ABSTRACT: In this paper, the work on the development and test of a basic design tool for the automatic performance of parameter studies for the optimisation of biomass combustion plants is presented. The model consists of parameterisation and optimisation routines linked with an in-house developed empirical packed bed combustion model as well as gas phase CFD models especially adapted for biomass grate furnaces. To test and verify the routine developed, it has been applied for the optimisation of a 180 kW pilot-scale grate furnace. The main focus was on the minimisation of CO emissions and the pressure loss by changing the diameter and angle of the secondary air nozzles. The simulation results show that the time of the optimisation process can be reduced considerably by the automatic routine developed and the evaluation of several independent design variables is possible. This new procedure forms an important milestone towards automatic CFD based furnace and boiler optimisations in the future.

Keywords: CFD, optimisation, combustion, biomass
2.2 Selection of the design variables

The secondary air nozzles are of special importance when designing and optimising a biomass furnace. They are the key factor for an efficient air staging without backflow in the primary combustion zone (NOx reduction by primary measures), for a good turbulent mixing and CO burnout, to reduce furnace volume and to lower excess air (increased efficiency). Therefore, the diameter and the angle of the secondary air nozzles were selected as design variables in order to achieve the best geometric configuration concerning low CO emissions and pressure losses over the secondary air nozzles.

2.3 Optimisation routine

A weight function has to be defined to combine the two optimisation parameters (CO emission, pressure loss over the secondary air nozzles) according to their relevance in a common function. While the energy demand of the fan linearly increases with the pressure loss over the secondary air nozzles, the relevance of the CO emissions substantially increases if a certain level of CO emissions is exceeded. Equation (1) shows the weight function.

\[ W = A \left( \frac{1}{Y_{CO}} \right)^{\alpha} + B \cdot \Delta P \]  (1)

A, B and \( \alpha \) are constants, \( \Delta P \) represents the pressure loss [Pa], \( Y_{CO} \) the mole fraction of CO [ppmv] and W the weight function. Here, for the pressure drop a linear correlation has been assumed (proportional to the energy demand of the fan). Regarding the CO emissions a polynomial function with a strong increase at a chosen emission limit (20 ppmv) was supposed.

The design variables and their variation range are shown in Table I. Within the optimisation process the design variables are varied and evaluated using the weight function. The optimisation cycle for a selected combination of design variables works as follows:

- Parameterisation of the geometry and definition of design points based on selected design variables
- Automatic performance of CFD simulations with Fluent for the defined design points within ANSYS Workbench
- Evaluation of the output parameters and calculation of the weight function for the design points
- Minimisation of the weight function to find the optimum geometric configuration (input parameters)

Table I: Design variables and their range of variations

<table>
<thead>
<tr>
<th>Design variable</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter [mm]</td>
<td>10-35</td>
</tr>
<tr>
<td>Angle [deg]</td>
<td>1-30</td>
</tr>
</tbody>
</table>

2.4 Case study description

To investigate the efficiency of the method developed, a design optimisation for a pilot-scale moving grate furnace equipped with a hot water fire tube boiler (180 KWth) using Miscanthus as fuel has been carried out. Table II provides the most relevant operational conditions of the furnace and the fuel composition.

Fig. 1 illustrates the different sections of the biomass combustion plant considered. The simulation domain comprises the combustion chamber from above the fuel bed up to the exit of the radiative fire tube. While the primary combustion zone is equipped with six flue gas recirculation nozzles, at the entrance of the secondary air combustion chamber, eight secondary air nozzles are located.

Table II: Operating conditions and fuel characteristics of the pilot-scale grate furnace

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler load</td>
<td>KWth</td>
<td>180</td>
</tr>
<tr>
<td>Adiabatic flame</td>
<td>°C</td>
<td>937</td>
</tr>
<tr>
<td>O2 content in the dry flue gas</td>
<td>Vol.%</td>
<td>8.4</td>
</tr>
<tr>
<td>Flue gas recirculation ratio</td>
<td></td>
<td>0.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel characteristics</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>wt.% d.b.</td>
<td>48.3</td>
</tr>
<tr>
<td>H</td>
<td>wt.% d.b.</td>
<td>5.9</td>
</tr>
<tr>
<td>O</td>
<td>wt.% d.b.</td>
<td>43.0</td>
</tr>
<tr>
<td>N</td>
<td>wt.% d.b.</td>
<td>0.3</td>
</tr>
<tr>
<td>Moisture content</td>
<td>wt.% w.b.</td>
<td>15.4</td>
</tr>
<tr>
<td>Ash</td>
<td>wt.% d.b.</td>
<td>2.5</td>
</tr>
<tr>
<td>NCV</td>
<td>kJ/kg w.b.</td>
<td>14.8</td>
</tr>
<tr>
<td>GCV</td>
<td>kJ/kg d.b.</td>
<td>19.3</td>
</tr>
</tbody>
</table>

3 RESULTS

To verify the efficiency of the optimisation strategy concerning the reduction of the overall time for the
performance of the case study in comparison to conventional manual methods, at first a manual optimisation run was carried out (as a reference). Since this method is very time consuming, only the diameter of the nozzles has been changed (for 10 design points). A computational grid with 700,000 cells in total was used in the manual optimisation study. In a next step, the automatic optimisation routine was performed for the two selected design variables for 80 design points. The number of computational cells was about one million for the automatic optimisation study using the tetrahedral cell type. Figs. 2 and 3 show the calculated results concerning CO emissions and pressure losses for the manual and the automatic optimisation method. The trends for both methods generally are in good agreement for the comparable design points.

The reduction of the diameter of the secondary air nozzles causes a higher velocity at nozzle exit. This results in a better mixing of secondary air with the flue gas due to a deeper penetration of the air jets into the flue gas. Furthermore, the pressure loss increases due to the higher kinetic energy loss with decreasing nozzle diameters.

![Figure 2: CO emissions calculated with the automatic and the manual optimisation method](image)

![Figure 3: Pressure losses calculated with the automatic and the manual optimisation method](image)

Fig. 4 shows the dependency of CO emissions on the angle of the secondary air nozzles for different diameter ranges. The results show that the CO dependency is low for smaller diameters and increases for larger diameters. On the other hand, for the same diameter range the variation of the angle of the nozzles nearly has no impact on the CO emissions. Generally, it has been found that the output variables are more dependent on diameter rather than on the angle.

![Figure 4: Dependence of CO emissions on the angle of secondary air nozzles for different diameter ranges.](image)

![Figure 5: Weight surface from automatic optimisation calculated based on 80 design points (tetrahedral mesh type with 1 million computation cells).](image)

Additionally, a further automatic parameter study has been carried out to investigate the influence of the grid type on the computation time and the accuracy. For this purpose, two sets of grid were studied: a tetrahedral mesh and a polyhedral mesh. While the first grid type has been used as reference grid with 1 million cells (high resolution), the polyhedral type was generated by a conversion of the tetrahedral mesh type. This method reduces the number of mesh cells to approximately 250,000 cells.

The influence of the different grids on the results is shown in Fig. 6. The CO emissions calculated with the polyhedral mesh show slight deviations from the results with the tetrahedral mesh, since the penetration of the secondary air is underestimated due to large cell sizes in the region of the nozzles. The calculated weight function for the different meshes is shown in Fig. 8. While at a diameter of approximately 15 mm the pressure drop is below 200 Pa, the CO concentration at the outlet of the secondary combustion chamber is still below 8 ppmv (see...
Although the CO emissions calculated with the polyhedral mesh show slight deviations from the values calculated with the tetrahedral mesh, the optimum of the weight function is located at the same position (see Fig. 7).

In case of the tetrahedral mesh type the overall optimisation time took one month considering two optimisation variables (diameter and angle for 80 design points). By using the polyhedral mesh, the optimum of the parameter study was found within 6 days. In contradiction, a manual design study would need approximately 8 months due to the comprehensive number of person-hours to create the numerical grid and to set-up the calculations for each design point.

Despite slight deviations in CO emission predictions from the reference grid, the polyhedral mesh shows a great potential to accelerate the optimisation cycle. A local mesh refinement in the region of secondary air jets is needed for an improved CO prediction and is expected to just slightly increases the mesh size and hence computation time.

4 SUMMARY AND CONCLUSIONS

A new automatic optimisation routine was developed and tested for a biomass pilot-scale grate furnace concerning the minimisation of CO emissions and pressure loss. The results showed that the diameter had a considerably higher impact on the pressure losses and CO emissions than the nozzle angle. The parameter variation performed automatically is by far more efficient than the manual case study due to the considerably lower simulation time and personnel demand. The overall simulation time for the calculation of 80 design points could be reduced by a factor of 8 in case of the tetrahedral mesh study and by a factor of 32 in case of the polyhedral mesh study. Although the CO emission trends were slightly differing for the two studied grid types the global minimums are located nearly at the same positions. However, the prediction accuracy of the coarser polyhedral mesh can be further improved at an acceptable increase of computational time by further increased local mesh refinement near the secondary air nozzles. Concluding, the new CFD optimisation routine proofed to work efficiently in terms of nozzle design optimisation and time demand. In future it shall be further extended to geometry optimisation issues.

5 REFERENCES

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