Pressure outlet
Numerical investigation of air staging

• **Purpose of the study:**
  – Determine the influence of the boundary conditions of SA supply inflow on the results of the numerical simulation of wood pellet combustion in the small-scale boiler.
  – Determine a simplified set of boundary conditions of the SA inflow and the walls of the SA supply assembly, that produced results with the lowest error compared to the base case (fully resolved).

• **Motivation:**
  – The inclusion of the SA supply diffuser and canal in the computational domain requires additional computational power, as temperatures of the thin walls are predicted not prescribed.
  – Additional processing power is also required to solve complex coupled systems, for example: preheating of SA with the heat flow from the flame and the fuel bed via convection and radiation.

• **Usability and practicality:**
  – Influence of correct choice of boundary conditions on quality (accuracy) of results.
  – Reducing the complexity of performing simulation increases the usability of such tools.
Simulation strategy

**Base simulation:**
The SA canal is included in the computational domain

**Modification of boundary condition of the SA supply**
- The SA diffuser is removed from the domain

**Modification of boundary conditions of the SA walls**
- The SA diffuser is removed from the domain

<table>
<thead>
<tr>
<th>Case</th>
<th>Air inflow parameters at the SA nozzles</th>
<th>SA walls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature</td>
<td>Mass flow</td>
</tr>
<tr>
<td>$T_a$</td>
<td>$m_{UN,a}$ / $m_{LN,a}$</td>
<td>Type</td>
</tr>
<tr>
<td>C0B</td>
<td>Calculated, i.e., realistic: SA channel included in the domain</td>
<td></td>
</tr>
<tr>
<td>C1N</td>
<td>Uniform: $T_{\text{room}}$</td>
<td>Uniform: geometric</td>
</tr>
<tr>
<td>C2N</td>
<td>Uniform: $T_{\text{ave}}$</td>
<td>Uniform: geometric</td>
</tr>
<tr>
<td>C3N</td>
<td>Uniform: $T_{\text{ave}}$</td>
<td>Uniform: realistic</td>
</tr>
<tr>
<td>C4N</td>
<td>Uniform: $T_{\text{ave}}$</td>
<td>Realistic</td>
</tr>
<tr>
<td>C5N</td>
<td>Realistic</td>
<td>Realistic</td>
</tr>
<tr>
<td>C6N</td>
<td>Realistic</td>
<td>Realistic</td>
</tr>
<tr>
<td>C7N</td>
<td>Realistic</td>
<td>Realistic</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Case</th>
<th>SA walls boundary conditions</th>
<th>SA inflow</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wall BC</td>
<td>Coupling</td>
</tr>
<tr>
<td>C0B</td>
<td>Calculated, i.e., realistic: Thin coupled walls with shell conduction</td>
<td></td>
</tr>
<tr>
<td>C1W</td>
<td>Uniform temperature: $T_{\text{ave}}$</td>
<td>NO</td>
</tr>
<tr>
<td>C2W</td>
<td>Uniform heat flux: $q_{\text{ave}}$</td>
<td>NO</td>
</tr>
<tr>
<td>C3W</td>
<td>Uniform convection: $h_{\text{ave}}$</td>
<td>YES</td>
</tr>
<tr>
<td>C4W</td>
<td>Uniform convection: $h_{\text{ave}}$</td>
<td>YES</td>
</tr>
</tbody>
</table>
Numerical models

- **Commercial code ANSYS FLUENT is used:**
  - Homogeneous combustion in the freeboard region is described by a two-step global mechanism with CO as the intermediate species.
  - **Finite rate/eddy dissipation** with modified model constants of $A = 0.6$ and $B = 0.5$ is used to describe the turbulence-chemistry interaction.
  - Turbulence is modelled by a realizable k-ε model, with scalable wall functions and full buoyancy effects. The fluid flow was solved with a SIMPLE solver algorithm.
  - The discrete ordinates (DO) model is used for the radiative heat transfer.
  - The Smith et al. air-fuel WSGGM domain-based concept is used to evaluate the absorption coefficient of the local gas mixture.

<table>
<thead>
<tr>
<th>Volatile combustion</th>
<th>Carbon monoxide combustion</th>
</tr>
</thead>
<tbody>
<tr>
<td>$CH_{2.529}O_{1.083}N_{0.009} + aO_2 \rightarrow CO + bH_2O + cN_2$</td>
<td>$CO + 0.5 O_2 \rightarrow CO_2$</td>
</tr>
<tr>
<td>$\frac{d[Volatiles]}{dt} = A \cdot e^{\frac{E}{RT}} \cdot [Volatiles]^{0.2} [O_2]^{1.3}$</td>
<td>$\frac{d[CO]}{dt} = A \cdot e^{\frac{E}{RT}} \cdot [CO][O_2]^{0.25}$</td>
</tr>
</tbody>
</table>
Base case validation

![Graph showing Temperature RMSE and AE for PS-CZ, S-CZ, and P-CZ.

Measured and predicted SA wall temperatures:

<table>
<thead>
<tr>
<th>Case</th>
<th>Temperature at the positions displayed in Figure 7 [°C]</th>
<th>Error [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>exp</td>
<td>669, 502, 514, 698, 438, 443</td>
<td>RMSE 63, AE -55</td>
</tr>
<tr>
<td>C0B</td>
<td>593, 484, 467, 587, 405, 397</td>
<td></td>
</tr>
</tbody>
</table>

\[
RMSE_{T,base} = \sqrt{\frac{\sum_{i=1}^{n}(T_{C0B,i} - T_{exp,i})^2}{n}}
\]

\[
AE_{T,base} = \frac{\sum_{i=1}^{n}(T_{C0B,i} - T_{exp,i})}{n}
\]
SA distribution between nozzles
Temperature prediction accuracy

\[ RMSE_{\text{case}} = \sqrt{\frac{\sum_{i=1}^{n}(T_{\text{case,}i} - T_{\text{CB,}i})^2}{n}} \]

\[ AE_{\text{case}} = \frac{\sum_{i=1}^{n}(T_{\text{case,}i} - T_{\text{CB,}i})}{n} \]
Contours of temperature
Contours of CO mass fraction
CO emission prediction

- **Comparison of CO concentration at domain output:**
  - The concentration of CO in flue gases in normal operation (experiment): $150 \text{ mg/m}^3 (10 \% \text{ O}_2)$.
  - The boundary conditions affect the CO emission results in a similar way as the temperatures.
  - There is a strong correlation between AE of temperature and AE of CO concentrations at the secondary combustion zone.
Velocity profile at nozzles

- **Reasons for different results:**
  - The “realistic” velocity profile is complex.
  - There is still some differences between the case C0B and C1W.
Computational effort

• Comparison of CO concentration at domain output:
  – The cases where the reduced mesh was used were computationally less expensive.
  – Case C1W required 29 % less time, to acquire a converged solution.
  – The computational mesh had 23 % less elements than the full mesh, which reduced the manipulation times of files (i.e., copying, saving and moving).
Conclusion and future work

• **The Impact of boundary conditions of SA flow on simulation results:**
  – Boundary conditions of SA flow significantly affect the accuracy of the temperature field results inside the combustion chamber and the CO concentration at the output of the domain.
  – The temperature of the SA inflow has a significant larger effect on the accuracy of the results than the distribution mass flow distribution through individual openings or the turbulence settings.

• **Impact of wall boundary conditions of the SA diffuser on simulation results:**
  – The different boundary condition of the SA diffuser walls have a significant impact on the accuracy of the temperature field results inside the combustion chamber and the CO concentration at the outlet.
  – It is essential that at least one type of wall boundary condition is assessed with sufficient precision (e.g., fixed temperature, heat flow, convection) as the adiabatic boundary condition is not appropriate.

• **Use of the reduced computational domain:**
  – It is possible to obtain comparable results using a reduced computational domain.
  – The computational mesh was reduced from 4.35e+6 to 3.34e+6 elements (23% reduction).
Thank you for your attention!