Innovative Approach for Improved Modelling Accuracy in Case of 3D CFD Sewage Sludge Combustion Simulations

A. Žnidarčič[1], T. Seljak[1], T. Katrašnik[1]

1. *LICeM Laboratory, Department of Energy Engineering, Faculty of Mechanical Engineering, University of Ljubljana, Slovenia*

INTRODUCTION

Furnace design and operation optimisation can be greatly improved with valid 3D CFD combustion simulations. A need for valid sewage sludge (SS) combustion modelling is recognized with increasing interest for SS thermal treatment prior to its final disposal. This is especially notable in case of small scale systems due to their dimensional and hence also thermal power constraints. In spite of these, such systems are interesting as they express higher public acceptance and manageable investment cases. The main obstacle in developing credible simulation models and thus simulations of them is recognized to be highly variable SS composition and small combustion chamber volumes in small scale systems. Furthermore, high ash and moisture mass fractions included in SS [1, 2] make it a challenging fuel. Additionally, the ash is present in a form of a porous matrix which entraps combustible matter [1]. Finally, vast amount of various volatiles is emitted upon thermal degradation at different temperatures, making SS more challenging to describe than other solid fuels [3]. Sludge composition and the processes taking place during its combustion are presented on Figure 1.

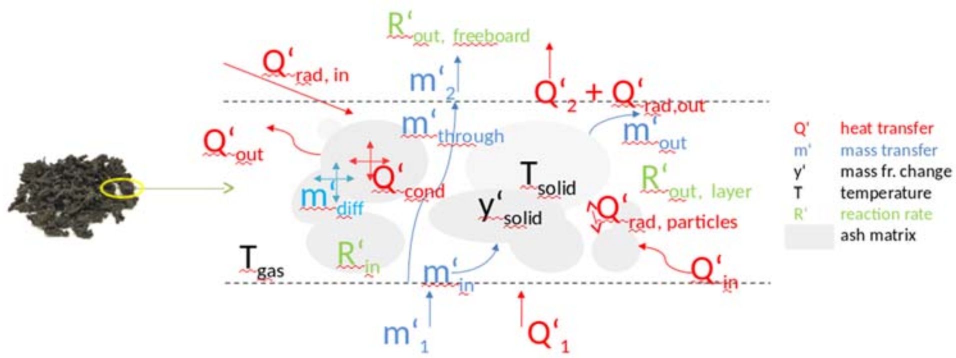

Figure 1: Sludge example (left) with depiction of its composition and processes taking place during the combustion (right)

The aforementioned need for valid 3D CFD modelling of sludge combustion thus requires a development of combustion model, which is capable of addressing different problematic aspects of SS composition. In the present work, the current modelling approach is explained at first, followed by the brief presentation of the model itself. This is then supported by the obtained results which depict main strongpoints of the current model. Finally, conclusions are given with the future work remarks.

corresponding author: *please indicate here name and email of the corresponding authors*

MODELING FRAMEWORK

Modelling approach was chosen considering SS complexity and legislative constrains, which impose limits on the lowest flue gas temperature (850 °C) and residence time (2 s) in furnaces for its incineration [4]. Successful modelling of SS combustion depends on the ability to capture the complexity of emitted volatiles and properly forecast their correct spatial distribution in a furnace, which is a challenging task due to heterogeneous composition of SS. The common point of these considerations are the processes in the gas phase. To keep the complexity low and provide a robust methodology which can suitably react to composition variations, an effective modelling approach based on fuel surrogates was chosen. The surrogate model is additionally supported with an external 0D bed model in order to include fuel bed effects on emitted surrogated species as well. Both choices are backed with the existence of experimental and thus also validation data, which originates from batch combustion of SS in a small scale laboratory furnace. The furnace and data example obtained from it are shown in Figure 2.

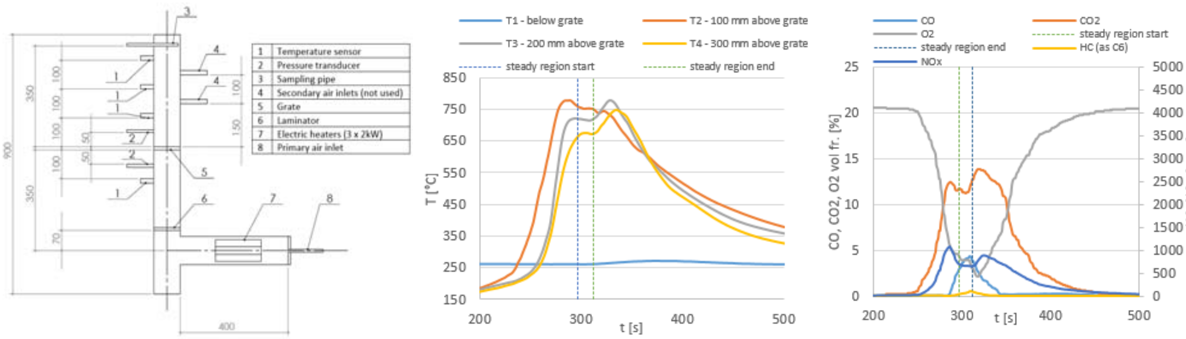

Figure 2: laboratory furnace and example of results obtained from SS batch combustion

DEVELOPED SURROGATE MODEL

The proposed surrogate model has its basis set on the short steady state interval during peak combustion (indicated in Figure 2), where the majority of volatiles is emitted and weighted influence of a proper surrogate composition is the highest. A successful simulation of this phase naturally confirms the suitability of the modelling approach for other combustion intervals as well. These intervals (start of combustion, post combustion) are omitted at this time since they contribute a relatively minor energy input and simpler volatile composition in comparison to peak combustion interval.

It is important to notice that combustible gases applied in 3D CFD simulations of solid fuels are usually composed of syngas components, where heavier hydrocarbons, if present, are applied through much simplified reaction mechanisms. This is a valid and accurate approach in many cases, such as [5, 6, 7]. In our case however, the mentioned complexity of the fuel, combined with the issues caused by spatial confinement of combustion chamber in small scale systems, demands a further step in this regard. As literature such as [3] shows, volatiles emitted from SS include considerable amount of heavier hydrocarbons alongside syngas components, which are otherwise the main volatile components [2]. The developed surrogate model is thus build with ability to allow a proposition of a surrogate mixture, which is in its main parts composed of syngas components and includes an arbitrary hydrocarbon in order to introduce heavier hydrocarbon effects. In order to ensure its suitability, the model is built on determining the quantity and composition of the surrogate on the basis of experimental data from a simple and reliable test run, which enables it to respect the mass balances of C, H and O. A further crucial point for its suitability is that at the same time, it allows for a heavier hydrocarbon representative addition in a ratio to the syngas components similar to the one found in literature such as [3]. It therefore follows that the model provides one a tool for definition of suitable surrogate composition without the use of complex measuring techniques such as TGA combined with MS.

To further increase the accuracy of the model, external 0D model of the fuel bed is used to obtain missing data on the appropriate fuel bed conditions such as temperature and mass fraction of fuel burnt in the bed. Through this, the inlet boundary conditions of the computational domain are also set. In such a way, mass and energy balances measured in experiments are respected, while the surrogate composition can be varied in realistic manner.

Appropriate surrogate composition is however still impossible to define without accurate reaction mechanisms. The model thus implies the use of detailed reaction mechanisms, for instance [8, 9], which include and are suitable for chosen heavier hydrocarbons. This approach is feasible in considered 3D CFD because of the small computational domain. Simulations with the developed surrogate model and applied detailed reaction mechanisms therefore allow one to propose a suitable surrogate composition, which enables more accurate modelling of gas phase processes. Consequently, it is possible to better design primary and secondary combustion chamber zones, since temperature and concentration fields are more accurately determined in small confined spaces than with existing models.

RESULTS

The model was applied in the presented small furnace case, where the combustion peak interval was simulated. Due to the use of surrogate approach the domain includes only the simple cylindrical geometry above the fuel bed. As mixing of various components in the domain is important, heterogeneous placement of surrogates on the inlet, separated into unburnt and burnt volatiles, was applied. Two types of surrogates were placed in an evenly dispersed manner, which was found to be the closest to real conditions.
Results, obtained up to now, show a clear impact of surrogate composition. Hydrogen mass fraction was found to have highest effect on combustion behaviour with higher H_2 presence leading to faster combustion, while at very low H_2 presence, combustion was impossible to be sustained. An example of this is shown on Figure 3, where surrogates without heavier hydrocarbons were applied. Importantly, presence and type of heavier hydrocarbon was also found to affect combustion as it was shown that, for instance, ethanol enables a much better match between simulated and measured CO mass fraction and temperature in flue gas than heptane. These results are shown on Figure 4.

Figure 3: temperature fields in simulations without heavy hydrocarbons included for 0,9 % (top), 1,7 % (middle) and 2,5 % (bottom) H_2 mass fraction in fresh surrogates

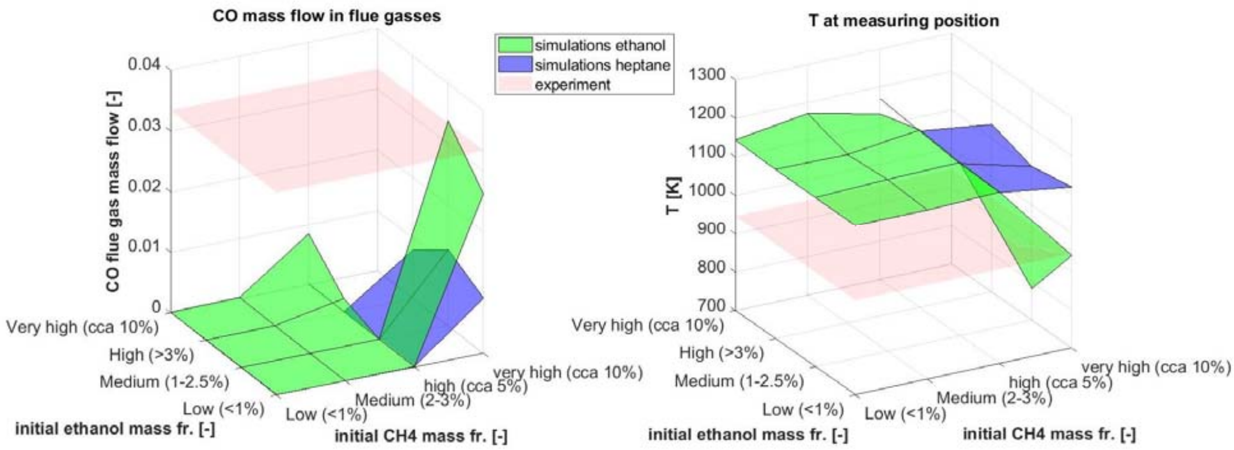

Figure 4: simulated and measured flue gas CO mass fraction (left) and temperature (right)

CONCLUSION

The abstract presents a new and innovative approach to SS combustion simulations, where considerable frontloading in development process is applied in order to achieve credible 3D CFD simulations of small to medium thermal power output furnaces. The developed surrogate model is the first step in this approach, with the capability of enabling one to find correct volatile description using simple 3D CFD simulations being its main contribution.

Results, obtained with the developed model show important effects of surrogate composition, especially the presence of H_2 and heavier hydrocarbons in it. They confirm that ability to achieve accurate description of phenomena in small to medium scale furnaces depends on these effects and that the developed surrogate model can be used in order to propose surrogates for all combustion intervals, which is one of the first topics of the future work. More importantly, the findings can be used to build more complex and accurate coupled fuel bed-freeboard models, since the appropriate volatile composition is known in advance. Thus the focus in the future modelling can be given solely to the interaction between the solid and gas phases.

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