31st International Conference
ENGINEERING MECHANICS 2025
Medlov, Czech Republic, May 12 –14, 2025
Paper #22, pp. 213–216, doi: 10.21495/em2025-213

FLY ASH FOULING INFLUENCE ON GRATE COMBUSTION CHAMBER THERMAL CALCULATION

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Abstract: *The article deals with the issue of parametrized fouling properties' influence on the standard thermal design calculation of grate combustion chambers as applied on modern medium-to-low capacity heat sources, burning sustainable lower-quality solid fuels.*

Keywords: Grate combustion, thermal design calculation, particulate fouling, boilers, solid fuels

1. Introduction

The current trend in sustainable energy, characterized by the application of decentralized boilers of medium and smaller thermal outputs to ensure energy supplies at the regional, communal or local level, is characterized by the combustion of non-traditional solid fuels and fuel mixes of a sustainable nature, which will allow reduction of coal used as a non-renewable and unsustainable solid fuel while achieving favourable environmental effects (Ciupek and Frąckowiak, 2024). Lower thermal output solid fuel boilers are coming to the forefront, mainly focused on the energy use of various types of biomass or biomass waste (Kalak, 2023), but also on the use of specific fuel mixes (Zabloudil et al. 2023) (for example, for the energy use of waste including sludge from waste water treatment, non-recyclable plastics, refuse derived fuels, hazardous medical waste, etc.)

Grate combustion is a sufficiently universal and reliable method of burning a wide range of solid fuels and is therefore dominantly used in the current sustainable energy applications. Depending on the nature of the fuel burned, the most suitable type of grate can be selected (e.g. fixed, reciprocating, vibrating etc.) supplemented with a system of optimal multi-stage distribution of combustion air – the most common is the division into primary (through the grate), and secondary (into the furnace) combustion air supply – with a suitable mixing system (e.g. tangential, radial, etc.) (Yin and Li, 2017). Figure 1 shows an example of a modern medium to low-power grate boiler for the combustion of various types of phytomass and biomass.

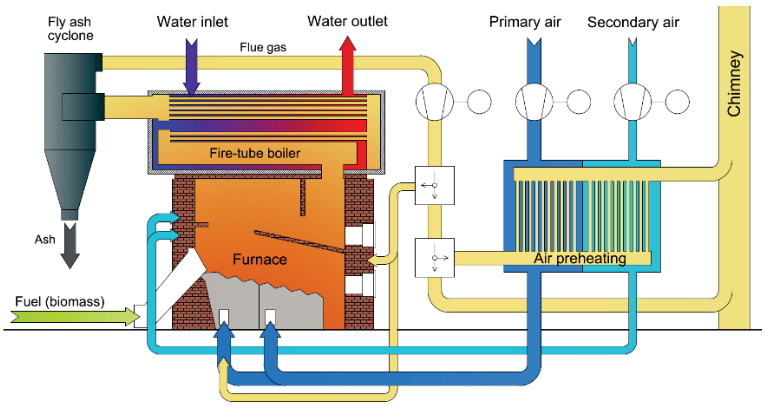

Fig. 1: Typical design of a lower output grate boiler (courtesy of EVECO Brno, s.r.o.)

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Modern economic and environmental solutions for medium to low-power grate boilers burning sustainable fuel mixes are typically characterized by a horizontal fire-tube boiler concept, consisting of a primary combustion chamber (PCC) with a grate and a connected horizontally oriented secondary combustion chamber (SCC) containing most often the first part of the fire-tube heat exchange system (see Fig. 1 above).

Depending on the nature of the fuel burned, such a boiler is usually supplemented with appropriate modern technologies for cleaning and recirculating flue gases and systems for effective use of waste heat, for example for preheating combustion air to optimize fuel consumption and the combustion process.

2. The importance and role of accurate thermal calculation of grate boiler combustion chambers

As demonstrate Ciupek and Frąckowiak (2024), design thermal calculations and their accuracy fundamentally influence the economic and ecological parameters of the designed boiler (i.e. boiler size, fuel consumption and emission production), the optimization of its design, operational behavior and thermal efficiency. An accurately performed thermal calculation allows to minimize energy losses and pollutant emissions, which fundamentally translates into better ecological parameters of the entire energy supply system.

The standard recognized method of thermal calculation of boiler combustion chambers is a globally widespread and used calculation method (often referred to as Gurvich method) based on the following semi-empirical formula (Basu et al. 2000):

$$\frac{T_{bw}}{T_{ad}} = \frac{Bo^{0,6}}{M \cdot a_f^{0,6} + Bo^{0,6}} \tag{1}$$

where:

- T_{bw} $[K]$ is the set and iteratively refined temperature of the flue gas at the exit from the combustion chamber (otherwise called bridgewall temperature)
- T_{ad} $[K]$ is the analytically calculated adiabatic flame temperature of the given fuel
- Bo $[-]$ is the Boltzmann dimensionless number (dependent on T_{ad} and expressing the radiation contribution to the overall heat transfer in combustion chamber)
- M $[-]$ coefficient characterizing the position of the flame in the given furnace
- a_f $[-]$ characteristic furnace emissivity

This method is very suitable for different combustion chamber types (such as grate type, burner type, fluidized bed type etc.) designed for higher capacities, but tends to lose accuracy with medium and low-capacity combustion chambers, as shown by Zabloudil et al. (2023).

The authors' experience shows that for grate boilers of medium to lower capacities, the accuracy of the calculation method will be significantly influenced by the type and properties of the fuel mix being burned and the conditions of its combustion. This is clearly demonstrated, for example, by comparing the operating parameters with the results of thermal calculations of the combustion chambers of two similar operating cases of fire-tube grate boilers from (Zabloudil et al., 2023), burning two different fuel mixes. Selected essential parameters of one of the devices are summarized in Tab. 1, as the same will be used in the following analysis in this paper.

Tab. 1: Operating and design parameters of the studied device in steady state operation

Parameter	Description	Value	Unit
Temperatures:	Mean furnace temperature	990,4	°C
	Furnace exit gas temperature (T_{bw}) - measured	927,6	°C
	Furnace exit gas temperature (T_{bw}) - calculated	943	°C
Fuel:	Type	Hospital waste	-
	Lower heating value (LHV)	15547	kJ/kg
Intermediate	Adiabatic flame temperature (T_{ad})	1053,1	°C
Calculations:	Boltzmann number (Bo)	19,0708	-
	Coefficient of flame position (M)	0,59	-
	Characteristic furnace emissivity (a_f)	0,0434	-

The accuracy of the calculation method could also be partially affected by the variability of the arrangement, design and interconnection of the two main parts of the grate boiler combustion chamber, i.e., its PCC and

SCC. For heat generation from some types of sustainable solid fuel mixes, a grate boiler with a vertical water-tube combustion chamber concept is designed and includes a cooled PCC containing a combustion grate with evaporation heat exchange systems on its walls and a vertical SCC placed above it, formed by the so-called membrane walls of the heat exchange system, while for other types of fuel mixes, a horizontal fire-tube boiler concept is better suited, including an uncooled refractory-lined PCC with a combustion grate and a connected horizontal SCC containing the first fire-tube bundle (see Fig. 1 above).

3. Improving the thermal calculation of combustion chambers of grate boilers

Mathematical analysis of the equation (1) shows that the Boltzmann number Bo has a dominant influence on the value of the flue-gas temperature ratio on the left side of the equation, compared to the other parameters appearing on the right side of the equation. To improve the accuracy of the thermal calculation of the combustion chambers of grate boilers based on equation (1), there are two options: (a) revision of the choice of empirical parameters entering the evaluation of Bo characterizing the events in the combustion chamber of the boiler or (b) introduction of an additional specific design and operational coefficient of the PCC-SCC system into equation (1).

Since the refinement of the model using option (b) already means a relatively fundamental intervention in the model used, the preferable goal of the research is to first refine the thermal calculation of the combustion chamber using option (a). This option of refining the model seems more natural also because deeper analysis of the equation for calculating the Boltzmann number showed it containing specific empirical parameters describing the properties of fly ash and ash fouling deposits, thus in an area that can be addressed with help of tools currently developed under another project of this paper's authors.

Following on from ongoing research performed within the flue-gas fouling testing device (so called 'TESTER') project previously presented at the EM 2024 conference (Zabloudil et al., 2024), this paper focuses on analysing the influence of selected parameters related to flue-gas fouling on the bridgewall temperature T_{bw} and thus on the accuracy of the design calculation of furnaces.

Therefore, a sensitivity analysis on the main parameters associated with flue-gas fouling and influencing T_{bw} calculation was performed – see Tab. 2. This paper aims to find a fouling characteristic with a wide enough range of realistically acceptable and practically achievable values, which might help to explain the previously found discrepancies between calculated and measured values of T_{bw}. Understanding of such a characteristic can then be deepened with data measurable using the TESTER device and used to improve accuracy of thermal calculations of lower output boilers.

Tab. 2: Identified empirical parameters describing fouling properties of flue-gas

Param.	Unit	Description	Affected by	Affects
μ	$\frac{g}{m_N^3}$	Fly ash concentration in flue gas	Ash content in the fuel, Wet flue gas volume	Charact. emissivity a_f
ξ	-	Furnace wall fouling coefficient, not to be confused with the fouling coefficient for heat exchangers - here the parameter describes with a higher number the surface with a tendency to absorb more heat	Empirically form $\xi \in < 0.1; 0.4 >$ (traditional values used for coal boilers)	Charact. emissivity a_f, Boltzmann number Bo
Z_C	%	Describes unburnt fuel heat loss, it is influenced by the content of unburnt residues in the slag and fly ash. Combustibles contained in entrained fly ash tend to alter its fouling properties when represented in sufficient percentage	Ash content in the fuel	Boltzmann number Bo

By manipulating the parameters entering the calculation within the range of technically achievable values (i.e. either manipulating directly the parameter under investigation or the fuel characteristic that influences it), it was found that neither the concentration of fly ash in the flue gas (μ), nor the heat loss by combustible matter contained therein (Z_C), does have a significant effect on the change in T_{bw} as the furnace surface fouling coefficient in the current calculation structure. Temperature differences caused by both were found to be minor under conditions that would not lead to such states as unallowable emissions.

Fly ashes from different fuels have different fouling properties. It is therefore clear that, for example, highly fouling fly ash from biomass burning or fly ash from certain components of combustible solid waste can lead to a change in the real ξ value. Fig. 2 clearly shows that the difference in T_{bw} found in the studied furnace would be (in case we omit other possible sources of error) covered by changing the value of parameter ξ from 0.1 to 0.136, which is still well within the boundaries of its acceptable values.

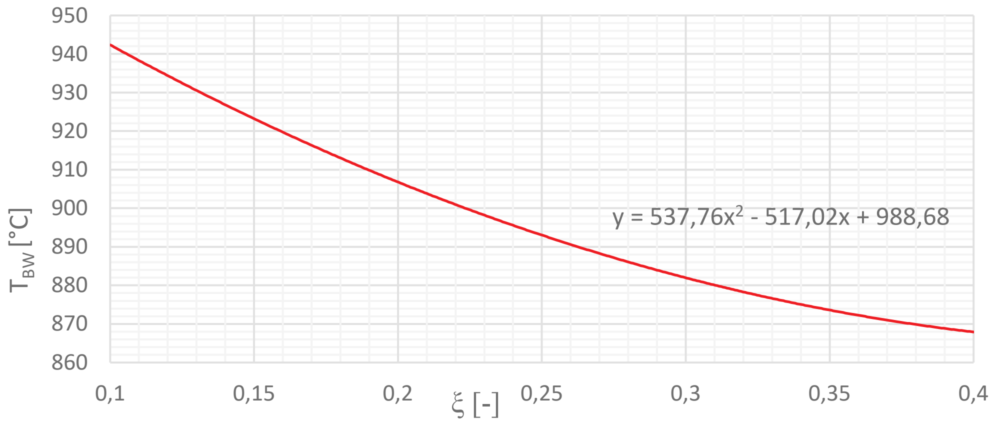

Fig. 2: Influence of furnace wall fouling coefficient ξ on flue-gas temperature T_{bw}

4. Conclusions

The presented work demonstrates, using the Gurvich method for thermal calculation of boiler combustion chambers, that systematic mathematical analysis can identify suitable options for ensuring the necessary increase in the accuracy of this thermal calculation for specific variable designs of combustion chambers of grate boilers of medium to lower capacities for the conditions of sustainable energy.

Using a case study of such a boiler, it is then specifically demonstrated how, by appropriate choice of the identified empirical parameter of boiler surface fouling, the accuracy of the thermal calculation of grate boilers can be adequately increased using tools developed as part of the research on fouling flue-gases, ongoing at Brno University of Technology (BUT). As part of future work, it therefore appears to be very useful and beneficial to develop an erudite and understandable methodology for determining this empirical parameter for fuels and fuel mixes of contemporary sustainable energy, which will allow the selection of the appropriate value of this parameter at the beginning of the design of a medium to low-power grate boiler for a more accurate thermal calculation of the designed grate combustion chamber.

Acknowledgement

The authors gratefully acknowledge the financial support provided by the Technology Agency of the Czech Republic within the research project No. TK05020076 “Development of a mobile tester for safe and reliable heat recovery from fouling flue gases and an ammonia generator for their cleaning”, GA BUT within research project No. FSI-S-23-8173 and by the EU project Strategic Partnership for Environmental technologies and Energy Production, funded as project No. CZ.02.1.01/0.0/0.0/16_026/0008413 by Czech Republic Operational Programme Research, Development and Education.

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