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DOWNSCALE APPLICATION OF BOILER THERMAL CALCULATION APPROACH

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Commonly used thermal calculation methods are intended primarily for large scale boilers. Hot water small scale boilers, which are commonly used for home heating have many specifics, that distinguish them from large scale boilers especially steam boilers. This paper is focused on application of thermal calculation procedure that is designed for large scale boilers, on a small scale boiler for biomass combustion of load capacity 25 kW. Special issue solved here is influence of formation of deposits on heat exchanging surfaces on efficiency of heat transfer and on overall boiler efficiency. In the paper are presented results of mathematical model created for this purpose and its verification by experimental measurement in this specific boiler.
Key words: small scale biomass boiler, thermal calculation methods, heat transfer,heat transfer surface deposits.

Toplinski proračun za toplovodni kotao u kućnoj uporabi. Najčešće korištene metode toplinskog proračuna namijenjene su prvenstveno velikim kotlovima. Toplovodni manji kotlovi, koji se obično koriste za zagrijavanje kuća imaju puno specifičnosti koje ih razlikuju od velikih kotlova, posebno parnih kotlova. Ovaj rad je usmjeren na primjenu toplinskog proračuna, koji je prvotno namijenjen za velike kotlove, na manji kotao za spaljivanje biomase kapaciteta 25 kW. Posebna tema razmatrana u ovom radu je utjecaj formiranja naslaga na površinama na kojima se izmjenjuje toplina na učinkovitost prijenosa topline i na ukupnu učinkovitost kotla. U radu su prikazani rezultati matematičkog modela stvorenog za tu svrhu i njihova verifikacija s eksperimentalnim mjerenjima provedenim na tom konkretnom kotlu.
Ključne riječi: manji kotlovi na biomasu, metode toplinskog proračuna, prijenos topline, prijenos topline uz površinske naslage.

INTRODUCTION

Heat supply for households is recently a very important part of field of energy systems. One of the typical approaches is installation of individual boilers for hot water production that burn biomass or coal. Generally, such boilers are classified by degree of fuel supply automation. On the market are available boilers with manual fuel feeding (e.g. gasification boilers for logwood) as well as automated boilers, typically using biomass pellets or sorted coal. Particular advantage of the automated boilers is user friendly operation.

This paper deals with thermal calculation of low scale boilersup to 25 kW. Heat exchanging surfaces in this type of boilers are typically designed and constructed by manufacturers on the basis of experience and testingrather than on the basis of calculation design. One of the possible reason is that the calculation methods are well developed particularly for large scale boilers. This paper therefore focuses on possibility of downscale application of thesecalculation approacheson proposal of possible improvements.

CALCULATION APPROACH OF LOW SCALE BOILERS

Small scale hot water boilers (up to 25 kW) have many specific features that significantly differ from large scale boilers, especially steam boilers. Approach ofthermal calculation below (based on [1]) follows these differences. Thermal calculation of boiler aims to clarify energy balances of each boiler component (combustion chamber, heat exchanging surfaces).

Energy balance of a boiler is performed in a way where the boiler is considered as entity which has its own inputs and outputs. The input is fuel with its energy content expressed by LHV. The output is heated water used for supplying the households. Heat of flue gas, which leaves boilers and goes to stack, causes stack loss. Stack loss is one of the most important loss thatreduces the thermal efficiency of a boiler. This is why there is an effort to cool down flue gas to a temperature as low as possible to minimize this energy loss. Other heat losses are products of incomplete combustion that is defined by means of chemical and mechanical unburned residues. Thickness of boiler insulation is a measure of losses by radiation and heat conduction to the surroundings.

Combustion chamber

Main requirement for combustion chamber is to ensure ignition and complete combustion of a fuel and removal of solid residues. In the small scale boilers is the combustion chamber typically uncooled, lined by of refractory ceramic materials (see Fig. 1).

Figure 1. Combustion chamber
Slika 1. Komora izgaranja

The procedure of combustion chamber calculation is focused on identification of outlet flue gas temperature t_{ok}, which is taken as a balance temperature in imaginary boundary between the combustion chamber and following parts of the boiler. Outlet flue gas temperature should not exceed deformation temperatures of ash to prevent deposit formation on heat exchanging surfaces.

Heat transfer in the combustion chamber isparticularly ensured by radiation mainly because of high temperatures. Calculations are based on similarity theory of thermal processes, which take place in combustion chamber. For calculations is usedsemi-empiricequationderived by Gurvič for the relative flue gas temperature at the outlet of combustion chamber in dependence to similarities of characteristics of combustion chamber.[2] From the difference of the adiabatic temperature of the flame that depends on fuel composition and excess air ratio, and t_{ok}temperature, could be expressed heatthat is releasedin the space of the combustion chamber. Certain percentage of this heat is absorbed by cooled parts of sides of combustion chamber. Rest of this heat leaves combustion chamber to other parts of boiler as radiant heat.

Transmission of heat

The flue gas further passes through the boiler and delivers heat to the heating water through heat exchanging surfaces. In the basic balance heat power delivered by flue gas stream is equal to that acquired by the water. In parallel the heat exchanging surface absorb radiant heat from the combustion chamber.

Heat exchange is realized by three mechanisms, heat transfer on flue gas side, conduction through the material and heat transfer on water side. Coefficient of heat transfer on water side is many times higher than on flue gas side, even if there is relatively small velocity and laminar character of water flow. Very high is heat conduction through the steel material aswell and as a low heat exchange resistance can be neglected. Problematic is heat resistance of formation of deposit at heat exchanging surfaceson flue gas side when solid fuels are combusted. There is the different between exchanging surfaces of the boiler after and before cleaning in Fig. 2. It is complicated to express heat resistance of deposits because of inaccurate measurement of thickness and unknown thermal conductivity of the deposits. This problem is solved by definition of the fouling factor ε, which is in relation of inverseproportion to velocity of flow of flue gas. Evaluation of this coefficient is not straightforward, because data for the flow conditions are not available in sources for large scale boilers and need to be found experimentally.

Figure 2. Heat exchanging surfacesof the boiler after and before cleaning
Slika 2. Površine kotla na kojima se izmjenjuje toplina nakon i prije čišćenja

Heat transfer is on the side of flue gas realized by radiation, which dominates by the temperature down to 400 °C, and convection. Convection is caused by movement of macroscopic particles of the heat exchanging fluid. This movement could be caused by ventilator or stack draft (forced convection). The other way of moving heat exchanging fluid is caused by heat sharing (heat difference between two points causes difference in density between this points and so the buoyancy is rising. This type of heat sharing is called free convection. Free convection can commonly be seen even in forced flows. Significance of the free convection increases with lower flow velocitiesand must be taken into account. [3] This phenomena is particularly importantin flue gas flows in the small scale boilers. Because of low velocity of flue gas (typically no higher than 2m/s), the flowrate iswithin laminar zone, and thus it is necessary to investigate influence of superimposed free convection on the heat transfer. To do this we need to know precise value of Grashof's number, which characterizes freeflow of fluids caused by temperature differences. Direction of flowdecides over influence of superimposed free convection on heat transfer. When the fluid is cooled upwards, the heat transfer is increased by superimposed convection. Opposite relation isvalid when the flow is cooled in downward motion.[4]

It is possible to find many empiric equations describing heat transfer in literature, but results of these equationsare often different. It is needed to pay high attention for any condition of use if they include influence of superimposedfree convection. One of the main goals of this experiment is to verify selection of possible equations thatcomplywith results of experimentwith a small scale biomass boiler. There is selected a suitable equation[4]for firetube heat exchanger:

$$Nu = \left(0{,}74 \cdot \varepsilon_1 \left(\mathrm{Re} \cdot \mathrm{Pr}\right)^{0{,}2} + K\left(\beta \cdot \vartheta\right)^{0{,}02}\right)\left(Gr \cdot \mathrm{Pr}\right)^{0{,}1} \quad (1)$$

Constraint: $Gr\,\mathrm{Pr} \le 3{,}6 \cdot 10^{6}$

$0{,}5 \le \mathrm{Pr} \le 12$

Where:

Gr	is Grashof ´s number
Pr	is Prandtl‘s number
ϑ (°C)	is difference between inlet and outlet temperature of flue gas $\vartheta = \pm(t_{in} - t_{out})$. By heater (+) and by cooling (-)
β (1/K)	flue gas volume expansion
K (-)	isconstant, which has the value K = 0 for horizontal pipe and K = ±1for vertical pipe se same (+) oropposite (-) direction of forced and free convection.
ε_1 (-)	is coefficient at the inlet area

EXPERIMENTAL VERIFICATION OF CALCULATION

Description of boiler and experiment

The combustion tests were done in CTU laboratory using automated biomass boiler of load capacity 25 kW. Combustion chamber was lined with heat resistant ceramic. Bottom of the chamber consists of a bed with moving grate that moves layer of fuel along the chamber.

Flue gas flows upwards from the combustion chamber by vertical pass and then continues through a double pass firetube heat exchanger and subsequently into outlet at stack. There is scheme of the combustion test in Fig. 3. Heat exchanger surfaces were divided into several parts due to complexity of the boiler body, see Fig. 4. To make energy balance for each heat exchanging surface the flue gas stream has to be fictively divided. Water side of the boiler body is even more complicated in terms of hydraulic conditions and had to be considered in the calculation as steady upward flow.

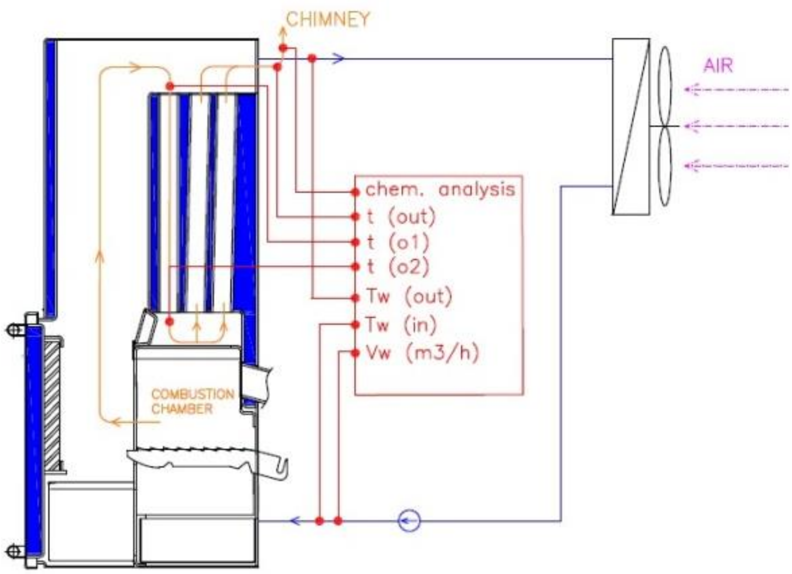

Figure 3. Scheme of the combustion test
Slika 3. Shema ispitivanja izgaranja

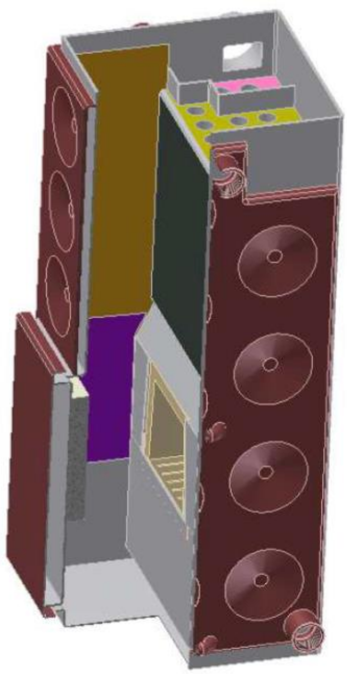

Figure 4. Graphic model of the boiler
Slika 4. Grafički model kotla

Combustion test have been done under two different codnditios – heat exchanging surfaces with and without fly ash deposits.Scheme of the experimental set-up is shown in figure 3. In principle, water is heated up in the boiler and then passesa cooling section. Boiler is equipped with measurement of temperatures of inlet and outlet water T_w (in) aT_w (out), flue gas in upper turnover t (o1) - before entering firetube part of the exchanger and lower turnover of boiler t (o2) - before first and second pass firetube part of the exchanger and temperature of flue gas outlett (out).. The cooling circuit is equipped with water flowrate measurement. Chemical composition of flue gas is measured by analytical system, the particular parameters required are concentration of pollutants and oxygen concentration for calculation of the excess air ratio. In addition is measured fuel consumptionby time balance of its mass.

Comparsion of the calculation with experiment

Table 1 summarizes results of the calculation and measured parameters for the experiment. It is noticeable, that measured and calculated temperatures donot differ significantly. For the case of boiler without deposits the value of fouling factor was found ε = 0,001 m^2·K/W, and the case with deposits ε = 0,03 m^2·K/W. Measured and calculated values do not differ more than 10 °C. Thus it can be said that choice of empiric equations was right due to conformity of mathematical and experimental results. When using other empiric equations there was no such conformity as above.

Table 1. Comparison of results mathematical model with results of the combustion tests
Tablica 1. Usporedba rezultata matematičkog modela s rezultatima ispitivanja izgaranja

	clean-measured	clean-model	fouled-measured	fouled -model
fouling factor ε [m^2K/W]	0,001		0,03	
flue gas temperature - upper turnover t (o1) [°C]	389	402	482	491
flue gas temperature - lower turnover t (o2) [°C]	279	268	350	354
outgoing flue gas temperature t (out) [°C]	169	176	254	251
boiler efficiency η [-]		0,842		0,782

From the results of measurement it can be seen that there is an influence of superimposed free convection to forced convection on heat transfer in all parts of the boiler, where convection is significant. If this influence is neglected, than the results of calculation would differ more from the results of experiments. Coefficient of heat transfer, when superimposed free convection is taken into calculations, differ up to 20%. In this case the influence is positive in all boiler. Only in first pass of firetube of exchanger is negative, because flue gas stream flowing downwards.

From the comparison of combustion test of boiler with and without deposits on the surfaces can be seen a large influence of formations of deposits on the temperatures of outlet flue gas, stack loss and efficiency. Cleaned boiler can cool flue gas by 85 °C better. That means increase of efficiency by 6 %, see Fig. 5.

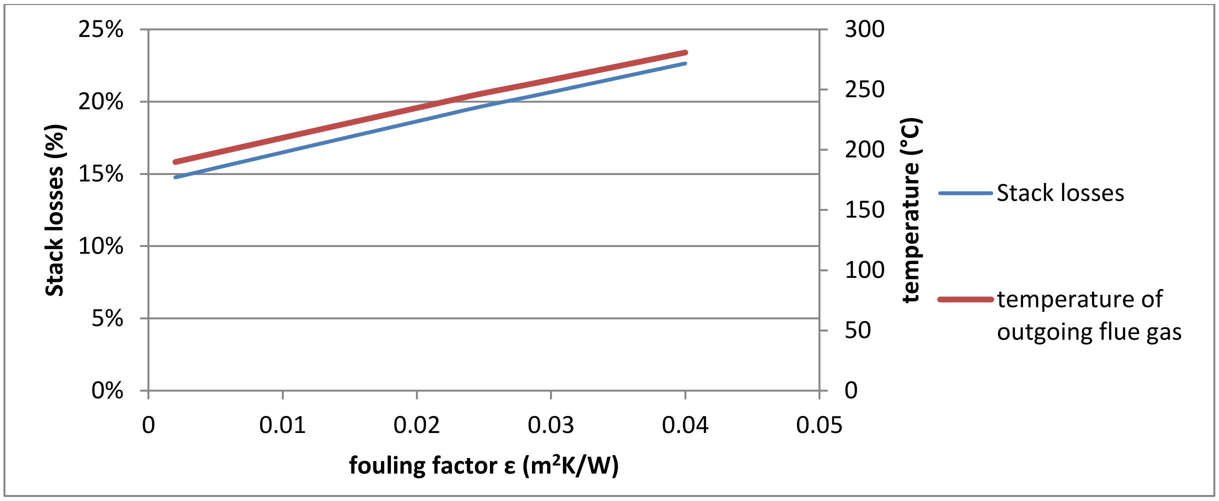

Figure 5. Influence of deposits formation on heat exchanging surfaces on stack loss
Slika 5. Utjecaj formiranja površinskih naslaga na gubitak izmijenjene topline

CONCLUSION

Approach of thermal calculation for the small scale boiler differs from a large scale boiler calculatio mainly by principles of heat exchange. In the small scale boilers is for flue gase typical laminar flow, which needs diffferent apporach evaluation of the heat exchange conditions. This includes influence of superimposed free convection. Equally laminar flow of heating water puts heat transfer negligible resistance and must be counted with.
Results of the calculations have been compared with measured values from combustion tests separately for boiler with and without deposits. By accurate choice of fouling factor it has been found that calculated and measured results do not differ significantly. Great difference in efficiency of fouled and cleaned boiler shows us importancy of frequent cleaning of thermal exchanging surfaces of boilers.. By comparison of calculated and measured values can be chosen most suitable empiric equation for heat transfer by convection in laminar flow.

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