REVIEW OF THE INVESTIGATIONS OF PULVERIZED COAL COMBUSTION PROCESSES IN LARGE POWER PLANTS IN LABORATORY FOR THERMAL ENGINEERING AND ENERGY – PART B

by

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Paper presents short review of research problems, applied methods for solving problems and main results obtained by the researchers in Laboratory for Thermal Engineering and Energy (LTE) of the "Vinča" Institute of Nuclear Sciences, Belgrade, Serbia dealing with pulverized coal combustion processes and technologies for reduction of pollutions problems at thermal power plants in a period since 2000. The presented results were published in numerous studies realized for different users, Ph. D., Masters, and Specialist thesis, in international and domestic scientific journals and monographs, presented at numerous international and domestic scientific conferences, etc. Presented research projects and results of applied research projects realized at pulverized coal combustion thermal power plants clearly show that LTE team was involved in key activities of rehabilitation and modernization, including implementation of best available technologies for pollution reduction at thermal power plants, in the region of South East Europe.

Keywords: *pulverized coal, combustion, boiler, diagnostics, burner, slagging, modelling, thermal power plants, pollution reduction technologies*

Introduction

Thermal power plants (TPP) on lignite and their technological systems in the South-Eastern Europe (SEE) countries are relatively old. In addition, since 1990, due to economy transition problems, local conflicts, war destructions and financial crisis, TPP in the SEE countries have been functioning under very difficult and specific exploitation conditions of disturbed and closed market, resulting in remarkable decrease in financial support for maintenance but with lot of exploitation problems. The problems of their life cycle extension, of capital repair, modernization, revitalization, introduction of new technologies especially to reduce pollution problems, and of building new capacities have been present since the 90's of 20th century. Researchers in the LTE have seen an opportunity for new impulse in applied research in laboratory including mathematical modelling of flow, combustion, and heat trans-

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fer in real-scale pulverized coal (PC) furnaces and especially, testing of the processes and equipment at TPP. Since 2000 a lot of new measuring probes have been developed, instruments bought, and in house/international standard methods were accredited according to ISO/IEC 17025 for performing testing in the laboratory and on site at TPP (http://www.registar.ats.rs/predmet/294/). As a result, since 2001, various measurements have been performed (based on contract with: national public companies for power generation in Serbia, BiH, Greece, and International companies: Alstom, General Electric, Mitsubishi Hitachi Power Systems Europe, MITSUI, Bilfinger Babcoock Borsig Steinmuller, Rafako, Hamon, Siemens, CMEC, *etc*. and regional companies Energoprojekt-Entel, Metka, Viaocel, Solergon, Termooprema, Feromont, ZK-Termochem, Euromontig, *etc*.) on TPP in SEE countries including Greece, Turkey, Iran, and Germany:

– more than 45 various testings of power plants (adjusting of boiler operating parameters, Acceptance – performance testings according to DIN 1942, EN-12952:15),
– more than 10 determinations of specific heat consumption (heat rate) of power plant units (according to DIN 1942, EN-12952:15 and DIN 1943, IEC 953-2),
– more than 7 testings with the aim to increase the boiler steam flow and unit power,
– more than 9 low NO_x combustion system testings,
– more than 13 mill testings, and
– more than 43 testings of electrostatic precipitator (ESP) and pollutants emission measurements.

Success of applied research since 2000, was based on modern measuring equipment, multidisciplinary expert team highly skilled for work at laboratory and on site at TPP, accredited standard international measuring methods and especially on the expert knowledge gained in previous fundamental and applied laboratory investigations of the fuel characteristics and processes in pulverized lignite fired boilers of TPP in SEE that was highly recognized at the international level (see paper in this issue: *Review of the Investigations of Pulverized Coal Combustion Processes in Large Power Plants in Laboratory LTE – Part A*, by Branislav S. Repić, Predrag Lj. Stefanović, Srdjan V. Belošević, Nenad Dj. Crnomarković, and Simeon N. Oka).

Paper presents short review of research problems, applied methods for solving problems and main results obtained by the researchers in the LTE dealing with PC combustion processes and technologies for reduction of pollutions problems at TPP.

Research of physical-chemical properties of coal, ashes, and slag

Physical-chemical properties of coal

Coal fired power plants are major sources of GHG, especially CO_2 and for precise determination of the emitted quantities, carbon emission factor (CEF) [t C/GJ] of local, low quality lignite should be experimentally determined on representative samples. Based on new laboratory experimental methodology including ultimate, proximate coal analysis, and calculations, correlation for net calorific value Q_{net} [kJ/kg] and CEF have been obtained for: Kolubara lignite [1, 2], lignite from open pit mine Drmno-Kostolac [3], lignite from open pit mine Borovica-Pljevlja [4], and lignite from open pit mine Bogutovo Selo Ugljevik [5]. Results of these applied research suggest that: a) low quality lignite in West Balkan region has lower net calorific value and higher CEF values than recommended by IPCC Guidelines for National Greenhouse Gas Inventories, Tier 1 method [1], b) using this methodology, for each open pit mine, based on representative lignite samples, regression correlation between CEF and net

calorific value should be established, periodically checked and used for CO_2 emission calculations, and c) lignite with higher content of carbonates in a mineral matter (widely present in SEE region) has lower net calorific value and increased CEF value *i.e*. increased CO_2 emission during combustion of such coal, compared to same coal without carbonates due to endothermic calcination reaction of decomposition calcium-carbonate to calcium-oxide and CO_2 at elevated temperature in the boiler.

High variation of open pit mined lignite quality in SEE has significant negative influence on combustion process, boiler efficiency, emission in air, slagging/fouling problems in the furnace/boiler, *etc*. [6]. Due to development and implementation of new technologies: on-line coal quality determination, selective mining, and homogenization of lignite, most of the combustion/exploitation problems in the boiler have been solved in developed countries. Applied research on methods for on-line coal quality determination has been started in Institute Vinča in the 1976 [7]. Experimental results based on transmission radiation method with ^{241}Am gama radiation source and detector with NaJ crystal for relative determination of ash content and capacitive method for moisture content determination, gave very good results but mostly due to security (radiation protection) problems for personal at TPP, implementation in practice was not achieved. Following successful implementation of these new technologies for lignite quality optimization in USA, Australia, Germany, and other developed countries, activities in PE Electric Power Industry of Serbia were increased since 2000. Once again, due to security (radiation protection) problems for personal at open pit mine, for on-line measurement of ash content, besides Transmission radiation method, lot of research had been focused on natural radiation of coal/mineral matter [8, 9]. Based on measured gamma-ray spectrum of 82 lignite samples from open pit mine Kolubara, activity concentrations of naturally occurring radionuclides: ^{235}U, ^{238}U, ^{226}Ra, ^{210}Pb, ^{232}Uh, and ^{40}K as determined, have shown that there is a negligible concentration of natural radionuclides. Assessed radiologic effects show that all calculated values of: radium equivalent activity Ra_{eq} [Bq/kg], external hazard index H_{ex} [Bq/kg], external gamma absorbed dose rate D [nGy/h], and annual effective dose rate [mSv/h] were below international recommended limits and that there is no enhanced radiation hazard for the population (both, working, and public) living nearby the open pit mines. Based on measured data, following correlations were obtained:

$$^{238}\text{U [Bq/kg]} = 1.2253 \times \text{Ash content [\%]} \text{ with correlation coefficient } R^2 = 0.6447$$

$$^{232}\text{Th [Bq/kg]} = 0.7613 \times \text{Ash content [\%]} \text{ with correlation coefficient } R^2 = 0.8022$$

$$^{40}\text{K [Bq/kg]} = 3.882 \times \text{Ash content [\%]} \text{ with correlation coefficient } R^2 = 0.6375$$

$$\text{Integral natural gamma radiation [cps/kg]} = 0.2578 \times \text{Ash content [\%]} \text{ with } R^2 = 0.7201$$

Additional analysis of different mineral matters sampled at open pit mines Kolubara have shown: clay samples (dominantly Kaolinite and/or Anorthite) have much higher activity concentration (up to 10 times for ^{238}U, up to 5 times for ^{232}Th, and up to 3.5 times for integral natural gamma radiation), compared to values for the sand (dominantly Quartz) samples from the same location. That was the reason for high discrepancy (low correlation coefficient) of correlated values.

Due to low concentration of natural radio nuclides in lignite samples (approximately 3 times lower compared to values for subbituminous and bituminous coals) and obtained low correlation coefficient, integral or specific natural gamma radiation method could not be used for on-line measurement of ash content in Kolubara lignite.

For transmission radiation method, Laboratory test of 100 mm thick coal layer with ^{241}Am, gama radiation source gave much higher sensitivity:

$$\text{Attenuation factor} = 0.1607 \times \text{Ash content [\%]} + 1.6183$$
$$\text{with correlation coefficient } R^2 = 0.7472$$

compared with ^{137}Cs gama radiation source:

$$\text{Attenuation factor} = 0.0146 \times \text{Ash content [\%]} + 1.5441$$
$$\text{with correlation coefficient } R^2 = 0.6661$$

Obtained low correlation coefficient (due to different chemical composition of mineral matter in coal samples) also indicates the problem of implementation of transmission radiation method for on line determination of ash content in Kolubara lignite, too.

Physical-chemical properties of ashes and slags

Homogenization of lignite, primary intended for standardization of net calorific value of the coal at TPP, can have impact on fouling/slagging problems in the furnace/boiler, too. Detail laboratory characterization of three lignite samples from different open pit mines in Kolubara basin and their blends in different mass ratio (3:1, 2:2, and 1:3) have shown that chemical and physical (including net calorific value) characteristics of the blend are additive values of the component coals, while tendency of fusibility *i.e*. fouling and slagging is not an additive value [10, 11]. On the other side research have shown that based on chemical composition of the ashes different criteria can be used for estimation of the coal ash tendency for fouling and slagging in the boiler. Between them for lignite samples from: Kolubara basin [11], Kostolac basin, Kosovo basin, and open pit mine Bogutovo selo-Ugljevik, tendency for slagging (deposition on the furnace walls) can be best estimated based on chemical composition of the ash and calculated criteria base/acid ratio B/A = $(Fe_2O_3 + CaO + MgO + Na_2O + K_2O)/(SiO_2 + Al_2O_3 + TiO_2)$: for B/A = 0.64-3.5 high slagging tendency, for B/A = 0.24-0.64 medium slagging tendency and for B/A < 0.24 and B/A > 3.5 low slagging tendency [12, 13]. Based on results of these research and experimental verification of transmission radiation method/activity concentrations of naturally occurring radionuclides in the representative lignite samples from Kolubara basin, it could be concluded that the best method for on-line detection of lignite quality is based on Prompt gamma neutron activation method combined with transmission radiation method for detection of coal bed high at the transport belt and microwave method for moisture detection. Prompt gamma neutron activation method can detect present chemical elements and their content in the coal. Based on these data, during homogenization/blending of the lignite from different open pit mines, blend can be formed that has approximately constant-standard net calorific value and approximately constant-standard chemical composition of the ash *i.e*. standard tendency for slagging and fouling in the boiler furnace.

In order to enhance the accuracy and precision of thermal calculation/computation of heat transfer in the furnace of pulverized lignite fired boilers with strong fouling (ash deposition) tendency, at some TPP in Serbia an investigation was done on thermal radiation characteristics of ash deposits. Through international cooperation with Kyoto University experimental installation was developed and determination of total and spectral normal emittance of lignite ash deposits formed on heat exchange surfaces in a boiler furnace of TPP Kosovo A and Kostolac B were determined and method for implementation of the results in the furnace thermal design calculations was proposed [14, 15].

Applied research aimed to solve exploitation problems of PC power boilers

Diagnostics of unsteady processes in the PC boiler

Steam boiler of unit 2 (125 MWe) at TPP Ptolemais, Greece, after the reconstruction and modernization suffered from great pressure oscillations in the flue gas tract. Previous activities with the installation of refractory belt on the evaporation tubes in the burner area of the furnace have partially solved the problem. Consumption of liquid fuel for fire support was reduced but lower power limit, higher furnace and boiler exit flue gas temperatures, high losses with unburned combustible matter, *etc*., characterized boiler operation. Extensive complex measurements were performed by LTE research team in attempt to detect the source of pressure oscillations. Between them, specially designed equipment and new measuring method for simultaneous dynamic measurements of pressure oscillations at nine different positions along burner-furnace-flue gas tract, fig. 1, were used for the first time in industrial conditions.

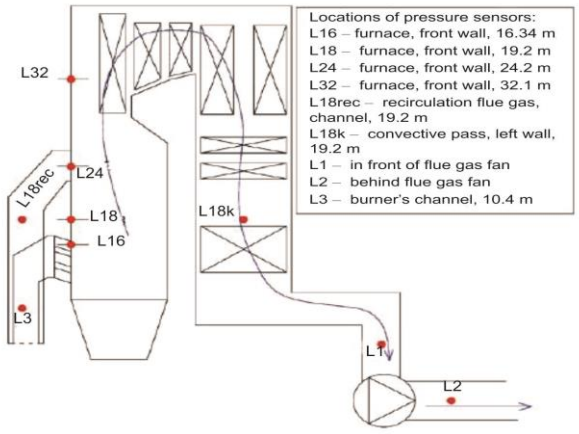


Figure 1. Schematic of PC steam boiler at Unit 2 TPP Ptolemais, Greece, with location of pressure probes

Based on laboratory experience with fast stagnation pressure measurements in a free jet flame [16], dynamic pressure probe was designed with a DC battery powered Siemens mini piezo pressure transducer and connected with properly shielded transmission lines to a PC with 8-channel, 16-bit Keithley's DAS-HRES acquisition card. This system had a direct memory access (DMA) in order to obtain high-speed acquisition (up to 5 kHz at 8 channels simultaneous) and storage of measured values. Considering that pressure waves propagate at the speed of sound and taking into account distance between piezo sensors, sampling frequency of 1 kHz was found to be high enough for representative data recording. Large amount of data was collected during each of three operational regimes (over $2.4 \cdot 10^6$ data per regime). These data were sufficient for correct time and frequency analysis that fully represent investigated phenomenon. Detailed analysis of the recorded data clearly shown that the origin of the pressure oscillations is in the furnace in the zone above burners [17-19]. Successful application of this experimental method which contributed to determination of location, intensity, and frequency of pressure disturbances, in addition with the results of other complex tests: milling system tests, thermal tests of furnace and flue gas fan tests, which were simultaneously performed, was of great help in achievement of stable boiler operation. Milling system tests have shown that pulverized lignite from all tested mills was coarser than designed and residual moisture content was much higher than designed, in all mills tests. Due to incorrect mills

operation, prolonged heating and drying of large and wet lignite particles takes place in the furnace/burner zone, and volatiles combustion is dislocated to the upper boiler zones. Processes of heating, drying, and evaporation of volatile matters are time consuming, so, above the burner zone, significant volumes of the very specific mixture composed of: volatile matters, fine combustible particles, and flue gases permanently arise. Very fast ignition and combustion of those discrete volumes, enriched in volatile matters during the time, is similar to explosion responsible to unstable combustion in the utility boiler. By applying some suitable measures, mainly the adjustment of milling system, burners and fresh air blowers, the problem was solved, and the unit reached a nominal power, followed by designed parameters during stable operation.

Applied research dealing problems of PC boiler life cycle extension, rehabilitation/modernization and boiler capacity/unit power level increase

At the beginning of the 21st century, almost all TPP in Serbia were at the end of their projected life time with increased number and prolonged unscheduled outages, mostly (>50%) due to damages on high pressure heat transfer tubes of the boiler, so urgent activities for life-extension and modernization were necessary. United complementary teams of experts from PE Electric Power Industry of Serbia and University of Belgrade: Faculty of Technology and Metallurgy, Faculty of Mechanical Engineering and Institute of Nuclear Sciences Vinča, performed applied research including detail sampling and analysis of tube samples damages and deposits (composition and specific mass per tube area) from all Units, to determine state of high pressure boiler tubing system and feed water quality and to propose measures to reduce damages and outages of the Units [20, 21]. This research has been later extended to internal chemical cleaning of water-steam tube systems process quality control at TPP Kostolac B2 [22], TPP Kostolac B1 [23], and TPP Kostolac A2 [24].

Rehabilitation of TPP in Serbia besides life cycle extension, included modernization, energy efficiency improvement, boiler capacity/unit power increasing and implementation of the best available technologies for reducing environmental pollution. As a part of these projects detail analysis of the process parameters, thermal and hydraulic calculations and measurements at the site were performed by team of experts from PE Electric Power Industry of Serbia, from power industry-designer-producer of the equipment and LTE. Typical example of these projects is rehabilitation, modernization, energy efficiency improvement, boiler capacity/unit power increasing by ECORAM program and new ESP at Unit 6 TPP Nikola Tesla A. This unit built in 1979, with nominal steam capacity 920 t/h and gross power 308 MWe, at the end of 2006 had more than 150000 hours on electric network, with 750 stop/starts and generated 235 GWh. In period 2006 to 2011 applied research including measurements and analysis, calculation and numerical simulation of mills/boiler process parameters made a basis for investment decision and step by step realization [25-32]. Improved mills capacity (up to 110 t/h), coal dust concentration distribution over main/vapour burner, and tightness of mills/air tract and boiler, enabled improved combustion process, higher heat generation in the whole furnace with originally projected flue gas temperature at the furnace exit and lower NO_x emission (from 440-510 mg/Nm^3 before to <330 mg/Nm^3 after rehabilitation and modernization). Rehabilitated boiler could have maximum steam capacity up to 1050 t/h and improved efficiency (from 84% before to 88% after). Modernized turbine with increase efficiency (turbine gross heat rate: before 7815 kJ/kWh and after 7719.5 kJ/kWh) have proved unit gross continuous power generation of 348.5 MWe. Same methodology have been implemented for the rehabilitation/modernization of Unit B1 TPP Nikola Tesla and B2 TPP Kostolac.

Applied research dealing problems of PC boiler fire support by thermal plasma

After successful experimental verification at TPP Kolubara A (in period 1984-1988) of LTE patented technology for start-up and fire support with swirl burner burning specially prepared pulverized lignite with fine particle size (from bunkers), due to complex explosion hazard manipulation and storage of coal dust, PE Electric Power Industry of Serbia initiated research on thermal plasma system for fire support only, but without bunkers [33, 34]. Based on detail calculations, modelling and design [35] pilot plasma experimental installation with 16 DC Plasma torches was built at boiler Unit 1, (210 MWe) TPP Nikola Tesla. Figure 2 schematically present milling system 12 (same is on opposite milling system 15) with position of plasma torches (4 lower burners channels were splited into 4×2 cylindrical channels each equipped with 100 kW plasma torch) and shutters for increasing coal dust concentration in the channels with plasma torches [36-41]. Figure 3 presents typical successful result of plasma ignition of coal dust-recirculation gas mixture in the burner channel 122: DC plasma torch no. 122 voltage and current records and coal-gas mixture temperature recorded at 2.5 m distance after plasma torch.

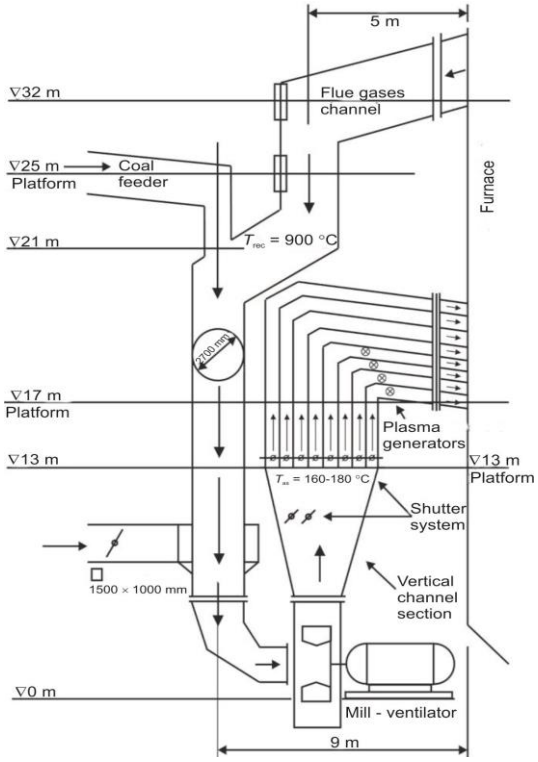
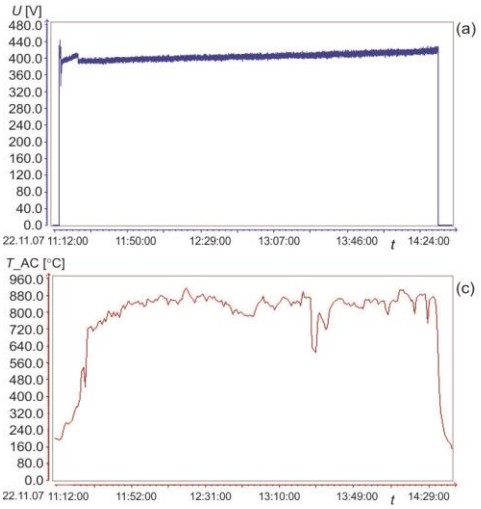


Figure 2. Schematics of milling system 12 with position of plasma torches and shutters at Unit A1 TPP "Nikola Tesla"

Experimental research have proved possibility of plasma-chemical coal gasifica-



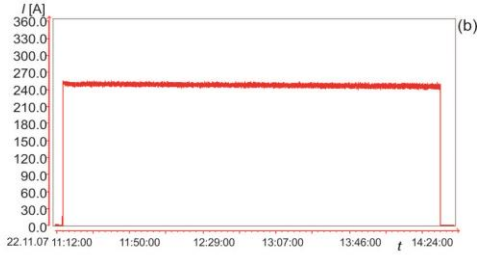


Figure 3. Plasma torch 122A (a) voltage, (b) DC current, and (c) temperature in the burner channel 2.5 m after plasma torch

tion for fire support, but due to technical limitation of the system for milling, drying (with recirculation hot gases from the boiler furnace) and transport of coal dust to the burner, necessary concentration of coal particles and oxygen for correct process could not be obtained simultaneously on all burner channels with plasma torches, so full expected effect of plasma system for fire support could be obtained only partially or only in special regimes. Additional experimental research in the LTE on start-up pilot 27 MWth PC swirl burner with 100 kW DC plasma torch, fig. 4, have proved that start-up and stable plasma gasification of pulverized lignite, with stable flame at the burner exit of temperature over 1200 °C, can be obtained in wide range of coal/air mass-flow rate and with ordinary lignite dust quality (moisture content <10% and granulometric composition R90 < 60%) at Unit 1 TPP Nikola Tesla A. It was concluded that plasma system could be used with previously patented LTE technology based on swirl burners with specially prepared dried pulverized lignite with fine particle size (from bunkers) for start-up and fire support (instead of liquid burners) which could allow much more flexibility of the Unit as needed nowadays in the electric network with renewable power sources.

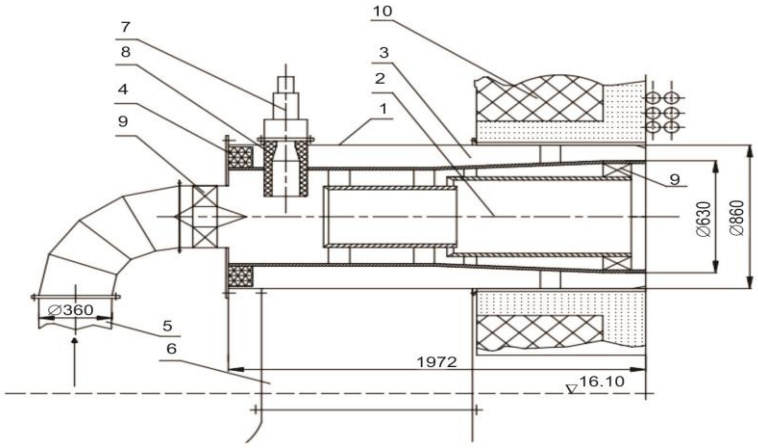


Figure 4. Start up swirl PC burner nominal thermal power 27 MWth with DC plasma torch 100 kW for boiler Unit A1 TPP „Nikola Tesla";
1, 4 – burner case, 2 – ceramic channel for plasma-chemical gasification, 3, 6 – secondary air channel, 5 – coal dust with primary air from the bunker, 7 – Plasma torch, 8 – ceramic nozzle, 9 – swirl element, 10 – boiler wall

Research dealing oxyfuel combustion in PC fired boilers

In last few decades different carbon capture and storage technologies were under constant development and investigation. Among them oxy-fuel combustion (combustion in a mixture of O_2 and recycled CO_2 rich flue gas) is especially attractive (for lignite in combination with pre-drying), mainly due to its potential to be implemented to existing boilers, and due to a fact that current technology level makes its implementation technically feasible. However, switching from conventional to oxy/fuel combustion brings significant changes in all phases of combustion process: devolatilization, ignition time delay, ignition mechanism, and char combustion. Char combustion phase is especially important due to its dominant influence on overall coal particle burnout, and subsequently due to its influence on power plant thermal efficiency. Extensive modelling research [42-47] has been performed for the devel-

opment of single char particle combustion model based on the percolation theory and Monte-Carlo simulations which will enable capturing of char burnout random nature based on char particle heterogeneous structure. The main novelty of the proposed model is that it takes into account both char oxidation due to reaction with O_2, as well as char gasification reaction (with CO_2). O_2 and CO_2 are represented using random walk technique. Thus, the suggested model is suitable for char combustion simulation in a wide range of operating condition (as example both in conventional and oxy-fuel conditions). The implementation of gasification reaction in the proposed statistical model enables quantifying its influence on particle temperature and burnout time, as well as on particle structure evolution during combustion. Suggested model performance was validated with experimental data obtained in single-particle reactor built at the Institute of Power Engineering, Warsaw, Poland. The validation against experimental data included comparison between model and measured values of particle temperature-time dependence, as well as total char burnout – time dependence.

Research dealing co-combustion of industrial and biomass waste in PC fired boilers

Researchers from LTE (as a consortium member of RECOFUEL FP 6 project [48]) were part of experimental team responsible for demonstration of direct solid recovered fuel (SRF) co-combustion in pulverized fuel power plants and implementation of a sustainable waste-to-energy technology in large scale energy production. Applied research, including industrial experimental trials at TPP Weisweiler [49] and TPP Ville Berrenrath in Germany [50], generated new knowledge and experience which was a base for a research study of potentials, needs and techno-economic aspects of the renewable fuels use in the processes of co-combustion with coal in TPP in PE Electric Power Industry of Serbia. In this study [51, 52], as renewable fuels were analysed: SRF and biomass as highest renewable energy potential in Serbia, especially agricultural by-product biomass waste [53, 54], for which analogue technology of co-combustion with coal in TPP can be used. Results indicated technical potential of more than 8% of electricity generated (and reduction of CO_2 emission) by co-combustion of renewable fuels in PC TPP in Serbia. Similar results were obtained in a study on 2020 GHG emission assessment for PE Electric Power Industry of Serbia [55]. Both studies concluded that at present conditions (without CO_2 taxes in Serbia) PE Electric Power Industry of Serbia has no economic interest of implementing this cheap technology. But conditions would be drastically changed with potential implementation of EU ETS system, than implementation of co-combustion of renewable fuels with lignite in TPP would be highly profitable projects with additional, high positive social/economic impact.

Research dealing energy efficiency improvement in PC fired boilers

Due to high energy consumption and complex process of energy transformation, energy efficiency of PC boiler and of whole Unit at TPP was in focus of research in LTE, especially since 2001. Heat balance, air balance and thermal efficiency experimental determination of PC boiler according to DIN 1942, EN-12952:15 was almost regular part of diagnostic research at site [25, 28-32]. Steam parameters and thermal efficiency determination of the PC boiler is a standard part of guarantee measurements of Low NO_x combustion systems for PC boilers at TPP in the region [80-82]. Energy efficiency, heat rate of steam turbine according to DIN 1943, IEC 953-2 for guarantee measurements [56] or part of TPP Unit normative heat rate measurements, were also part of complex diagnostic research at site [57-59]. Results of

experimental research at TPP site and analysis of the equipment and processes at TPP are systematically review as a part of study on energy efficiency (as a base for implementation ISO 50001:2011) in PE Electric Power Industry of Serbia [60]. Research in the laboratory was mostly devoted to the process of pre-drying of lignite in a stagnant or fluidized bed and its application at industrial/power PC boilers [61]. Analysis has confirmed that newly developed, demonstrated RWE lignite pre-drying technology, when integrated in a TPP steam cycle can improve energy efficiency of the unit, eliminate liquid fuel for start-up and fire support and increase flexibility of the Unit as requested by electric network with RES. Due to high moisture content (~50%) in lignite from Kolubara basin and Drmno open pit mine (~40%) implementation of pre-drying technology and use of dried lignite powder from silos/bunkers with plasma swirl burners instead of liquid burners for start-up and fire support in TPP, would be highly profitable projects in PE Electric Power Industry of Serbia with additional, high positive social/economic impact. Base on that conclusions, experimental research at LTE on pre-drying process of domestic lignite were organized [62-64].

Applied research dealing air pollution reduction from PC fired boilers

Implementation of best available technologies for emission reduction from Large PC combustion plants was the obligation in SEE since 2005 according to Energy Community of the SEE Treaty. Applied research activities in the LTE were focused on implementation of these technologies at TPP in the region [65]. Based on extensive data base generated by Guarantee tests A and B (one year later after test A) on most ESP of the lignite fired PC boilers in the region [66-71] including velocity distribution measurements in ESP chamber [72] and periodic measurements of pollutants emission in to air from TPP PE Electric Power Industry of Serbia, researchers from LTE implemented generated applied knowledge, new measuring method and modelling for the improvement of velocity distribution in the ESP chamber (by implementing new design of flue gas guide vanes) at Unit A4 TPP Nikola Tesla resulting in significant decrease of particulate matter (PM) emission (to the level much below 50 mg/Nm^3) compared to PM emission prior improvement of velocity distribution [73]. Continuing experimental investigation of ESP performance, new methodology was development [74] for the onsite experimental determination of performance line, fig. 5, characteristics of the ESP collection efficiency η [%] or slip = 1 – η [%] *vs.* Deutsch number [kV^{2}m^2/(m^3/s)] = U^2A/V where U [kV] is a voltage level between ESP electrodes, A [m^2] surface are of the ESP collecting electrodes, and V [m^3/s] volumetric flow rate of flue gas through ESP. As determined by measurements on site, this characteristics present ESP effective performance, but even more it can be very useful for the analysis of possible modes of modernization for the improvement of collection efficiency.

For the implementation of primary measures for NO_x emission reduction on PC combustion boilers, granulometric composition of the coal dust and its distribution along the furnace hight (including distribution of primary/secondary air) is very important. It means that mills operation parameters and coal dust/gas distribution to different burner levels has to be fitted for successful application of primary measures for NO_x emission reduction (by air staging and fuel staging). Due to that, problem of coarse grained lignite dust (and high percentage of noncombusted matters in bottom ash and in fly ash) at units A3-A5 TPP „Nikola Tesla“ in previous period of exploitation, had to be solved by modernization of DGS mills that were originally installed on these units [75-79]. Based on proper operation of mill system, correct design of burner and overfire air (OFA) system and advanced combustion control system, successful implementation of

primary measures for NO_x emission reduction while maintaining steam parameters and energy efficiency of the boiler (at the same level as before implementation) have been obtained on few 300 MWe lignite fired Units under fuel constant quality regimes (within the designed fuel quality range) [80-83].

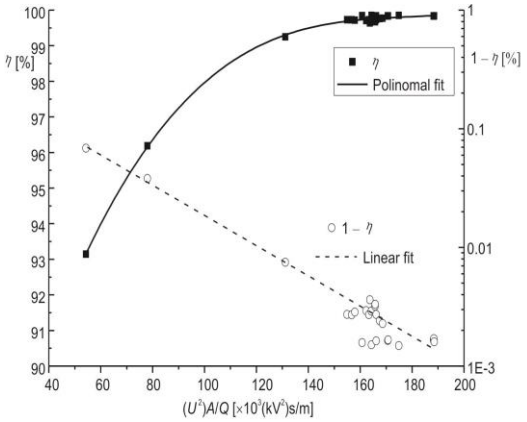


Figure 5. Performance line of ESP Unit B2 TPP Kostoac B;
collection efficiency, η [%] and slip = 1 – η [%] *vs. Deutsch number* = U^2A/V [$kV^2m^2/(m^3/s)$]

Applied research dealing problems of artificial intelligence systems for energy efficiency improvement and emission reduction

Proper combustion control system is a key element for constant high energy efficiency of the processes in boiler and simultaneous low pollutant (PM, NO_x, and SO_x) emission in to air. Design and simulation of complex combustion processes by CFD models can give high quality result but require extensive computational resources and very long computation time. Due to that they are impractical for on-line control. Problem of proper combustion control system is especially pronounced in case of high and sudden fuel quality change as it is practice with lignite from open pit mines in SEE (like lignite from Kolubara basin). Advanced control technologies for improving TPP efficiency, operability and maintaining minimal pollutant emission, based on artificial intelligence could be good approach for controlling large and non-linear PC combustion processes. Researchers from LTE (as a consortium member of WBalkICT-SEE ERA PLUS-Project 093: "Supporting Common RTD actions in WBC for developing low cost and low risk ICT based solutions for TPP Energy Efficiency increasing (WBalkICT) [84]) participated in scientific co-operation research project with innovative approaches in order to correlate ICT last generation solutions, procedures and techniques from fossil fuel combustion processes thermodynamics, mathematical modelling, flue gas analysis into artificial intelligence combustion expert control system. Artificial intelligence systems can learn from examples, they are fault tolerant in the sense that they are able to handle noisy and incomplete data, they are able to deal with non-linear problems, and once trained, they can perform prediction and generalization at high speed. Data for learning algorithm were extracted from minute based field measurements on the 650 MWe TPP Nikola Tesla B, Obrenovac, Serbia. Parameters, with resolution of 1 minute, selected for the purposes of neuro-fuzzy learning algorithm were: power output [MWe], coal/heavy oil flow rate [%/m^3/h], total air quantity [Nm^3/h], oxygen content in furnace/flue gasses [%], feeder loads [%], secondary and tertiary air flow [Nm^3/h], fuel (coal and heavy oil) composition and air temperature [°C]. Based on these data advanced self-learning controller has been developed and the

effects of advanced control concept on combustion process have been analysed using artificial neural network based parameter prediction model. Simulation results suggests that by improved fuel and air distribution, NO_x formation and emission could be decreased *i.e.* kept minimal while maintaining boiler energy efficiency [85, 86].

Conclusions

Thermal power plants on lignite and their technological systems in the South-Eastern Europe countries are designed and build according to relatively old technologies with lower efficiency and under lower emission restriction practice. In addition, since 1990, due to economy transition problems, local conflicts, war destructions and financial crisis, TPP in the SEE countries have been functioning in a very difficult and specific exploitation conditions of disturbed and closed market, resulting in remarkable decrease in financial support for maintenance but with lot of exploitation problems. Since 2005 according to Energy Community of the South Eastern Europe Treaty, new obligations and financial opportunities for TPP life cycle extension, capital repair, revitalization, modernization and introduction of new technologies especially for reduction of pollution problems, came out. The LTE research team have seen an opportunity for new impulse in applied research in the field PC combustion processes in large TPP. Research trends in EU and developed countries on new technologies were constantly analysed and together with successful participation in few EU projects, generated new knowledge, experience and possibility to buy best instrumentation for onsite process parameters measurement, same as used by power energy companies in EU.

Presented research projects and results of applied research projects realized at PC combustion TPP clearly show that LTE team was involved in key activities of rehabilitation and modernization including implementation of best available technologies for pollution reduction in SEE TPP. Success in these LTE research activities was based on modern measuring equipment, multidisciplinary expert team highly skilled for work at laboratory and on site at TPP, accredited standard international measuring methods and especially expert knowledge of the fuel characteristics and processes in pulverized lignite fired boilers of TPP in SEE. This success was highly recognized by the managements in TPP and at the international level by international energy know-how companies and equipment manufacturers and LTE team became a necessary link for successful implementation of modern technologies in pulverized lignite fired TPP in SEE countries.

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