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Methods and Tools for Reliable Design of Equipment in Waste-to-Energy Units

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Waste-to-energy (WtE) units represent specific technologies that process problematic raw materials (i.e., wastes) and deal with equally problematic products such as flue gasses or solid residues (these often induce fouling and are considerable pollutants). Reliable design of apparatuses which in the respective units carry out the actual waste processing and energy recovery must, therefore, utilize suitable, up-to-date methods and tools while these must, in turn, be able to take into account all the relevant and necessary factors.
Through an industrial example, the paper presents new trends in equipment design for up-to-date WtE units and new design methods and calculation tools which the authors have been developing to ensure high design accuracy and operating reliability of such new equipment.
The developed methods and tools employed within the complex design framework are unique and beneficial in the sense that they have been based not only on theoretical knowledge but also on practical knowledge and experience in designing of the respective non-standard process equipment. Moreover, it is also clearly shown that the corresponding methods and tools can be efficiently used in case of both the design of equipment intended for new WtE units as well as troubleshooting of equipment in units which are already being operated.

1. Introduction

Waste management is a complex problem where the desired result can be achieved in many different ways. These include (i) lower rate of waste generation (i.e., prevention of waste being produced) which leads to obvious reduction in the amount of waste to be dealt with; (ii) landfilling, which is generally unsuitable considering greenhouse gases and potential deterioration of water sources and soil; (iii) separation of individual waste fractions in order to recover various materials; (iv) mechanical-biological treatment; and (v) incineration which is the preferred manner of dealing with the remaining waste (Stehlík, 2016).
The generally recommended approach as per the 2008/98/EC Directive (European Parliament and the Council of the European Union, 2008) is to minimize waste production, reuse and recycle as much as possible, and only then process the remaining waste in other ways. In terms of sustainability, the preferred, up-to-date, and efficient solution is waste reuse and recycling followed by energy utilization of the remainder in WtE plants. This holds true not only regarding specific geographic regions but also many industrial scenarios in which materials cannot be effectively recovered from the residual waste (Stehlík, 2016).

2. New trends in equipment design for up-to-date WtE units

A typical, up-to-date WtE plant consists of three main parts: (i) thermal system, (ii) energy recovery system, and (iii) off-gas cleaning system. This can be easily illustrated via Figure 1 which features a simplified schematic of an industrial process waste gas incineration unit.
New trends in the design of individual pieces of equipment in up-to-date WtE plants are a gradual decrease in spatial requirements (i.e., a move towards higher compactness) and investment and operating costs together with an increase in overall effectiveness of the plant.

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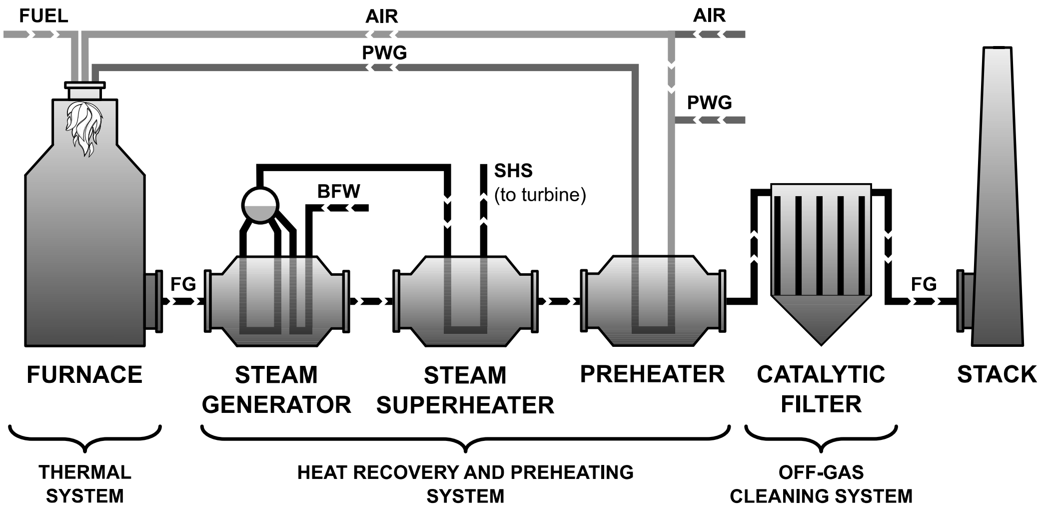

Figure 1: Simplified schematic of an industrial process waste gas incineration unit; FG denotes flue gas, PWG process waste gas, BFW boiler feed water, and SHS superheated steam

This can only be achieved by the reduction in the number of apparatuses and merging functionally different pieces of equipment into singular units. In case of the WtE plant from Figure 1, these new trends can result for example in what is shown in Figures 2 and 3.
For a proper and reliable design of these multifunctional apparatuses, it is necessary to have available a suitable design method. Several such new design method and tools developed for this purpose are presented below.

3. Novel methods and tools for design of new equipment

Given the new trends mentioned in the previous paragraphs, reliable WtE equipment design methods and tools must be available. In case of the WtE unit shown in Figure 2 the areas where improvement is critical are (i) determining the actual heat flux profile for the burner (i.e., how much heat passes from the burner to which part of the heat transfer surface in the combustion chamber) in order for the combustion equipment to be designed properly, (ii) reliable design method for the multifunction regenerative heat exchanger, and (iii) accurate-enough yet fast tool for flow distribution assessment in such equipment. The following sections discuss current research activities pertaining to these three areas.

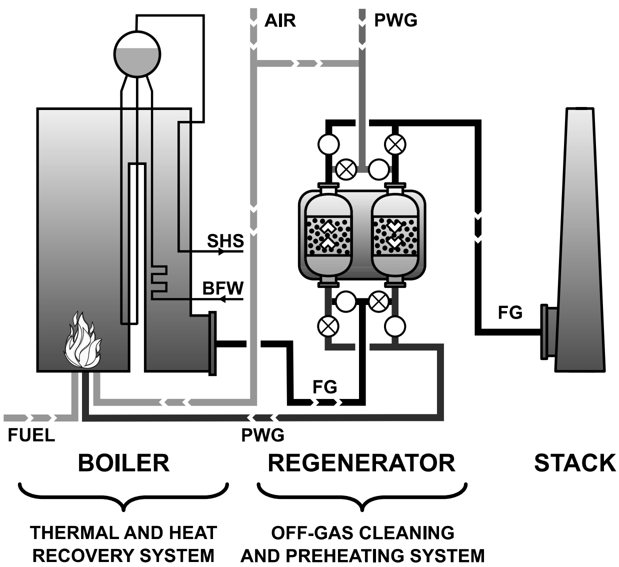

Figure 2: Simplified schematic of the updated process waste gas incineration unit; SHS denotes superheated steam, BFW boiler feed water, FG flue gas, and PWG process waste gas

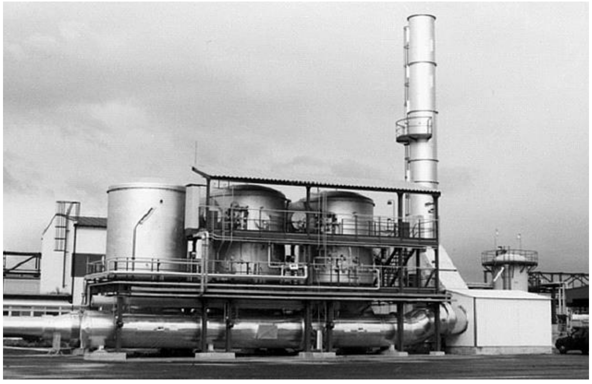

Figure 3: Photograph of the unit from Figure 2; regenerator consists of the two darker vessels left of the stack

3.1 Method for accurate thermal design or evaluation of combustion equipment

A new, accurate thermal calculation method for proper design and evaluation of combustion and radiant chambers with an inbuilt tubular heat transfer system was formulated by Jegla et al. (2016). It takes into account the actual thermal behavior of modern burners (including low-NO_x types) and it aims to be a practical yet accurate method to evaluate heat transfer from the burners to the inbuilt tubular heat transfer system. This must be known to the designer because – in WtE applications where waste or waste-derived fuels are used – thermal behavior of the burners dominantly influences accuracy of prediction of thermal-hydraulic behavior of the fluid which is heated inside the tubular system as well as mechanical loading of this system and its service life with respect to the used materials.

These reasons led to the formulation of a new method involving the excellently-performing Modified Plug-Flow (MPF) model, which has been developed and experimentally shown via tests in a burner testing facility to provide data corresponding to the actual thermal behavior (Jegla et al., 2016). The method consists of three steps: (i) measurement (using a burner testing facility) of the actual heat flux profile of the industrial burner or burners which are to be installed in the combustion or radiant chamber together with the given inbuilt tubular heat transfer system; (ii) conversion of the measured data via the MPF model to a set of parameters that are required for further computations, i.e., calculating the corresponding fuel burnout profile of the burner such that it results in the experimentally measured burner heat flux profile (these parameters represent all the individual thermal characteristics of the burner(s) such as flame length and width, heat release rate along the chamber, etc.); and (iii) accurate thermal design or evaluation of the respective industrial combustion or radiant chamber, containing the tubular heat transfer system in question, carried out using a suitable adapted zonal or plug-flow model which takes into account this heat transfer system and the burner-related data obtained in the previous step.

The latest research results by Jegla (2016) confirm that the Adapted Modified Plug-Flow (AMPF) thermal calculation model is accurate and fully compatible with the third step of the new thermal method because it is derived from the MPF model itself. Validation of the AMPF model, which can be found in the same paper, was carried out by means of comparative industrial operating measurements of local heat fluxes in several parts of the radiant chamber of a fired heater in which a complex system of six low-NO_x burners was installed.

As an example, Figure 4 compares data measured on the radiant chamber of a fired heater with specific high-intensity, low-emission burners being installed and results obtained using the new method employing the AMPF model (Jegla, 2016) with recent recommendations of widely-accepted design standards (in this case of Pelini, 2008). This is presented as a dependence of dimensionless combustion (or radiant) chamber length (or height in case of upward firing) on dimensionless longitudinal heat flux non-uniformity factor, F_L. The figure clearly demonstrates that thermal behavior predicted for modern, low-emission burners using traditional methods, which are still being recommended for design of combustion (or radiant) chambers, differs significantly from what is measured and predicted by up-to-date methods. Consequently, also the predictions of thermal-hydraulic behavior of the heated fluid flowing inside the inbuilt tubular system, mechanical loading of the system, and service life of the apparatus with respect to the used materials would be vastly different. Usefulness of the respective new method for accurate thermal design or evaluation of not only combustion equipment in WtE units but process combustion equipment in general (see e.g. Martin, 1998) is, therefore, obvious.

3.2 Method for reliable design of regenerative heat exchangers

Regenerators are compact heat exchangers in which heat is alternately stored in and removed from a heat storage material (packed bed). Generally, regenerators can be divided into two groups: fixed-bed and rotary. In

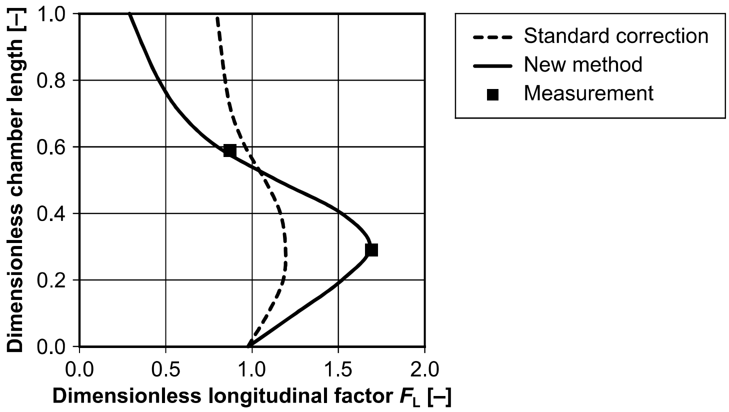

Figure 4: Longitudinal heat flux non-uniformity factor (F_L) for high-intensity, low-emission burners – comparison of the standard (recommended) profile which does not take the actual burner behaviour into account, profile obtained using the discussed thermal method, and results obtained via experimental measurement

our research, we focus on fixed-bed ones which are being frequently used as multifunctional equipment in up-to-date WtE units (as shown in Figures 2 and 3) and therefore the following information is related to this specific type of heat and mass transfer equipment.

The advantage of regenerators over recuperators is that they have much higher surface area for a given volume. Heat storage materials also have partial self-cleaning capability, reducing fluid-side fouling and corrosion. Regenerators are thus ideal for gas-gas heat exchange as waste heat recovery systems. These characteristics predestine regenerators to simultaneous usage as both heat exchangers and reactors, where cleaning of waste can take place (Kilkovský and Jegla, 2016). Implementation of such 2-in-1 units can lead to decrease in investment cost and hence research of this solution is our aim. The main step here is creating a comprehensive calculation system with which the respective behavior of the regenerator/reactor would be estimated.

Accurate regenerator calculation methods involve differential equations and can be classified into two groups: open and closed. Each of these two then comprises two subgroups, namely linear and non-linear methods according to the way in which thermo-physical properties are calculated for the gas and the storage material.

Our calculation system is based on several open and closed methods. As for open methods, in which the cyclic behavior of the regenerator is simulated iteratively, Willmott (1964) is the basis of the linear model and Willmott (1968) if the model is non-linear. In these methods, differential equations are replaced by finite difference formulae obtained using the trapezoidal rule. However, prediction of regenerator heat duty at cyclic equilibrium using open methods can be computationally demanding if many cycles of operation are required to reach the equilibrium state, which is especially the case of non-linear models. This disadvantage does not apply to closed methods where the boundary conditions are incorporated directly into the respective equations. The cyclic equilibrium performance is then computed without the need to iterate over many periods of operation. Here, our system is based on the method by Hill and Willmott (1987) in case of the linear model, which is numerically stable for all practical applications, and the method by Hill and Willmott (1991) if non-linear model is required.

Open and closed methods yield the same solution at cyclic equilibrium for the linear as well as the non-linear model. A combination of the stable closed method together with the open method then provides a comprehensive calculation system for the study of both transient-state and cyclic equilibrium behavior.

Other important tasks are finding heat transfer coefficient, which must include the effect of both convection and radiation, and calculating pressure drops for both streams. Heat transfer coefficient depends predominantly on the type of storage material. The respective equations for convective heat transfer were published e.g. by Sadrameli and Heggs (1997) while for radiative heat transfer they were discussed e.g. by Narayanan and Pramanick (2014). Pressure drop in the packed bed is commonly calculated using the Ergun equation, however, this equation very often over-predicts the respective value and thus we use methods tailored to specific storage materials which are based on experimental data (Allen et al., 2013). Because the aim is to employ the regenerative heat exchanger also as a reactor, a very important part of the calculation method, which must yet be added, will cover chemical reactions in order to predict gas behavior in the catalytic bed.

3.3 Tools for fast and accurate evaluation of fluid flow distribution and for shape optimization

In order to increase equipment efficiency, many types of apparatuses (e.g. heat exchangers) are designed in such a way that the primary fluid stream is massively parallelized. Regarding the requirements on equipment reliability, one of the main phenomena that must then be investigated is flow distribution. This can be done in several different ways, each of which has its advantages and disadvantages. Also, often it is desirable to carry out shape optimization of various parts of the apparatus to further improve performance.

The most efficient approach to estimating flow distribution, albeit the least accurate one, is via a very simple model using only algebraic equations as discussed e.g. by Pustylnik et al. (2010) in case of typical flow systems or by Turek et al. (2014) in case of catalytic converters. Equations of this kind cannot describe the complex flow behavior properly and thus special correction coefficients are employed to improve accuracy. Still, due to its very low computation demand the model can easily be implemented in various optimization algorithms.

The other end of the spectrum is represented by the usual computational fluid dynamics (CFD) models such as the ones implemented in ANSYS Fluent (ANSYS, 2015) which, if the results are to be reliable, necessitate usage of fine-enough meshes and, consequently, powerful computing hardware. Due to the inevitably long evaluation times, in terms of shape optimization such an approach is highly disadvantageous, although still feasible (Turek et al., 2012). On the other hand, this allows one to inspect solution data minutely and evaluate quantities which would be measurable with much difficulty or not at all.

A practical compromise between these two approaches is simplified CFD presented by Turek et al. (2016). It uses (i) a largely simplified mesh consisting of a very limited number of purely cuboid cells and (ii) somewhat simplified mathematical model employing only mass, momentum, and energy transport equations with artificially adjusted molecular viscosity and computationally less demanding differencing scheme and pressure-velocity coupling – e.g. the Power Law Scheme (Patankar, 1981) together with SIMPLEC (Van Doormaal and Raithby, 1984). This results in slightly less accurate results but extremely short computation times. Efficiency of this type of models makes it possible to implement them in optimization algorithms. Nonetheless, gradient optimization methods cannot be used because there is no objective function directly linking input data to the resulting flow distribution, pressure drop, etc. – these are yielded by a series of computation steps.

Given the fact that evaluation time per single geometry is the limiting factor here, the number of points at which the solution is obtained influences the total optimization time significantly more than complexity of the optimization algorithm itself. A composite, derivative-free algorithm suitable for low-degree of freedom optimization problems is therefore recommended. As an example, an algorithm based on the Golden-section method and the Hooke and Jeeves method can be mentioned. First, the actual dimension of the optimization domain is determined from the ranges of individual key dimensions of the element whose shape is to be optimized. If the domain is one-dimensional, then the Golden-section method (Kiefer, 1953) is utilized. If, however, the dimension is larger than one, then a modified method by Hooke and Jeeves (1961) is employed. The implemented modifications are as follows: (i) intelligent selection of initial estimate, (ii) repeated pattern steps of variable lengths, and (iii) searchable list of evaluated flow system geometries. Although the last modification may seem counter-intuitive because searching the list itself takes non-zero time, overall this pays off due to the huge difference between time spent by searching and time spent by evaluating a geometry anew.

4. Conclusions

This paper discusses some of the new trends appearing in equipment design for up-to-date WtE units. Adequate novel design methods and calculation tools are introduced which the authors have been developing to ensure high design accuracy and operating reliability of such new multifunctional equipment; namely, an accurate method for thermal evaluation of combustion and radiant chambers with inbuilt heat transfer systems, a calculation system for design of multifunctional regenerative equipment for combined heat and mass transfer, and a calculation and optimization tool for flow analysis in equipment with massively distributed process streams.

The main advantage of the new thermal calculation method for proper design and evaluation of combustion and radiant chambers is that it, in a systematic way, considers the actual thermal behavior of modern, low-NO_x burners and makes it possible to include results of experimental testing of individual burners directly into the combustion chamber thermal evaluation procedure. This is very important because it significantly increases the accuracy of the predicted thermal-hydraulic behavior of the fluid, which is being heated inside the tubular system, as well as the predicted mechanical loading of this system and its service life with respect to the used materials. In spite of this, the method in question still remains uncomplicated and user-friendly.

The multifunctional regenerative equipment calculation system enables one to design such heat exchangers not only for heat recovery from flue gas but simultaneously also for cleaning of this stream in the catalytic bed, which decreases spatial requirements and investment cost. Also, both transient-state and cyclic equilibrium behavior of these apparatuses can be analyzed using the calculation system. Still, it is essential that chemical reactions taking place in the catalytic bed are modeled, too, by this system for it to be comprehensive.

As for the flow distribution evaluation tool, based on the tests carried out by the authors, the employed simplified CFD approach can yield rather high-quality data for a wide range of equipment geometries and operating conditions. What is more, in case of multiple-dimension shape optimization the discussed composite algorithm seems to be much more efficient than the original Hooke and Jeeves method (generally three to five times as fast depending on the actual optimization domain and flow behavior). A new, extended version of the tool introduced in (Turek et al., 2016) is therefore currently being developed which, in addition to evaluation of flow behavior, would also be able to carry out shape optimization of key flow distribution system parts.

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