RELIABLE SIMPLE ZONAL METHOD OF THE FURNACE THERMAL CALCULATION

by

Vladan B. Ivanović

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The calculation of the furnace in the industrial and power boilers is the most important and the most responsible part of the thermal calculation, and it has important influence on the rationalization of energy consumption.
In the paper one-dimensional zonal method of the furnace thermal calculation of steam boilers is presented. It can successfully define disposition of flue gas temperature and specific thermal load of screen walls with height of the furnace in case of uneven deposits distribution which vary in size and quality.
Its greatest use is for comparing furnace performance under various operating conditions.

Key words: *thermal calculation, boiler furnace, zonal method, furnace designing, slagging*

Introduction

The most important applications of radiant heat transfer calculations are encountered in the design of steam generating power and industrial boilers. An analytical solution of the problem of heat transfer in the furnace of a steam generating unit is extremely complex, and it is impossible to calculate furnace temperature counters by theoretical methods alone [1]. Since the art of the construction of these units developed before the theory, empirical methods were envolved for the furnace thermal calculation first. Various contributions to the thermal science in general and specific radiant heat transfer problems have made possible a more fundamental approach to furnace design [1-10]. Many empirical, semi-theoretical and analytical methods for the furnace thermal calculations are now available. Each of the existing methods has its drawbacks and the limited field of application [2].

Numerical simulation models have become an increasingly important design and analysis tool for the simulation of flow, heat transfer and combustion phenomena surrounding boiler components and auxiliary equipment. The simulation is completed with the use of computational fluid dinamics (CFD) software executing on high speed, large memory desktop workstation computers. Experience has demonstrated that purchased software packages by themselves are not adequate to produce reliable numerical results [3]. Reliable results are achived when the numerical results are used to augment traditional boiler design and analysis tools and empirical data.

Main problem is solving the equations of radiative transfer and the energy equation in participating media when energy transfer modes or sources are present in addition to radiation. In cited literature we met a great number of various methods for solving the radiation transfer relations for problems with radiation only and for those in which radiation is combined with other heat transfer modes (conduction, forced and free convection): the Monte Carlo method, approximation of spherical harmonics, method of radiation elements, method of characteristics, differential method, Hotell zone method [4] and its many variations, and so on. One of the recent trends in the procedure of solving the radiation transfer equation are combinations of the discrete-ordinate method with the finite-difference method or the finite-elements method.

Each of the methods for obtaining the local radiativ source distribution has advantages and disadvantages when it is applied to multimode problems, and considerable effort is still needed to improve numerical methods for solving that problems [5].

Finally, at the present time, there is no sufficiently reliable and efficient simple engineering method for pulverized coal fired furnaces, especially for the coal with relative intense reaction capability and slagging tendency, such as Kosovo lignite.

Mathematical model

Mathematical model [11] is based on the Normative standard zonal method CKTI and VTI-ENIN [12] and Constructive standard method [13] with the determination of relevant influence parameters according to the characteristics of Kosovo lignite [14].

Basic eq. (1) for the zonal method which determine flue gases temperature disposition with furnace height is the equation of the thermal balance of the zone, which, for stationary conditions, defines relationship between released and exchanged heat in the single zone of the furnace. The calculation of flue gases temperature in each zone proceed from released heat ratio, flue gases enthalpy changing, and ratio of heat that is led out of the zone.

When we take into thermal calculation the heat surface thermal efficiency factor [15] calculated by eq. (3) in which the value of the thermal efficiency factor depends only on the radiation characteristics and the temperatures of the radiation heat transfer participants, calculation is more complicated compared to the Normative standard zonal method, because previous calculating of the temperature of tube deposits surface is necessary. For that reason in thermal calculation is taken into the equation of conduction through slag deposits on tubes wall (2) and the equation for calculating the effective emissivity of the furnace in the main zone (4).

Flue gases temperature on the exit of the main zone is calculated in the stepwise manner by calculating next equation system:

$$t_{\mathrm{mz}} \quad \frac{H_1 \dfrac{\beta_{\mathrm{com}}}{\gamma} \quad Q_{\mathrm{a}} \quad Q_{\mathrm{F}} \quad \Sigma r I_{\mathrm{g}}^{\mathrm{rc}} \quad Q_{6\mathrm{sl}}}{(Vc)} \quad \frac{\sigma_0 \varepsilon_{\mathrm{f}} (T_{\mathrm{mz}})^4}{B_w (Vc)} H_{\mathrm{ef}}^{\mathrm{mz}} \tag{1}$$

$$T_{\mathrm{d}} \quad T_{\mathrm{wf}} \quad q_{\mathrm{r}} R_{\mathrm{hs}} \quad T_{\mathrm{wf}} \quad \sigma_0 \Psi \varepsilon_{\mathrm{f}} (T_{\mathrm{mz}})^4 R_{\mathrm{hs}} \tag{2}$$

$$\Psi \quad \frac{\varepsilon_{\mathrm{d}} \varepsilon_{\mathrm{fl}}}{\varepsilon_{\mathrm{fl}} \quad (1 \quad \varepsilon_{\mathrm{fl}}) \varepsilon_{\mathrm{d}} \left(\frac{T_{\mathrm{d}}}{T_{\mathrm{mz}}} \right)^4} \quad 1 \quad \left(\frac{T_{\mathrm{d}}}{T_{\mathrm{mz}}} \right)^4 \tag{3}$$

$$\varepsilon_{\mathrm{f}} \quad \frac{\varepsilon_{\mathrm{fl}}}{\varepsilon_{\mathrm{fl}} \quad (1 \quad \varepsilon_{\mathrm{fl}})} \tag{4}$$

where $H_{\mathrm{ef}}^{\mathrm{mz}}$ is effective refractory surface in the main zone, calculated as a product of the thermal efficiency factor and the total area of main zone surface:

$$H_{\mathrm{ef}}^{\mathrm{mz}} \quad \Psi F \quad \Psi_{\mathrm{mz}} F_{\mathrm{mz}} \quad \Psi F_1 \quad \Psi F_2 \tag{5}$$

In these equations all influence coefficients and parameters directly depend on temperature, and because of that, it is obvious that this equation systems can be solved only by using the iterative procedure. It is adopted $'' = {}_{z}$, where ${}_{z}$ is the value of at the height h_z.

Flue gases temperature on the exit of the zone, which is over main zone, is also calculated in the stepwise manner by calculating next equation system:

$$t_{\mathrm{pz}} \quad \frac{\Delta\beta_{\mathrm{com}} H_1 \quad (Vc)\, t}{(Vc)} \quad 1 \quad \left(\frac{T}{T} \right)^4 \quad \frac{\sigma_0 \varepsilon_{\mathrm{f}} (T\ )^4}{2B_{\mathrm{w}} (Vc)} H_{\mathrm{ef}}^{\mathrm{pz}} \tag{6}$$

$$T_{\mathrm{d}} \quad T_{\mathrm{wf}} \quad \sigma_0 \Psi \varepsilon_{\mathrm{f}} T_{\mathrm{m}}^4 R_{\mathrm{hs}} \tag{7}$$

$$\Psi \quad \frac{\varepsilon_{\mathrm{d}} \varepsilon_{\mathrm{fl}}}{\varepsilon_{\mathrm{fl}} \quad (1 \quad \varepsilon_{\mathrm{fl}}) \varepsilon_{\mathrm{d}} \left(\frac{T_{\mathrm{d}}}{T_{\mathrm{m}}} \right)^4} \quad 1 \quad \left(\frac{T_{\mathrm{d}}}{T_{\mathrm{m}}} \right)^4 \tag{8}$$

$$\varepsilon_{\mathrm{f}} \quad \frac{\varepsilon_{\mathrm{fl}}}{\varepsilon_{\mathrm{fl}} \quad (1 \quad \varepsilon_{\mathrm{fl}})} \tag{9}$$

and where $H_{\mathrm{ef}}^{\mathrm{pz}}$ is effective refractory surface in the passage zone:

$$H_{\mathrm{ef}}^{\mathrm{pz}} \quad \Psi_{\mathrm{pz}} F_{\mathrm{pz}} \quad \Delta\Psi F_{\mathrm{m}} \tag{10}$$

After the calculation of flue gases temperature on the inlet and the outlet for every zone, the heat flow rate for the radiant surface is calculated by equation:

$$q_{\mathrm{r}} \quad \sigma_0 \Psi \varepsilon_{\mathrm{f}} T_{\mathrm{m}}^4 \tag{11}$$

where T_{m} is mean flue gases absolute temperature in the observing zone:

$$T_{\mathrm{m}} \quad \sqrt[4]{\frac{(T\ )^4 \quad (T\ )^4}{2}} \tag{12}$$

In accordance with mean value of q_{r} for each zone we can get dependence of heat flow rate of furnace height, from which we can get heat flow rate for every cross section over the furnace height.

It is important to mention that the values for appropriate coefficients were adopted from recommendations [13, 16], only when the appropriate experimental data for Kosovo lignite do not exist [14].

Testing model

For thermal calculations, based on the modified zonal method as a testing model, power generating radiant steam boiler with dry-ash removal furnace is chosen. Steam boiler OP-650b, manufactured by Rafako, Poland, is built in Thermal Power Plant "Kosovo–A" on the blocks III, IV, and V.

Thermal calculation of the furnace, based on the modified zonal method, is done for four different capacities, from nominal power rating, *e. g.* maximum continuous rate, to 70% of power rating.

Furnace is divided into four zones (main zone, passage zone, recirculation zone, outlet zone) and the furnace hopper. The geometry of the furnace with all dimensions which is necessary for thermal calculation is shown on fig. 1.

Thermal calculation data are confirmed by comparison with extensive existing measuring results from the testing models. The majority of measuring is done because of slagging problem in the furnace and superheaters during Kosovo lignite combustion. The largest number of examinations and field tests, described in detail in [14], is done by the Laboratory for Thermal Engineering and Energy from VINČA Institute of Nuclear Science and Mining Institute from Belgrade.

Computer program

Based on the presented mathematical model, computer program in Visual Basic programmer's language is made. Complete furnace thermal calculation program consists of several parts: part of the program in which the elements connected with fuel are calculated, part of the program which process the thermal balance of the steam boiler, part of the program for material and thermal balance of milling drying, part of the program for control thermal calculation of the furnace and, at the end, part of the program which pro-

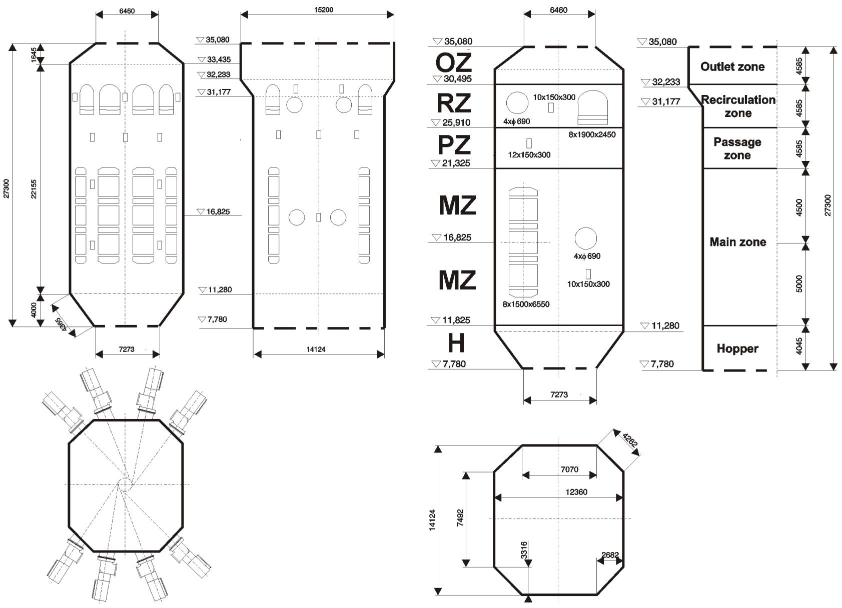

Figure 1. Geometry classification of the furnace into the zones

cess the zonal calculation of the steam boiler furnace. Besides these main elements of the program, thermal calculation program contains and a series of function subprograms, which provide necessary data, which are in literature mostly tabular assigned.

Complex thermal calculation, like this one, can not be done by simple addition of all parts of the programs and subprograms to one entity, because the series of their parts appear in program for the several times and cross mutually. Almost all results are obtained by iteration procedure and this feature present thermal calculation of the steam boiler furnace as a very attractive and complex for computer realize.

Thermal calculation results

A lot of entry parameters (119 for furnace of steam boiler OP-650b) are necessary to provide these one-dimensional zonal method of the furnace thermal calculation.

These entry parameters define following: geometry characteristics of the furnace and of the zones in which the furnace is divided, conditions and parameters of the working fluid, temperatures and characteristics of the fuel and air needed for combustion, characteristics of the mill plant and the geometry characteristics of the heating surfaces areas. We cannot influence on those parameters because they are determined by the mathematical model of thermal calculation itself, as well as by constructive characteristics of chosen testing model and by operation parameters of thermal plant.

The only "free" entry parameter with which thermal calculation model is defined and controlled is thermal resistance of the deposits on the heating surfaces. It is directly connected with thickness and quality of the deposits on the heating surfaces.

Created deposits negatively influence on the efficiency and operating availability, *i. e*. on economical operation of the plant in several ways. The direct and the largest negative influence of deposits is in increasing thermal resistance of the heating exchange surface between flue gases and boiler working fluid. Even a small thickness of ash and slag deposits on the tubes reduce heat absorption and increase reradiation. That takes to uneconomical or reduced production as an effect of disturbance of thermal balance of the steam boiler.

In order to establish a state of heating surface during steam boiler plant operation, for chosen testing model, thermal calculations of the furnace are realized in all diapasons of dirtiness of heating surfaces: clean, normally dirty, slagged, very slagged, and intensively slagged.

With the one-dimensional zonal method of the furnace thermal calculation we receive a lot of output results that characterize heat exchange, for the furnace on the whole as for the zones in which the furnace is divided. However, the most important are temperature of flue gases and specific heat flow rate along the height of the furnace. Therefore those two parameters are specially separated and, for easier analysis, graphically represented.

Calculation results based on zonal method and the average results of experimental researches are together given on the fig. 2. The experimental researches are performed at various operation conditions, immediately after repairing and cleaning heating surfaces as well as after several days of continuous work, and that is why the graphic presentation of calculating operating conditions for normally dirty and very slagged heating surface are chosen.

During analysis less or more disagreements of calculation and experimental results were noticed. It is necessary to mention important supposition in which this calculations are done, that is uniform disposition of deposits along the furnace and their constant thickness, more precisely – thermal resistance of deposits is even.

Analyzing temperature distribution and specific heat flow rate of heating surface along the height of the furnace we can notice that in some zones the calculation results follow closely the results of measuring, as one should expect, while in some zones that is not the case (especially measurement N° 3).

Changeability of radiation parameters of flue gases environment and thickness of deposits on the screen tubes influence on temperature and radiation characteristics of surface deposits, as well as the effectiveness factor, looking through the space and time, cause distinction in presented flue gases temperatures and thermal flow rates distribution for some operation condition.

On the other side, the way of temperature measuring and falling thermal flux measuring, involve measuring errors too, which also, affects on a difference of observed distributions. The main cause of this disagreements, beside different number and ar-

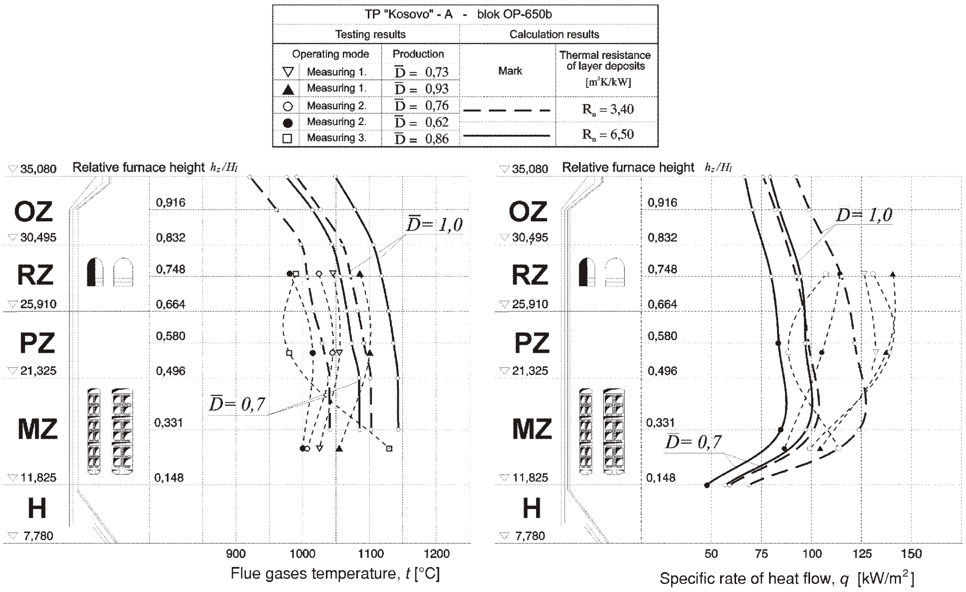

Figure 2. Comparison of calculation and measuring results for flue gases temperature and the specific heat flow rate along the furnace height

rangement of mills in a work, is unequal thickness of created deposits on absorption part of flux-meter and screen tubes themselves. Bearing this in mind, and according to the fact that the number of flux-meters that are built in is relatively small, presented distribution field of measuring values of falling thermal fluxes and of flue gases temperatures should be accepted as conditionally correct.

Also, algorithm of calculation, based on presented method, does not include disturbances caused by aerodynamics (working interruption of one or more fan mills), unexpected local slagging of some parts of screen walls and other operational factors, which in specific way, influence on combustion process and heat exchange in the furnace.

Two examinations are chosen from testing measurements N° 1 for which there were enough information for calculation to be done. First calculation was performed for production of 93% of nominal power rating with the Kosovo lignite low heat level H_l = = 7644 kJ/kg, and a second for production of 73% of nominal power rating with the Kosovo lignite low heat level H_l = 6720 kJ/kg.

At the first calculation, considering high steam production, assuming the areas around burners in the main zone are mostly slagged and that the level of slagging is falling in the direction of furnace outlet, then average value of thermal resistance of deposits is calculated as 4.37 m^{2}K/kW. For second calculation it is assumed that the main zone and the outlet zone are most slagged, while the passage zone and the recirculation zone are normally slagged. The average value of thermal resistance of deposits is calculated as 5.00 m^{2}K/kW (fig. 3).

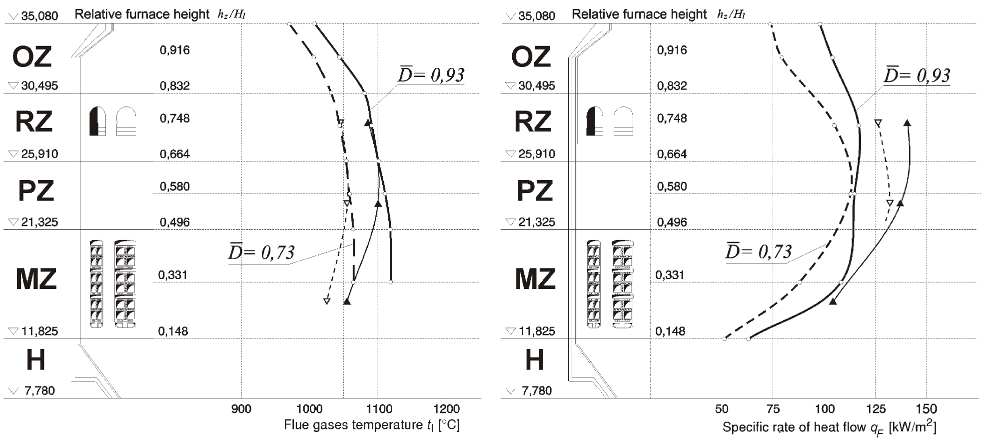

Figure 3. Comparison of calculation and measuring results for flue gases temperature and the specific heat flow rate along the furnace height for chosen measurements

It is easy to notice that the obtained calculation results match very well with the results of experimental testing, especially for the temperature in the middle of the furnace, and that some disagreements, presented mostly in the active combustion zone, are located between measuring accurate limits.

Considering that characteristics of combustion lignite are somewhat different from characteristics of guaranteed lignite with which the calculations are done, as well as that operational factors during the experimental testing were slightly different from the calculated one, agreements of calculated and experimental results are satisfactory.

Analysis of the specific heat flow rate of heating surface demonstrate very large influence of heating surface dirtiness factor on thermal flux absorption rate, which is understandable. It is noticed that by increasing of production rate of the boiler and level of slagging, the active zone of combustion increases too. The region with raising temperatures and heat flow rates increases, and not only along the height of the furnace, but also along the width of the furnace. Exceptional influence of the deposits on the asymmetry of the thermal picture in the furnace is noticeable on all figures.

At the same time a very large flexibilities of the proposed modified zonal method of calculation are noticed, which result in an excellent possibility for mathematical simulation of almost every operational situation which can appear during operating and plant exploitation.

Conclusion

With the appropriate computer program numerous thermal calculations of the furnace are done, based on the presented one-dimensional zonal method. The results of the calculation are compared with the results of measuring of testing model: Furnace chamber of steam boiler unit OP-650b in TP Kosovo-A, Obilić, Serbia and Montenegro.

Comparison of the calculating results and measuring results lead to conclusion that the proposed method is suitable for the calculation of thermal regime in a furnace chamber of large power boilers in the case when thermal resistance of deposits is great, variable in time and different in some parts. Also, the method is very suitable for analysis of real conditions in the furnace in which the conditions of furnace work are different from the projected one, as well as for simulation of various operating conditions.

Nomenclature

B_w – working fuel consumption, [kg/s]
$\overline{D}$ – ratio between steam production and nominal steam production during tests, [–]
F – area of observing zone walls, [m^2]
F_m – mean cross-sectional area in observing zone, [$= (F_1 + F_2)/2$], [m^2]
F_1 – cross-sectional area which limit zone for the upper side, [m^2]
F_2 – cross-sectional area which limit zone for the lower side, [m^2]
H_l – low heat value of the fuel, [kJ/kg]
H_f – height of the furnace, [m]
h_z – height from the bottom of the furnace, [m]
Q_a – heat brought in furnace by preheated air, [kJ/kg]
Q_F – sensible heat of fuel brought in furnace, [kJ/kg]
Q_{6sl} – heat loss with slag, sensible heat which is leaving the zone, [kJ/kg]
q_r – specific heat flow rate transfer in zone, [kW/m^2]
R_{hs} – thermal resistance of the heating surface, [m^{2}K/W]
$\Sigma r I_g^{rc}$ – heat in recirculated flue gases, [kJ/kg]
T_d – absolute temperature of surface deposits, [K]
T_{wf} – absolute temperature of working fluid that flows through the tubes of heat receiver, [K]
t, T – flue gases temperature in [°C] and corresponding absolute flue gases temperature in [K],
(Vc) – average specific heat of flue gases of 1 kg fuel at the temperature of the observing zone, [kJ/kgK]
$(Vc)'$ – average specific heat of flue gases of 1 kg fuel at t', [kJ/kgK]
$(Vc)''$ – average specific heat of flue gases of 1 kg fuel at t'', [kJ/kgK]

Greek letters

β_{com} – level of combustion; this level show which part of the fuel is burned in observing zone; adopted according to a recommendation into depend of type of fuel and relative furnace height h_z/H_f, [–]
$\Delta\beta_{com}$ – part of fuel combustion in observing zone, (β_{com} β_{com}), [–]
γ – ratio among brought and burned quantity of fuel, [–]
ε_d – emissivity of tube-wall surface covered by deposits, [–]
ε_f – emissivity of the furnace, [–]
ε_{fl} – emissivity of the flame, [–]
σ_0 – Stefan-Boltzmann constant, [kW/kgK^4]
Ψ – thermal efficiency factor of heating surface in the zone, [–]

ΔΨ – factor that determines radiant heat flow rate from lower zone, that is the upper zone, (Ψ Ψ), [–]

Ψ' – factor that determines radiant heat flow rate to the upper zone; it is determined in accordance with recommendations depending on type of the fuel and combustion conditions, [–]

Ψ″ – factor that determines radiant heat flow rate to the bottom end or furnace hopper

Superscripts

' – inlet of the observing zone

" – outlet of the observing zone

Abbreviations

mz – main zone

pz – passage zone

m – mean value

References

[1] Stultz, S. C. *at al*., Steam/Its Generation and Use, 40th ed., The Babcock & Wilcox Company, Barberton, OH, USA, 1992

[2] German, M. I. *at al*., An Engineering Method for Calculating a Temperature Regime in the Furnace of a Fire Tube Boiler with a Reverse Flame, *Heat Transfer Research, 33* (2002), 7&8, pp. 557-571

[3] Mull, T. V. *at al*., Numerical Simulation Models for a Modern Boiler Design, Power-Gen International, Orlando, FL, USA, 1996

[4] Hotell, H. C., Serofim, A. F., Radiative Transfer, McGraw Hill, New York, 1967

[5] Siegel, R., Howell, J.R., Thermal Radiation Heat Transfer, 3rd ed., Hemisphere Publishing Corporation, New York, 1992

[6] Menter, F. R. *at al*., Heat Transfer Predictions Using Advanced Two-Equation Turbulence Models, CFX Technical Memorandum: CFX-VAL10/0602, 2002

[7] Rogers, K. *at al*., Numerical Modeling for Design Optimization of SCR Applications, ICAC NO Forum, Washington D.C., 2000

[8] Mozes, E., On the Development of High Capacity Water Boiler, Febodruk BV, Enschede, Utrecht, The Netherlands, 2001

[9] Pletcher, R. H. *at al.*, Handbook of Numerical Heat Transfer, John Wiley and Sons, New York, 1988

[10] Bloh, A. G. *at al*., Heat Transfer in Steam Boiler Furnaces (in Russian), Energoatomizdat, Leningrad, USSR, 1984

[11] Ivanović V., The One-Dimensional Zonal Method of the Furnace Thermal Calculation, *Proceedings*, 6th European Conference on Industrial Furnaces and Boilers – JNFUB 2002, Modelling of Furnaces and Combustion Systems, Estoril, Lisbon, April 2-5, 2002, Vol. III, pp. 281-290

[12] Kuznecov, N. V., Mitor, V. V., Thermal Calculation Method of Steam Boiler Units, Normative Standard Method (in Russian), Energy, Moskow 1973

[13] Mitor, V. V., Marshak, L. L., Design of the Furnaces with Dry-Ash Removal (in Russian), NPO CKTI, Leningrad, USSR, 1981

[14] Ivanović, V., Contribution to the Investigation of Heat Transfer in the Furnace of Steam Boiler Units which Burning Kosovo Lignite by Using Modified Zonal Calculation Method (in Serbian), Mechanical Faculty, University of Prishtina, 1998
[15] Bloh, A. G. *at al*., Radiant Heat Transfer (in Russian), Energoatomizdat, Moskow, 1991
[16] Brkić, Lj. *at al.*, Thermal Calculation of Steam Boilers (in Serbian), Faculty of Mechanical Engineering, University of Belgrade, 1997

Author's address:

V. Ivanović
Faculty of Mechanical Engineering, Department of Energetics
University of Montenegro
81000 Podgorica
Cetinjski put bb
Serbia and Montenegro

E-mail: vladaniv@cg.ac.yu

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