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Optimising design of secondary combustion chambers using CFD

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Abstract

Secondary combustion chambers belong to key equipment in units for thermal processing of waste, including waste to energy systems. This work uses a real industrial chamber as a baseline in simulations. Work presented here continues with finding of ideal proportions of cylindrical secondary combustion chamber (height/diameter ratio). The aim of this work is to find minimal tolerable height/diameter ratio which will secure the environmental limits and which will have the minimum investment costs. For this purpose, the baseline geometry has been slightly modified to compare with other simulated geometries. Total count of five alternative geometries has been simulated and results have been compared.

Keywords

CFD optimisation, CFD modelling, CFD simulation, Secondary combustion chamber, Afterburner chamber

1. Introduction

Hazardous waste incinerators incorporate secondary combustion chambers (afterburner chambers) as means for providing necessary temperature and residence time to oxidize all combustible compounds contained in raw flue gas. Secondary combustion chamber treats the flue gas produced in first stage of an incinerator, typically a rotary kiln or a gasification reactor. It is usually equipped by one or more burners that heat up the raw flue gas to a required temperature level, which depends on composition of the waste and is usually prescribed by the local legislation together with some other parameters.

1.1. Legislation

For the purpose of the present work, the prescribed temperature and residence time are given by the valid legislation of the EU, i.e. EC (1994) and EC (2000). The required residence time is at least 2 seconds and the required temperature “after the last combustion air inlet” is 850°C or 1 100°C, where the second value is valid for hazardous waste containing more than 1 % of chlorine on mass basis. It should be noted that the legislation does not specify whether combustion process should be performed in one or more stages. In practice it has however been verified that almost perfect decomposition and oxidation may be achieved by a two-stage process.

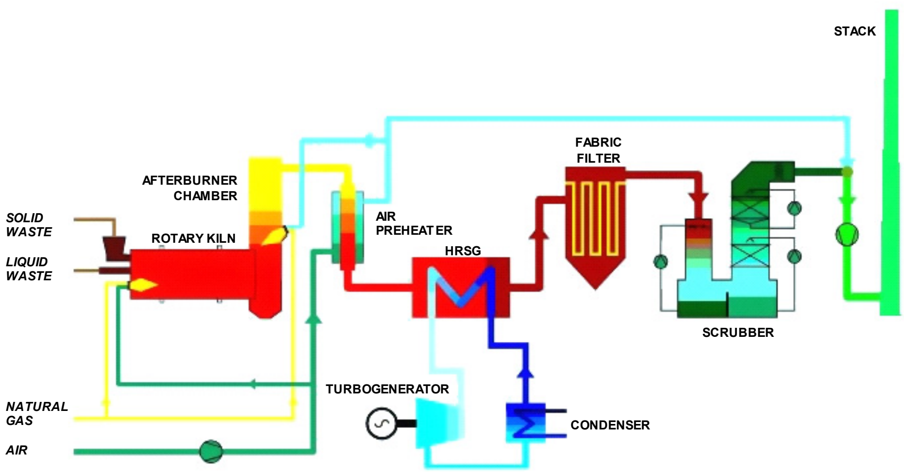

Figure 1 Simplified flow diagram of the investigated hazardous waste incineration plant

1.2. Simulated plant

The overall incinerator’s process flow diagram is displayed in Figure 1. Waste treatment capacity of the plant is given by maximum heat duty of about 10 MW. The incinerator treats industrial hazardous waste from petrochemical production plant with calorific value from 8 to 30 MJ/kg. Heat generated by the process is utilised for combustion air preheating but also for steam and hot service water production, which is quite unusual for an incinerator of this size – see the heat recovery steam generator (HRSG), turbogenerator and condenser in the flow diagram. Flue gas cleaning is performed by a fabric filter and a three-stage wet scrubber.

2. Objectives

This work continues with the investigation of the ideal proportions of cylindrical secondary combustion chamber. It bases on the conclusions of the former work, in which the industrial secondary combustion chamber was analysed under various conditions and additionally, an alternative geometries were simulated to provide information about optimum afterburner chamber design. In this work, the baseline design is compared with 5 different geometrical alternatives in order to find approximate relation of resident time on height/diameter ratio. The work leads to a definition of methodology for design optimisation of secondary combustion chambers that shall serve as direction indicator for further work.

3. Case study

3.1. Adopted approach

In most cases in practice, afterburner chambers are geometrically very simple devices, typically formed by an extended circular cylindrical part of flue gas duct with attached additional burners. Such design simplicity is clearly advantageous from the point of view of investment costs. It also yields to a simple balance analysis, assuming plug flow. A question we therefore ask in the first place is – what are the optimum proportions of such cylindrical afterburner chamber?

Thus it becomes apparent that the design of secondary combustion chambers is not a simple and straightforward task. In the past, only intuitive design or trial and error approach were available as tools for improving secondary combustion chamber performance. Nowadays we can use much more rigorous approaches, based on computational fluid dynamics (CFD) simulations. CFD can provide the values of important parameters like temperatures, residence times, oxygen concentration levels etc., thus enabling full design optimisation of secondary combustion chambers during their design phase.

The present work analyses the first fundamental question raised in this section, i.e. *what are the optimum proportions of a cylindrical secondary combustion chamber*. The answer to this question is of course dependent on implicit assumptions about the number, position and design of burners, way of introducing raw flue gas into the afterburner chamber and way of leading it off. These constraints are to some degree dependent on the process specifications; otherwise they are based on rather arbitrary designer's judgement.

3.2. Simulated alternatives

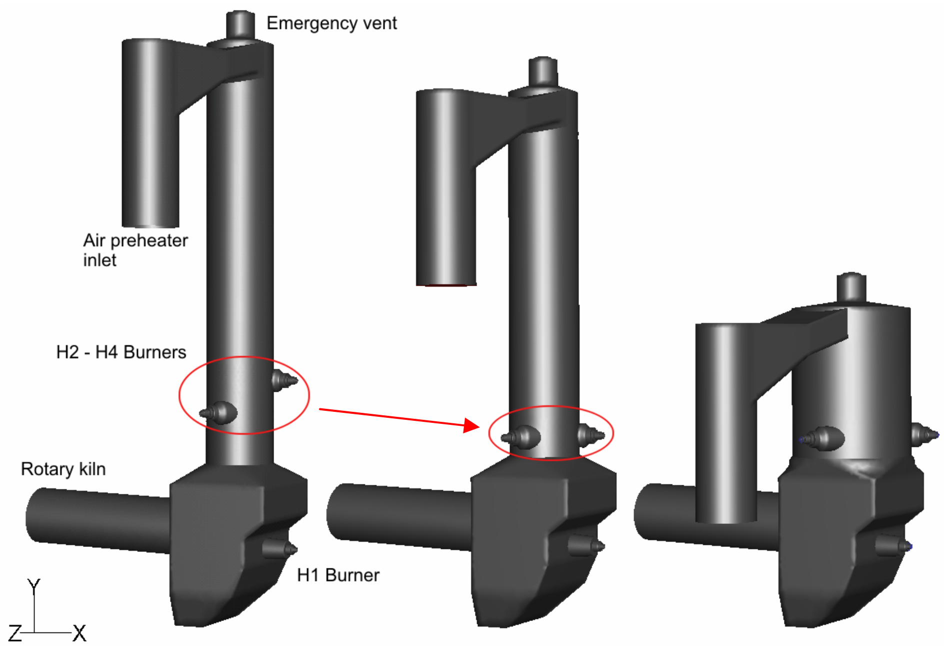

Figure 2 Geometry of simulated alternatives (from left: baseline, alternative 1, alternative 5)

Figure 2 shows some of the simulated alternatives. Five comparable alternatives were derived from baseline by lowering three additional burners down and to the same level and by modifying height/diameter ratio. Five alternatives with diameters 2.6, 3.0, 3.5, 4.0 and 4.4 m represent height/diameter ratios 4.7, 3.1, 1.9, 1.3 and 1.0 respectively.

3.3. Computational model setup

The CFD simulations have been performed by the FLUENT 6.2 (2005) solver. Full system of five Navier-Stokes equations (continuity, three momentum equations and energy) was solved together with seven equations of Reynolds-Stress turbulence model (turbulent energy dissipation rate and six equations for turbulent stresses), five equations of species transport (chemical reaction mechanism was a two-step methane combustion model and the reaction kinetics was governed by an eddy-dissipation model) for the six participating chemical species (CH_4, N_2, O_2, CO_2, H_2O and CO), and the radiative heat transfer equation (discrete-ordinates method). Natural gas was substituted by pure methane.

Numerical solution was performed with a second-order discretisation in pressure, density and velocity equations. The remaining equations were discretised by a first-order upwind scheme. Coupling of the pressure and momentum equations was provided by the SIMPLE method.
The boundary conditions were set according to the operating conditions of the real industrial chamber, which acts as a baseline case. It means 100 % of waste capacity is used and burners in secondary combustion chamber are operating at their nominal power, i.e. 2.2 MW for H1 burner and 850 kW for H2 - H4 burners.

3.4. Summary of results

Since the temperatures in all simulated alternatives are sufficient and fulfil the legislation the results presented herein are concerned with the residence time which varies through the alternatives. Table 1 specifies the resident times in baseline and five alternatives. It is obvious that only baseline fulfil the legislation limit which demands the minimum residence time 2 s. All other simulations performed did not meet the requirements, even the alternative 1 which has the same height/diameter ratio as baseline.

	Height/ diameter ratio	Elapsed time [s]			
		Minimum	Maximum	Average	Standard deviation
Baseline	4.7	2.09	3.56	2.48	0.35
Alternative 1	4.7	1.88	5.84	2.56	0.73
Alternative 2	3.1	1.85	6.00	2.67	0.48
Alternative 3	1.9	1.57	5.94	2.52	0.75
Alternative 4	1.3	1.74	4.50	2.75	0.59
Alternative 5	1.0	1.79	3.24	2.36	0.36

Table 1 Statistical summary of residence times

4. Conclusions

The present work proved that the height/diameter ratio of cylindrical part of secondary combustion chamber is definitely not the only parameter which affects the residence time. Comparison between two alternatives with same height/diameter ratio but different geometrical arrangement of burners is interesting. It is obvious that the geometrical arrangement also "before the last combustion air inlet" has big influence onto flue gas stream behaviour after it. Different burners' setup in baseline is causing more intensive and more homogenous swirl in the chamber and the flow is closer to the ideal plug flow than by the alternative 1, where, after more detailed investigation, the thin axial bypass was identified. This bypass is causing lower minimum particle resident time.

The aim of this work, which was to find minimal tolerable height/diameter ratio, was not completely carried out, since none from simulated alternatives fulfils the legislation residence time request. However the obtained results are giving some clue to solve this problem. Assuming that by the changing of burners' arrangement the minimum particle residence time could be approximately 0.2 to 0.3 s increased, the desired minimal height/diameter ratio could be about 3, which corresponds to former conclusions of Ficarella and Laforgia (2000).

To define a methodology for design optimisation of secondary combustion chamber is a very difficult task. The afterburner chamber is usually unique equipment which definitely is not an object of serial production. It is always necessary to taking to account that it is a part of complex system a there are many factors affecting its performance.

Acknowledgements

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