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

by

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The paper presents an overview of the results of the investigations of the processes that take place in pulverized coal combustion boilers and power plants which, in a longer period of time, were realized in the Laboratory for Thermal Engineering and Energy of the "Vinča" Institute of Nuclear Sciences. The presented results were published in numerous studies realized for different users, Ph. D., M. Sc., and specialist thesis, in international and domestic scientific journals and monographs, presented at numerous international and domestic scientific meetings, etc. The main goal of the paper is to chronologically present the results of domestic research that at one time were at an enviable international level, with concrete practical applications for domestic users. This is especially important to contrast the present situation when domestic research in this area is scarce and when the energy sector relies practically only on imported technologies and foreign consultancy.

Keywords: *coal, pulverized coal, combustion, boiler, furnace, burner, slagging, modelling, technologies*

History and introduction

In the mid-1960's, the Vinča Institute of Nuclear Sciences and the Laboratory (then called the Laboratory for Reactor Thermal Engineering) encountered a serious program and financial crisis. The financing of the Federal Nuclear Program was suspended, as it was concluded that Yugoslavia has no financial, technological and scientific conditions to independently develop equipment for nuclear power plants – nuclear reactors, uranium for fuel, fuel elements for nuclear reactors, heat exchangers, and other necessary equipment. Of the three nuclear institutes in former Yugoslavia (Vinča, Rudjer Bošković in Zagreb, and Jožef Štefan in Ljubljana) the Institute in Vinča was in the worst situation, because its program solely focused on the applied research and development of nuclear technologies.

Based on a detailed analysis of the developments in the field of energy technologies in the world, as well as technologies in the process industry, visits to dozens of domestic factories and in particular talks with the leadership of Electric Power Industry of Serbia – EPS,

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the principal laboratory researchers prepared in 1972 an internal document: *Long Term Program in Laboratory for Thermal Physics and Technique* (authors P. Anastasijević, N. Afgan, Z. Zarić, S. Oka, V. Jovašević, M. Stefanović, B. Maršićanin, V. Pišlar, and K. Maglić), which defined the long-term scientific policy and the name of the laboratory was changed into the *Laboratory for Thermal Physics and Technique* (later the name was further changed to the Laboratory for Thermal Engineering and Energy – LTE).

Further development of the Laboratory, even up to the present day, is based on the principles formulated in this program document, and later more precisely formulated 1977 in a new internal document. The correctness of the new scientific and business orientation of the Laboratory is confirmed in this document by the following data: *From 1973 to 1975 the total income of the Laboratory increased twice. In 1976, a further increase in revenue was achieved by 30%, and in 1977, again by 30%. The share of revenues from the funds of the Republic Union of Serbian Science fell from 80% in 1973 to 40% in 1976 and 35% in 1977, of the total revenues*.

The starting principles for the preparation of the Laboratory's long-term research and business program were:

– The existing human and scientific resources, as well as the acquired knowledge and research results in the previous period are the most important and sufficient basis for the opening of new research areas necessary for the development of modern technologies and equipments that are needed for the domestic economy.
– Thermal processes are a key and often limiting factor in many (if not in all) technologies and equipment, and in environmental protection, and represent an inexhaustible source of research goals.
– The characteristics of the future research should be a combination of basic and applied research with the aim of developing and/or applying new technologies and equipment and solving the plant's exploitation problems, but also for studying processes around the energy plant.
– Research should be directed towards the requirements of the domestic economy and efficient use of available energy sources, taking into account the characteristics of coals as the largest domestic energy source.
– Research should enable the domestic industry to independently develop new technologies and the production of modern equipment.

The basic idea of the new program was that problems of heat and mass transfer occur in all areas of technique – thermal energy, transport and process engineering, civil engineering, electrical engineering, agriculture, biosphere pollution, and that the area of interest and work of the researchers in the Laboratory should be all these areas and not just nuclear energy.

The long-term research program is also based on the following two decisions:

– It is necessary to continually educate young research staff in the Laboratory and in the world famous scientific institutions, with production of masters and Ph. D. theses, and publication of papers in International Scientific Journals.
– New areas of research must be initiated, based on the existing and new knowledge and on the results of basic research in fluid mechanics (turbulence), thermal processes (heat and mass transfer), combustion, *etc*.

Specifically oriented basic research has begun in the following areas:

– Experimental investigations of turbulent flows of single-phase fluids on rough surfaces, around a single cylinder and a group of cylinders, on surfaces with a pressure gradient, to

be later directed to study of the free flame flow, high temperature solid-state flows, and the low temperature plasma flow [1]. Under the leadership of the early deceased academician Dr. Zoran Zarić, mathematical models for the calculation of turbulent flows – cooling towers plume, the spreading and mixing of hot water from the cooling systems of Thermal Power Plants – TPP, classic and nuclear, in rivers, lakes and seas, and models for calculation of thermal capacity of river basins were developed. Mathematical modelling of turbulent flow from this moment became one of the main research tasks of the Laboratory.
– Investigation of heat transfer with phase change – experimental study of boiling on smooth surfaces, two-phase flows of the water-steam system, and later the study of temperature and concentration fields and the transfer of moisture in solid porous materials, and investigation of the heat and mass transfer processes at the phase boundaries.

The applied research was organized in four areas in which cooperation was achieved with industrial partners:

– *Thermal energy*: area in which research was directed according to the requirements of the electric power industry: combustion of pulverized coal (PC) in large energy boiler furnaces, heat transfer from boiler surfaces, cooling towers, thermophysical characterization of fuel and ash, operating problems of thermal energy facilities, combustion of coal and biomass in fluidized bed [2]. It is interesting to note that at that time, the Laboratory's research strategy included the use of biomass for energy production, as the study found that from all renewable sources biomass energy is the largest energy source in former Yugoslavia, but also significant problems for which fundamental and applied research was necessary [3, 4]. Later in 2016 in the Energy Development Strategy of Serbia it is emphasized that biomass is the largest renewable energy sources in Serbia.
– *Nuclear energy*: area in which focus was on operation safety and nuclear plants accident analysis. This represented a major reorientation from the design, construction and development of nuclear reactors, although investigation of two phase flow of water/water vapour system remained to a certain extent.
– *Process technology*: area which encompassed development of new technologies for drying agricultural products such as grain, fruits and vegetables, as well as industrial burners.
– *Metrology*: area in which research and investigations included thermophysical characterization of materials, establishment of standard reference materials for thermophysical properties, development of temperature reference standards (etalons), and development of measurement methods for fluid-flow and heat and mass transfer investigations.

In accordance with this new research and business orientation of the Laboratory, the modernization of the experimental base and measuring equipments was undertaken. Own experimental equipment and apparatuses were designed and constructed for measuring in conditions as close to the real plant operation as possible. At the same time, computerization of the Laboratory started and acquirement of equipment for automatic data collection and processing, not only for using in experiments in the Laboratory, but also in industrial measurements, in real conditions.

The list of industrial partners with whom the Laboratory realized cooperation in the field of technology R&D was impressive: Electric Power Industry of Serbia and other former Yugoslav Republics, all TPP in former Yugoslavia, Federal Institute for Measures and Precious Metals, CER Factory – Čačak, Wagon Factory – Kraljevo, JUGEL (Consortium of Yugoslav Electric Energy Producers), Mining and energy corporation Obilić in Kosmet, Internal combustion engine factory *21 May* in Rakovica, Factory *Soko* in Mostar, MINEL Belgrade, heat exchangers for car industry factory Ikarus, Belgrade, *etc*.

Two-way co-operation was established with many scientific institutions in Europe (England, France, Italy, Sweden, Finland, USSR, Germany, and the Netherlands) with whom exchange of study visits were carried out, and longer stays of young researchers for the preparation of Ph. D. thesis or adoption of new measuring and/or mathematical modelling methods. The foundation of the *International Center for Heat and Mass Transfer* with head office in Vinča Institute was a result of the respect it had in the scientific community in the world. It is important to mention other significant achievements related to Laboratory's involvement in international scientific cooperation: organization of the 6th European Conference on thermophysical properties of materials 1978 in Dubrovnik, participation of Dr. K. Maglić since 1979 in a major international venture for establishing standardization methods for thermophysical characterization of materials, full membership in of the IEA's FBC Implementing Agreement the OECD countries, including one-year chairmanship in 1990.

Dr. N. Afgan and Dr. Lj. Jovanović played a key role in opening co-operation with EPS. Contrary to our expectations that the research should focus on the combustion and heat exchange processes in the boiler furnaces, and the flow of the two-phase mixture of water-vapour in the furnace tubes, heat exchange of combustion products and water heaters, steam heaters and air heaters, EPS requested that focus should be oriented towards processes of formation of deposits of ash on the heating surfaces and investigation of the impact of the characteristics of domestic lignites and their ash on combustion and deposit formation processes. These were problems that Laboratory researchers have never encountered before.

In the 1st period (from 1970 to 2000), the measurement methods were developed and measuring probes constructed and for measuring in TPP boilers in real conditions, and then systematically investigations started of the physical and chemical properties of domestic lignites, the behaviour of ash in the furnace, and processes and conditions of formation of deposits on heating surfaces. Combustion of pulverized lignites and the conditions and measures for reducing the formation rate of deposits have been experimentally investigated in real and laboratory conditions. With the construction of a large experimental furnace, the development of modern swirl burners for boiler start-up and fire support and reduction of NO_x emissions started.

In the 2nd period (from 2000 to the present), the research has been focused on the mathematical modelling of the boiler furnace processes, the methods of boilers start-up with low temperature plasma and the improvement of the diagnostics methods and processes in the boilers in order to increase the power and energy efficiency of the plant.

Research results in the period from 1972 to 2000

Development of measuring methods and equipment for in boiler furnaces measurements

For the proper and reliable operation of power plants, it is important to examine the suitability of the selected furnace design for the fuel that is used. The program of power plants testing therefore included an analysis of the conditions in the furnace, and influence of temperature, coal and ash characteristics, gas and particle motion on thermal transformations, behaviour and destiny of the fuel and ash particles.

Measurement of heat and aerodynamic parameters in the boiler furnace and gas duct is essential for the assessment of the thermal and other conditions that exist in the boiler and which affect the specific thermal behaviour of the fuel. The most important are the measurements of the temperature, gas composition and radiation heat flux, as well as sampling of furnace ash particles along the furnace height and along cross-section.

Measurements of gas temperature along the height of the boiler furnace provides information on the objective thermal conditions that influence thermal treatment and transformations of fuel and ash particles from introduction into the furnace until it exit. Taking fly ash samples from several levels in furnace and their instant *freezing* allows the determination of the degree of unburned char in ash particles. These measurements, coupled with gas analysis at the same places, enabled evaluation of the combustion process of fuel particles along the height of the furnace, *i. e.* transformation of mineral matters into ash and determination of the by-products of these transformations. Analysis of these results enabled formulating recommendations for changing the combustion regime with the aim to avoid the formation of compounds that disturb the regular operation of the boiler. Measurement of the composition of gaseous combustion products is also of great importance for the prediction of environmental measures even in the design stage of the boiler.

Distribution of the radiation heat flux on the heat exchange surfaces in the furnace is indirectly related to the temperature of the gases, and this data is important to assess the state of operation of the boiler in different regimes, as well as to determine the potential slagging zones in the furnace. This data, together with the values of the measured heat flux using flux meters installed on the screen tubes, can be of great practical benefit for the regular monitoring of the conditions of the heating surfaces in the plant by the plant's personnel. Monitoring of the fouling process using portable probes can assist in designing boiler plants and in anticipating measures to remove ash deposits, as well as to predict if there is a risk of high ash deposit on boiler heat transfer surfaces.

On the basis of the previous studies [5-7], a set of numerous specific and special probes for measurements on boilers in operation, as well as in laboratory facilities, has been completed:

– *Aspiration (suction) pyrometer for gas temperature measurement:* The complex heat transfer in the furnace, as well as the considerable amount of ash and slag in a suspension that can be in solid or plastic state (depending on the temperature), pose a significant problem for gas temperature measurements. A temperature sensitive element situated in such an environment measures its own equilibrium temperature as a result of several processes. The real gas temperature can only be determined by measuring the gas temperature with the aspiration pyrometer, where the gas temperature is measured under known conditions, and can be corrected based on previously performed calibration. As a temperature sensitive element, a Cr-Al thermocouple was selected, which allows the gas temperature measurements up to 1300 ^{o}C. The length of the water cooled aspiration pyrometer is 2.5 m, which allowed the measurements of gas temperature up to 2.5 m from the furnace walls. It was established that the aspiration rate of the measuring element of 52 m/s achieved satisfactory accuracy in real conditions [8].
– *Aspiration pyrometer with ejector effect for gas temperature measurement:* Using the aspiration pyrometer with the ejector effect, the problem of the probe cooling with water was solved [9]. The suction of the gas whose temperature is measured is done in the pyrometer head itself where the air ejector is installed. The pipe carrier of the pyrometer is cooled by air, which is also used for aspiration. Three portable air-cooled pyrometers with lengths of 3.5, 4.5, and 4.7 m were made.
– *Simultaneously measurement of velocity, temperature, particles and gases concentration in boiler furnaces:* It is advantageous to measure the gas velocity, temperature, gas composition, and particle concentration in the furnace simultaneously. These measurements were made using the so called *universal probe* with aspiration pyrometer, which enabled

simultaneous measurements of temperature, gas velocity and at the same time taking samples of gas and particles. The probe material and the probe cooling enabled the temperature measurements up to 1300 °C. The probe is equipped with an aspiration-type thermometer with Pt-PtRh thermocouple with isokinetic suction conditions when taking representative particle samples. A total of 5 universal probes, 5.0, 5.5, and 6.0 m long, were made. All probes with accompanying auxiliary equipment were calibrated in the aerodynamic channel at speeds of up to 20 m/s and in furnace at temperatures of up to 1300 °C [10].

– *Measurement of the heat flux and the rate of ash deposit formation on the furnace screen surface:* The radiant heat flux measurement on the screen surfaces of the furnace was performed by own inertial portable flux probe. The receiving element of this probe is a metal disk that is isolated sidewise and on the back side, mimicking an element of an infinite plate whose one surface is isolated and the other exposed to the heat source, fig. 1(a). The heat flux is determined by measuring the heating rate of the receiving disk in the quasi-stationary regime of heat transfer through the disk. For this, the temperature rise of the disk was followed at certain time intervals. Three inertial probes have been constructed with the following dimensions: two straight probes of 1 m length, with diameters ∅45 and ∅70 mm, and one *curved* probe 1 m long, having a diameter of ∅45 mm.
  For measurements of the thermal efficiency of the screen surfaces, the so-called two-sided probe with two flux meters and a circular plate was constructed, fig. 1(b). The receiving surfaces of the flux meters are positioned in such a way so that one is oriented towards the flame in the furnace and the other to the furnace walls. The value of the coefficient of thermal efficiency of the screen surfaces is obtained on the basis of the measurement of the receiving flux and thermal flux of reverse radiation from the screen surfaces [11]. Also developed were flux meters which enabled determining the heat flux per unit area which the working fluid in the boiler receives, fig. 2.

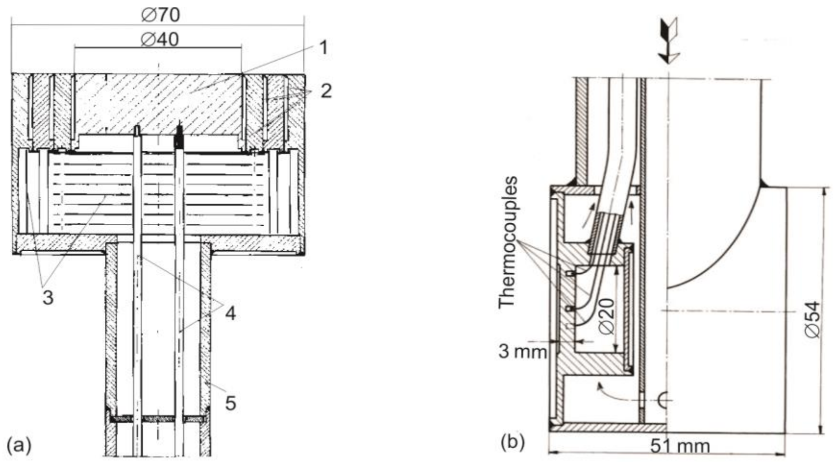


Figure 1. Inertial flux probe (a) and two-sided flux probe (b) [11]
1 – 5 are constructive details of the probe

– *Gas velocity measurement:* A five-hole Pitot probe, the so cold *Cobra probe*, was built for measurements of gas velocity and determination of the flow field in the furnace. The probe length is 4.7 m and the probe head is disassembled. The head of the probe is calibrated in the aerodynamic channel at two speeds of ≈3 m/s and ≈6.2 m/s [12]. Data on the flow field in the boiler furnace is necessary for proper construction, calculation and design of the furnace, as well as for its proper exploitation or elimination of defects observed during operation.

– *Ash deposit formation measurement:* Taking deposits in the zones near screen and superheating surfaces in the furnace is carried out by specially designed probes, so-called *straight* and *curved* probe. The *curved* probe is placed along the wall of the boiler, parallel to the screen tubes, while the straight probe is introduced into the furnace to a depth of about 4 m. The probes are mobile and cooled with water, while the working part of the probe on which the deposits are accumulated is made from the original screen or superheating steam pipes and cooled with air. Two *straight* moving probes with length 5.5 and 6 m and two *curved* probes with total length of 1.8 m were made.

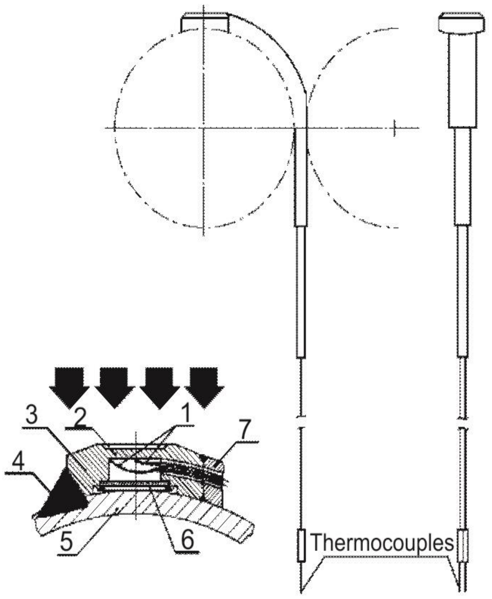


Figure 2. Flux meter for measuring heat fluxes in boiler furnaces; *1 – 7 are constructive details of the flux meter*

– *Flue gas analysis:* The flue gas samples taken from the furnace or gas duct of the boiler enables an assessment of the degree of completion of the combustion process (determining the losses from the chemical incompleteness of the combustion), excess air coefficient, the character of fuel combustion in separated furnace zones (dynamics of the combustion process); extent of air intake by gas tract, furnace regime and design characteristics of the boiler, as well as emissions of pollutants into the atmosphere. For this purpose a universal water-cooled probe was used at several characteristic levels in the furnace, up to a depth of 5.5 m. Non-cooled probes were used at lower temperatures. The concentration of CO, CO_2, O_2, NO, NO_2, and SO_2 was determined. Several types of gas analysers were used: at the beginning Orsat and Dreger, and later the analysers with paramagnetic and electrochemical sensors.

Using the previous described measuring equipment measurements at a large number of plants in the former Yugoslavia were performed, according to a specially designed measuring program that was adapted to each specific boiler and which was harmonized with the user of the tests. These tests were undertaken with the aim to solve the existing exploitation problems, determine the optimal operating conditions and reduce the ash deposit formation on the heat exchange surfaces.

The list of TPP on which specific measurements were performed is very wide: *Nikola Tesla* [13], *Kolubara* [14], *Kostolac* [15], *Morava* [16], *Kosovo* [17], *Gacko* [18], *Ugljevik* [19], *Tuzla* [20], *Kakanj* [21], *Plomin* [22] and at a number of smaller industrial facilities. The results of the measurements were presented to the users in the form of reports, but were regularly presented at the meetings of domestic experts organized by the *Society of Thermal Engineers* of Serbia and Yugoslavia and JUGEL, with the participation of a large number of experts from the electric power and domestic industry.

Research of physical-chemical properties of coal

Long-term research in the LTE resulted in an extremely important and extensive database of the physical and chemical properties of more than 40 Yugoslav coals, predominantly lignites, has been collected. For some open mines (Kolubara, Kostolac, Kosovo, Gacko, Ugljevik, and Plomin), there are detailed data for the different fields of these mines, both those in exploitation and those whose exploitation is under preparation. The data is related to the organic and mineral matter of coal, with particularly detailed data on the chemical composition of ash [5].

As a result of frequent requests from EPS since 1973, LTE has undertaken an extensive research program with the aim to estimate characteristics and chemical composition of the mineral part of the coal and its tendency to slagging and fouling on screen and convective surfaces of the boilers. In the first phase of these investigations, lignites from Kolubara, Kostolac, and Kosovo basins were examined. Later, the same original testing methodology was applied to many other coals: Raša, Kakanj, Gacko, Ugljevik, Banovići, Bitola, and others. [5-7, 10, 19, 21, 23].

The categorization of domestic lignites and numerous other Yugoslav coals was done, based on the tendency towards deposit formation on the heating surfaces of boilers. For this purpose evaluation of the dependence of the melting (fusion) temperature versus the so called basic number, fig. 3(a), and the ash viscosity versus temperature relationship, fig. 3(b), was used. Based on the determination of the content of mineral matter in the fuel that can be soluble and unsaturated and their relationship, the boundaries of ash behaviour have been defined: melting (melting temperature up to 1200 °C), soluble (1200-1350 °C), unsaturated (1350-1650 °C) and almost insoluble (over 1650 °C) [5, 6]. The developed standard methodology for testing and determining the tendencies of ash slagging was accepted by EPS as a standard procedure in cases where it is necessary to eliminate problems in the boiler exploitation or to predict the behaviour of coal during combustion in new boilers.

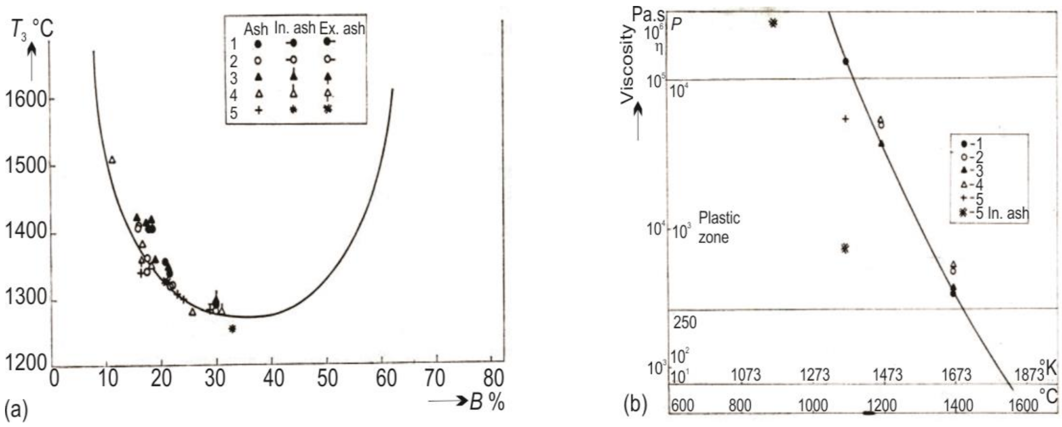


Figure 3. Basic number-fusion temperature (a) and viscosity-temperature dependence (b):
1-5 – coal samples from the open cut Drmno **[5]**

Testing of coal behaviour during combustion in PC boiler furnaces

After the first phase of research on PC combustion, which was oriented to understanding and eliminating exploitation problems of the boilers in large TPP, it was concluded that fundamental and applied research of the characteristics of domestic coal during the combustion process must be investigated [24].

The investigation of PC combustion was carried out both in laboratory and industrial conditions. For laboratory research, taking into account the experience worldwide at that time [7, 25, 26], the necessary experimental base was built: a vertical tubular furnace with a capacity of 0.5-3 kg/h PC, fig. 4(a), with inner diameter 71 mm and 3200 mm long, suitable for comparative studies of the kinetics of combustion and ash deposit formation of different coals [23, 27, 28], and horizontal experimental furnace, fig. 4(b), with diameter 800 mm cross-section, 3000 mm length and capacity 30-100 kg/h PC [29]. Results of laboratory investigations were compared with measurements at the real boilers in operation at TPP, as described earlier. Detailed comparative investigations of the kinetics of PC combustion of different coals, depending on the origin of coal, its composition, particle size distribution and humidity [29, 30], were carried out on these experimental furnaces. For the first time, combustion rate constants – the activation energy and pre-exponential term [31, 32] for domestic lignites Kolubara (field D and Tamnava), Kostolac (Ćirikovac and Drmno), and Kosovo (Belaćevac, Dobro selo), were obtained. These studies have served as a basis for the subsequent development of equipment for energy boilers start-up using specially prepared PC, instead of liquid fuel and for the development of burners with reduced NOx emissions.

(a) (b)

Figure 4. Vertical (a) and horizontal experimental furnace (b)

Research aimed to solve exploitation problems and design of power boilers

Research aimed at solving the exploitation problems of energy boilers is the most important part of the Laboratory's activity in the field of coal combustion. In a long period of time, the financing of long-term studies and experimental programs EPS engaged a significant part of the scientific research staff of the Laboratory in order to solve the exploitation problems of TPP. The results of these investigations have led to the initiation of many fundamental and applied investigations of the combustion process and physical and chemical transformations of the organic and mineral part of the fuel.

Diagnostics of the process in boiler furnaces and warranty tests of boilers

The solution of the boiler's exploitation problems was based on the measurement of the most important flow and thermodynamic parameters of the process in the boiler furnace and the gas duct. The previously described self-developed measuring methods and equipment for the measurement inside the boiler and in the gas tract to the chimney enabled measurements of: the gas temperature and velocity, the concentration of particles and gases, the emitted, received and reflected heat flux on the walls of the screen tubes and on convective heating surfaces, flow and pressure on the water side of the boiler, the temperature of the metal of the pipe walls, *etc*. Measurements were carried out on almost all boiler units in the former Yugoslavia and a comprehensive data base was created on the behaviour of plants burning domestic coals [13-22, 33].

The intensity of deposits formation on the boiler heating surfaces

On the basis of a series of measurements carried out with numerous coal, both in laboratory and in real exploitation conditions, criteria for estimating the tendency of coal ash to form deposits have been established and the influence of operating parameters (gases temperature and heat flux) on the kinetics of deposits formation has been determined. Recommendations for the selection of the type and conceptual design of a boiler plant based on domestic coals were defined [34], as well as critical furnace values (temperature at the furnace exit, heat release rate in furnace and mean heat release rate per unit area), which correspond to the properties of the combusted coal [16, 19, 33-35]. These recommendations were formulated and finally accepted by the EPS in the early 1980's, and used for the selection of parameters of new boilers, and even today for the analysis of the exploitation problems of TPP.

Exploitation control of metal pipes systems and steam tubes in energy boilers

Bearing in mind the long period of exploitation of different boiler units, EPS started financing in the mid-1980's a complex program for determining the methodology and the acquisition procedures for determining the state of the embedded metal in the boiler units and determining the remaining lifetime of the vital elements of the boilers. These studies included an analysis of the conditions and causes of the ruptures of screening surfaces, which leads to a reduction in the availability of TPP. The program was realized by LTE in cooperation with the Institute for material testing of Serbia and Faculty of technology and metallurgy in Belgrade.

The necessary measuring equipment for the diagnostics of the regime parameters, important for the assessment of the remaining working lifetime, has been developed. Evaluation of the measurement results and the operating experience, a methodology for determining the remaining working lifetime of the metals of the vital components of the boiler and steam tubes has been established, as well as the methodology for determining the causes of the occurring failures. By using this methodology the working lifetime of TPP Kolubara, Tuzla, and Kakanj has been assessed. The results of these investigations have been systematized in a monography [36].

Introduction of modern diagnostic methods and "condition monitoring" maintenance of plant and equipment in TPP

At the end of the eighties, the EPS started an ambitious project of modernizing measuring equipment with the aim to introduce new diagnostic methods which could enable well-timed maintenance based on *condition monitoring*. The LTE's employees have demonstrated over many years of their work that technical diagnostics is a powerful tool for increasing the safety, economy and reliability of the power plants in operation, and that it has an important role in determining the state of equipment's working capability in plant exploitation (*condition monitoring* maintenance) and in repairs (repairs diagnostics). It can also be used to determine the parameters relevant for estimating the optimal time-table for maintenance of TPP. Review and selection of diagnostic methods and procedures, organization of the diagnostic system at the level of TPP and at the EPS level, harmonization of the of maintenance duration and the duration in between maintenance in function of the operating conditions and the size of the thermo-blocks of EPS, alongside with the critical analysis of the experience and the working methods used in the developed countries are given in papers [37-39]. Most of the proposed LTE's *condition monitoring* maintenance methods have been introduced in the practical application at EPS power plants.

Development of an expert system for monitoring the deposits formation and the flame position in power boilers furnaces

Based on the experience during many years of experience with the problem of slugging and fouling of boiler heating surfaces the following expert monitoring systems have been developed: the flame detection methods [11, 40], expert system for monitoring furnace fouling, fig. 5(a), and the flame position determination in the boiler furnace, fig. 5(b) [41]. The basic elements of the developed monitoring systems at the industrial level are: instruments for radiant heat measurement (fig. 2), automatic acquisition system of the diagnostic parameters, criteria for positioning of the diagnostic instruments in the furnace, and a criterion for estimating the deposit thickness on the heating surfaces. The system for automatic acquisition and data processing was developed and applied on one 300 MW power boiler.

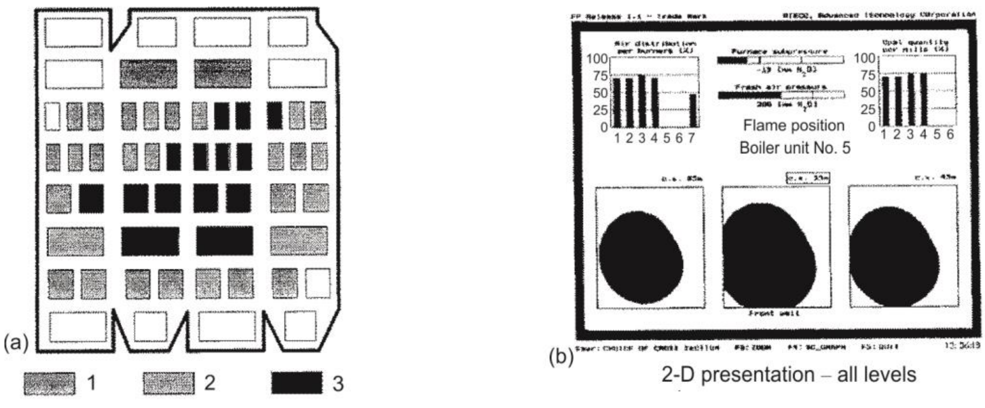


Figure 5. Expert system for monitoring deposit formation; (a) (*1 – low, 2 – medium, 3 – critical fouling***) and flame position in the boiler furnace (b) [41]**

Research with the aim to improve conventional combustion technologies

The classic PC combustion technology using jet burners has been in practice for many years. This conventional coal combustion technology cannot satisfy the growing needs and demands of in relation to energy efficiency. In addition, the conventional PC combustion technology, now used in domestic TPP, is not able to satisfy modern environmental requirements [42].

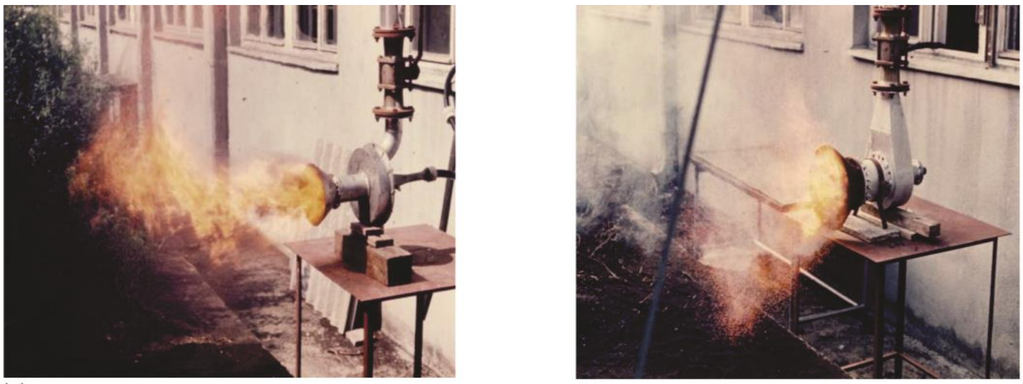
Environmental pollution reduction from power plants is one of the primary goals of the research carried out in LTE and is a part of a global process that is being implemented under the name of *clean coal technology* [43]. Part of the development refers to increasing the efficiency of the existing technologies and to develop new ones with a higher efficiency. The second part of development relates to find technologies for flue gases cleaning. The first activities within the development of clean coal technologies were related to the analysis of thermal pollution of the environment in order to later focus on the development of burners with the minimum NO_x emission burning domestic lignite and suitable to be used in the existing TPP.

Development of swirl burners and systems for boilers start-up and fire support using PC

The PC combustion with swirl burners, utilizing the swirl effect, is very significant and is widely used. Swirling flows are commonly used for stabilizing and intensifying the combustion process and for the reduction of NO_x emissions. Optimum combustion conditions depend on the fuel type and the characteristics of the burner.

Development of swirl burners started at the request of EPS, which planned an ambitious program for the replacement of liquid fuels with specially prepared PC for boilers start-up and fire support at TPP. An experimental horizontal combustion chamber was constructed in LTE [29] to test the models of various types of swirl burners with powers of up to 500 kW_t, fig. 4(b). On a block of 110 MW_e in the TPP Kolubara, a pilot plant for start-up and fire support of 32 MWe and 110 MWe boilers was constructed [44], based on burning specially prepared PC with fine particle size obtained by LTE patented technology [45, 46]. For operation in the real operating conditions of this TPP, swirl burners with power of 4.5 and 27 MW_t were built [47, 48].

Based on the investigation of the combustion kinetics of domestic pulverized lignite, a series of own swirl burner constructions have been developed. In order to determine the operating and design parameters, several models of these burners have been tested: tangential, with movable blocks for air swirling, fig. 6(a) and axial-blade fig. 6(b).



(a) (b)

Figure 6. Burner with movable blocks (a) and with axial-blades (b)

Investigations on models and prototypes of swirl burners showed that energy boilers start-up can be achieved using PC instead of liquid fuel [44, 48]. Experimental testing of coals for use in boiler start-up combustion systems has been carried out for a number of TPP in former Yugoslavia. Using the software for the calculation of swirl burners, conceptual solutions and projects for the introduction of start-up and fire support systems were made [49, 50]. Unfortunately, except in the TPP Kolubara, where after testing this system was used for a short period of time, boilers start-up using PC was not introduced on other plants. Low oil prices, low economic activity, as well as resistance to the introduction of new systems and technologies prevented the realization of this highly successful independent domestic development of modern technologies. At the same time, such systems are successfully used in Germany and other countries. It is important to note that such burners can be successfully used on small and medium energy boilers as well.

Development of burners for PC combustion with reduced NO_x emission

In cooperation with boiler factory *Minel Kotlogradnja*, research and development of burners with reduced NO_x emission was undertaken. Theoretical and experimental investigation of the process of PC combustion in swirl burners has been carried out in order to define and experimentally determine the influence of the design and operation parameters of the burners and influence of the fuel characteristics on ignition and combustion of PC and the formation of harmful coal combustion products [51]. The formation of the NO_x compounds is influenced by the swirl number, the velocity and ratio of the flow of primary and secondary air, diffuser and its spreading angle, and other. The experiments carried out on experimental horizontal furnace with several models of swirl burners and with several types of coal (lignite, brown, hard) enabled us to make our own designs [52, 53]. Unfortunately, due to the situation in the mechanical engineering industry, the specific application of the developed technology in industrial conditions was not realized.

Research on "clean coal technologies" usage

At the request of EPS, a detailed analysis of the current state of development of the technologies applied in order to reduce the NO_x emissions was carried out. A program was proposed for reconstruction of combustion facilities and changes in the organization of the combustion process in TPP, fig. 7, that would enable compliance with domestic legislation [54, 55]. The introduction of the so-called primary measures were proposed and introduced progressively tailored to the characteristics of domestic coal, and having in mind the ability of the domestic industry. The technologies then proposed by LTE for domestic boilers (flue gas

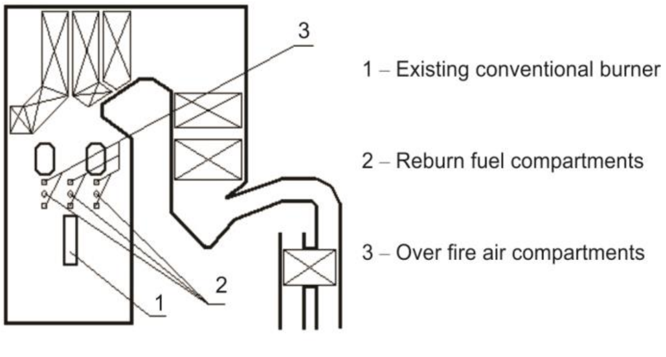


Figure 7. In-furnace NO_x reduction techniques [54]

re-circulation, two-stage combustion, staged air injection into the furnace, *i. e*. over fire air technique, staged fuel injection, increasing coal fineness, *etc*.) have been introduced in practical applications just in recent years, but through the engagement of foreign companies.

In order to develop, design and construct equipment for the application of these technologies, experimental research was started to determine the influence of nitrogen content in coal on NO_x emissions. Experimental testing of several types of domestic coals (lignite, sub-bituminous, hard), with different granulations, has established a correlation between N which is released from volatiles and the content of volatiles matter in coal [56].

Calculations procedures and process modelling

The development of different calculation procedures for heat and mass balances, adapted for computer use, began in LTE in the mid-70's. For the needs of boiler factory *Minel Kotlogradnja*, a computer program for the thermal calculation of block, industrial and energy boilers, based on the normative method was developed [57]. In addition to the experimental combustion research, a mathematical model has been developed which, based on the chemical thermodynamic equilibrium of the *fuel-air* system, predicts the concentration of different compounds (NO, NO_2, N_2, H_2, S_2, O_2, SO, SO_2, H_2O, CO, CO_2, OH, CH_4, C_2H_2, H_2S, and NH) in combustion products at different combustion temperatures [58]. The obtained data on the composition of gaseous combustion products enable further calculation of the process of reduction of nitrogen and other oxides by adequate organization and adjustment of combustion conditions. The results showed good agreement with the measurements in the PC flame.

The development of swirl burners was further supported by combustion aerodynamics modelling work. Numerical calculation models of turbulent flows with particles in free and limited jet, with and without chemical reactions have been developed [59-61]. These studies continued and extended in the late 1990's and early 2000's into modern mathematical modelling of CFD of the all processes in the furnace. Part of this research has already been presented in [1], while the previously mentioned recent research will be presented in the next section which refers to the complex modelling of the processes in furnaces, as a base for process control in operation.

Modeling of flow, combustion and heat transfer in real-scale pulverized coal-fired furnaces

Since 2000, a considerable research effort has been given to both the development and application of mathematical models and numerical codes for the purpose of numerical analyses and optimizations of complex processes in real thermal energy conversion systems, like utility-scale PC-fired boilers and furnaces. In-house developed models and software may contribute to efficient, environmental friendly and cost-effective exploitation and operation life extension of domestic power plants, with software solutions corresponding to international experience, high level analysis of boilers and furnaces operation and technology transfer to end-users. Main investigations in the field in regard to the modelling of entire complex furnace processes, thermal radiation modelling, numerical prediction and analysis of environmental aspects, reduction of harmful emissions from steam boilers and plasma-assisted PC ignition and combustion stabilization. In order to implement developed models and codes for the processes optimization and control of Serbian TPP boiler furnaces in exploitation, a cooperation between the Institute Vinča Laboratory – LTE, Faculty of Mechanical Engineering in Belgrade, and the EPS began during this period and has been developing ever since.

The 3-D comprehensive combustion code to predict processes in a utility-scale furnace

On theoretical basis [62] and extending previous experiences with modelling of PC combustion in laboratory-scale axisymmetric flow reactors [59, 63], a 3-D differential mathematical model and numerical code were developed in-house, step-by-step, to predict reactive turbulent gas-particle flow in PC-fired industrial-scale boiler furnaces at stationary conditions. Such a complex model was the first of a kind developed in Serbian research institutions, offering a composition of modelling approaches balancing between sub-models sophistication and computational efficiency. Selected two-equation turbulence model was validated in 3-D field [64], while Lagrangian particle tracking in conjunction with diffusion model of particle dispersion was verified in complex swirling isothermal gas-particle flow with re-circulation [65]. Selecting differencing scheme in conjunction with optimal solver to enable both the stability and the convergence of solutions, when predicting turbulent flow in real-scale 3-D geometry of the case-study boiler furnace, was not an easy task, even when considering monophase flow, but set the basis for further development of the code. The research resulted in Ph. D. thesis (under the mentorship of Prof. S. Oka), describing in details individual steps in development and validation of the model against available measurements [66]. Turbulent gas-particle flow was considered in Eulerian-Lagrangian frame, with k-ε turbulence model and Particle-Source-in-Cell method for coupling of phases. Six-flux model was used to describe radiation heat exchange. Coal particle reaction rate was considered in combined kinetic-diffusion regime. Heterogeneous reactions were described within a *shrinking core* concept and char oxidation model, based on global particle reaction rate determined for Serbian lignites in vertical cylindrical 15 kW experimental laboratory furnaces [30, 31]; homogeneous reactions could be added without difficulties. The computer code provides 3-D fields, *i. e.* spatial distributions of relevant quantities, such as velocity components and vectors, temperature, heat flux and gas mixture components concentrations, as well as trajectories of coal particles and global indicators, like furnace exit gas temperature (FEGT). The model was applied for predictions and comprehensive parametric analyses of flow, heat and mass transfer processes in PC tangentially-fired furnace of the TPP Nikola Tesla 210 MW_e steam boiler unit [67]. In cooperation with the EPS, the comprehensive model was adapted to the PC-fired 350 MW_e TPP Kostolac B boiler unit furnace and additionally validated [68, 69]. The code was used to study specific aspects of operation under different conditions, like control of PC flame geometry and position within the furnace. Input of data was enabled through user-interface of the code itself, or by coupling with the computer program for prediction of air-coal dust mixture and preheated air distribution between the burners' tiers [70]. A proper distribution of both the fuel and air over individual tiers of tangentially arranged jet burners critically affected the entire flow and temperature situation in both the combustion chamber and the boiler unit [71, 72]. The control of the flame vertical position and FEGT by means of the pulverized fuel distribution over the burner tiers is presented in fig. 8. Injection of more fuel through the lower-stage (*i. e.* main) burner tiers is expected to descend the flame, as it clearly is in the case (b) with respect to (a). Difference between the cases (c) and (b) could be attributed mostly to a significantly higher amount of coal (49.1%) injected through the upper-stage of main burners in the case (c), compared with 24.5% of fuel in (b). The analysis emphasizes the importance of careful control of the fuel distribution over each individual burner tier.

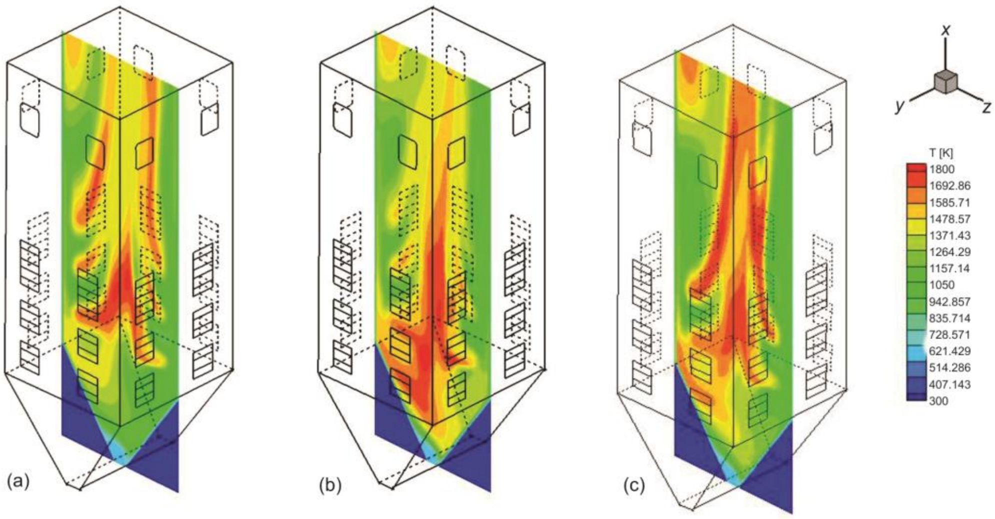


Figure 8. Flame in the case-study furnace of TPP Kostolac B boiler unit in dependence on the PC distribution over the burner tiers; (a) 56%, (b) 70%, and (c) 84% of fuel injected through the lower-stage (main) burners (FEGT = 1093 °C, 1029 °C, and 1020 °C, respectively)
(for color image see journal web site)

Thermal radiation modelling in PC-fired furnaces

Radiative heat transfer inside large furnaces fired by PC was investigated as the most important mode of heat transfer. The research was conducted using the flow conditions and geometry of the 210 MW monoblock thermal unit furnaces.

A PC flame is a two-phase radiation absorbing, emitting, and scattering medium comprising two phases: the gas phase and the dispersed phase. Investigation of the radiation heat transfer included effects of the flame radiative properties (total extinction coefficient, scattering albedo, and scattering phase function), influence of the gas phase radiative properties, and improvement of the radiation model application. Two models of the radiative heat transfer were used: six-flux model and Hottel's zonal model. Investigation of the influence of the scattering phase function showed that the real scattering phase function could be replaced by the isotropic function [73].

Application of the Hottel's zonal model began with the defined method of calculation of direct and total exchange areas for the selected furnace, within the research for Ph. D. thesis [74]. Comparison of the results with six-flux and Hottel's zonal models as the radiation models showed small differences of the results. Work on the effects of the flame radiative properties on the calculation of the radiative heat exchange indicated the real values of the flame radiative properties [75]. Influence of the gas phase radiative property models was also investigated. Two models of the gas phase radiative properties were used: the simple gray gas and the weighted sum of gray gases. The small differences in the results showed that the simple gray gas model could be used instead of the weighted sum of gray gases model [76]. It was a consequence of the presence of gray fly ash particles, which contributed to the grayness of the flame. Further work on the subject of the weighted sum of gray gases model indicated possible optimization of the number of gray gases. The number of the significant figures in the coefficients of the polynomials which approximated the weighting coefficients was found the necessary condition for the optimization [77]. In development of the radiation models, the objective was to provide the method for determination of the wall variables, such as wall emissivity, temperatures and heat fluxes, with Hottel's zonal model of radiation. The research included the existence of the ash deposit layer on the furnace walls.

Environmental aspects of PC-fired utility boilers – modelling and analysis

In order to enable analysis of processes for NO_x/SO_2 emission reduction, submodels of NO_x formation/destruction reactions and Ca-based sorbent calcination/sintering/sulfation reactions were selected, coupled with the in-house developed combustion code and applied for investigation of de-NO_x primary measures and de-SO_2 by Furnace Sorbent Injection (FSI) method [78-86]. In order to enable efficient data input and meet the real engineering needs, a new user-friendly software interface, was developed as well [80, 83]. The interface facilitates variation of operation parameters and provides convergence monitoring, so that the software can be used without difficulties also by engineering staff dealing with the process analysis in boiler units.

An extensive numerical study, first of its kind in Serbia, was performed for the EPS to optimize the primary measures in the tangentially fired pulverized lignite furnaces of 350 MW_e TPP Kostolac B boiler units [78]. Optimal combustion modifications in the case-study furnaces were suggested: injection of 85% of coal through the main (lower-stage) burners, local excess air control by proper distribution of preheated air between the burner tiers and the usage of finer grinding of coal, enabling over 30% of NO_x emission reduction and simultaneous control of the flame position; standalone application of over-fire air provided 25% of the NO_x emission abatement [79, 80]. Effects of the measures on the steam boiler efficiency and safety were examined by thermal calculations, in cooperation with the Faculty of Mechanical Engineering Belgrade. Interactions between gas-particle turbulent flow, diffusion flame and NO_x formation/depletion, as well as de-NO_x by combustion tuning under different conditions, like utility boiler loads, cold air ingress, flue gas recirculation and fuel-bound nitrogen content, were also studied [83].

Numerical analyses of in-furnace desulfurization demonstrated that a proper distribution of finely ground sorbent (limestone) particles could provide an efficient SO_2 absorption by FSI in the pulverized lignite-fired furnace of the TPP Kostolac B utility boiler unit 2. The sorbent injection location was found to have an outstanding importance, affecting the particle residence time and local gas temperature surrounding, while the effects of Ca/S ratio and sulfur content of coal were emphasized as well. These investigations resulted also in Ph. D. *thesis* [85]. In calcination process $CaCO_3$ transforms to CaO. Sulfation of CaO is described by partially sintered spheres model. The sorbent particles are assumed to consist of spherical, connected grains, which overlap due to sintering at high temperatures, reducing the reactive surface of particle. The model was validated with available measurements from drop down reactors [81]. Comprehensive study of in-furnace SO_2 control was done over a wide range of operating conditions. Injecting 10 μm $CaCO_3$ particles into the case-study furnace through the burner tiers provided SO_2 reduction of over 45% at the furnace exit [82, 84-86].

Direct co-firing of PC with biomass is a promising technology that can help in both the efficient biomass utilization and the global emission reduction of GHG, in particular CO_2, but it also may contribute to reducing nitrogen and sulfur oxides. Theoretical basis for modelling of the co-firing process was established [87] and a new model was developed to describe devolatilization, homogeneous and heterogeneous combustion of different pulverized fuels [88]. The model describes evaporation, devolatilization, volatiles combustion, and char oxidation. An empirical devolatilization model is used for coal and modified for biomass. Devolatilization products contain the primary volatiles and tar, while the tar decomposes to the secondary volatiles and residual soot. The soot and fixed carbon from char oxidize through heterogeneous reactions in combined kinetic-diffusion regime. Homogeneous combustion is determined by slower of competing mechanisms: chemical kinetics and turbulent mixing. The model was tested and applied for optimization of the coal and biomass (agricultural waste) direct co-firing process in real-scale TPP Kostolac B boiler furnace within research for Ph. D. thesis [89].

Modeling of plasma-assisted PC ignition and combustion stabilization

Use of the plasma-assisted system for PC ignition and combustion stabilization in utility boiler furnaces offers the possibility of considerable savings, compared with the heavy oil burners. For this purpose, the low temperature (~5000 K) air-plasma torches can be built within air-coal dust mixture ducts between the mills and coal burners.

A 3-D differential mathematical model was developed to predict reacting turbulent gas-particle flow in rectangular duct, validated against laboratory measurements, and applied to optimize the process with two opposite plasma torches (total power output of 200 kW) for 210 MW_e boiler unit firing pulverized Serbian lignite [90-92].

Selected numerical results for gas temperature field in horizontal plane through the plasma jet inlet are shown in fig. 9 [91]. Hot plasma initiates the reactions of complete and partial oxidation of coal in the air-coal dust mixture duct. There are local zones of intensive reactions and high temperatures due to the plasma effect and wide relatively inert field in the duct due to a considerable mass flow rate of colder air-coal dust mixture and much larger cross-section of the duct in comparison with the jet. Sub-stoichiometric conditions prevail in the duct and the coal gasification and combustion of gaseous products exert a major effect. Endothermic reactions of coal gasification consume a portion of plasma thermal energy and energy from exothermic combustion reactions. Gasification products from the plasma jet region flow into the downstream zone rich in unconsumed oxygen where rapid homogeneous combustion of CO and hydrogen occurs. The steady-state is reached rapidly with the level of gas thermal energy at the furnace inlet necessary for successful PC ignition and stable combustion.

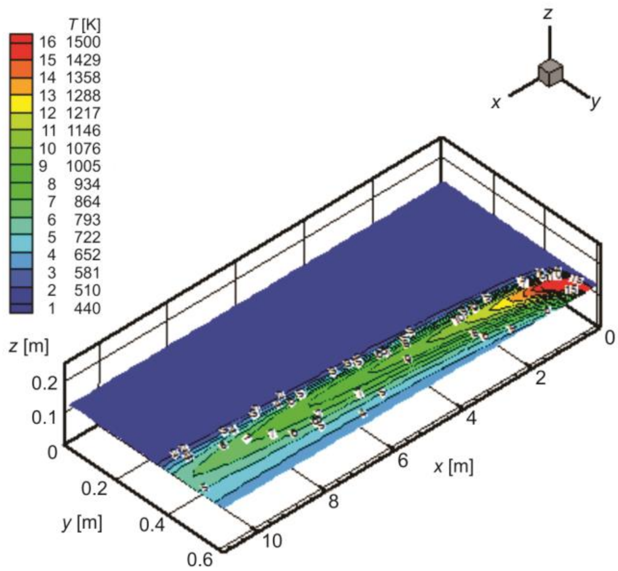


Figure 9. Gas temperature field in the air-coal dust mixture duct with plasma-assisted PC ignition system
(for color image see journal web site)

The plasma-system thermal effect was discussed with respect to the savings of liquid fuel in real operating conditions [92]. The thermal effect is a difference between energy output (thermal energy of gas and particles and chemical energy of unburned products of gasification) and thermal energy of air-coal dust mixture transport fluid and particles entering the duct. The analysis can help in optimizing the length of air-coal dust mixture duct and evaluating the power of plasma torches required to replace heavy oil burners.

The simulations can be applied for optimization of PC ignition and combustion stabilization, enable efficient and cost-effective scaling-up procedure from laboratory to industrial-scale and help to reduce expenses and development period for the technology.

Conclusions

A review of the long-term results achieved in the Laboratory for Thermal Engineering and Energy in the period from 1972-2000 in the field of thermal energy and coal combustion shows clearly several important conclusions and characteristics of the research in the past period:

- Overall, research and development in the area of coal combustion represented a complete entity, which included all significant aspects of the use of coal for the production of energy.
- An important database of the characteristics of domestic coals and their behaviour in combustion in boilers of different types has been created.
- Many very valuable scientific results have remained unused.
- Many self-developed energy technologies and equipment have not been introduced in practical applications due to lack of funds for the construction of demonstration plants. Some of these technologies, developed by LTE researchers, especially in the area of environmental protection, are just now being introduced into practical applications at domestic TPP plants, but by engagement of foreign companies and foreign equipment manufacturers.

Without realisation of presented important research and experimental base, will not be possible further research in this area which has been undertaken after the year 2000, and permanent research activity existing up to now.

Research in the field of PC combustion and power generation in TPP based on previous research results, knowledge and experimental base, taking into account actual problems of lignite fired TPP in the South East Europe: exploitation problems, life cycle extension problems, problems of capital repair, modernization, revitalization, introduction of new technologies especially for pollution reduction, got a new impulse since 2000. Review of this research results will be presented in the second part of this paper.

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