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Plasma assisted coal combustion. Theory and experiment

Coal fired utility boilers face two problems, the first being the necessity to use expensive oil for start-up and the second being the increased commercial pressure requiring operators to burn a broader range of coals, possibly beyond the quality envisaged by the manufacturer's assurances for the combustion equipment. Each problem produces a subsequent negative environmental impact. Oil-firing for start-up increases the gaseous and particulate burden of the plant. The firing of poorer quality coals has two disadvantages: reduced flame stability performance necessitating oil support and its consequential emissions and cost implications; and reduced combustion efficiency due to a higher amount of carbon in the residual ash, resulting in an increase in the amount of emissions per MW of power generated. Plasma assisted coal combustion represents a new effective and ecological friendly technology, which is equally applicable to alternative 'green' solid fuels. One of the prospective technologies is Thermochemical Plasma Preparation of Coals for Burning (TCPPCB). This technology addresses the above problems in Thermal Power Plants (TPP). The realisation of the TCPPCB technology project comprises two main steps. The first is the execution of a numerical simulation and the second involves full-scale trials of plasma supported coal combustion through plasma-fuel systems (PFS) mounted at TPP boilers. For both the numerical simulation and the further full-scale trials, the boiler of 200 MW power of Gusinoozersk TPP (Russia) was selected. Four PFS are mounted on the furnace and used for boiler start-up and low-rank coal flame stabilisation. The numerical simulation was fullfilled with the help of the Cinar ICE 'CFD' code. Cinar ICE has been designed to provide computational solutions to industrial problems related to combustion and fluid mechanics. The Cinar code solves equations for mass, momentum and energy conservation. Physical models are employed for devolatilisation, volatiles combustion (fast un-premixed combustion), the char burnout and the turbulence (k-ε). Comparison of the calculations with the trials data showed good agreement. The maximal devergency between mesured and calculated temperatures in the outlet of the furnace does not exeed 15%. Note: this is bound to be true from a simple heat balance if the data are any good. Numerical simulation and full-scale trials enabled the following technological recommendations for improvement of existing conventional TPP to be made. It is concluded that the developed and industrially tested PFS improves coal combustion efficiency, decreases harmful emission from pulverized coal fired TPP. Prior to the wider implementation of PFS, additional data relating to further coal types and their blends are required.

Keywords: Coal combustion, coal thermo chemical preparation, plasma-fuel system, simulation, full-scale experiment.

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Сжигание угля с плазменным сопровождением. Теория и эксперимент

Сжиганию угля в промышленных котлах сопутствует две проблемы, первая из которых – это необходимость использования дорогостоящего мазута для пуска котла, и вторая – необходимость сжигать широкий спектр непроектных углей. Каждая из этих проблем отрицательно влияет на окружающую среду. Сжигание мазута для растопки котлоагрегата увеличивает залповые выбросы вредных газов и сажи в атмосферу. Сжигание низкосортных углей имеет два недостатка: снижение устойчивости горения пылеугольного факела, требующее стабилизации его горения топочным мазутом, следствием чего является повышение пылегазовых выбросов и затрат, а также снижение эффективности сжигания угля из-за более высокого механического недожога топлива. В результате наблюдается повышение стоимости установленного кВт вырабатываемой электрической мощности. Плазменная технология сжигания угля представляет собой новый эффективный и экологически приемлемый метод, близкий к «зеленой технологии» использования твердых топлив. Плазменная термохимическая подготовка топлива к сжиганию (ПТПТС) устраняет вышеупомянутые проблемы на пылеугольных тепловых электростанциях (ТЭС). Реализация технологии ПТПТС включает в себя два основных этапа. Первый – численное моделирование, а второй – полномасштабные испытания сжигания угля с использованием плазменно-топливных систем (ПТС), установленных на котлах ТЭС. Для численного моделирования и дальнейших испытаний ПТС был выбран котел мощностью 200 МВт Гусиноозерской ГРЭС (Россия). Четыре ПТС были установлены в топке котла для его безмазутной растопки и стабилизации горения пылеугольного факела. Численное моделирование было выполнено с помощью 3D программы Cinar ICE, которая была разработана для решения прикладных задач горения и газодинамики в топках промышленных котлов. Программа Cinar ICE основана на решении уравнений тепло- массообмена, импульса и энергии, с использованием физических моделей для описания выхода летучих угля, их горения (упрощенная кинетическая схема горючей смеси), выгорания углерода и турбулентности (к-ε-модель). Сравнение расчетов с результатами испытаний ПТС показало хорошее согласие. Максимальное расхождение между измеренными и рассчитанными значениями температуры на выходе из топки не превышало 15%. Заметим, что эта величина не превышает невязки теплового баланса топки котла. Численное моделирование и натурные испытания ПТС позволили разработать технологические рекомендации по совершенствованию существующих ТЭС. Разработанные и испытанные на промышленном пылеугольном котле ПТС повышают эффективность сжигания угля и уменьшают вредные выбросы. Для широкого внедрения ПТС требуются дополнительные данные по плазменному сжиганию различных типов углей и их смесей.

Ключевые слова: сжигание угля, термохимическая подготовка угля, плазменно-топливная система, моделирование, натурный эксперимент.

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Плазмалық қостаумен көмірді жағу. Теория және эксперимент

Өнеркәсіп қазандарда көмірді жағу екі мәселені тудырады, бірінші – ол қазанды жіберу үшін аса қымбат мазутты пайдалану қажеттілігі және екінші – бірнеше жобалық емес көмірлерді жағу. Осы мәселелердің әр қайсысы қоршаған ортаға кері әсер етеді. Қазандардан тұратын агрегатты жандыруға қажет мазутты жағу атмосфераға зарарлы газ және күйенің шығаруын асырады. Төмен сортты көмірлерді жағудың екі кемшілігі бар: тозаңды көмірлік алауды тұрақтандыру үшін жандыру мазутты қажет ететін жанудың қалыпты күйінің төмендеуі, оның салдары тозаң газды шығарулар мен шығындардың көбеюі және сонымен қатар отынды механикалық түрде жандыру керек болғандықтан көмірдің жану тиімділігі төмендеуі болып табылады. Нәтижесінде электрлік қуаттың белгіленген кВт-ң бағасының өсуі байқалады. Көмірдің плазмалық жағуы жаңа тиімді және экологиялық таза әдіс, бұл әдіс қатты отынды қолдану «жасыл технологиясына» жақын. Отынды жағуға плазмалық термохимиялық дайындау (ОЖПТД) аталған мәселелерді тозаң көмірлік жылу электрстанцияларында (ЖЭС) шешеді. ОЖПТД технологиясы екі этаптан тұрады. Бірінші – сандық модельдеу, ал екініші – ЖЭС қазандарында орнатылған плазма-отындық жүйелерді (ПОЖ) қолдану арқылы көмірді жағудың толық түрде сынауы. Сандық модельдеу және ПОЖ әрі қарай сынаудан өткізу үшін қуаты 200 МВт-тық Ресей еліндегі Гусинозерск ГРЭС қазаны алынды. Қазанға төрт ПОЖ орнатылды, олар қазанды мазутсыз жағуға және тозаң көмірлік алауды тұрақтырандыруға арналған. Сандық модельдеу өнеркәсіп қазандардың жандыру құралдарында жану және газодинамиканың қолданбалы есептерінің шешуге арналған Cinar ICE 3D программасы арқылы орындалды. Cinar ICE программасы көмірдің шығу және жану үдерісін (жану қоспаның қысқартылған кинетикалық моделі), оттегінің жану мен турбуленттіліктің (к-ε-модель) сипаттайтын физикалық модельдері арқылы көмір жылу масса алмасу, импульс және энергияның теңдіктерін шешуге негізделген. Есептеулердің ПОЖ сынақтарының нәтижесімен салыстыруы жақсы келісімде екенін көрінді. Оттықтың шығысындағы температураның өлшенген мен есептелген мәннің максималды айырмашылығы 15%-дан аспады. Сандық модельдеу және ПОЖ-ң заттық сынақтары ЖЭС-ды жақсарту үшін технологиялық сынақнамаларды құрастыруға мүмкіндік берді. Құрылған және өнеркәсіптік тозаң көмірлік қазанда сынаудан өткізілген ПОЖ көмірді жағу тиімділігін асырады және зарарлы шығындарды азайтады. ПОЖ-ді енгізу үшін әртүрлі типті көмірлердің және олардың қоспаларының плазмалық жандыруының қосымша деректері қажет етіледі.

Түйін сөздер: көмірді жағу, көмірді жылухимиялық даярлау, плазмалы-отындық жүйе, модельдеу, заттық эксперимент.

Introduction

Plasma assisted coal combustion is a relatively unexplored area in coal combustion science and only a few references are available on this subject [1]. Coal fired utility boilers face two problems, the first being the necessity to use expensive oil for start-up and the second being the increased commercial pressure requiring operators to burn a broader range of coals, possibly outside the specifications envisaged by the manufacturer's assurances for the combustion equipment. Each of these problems results in a negative environmental impact. Oil firing for start-up increases the gaseous and particulate burden of the plant. The firing of poorer quality coals has two disad-vantages: reduced flame stability performance necessitating oil support and its consequential emis-sions and cost implications; and reduced combustion efficiency due to a increased amounts of car-bon in the residual ash, resulting in an increase of emissions per MW of power generated. Plasma assisted coal combustion represents a new effective and ecological friendly technology, which is equally applicable to alternative 'green' solid fuels.

Thy technology Thermo Chemical Plasma Preparation of Coals for Burning (TCPPCB) addresses the above problems in Thermal Power Plants (TPP). The realisation of the TCPPCB technology comprises two main steps. The first includes numerical simulations and the second involves full-scale trials of plasma supported coal combustion in a TPP boiler. For both the numerical study and full-scale trials, the boiler of 200 MW power of Gusinoozersk TPP (Russia) was selected. Four PFS are mounted on the furnace and used for boiler start-up and low-rank coal flame stabilisation.

The numerical simulations were performed using the Cinar ICE 'CFD' code [2]. Cinar ICE has been designed to provide computational solutions to industrial problems related to combustion and fluid mechanics. The Cinar code solves equations for mass, momentum and energy conserva-tion. Physical models are employed for devolatilisation, volatiles combustion (fast un-premixed combustion), the combustion of char and the turbulence (k-ε). Comparison of the calculations with data generally reveals excellent agreement. The maximal discrepancies between measured and cal-culated furnace temperatures do not exceed 15%.

Structure of the paper

The simulation of coal combustion using plasmas in industrial scale applications includes several steps. This paper is correspondingly structured (Fig. 1). In the first step, the performance of plasma generator is simulated and the results are compared with the experimentally measured tem-perature contour lines. The second step involves the simulation of the thermo chemical preparation for combustion of pulverised coal (Tugnuiski bituminous coal, Russia) within the PFS (plasma burner 1). The results obtained from the numerical simulations of this phase were validated against experimental results [3, 4]. The numerical calculations include the implementation of several differ-ent approaches of combustion modelling as a numerical study towards the clarification of physical and chemical behaviour of pulverised coal-plasma interaction. The methodology used for the com-bustion modelling includes the following approaches: fast chemistry (simple reacting chemical sys-tem); a laminar flamelet model; and a thermal equilibrium model. Comparing the results obtained from all the models, the thermal equilibrium model showed the closest results to the experimental data.

The geometry of the plasma burner 2 of the BKZ-640 boiler and the type of the fuel differ from the data used for the modelling of plasma burner 1. The simulation of the plasma burner 1 was used for the validation of the numerical results since experimental measurements exist only for this burner.

In step 3, the selected modelling approach (thermal equilibrium) was used for simulation of a new PFS (plasma burner 2) and another type of coal (Kholboldjinski brown coal, Russia). The results obtained from this study were used as an input values for the calculation of the boiler perfor-mance working in the ‘plasma-assisted’ operational regime. The final step of the numerical study (Step 4) includes the simulation of industrial boiler operation in the conventional and plasma-assisted regimes. As a test case of the industrial application of The BKZ 640 boiler of the Gusinoozersk TPP in Russia was selected for this exercise.

Finally, the data obtained from full-scale trials of the BKZ-640-140 boiler starting-up with help of PFS are presented, and compared with the numerical results.

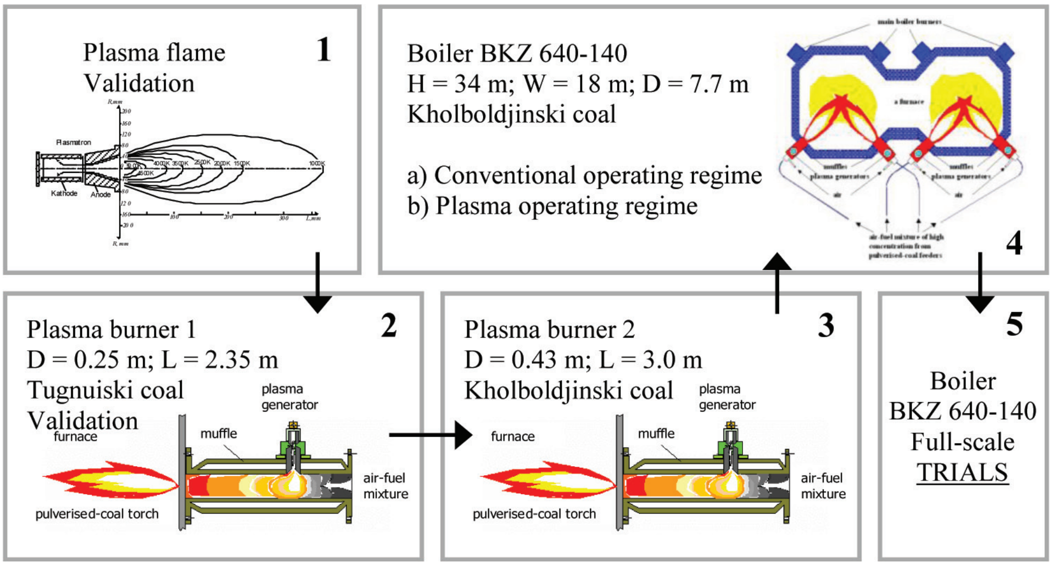

Figure 1 – Schematic view of the work performed

Numerical and experimental investigation of plasma flame

The plasma generator creates a low-temperature plasma flame using air as the plasma gas, blown through the arc formation region. The high concentration of electrical energy heats the air forming the plasma flame. The mass-averaged temperature of the plasma flame is within the range of 2500-5000K, depending on the electric power supply. The plasma generator is placed on the plasma burner to provide the heat necessary for the thermo chemical preparation of the coal prior to its combustion.

The measured temperature contours for a typical plasma flame are presented in Fig. 2. The measurements were taken for an unconfined air plasma flame. The mean temperature of the plasma flame at the outlet of the plasma generator is about 5000 K for an air mass flow through the nozzle of around 36 kg/h and a power input of 100 kW.

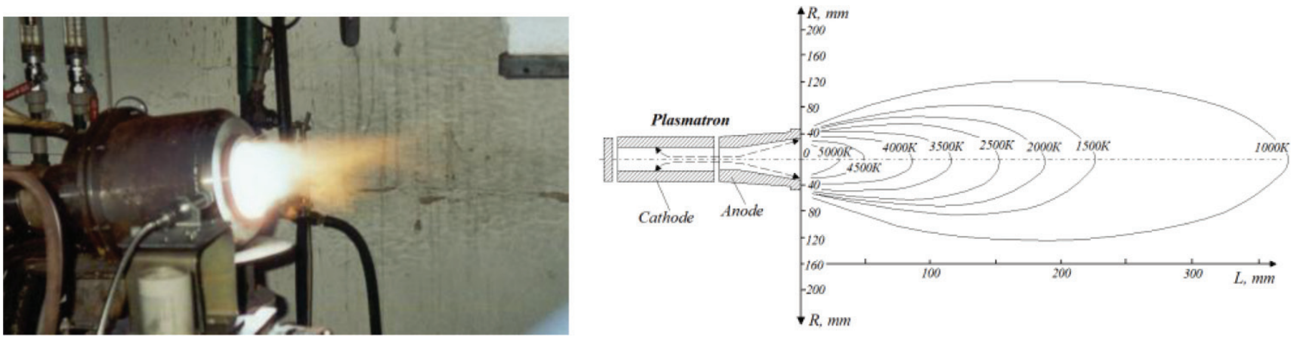

Figure 2 – Experimental plasma flame and its measured isotherms

In preliminary calculations, the spreading rate of the plasma jet emerging from the plasma generator nozzle was simulated. The divergent nozzle expands from 40 to 60 mm over a length of 80mm (Fig. 2).

Predicted isotherms profiles are shown in Fig. 3. Comparisons with the experimental data, taken from Fig. 2, are presented in Table 1. It can be seen that predicted and measured results are generally in quite good agreement.

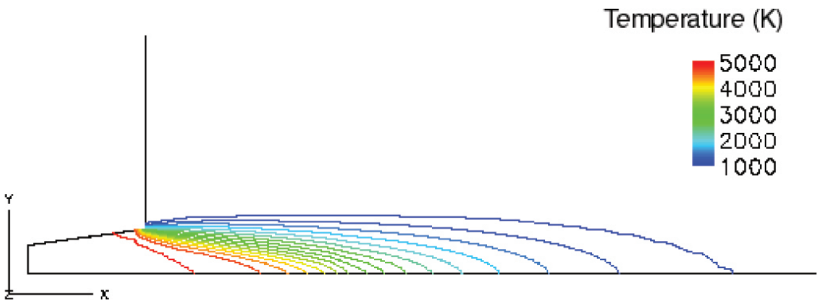

Figure 3 – Predicted isotherms of air-plasma flow from the plasma generator

Table 1 – Comparison of measured and predicted values of the temperatures along the air plasma flame
Temperature (K)

Distance along axis (m)	5000	4500	4000	3500	2500	2000	1500	1000
Experiment	0.03	0.05	0.086	0.116	0.153	0.188	0.227	0.375
Simulation	0.03	0.086	0.109	0.123	0.167	0.202	0.255	0.37

Numerical and experimental investigation of PFS

The plasma burner is a cylinder with the plasma generator placed on the burner body, as shown in Fig. 4.

The mechanism of the thermo chemical preparation of pulverised coal for combustion can be explained as follows. Primary air-coal mixture is fed through the pipes to the burners. If the burner is not equipped with a plasma generator, the air-coal mixture is introduced into the furnace where it is ignited and combusted as in conventional boilers. If the burner is equipped with a plasma generator, the plasma flame heats up the pulverised coal. In this case, the volatiles are released, while the remaining char is partially gasified. Since the primary mixture is deficient in oxygen, the carbon is oxidised mainly to carbon monoxide. As a result, at the exit from the burner a highly reactive mixture is formed of combustible gases and partially burned char particles, together with products of combustion, while the temperature of the gaseous mixture is around 1300K. Further mixing with the secondary air, upon the introduction of the mixture into the furnace, promotes ignition and complete combustion of the prepared fuel, without the need for supplementary fuel (oil or natural gas).

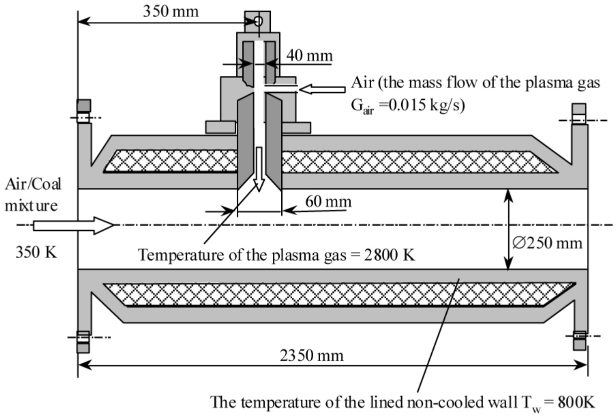

Figure 4 – Schematic view of cylindrical direct flow burner (PFS)

The numerical experiments were performed for a cylindrical direct flow burner (Fig. 4), 0.25 m in diameter and 2.35 m in length, equipped with the plasma generator. The nominal electric power supply for the plasma generator was 100 kW. At this power consumption, the efficiency of plasma generator is around 85% and the plasma gas mass flow rate is 54 kg/h, while the mass averaged temperature of the flame is some 2800 K (Table 2).

The coal and air mass flow rates through the burner were 1.75 t/h and 3.5 t/h respectively; while the coal-air mixture inlet temperature was 350 K. The mass flow specifications gives coal dust concentration of around 0.5 kg of coal per kg of air. Such concentration provides high fuel-rich conditions within the plasma chamber with the equivalence factor of around 3.0 [5]. The specification of working parameters for plasma generator and chamber can be found in Table 2.

'Tugnuiski' bituminous coal was used for the experiments. Its proximate and ultimate analyses and particle size distribution are presented in Table 3. From the available experimental data of the plasma burner operation, the measured composition of the gas phase at the outlet of the burner was (volume %): CO=28.5; H_2=8.0; CH_4=1.5; CO_2=2.0; N_2=59.5; O_2=0.0; others = 0.5, including NOX=50 mg/nm3.

The measured temperature profiles are shown in Fig. 5. In the initial section of the PFS (line 1) the temperature profile has only one maximum and it is not axis-symmetric. This is due to the influ-ence of the plasma flame. The temperature profile at the exit from the plasma burner shows axis-symmetrical behaviour.

Table 2 – Specification of Operating Parameters for Plasma Burner

OPERATING DATA	
Plasma burner (muffle)	
Length (m)	2.35
Inner diameter (m)	0.25
Plasma Generator	
Electric power (kW)	100
Plasma gas	Air
Mass flow (kg/h)	54
Inlet air temperature (K)	298
Outlet air temperature (K)	2800
Inner diameter (m)	0.04
Outlet velocity (m/s)	118.2
Primary air	
Air flow (kg/h)	3500
Velocity (m/s)	20.0
Temperature (K)	350
Coal dust concentration (kg/kg)	0.50

Table 3 – Specification of Tugnuiski bituminous Coal

Tugnuiski coal		
Proximate analysis	mass %	Particle size distribution *
Moisture	14.00	160 μm – 10% 130 μm – 10% 74 μm – 20% 50 μm – 40% 24 μm – 20%
Volat.Matter	36.27	
Fixed car-bon	44.33	
Ash	19.40	
Ultimate analysis	mass %	
Carbon	61.7	Lower calorific value: 5500 kcal/kg
Hydrogen	4.10	
Nitrogen	1.20	
Sulphur	0.39	Coal feed rate: 1750 kg/h
Oxygen	13.20	

* assumed particles size distribution

The coal thermo chemical preparation numerical calculations are performed for the plasma burner of Fig. 4. The specification of the coal and the plasma burner operating parameters used for the numerical calculation have been given in Tables 2 and 3. The flame from the plasma generator feeds the burner 0.35 m in axial direction upstream of the burner inlet plane (Fig. 6). To enable the modelling exercise the plasma flame is assumed as a heat/mass source defined with the exit temperature of 2800 K and the mass flow of 54 kg/h.

The numerical results for the radial temperature profiles at the burner exit are presented in Figure 7, while Figure 6 shows the predicted temperature contours along the burner axial direction. The numerical results are validated with the measured data only at the exit of the PFS. The radial temperature profile is shown for an axial location of 2.0 m from plasma generator axis (x = 2.35 m). The predicted profile is revealed to be axis-symmetric in accordance with the experimental profile.

Although the measured profile shows a distinctive temperature minimum at the chamber cen-tral line,

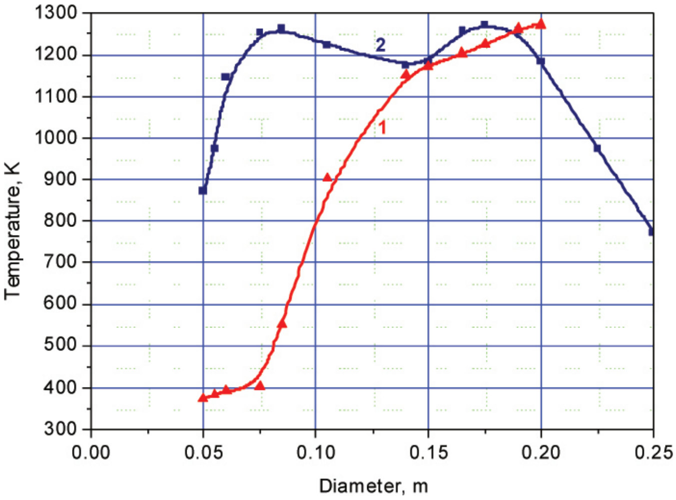

Figure 5 – Measured temperature profiles inside the PFS
1 –750 mm downstream of the plasma generator; 2 –outlet of the PFS

Figure 6 – Predicted temperature contours along the burner axial direction

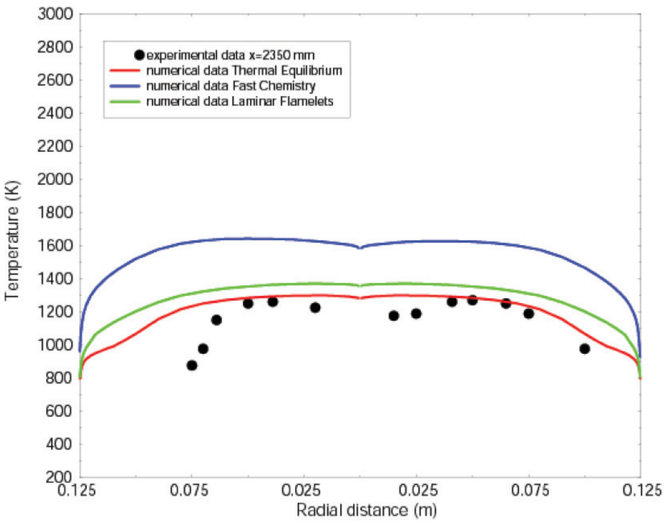

Figure 7 – Predicted temperature radial profiles at the exit of plasma burner 1

in the case of predicted temperature profile this minimum is insignificant. This could be the reason of under-predicted penetration of the plasma jet into the co-flowing stream of air-coal mixture. In the real situation, it may be expected that the plasma jet will separate the air-coal mixture flow into two streams, leaving the central part of the flow with lower fuel concentration. The high-energy concentrated plasma jet, with high initial momentum, may act as a solid body [6] penetrating through the cross flow, while the coal particles trajectories are divided into two streams, showing two temperatures maxima on both sides of the centre line.

As can be seen from Fig. 7, when using the fast chemistry model the code over predicts the temperature level of combustion. The averaged temperature at the exit from plasma burner is 1600 K while the experimental one was 1200 K. This discrepancy in temperature, as well in species concentrations, may be attributed to the nature of combustion model used, since the fast chemistry model takes into account only global nature of the combustion process. Thus, it was necessary to employ the model that includes the finite rate chemical reactions, such as laminar flamelet model.

The laminar flamelet approach involves detailed chemical mechanism of volatiles species combustion, with some 250 chemical reactions included in the calculation (standard GRI-mechanism). The 'Flame Master' code [9] was used for creating the libraries carrying the infor-mation of species concentration as a function of mixture fraction. This approach gives more data on intermediate species concentration and improved the predictions of the temperature level. However, the species concentrations, mainly of CO, were generally under predicted.

The modification of the fast chemistry model introducing the reactions of char gasification (char + CO2 and char + H_2O) gave slightly better predictions than the standard fast chemistry mod-el. During the parametric study, it was observed that the activation energy of char gasification reac-tions was too high to produce the required amount of unburned gases such as CO and H_2. According to [7], the activation energy for both gasification reactions are likely to decrease as a result of the existence of electric and magnetic fields coming from the plasma flame. This would increase the reactivity of the residual char, while their values have to be obtained from the experimental measurements. These results are not presented in this paper.

For the thermal equilibrium calculations, the TERRA code was used. The application of the thermal and chemical equilibrium approach gave the closest results to the experimental data. This method included the formation of the libraries containing the values of species concentrations as a function of the mixture fraction and temperature level. The improvement of temperature level prediction and species concentrations is evident in Fig. 7 and 8. Although the combustion is not a thermal equilibrium process, the application of this approach could be justified by the existence of charged species and radicals, which are highly active and probably act as a catalyst increasing the rate of chemical reactions. In addition to this, the high-energy input and maximum temperature level make the chemical reactions fast so that they are probably close to the equilibrium condition. The thermal and chemical equilibrium approach was selected for the calculations of the plasma burner 2 (Fig. 1).

Simulation of PFS 2

The properties and working parameters of the plasma burner 2 differ from the plasma burner 1 in the geometry and the type of coal used. Generally, the geometry of the plasma burner 2 is similar to the geometry of that of 1 (Fig. 4), the only difference being a burner length (L = 3.0 m) and di-ameter (D = 0.43 m). In this case, the pulverised coal was Kholboldjinski brown coal (Table 4).

The prediction of the temperature level at the exit from the plasma burner is uniform attaining a maximum level of some 1400K (Fig. 9). For calculation of the second plasma burner just the thermal equilibrium method was used. This approach gave the closest results to experimental data in case of plasma burner 1 (paragraph 3). The predicted species concentrations at the exit from plasma burner are presented in Fig. 10. The values of the temperature level and species concentrations were used input values for the numerical simulation of the boiler working in the plasma regime.

Numerical investigation of the furnace

The plasma burner 2 was incorporated in the furnace of a full-scale boiler with a steam productivity of 640 t/h (Gusinoozersk Thermal Power Plant, Eastern Siberia, Russia). The schematic view of the boiler equipped with PFS (muffles) and its primary dimensions are shown in Fig. 11. The furnace is characterised by two symmetrical combustion chambers, each having 4 tangentially directed main double burners in two layers. Waste burners are situated in a top layer. Each of the main burners is divided in two sections. They are the section of air-fuel mixture supply and the sec-tion of secondary air supply. The waste burners supply a low coal concentration in the air-fuel mix-ture (< 0.1 kg/kg), so their effect on combustion is very small. Combustion chambers are joined by a central section. The cooling chamber is above of the combustion

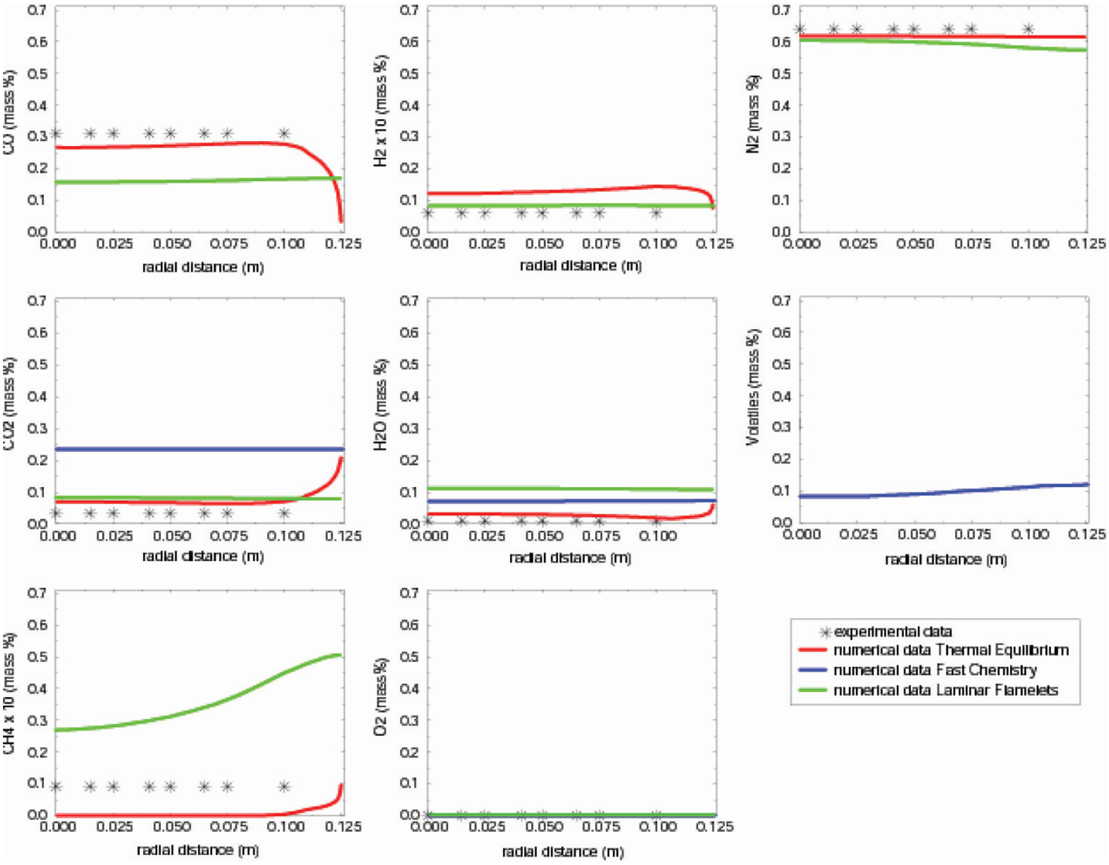

Figure 8 – Predicted radial profiles for species concentrations at the exit of plasma burner 1

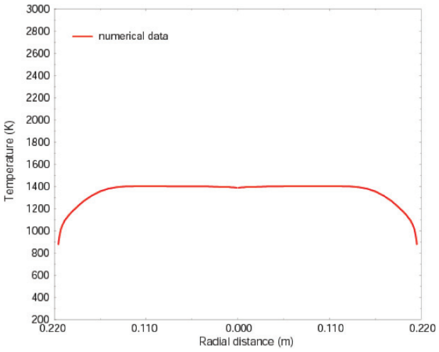

Figure 9 – Predicted temperature radial profile at the exit of plasma burner 2

chambers and then turning chamber follows. The technical specification and operating data for the BKZ 640-140 boiler along with the Kholboldjinski brown coal specification are presented in Table 4.

Four PFS (plasma burners 2) are mounted instead of four lower sections of the main double burners as it is shown in Fig. 11 (on the right). During the period of boiler warm- up and flame sta-bilisation, the plasma generators are operating. When the boiler performance is stabilised, the plasma generators are switched off and plasma burners work as conventional burners for pulverised coal. In the case of flame instabilities, the plasma generators are easily switched on.

The grid configuration for the mathematical simulation and a 3D view of the generated grid profile can be found in Fig. 12. The grid is defined by 118 x 52 x 68 grid lines in three directions (x, y and z).

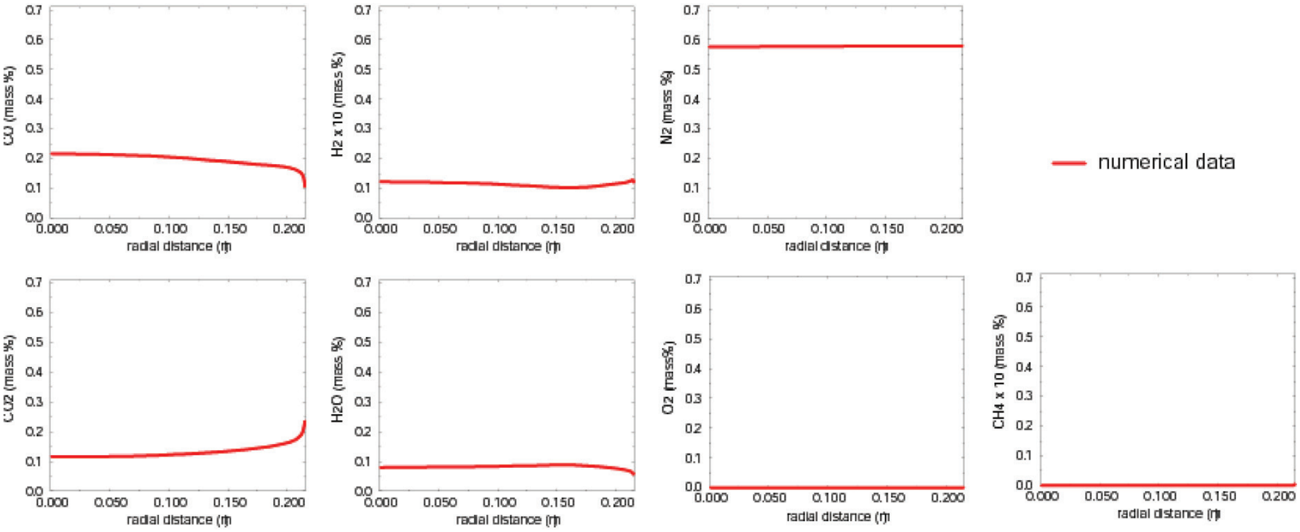

Figure 10 – Predicted radial profiles for species concentrations at the exit of plasma burner 2

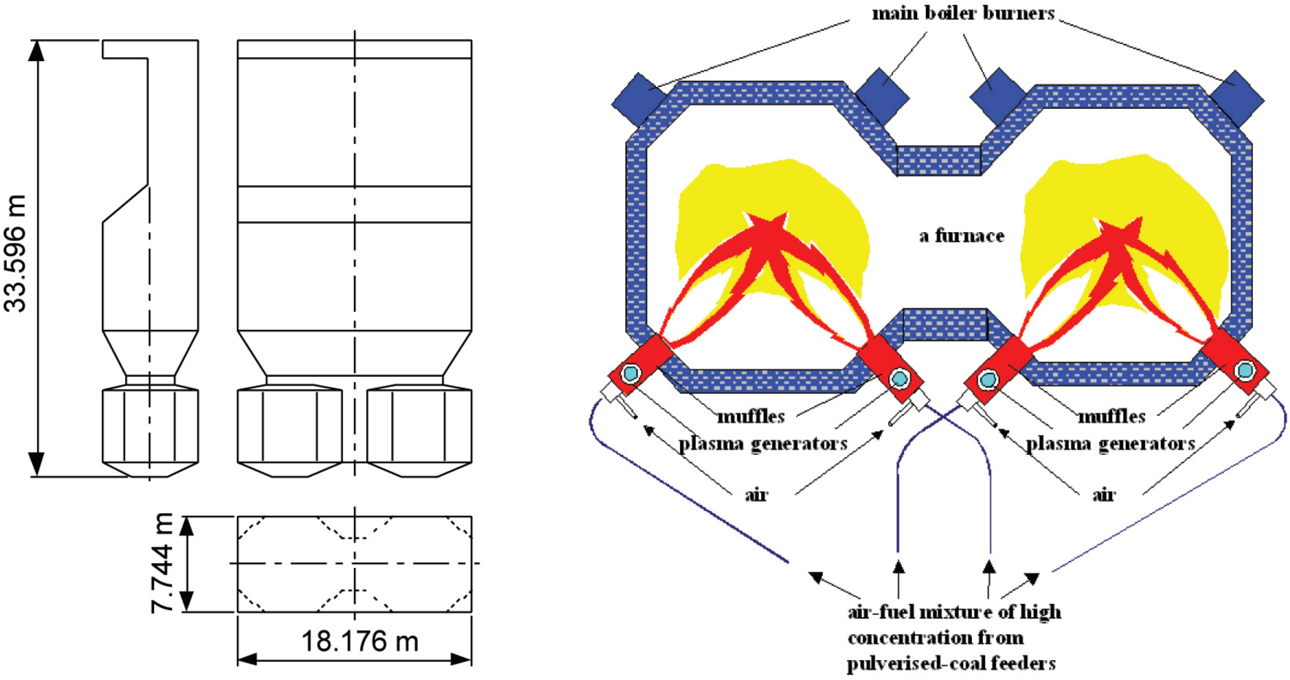

Figure 11 – Scheme of a full-scale industrial furnace, BKZ 640-140 boiler

The main results from numerical experiments for the furnace, velocity vectors, temperature profiles and oxygen concentrations, are presented in Fig. 13-15. In Fig. 14 and 15, panel 1 presents the predicted values for the centre line along the furnace height, while panel 2 gives the values at the exit, along the furnace width. The numerical results represent the boiler performance for the standard operational regime and for operation in plasma regime. Due to the lack of measured data, only values of boiler performance in standard regime and at the exit from the furnace could be vali-dated. The measured averaged temperature at the exit is around 1400 K, and this value agrees with the numerical results, while the averaged concentration of measured oxygen is around 4%.

In the plasma regime (Fig. 15) the temperature levels along the furnace height are lower, while rapid com-bustion of pulverised fuel within the combustion chamber results from the introduction of the mix-ture of hot combustible gases and unburned char from the plasma burners.

Table 4 – Specification of the Coal, Technical and Operating Parameters for BKZ 640-140 Boiler

№	Characteristics	Dimension	Notation	Value
1	Fuel consumption on the boiler	kg/h	B	121300
2	Fuel consumption on the burner	kg/h	B_b	15160
3	Fuel – Kholboldjinski Brown Coal: Coal composition	%	S C H O N	0.38 47.56 3.81 17.12 0.83
			FC VM W A	24.94 31.66 18.80 24.60
4	Heat of combustion	MJ/kg	Q^w_L	14350
5	Theoretically required quantity of air for burning 1 kg of coal	Nm^3/kg	V_0	3.8
6	Total amount of air on the boiler	Nm^3/h	V	553128
7	Milling fineness	%	R_{90}	50
8	Coefficient of air surplus on the fire-chamber's outlet		αт	1.2
9	Air inflow in the fire-chamber	%	$\Delta\alpha$	30
10	Part of primary air from the total quantity of air supplied in fire-chamber	%	$A_{primary}$	27
11	Fire-chamber's height	mm	z(H)	7096
12	Fire-chamber's width	mm	Y	18176
13	Fire-chamber's depth	mm	X	7744
14	Cooling chamber's height	mm	z_1	26500
15	Cooling chamber's width	mm	Y_1	18176
16	Cooling chamber's depth	mm	X_1	7744
17	Type of the using burners		fan-tail burner	
18	Number of double burners		n	8
19	Section of the burner on primary air	m^2	F_P	0.364
20	Section of the burner on secondary air	m^2	F_S	0.538
21	Air-fuel mixture velocity	m/s	W_1	20
22	Secondary air velocity	m/s	W_2	44
23	Temperature of air-fuel mixture	°C	ta	80
24	Temperature of the secondary air	°C	t_S	350
25	Concentration of coal dust in air-fuel mixture	kg/kg	μ	0.628
26	Number of waste burners		n_1	8
27	Diameter of waste burners	mm	d_S/dP	630/530
28	Air-fuel mixture velocity	m/s	W_1	30.9
29	Secondary air velocity	m/s	W_2	32.3
30	Temperature of air-fuel mixture	°C	t_a	80
31	Temperature of the secondary air	°C	t_S	350
32	Concentration of coal dust in air-fuel mixture	kg/kg	μ	≤ 0.1

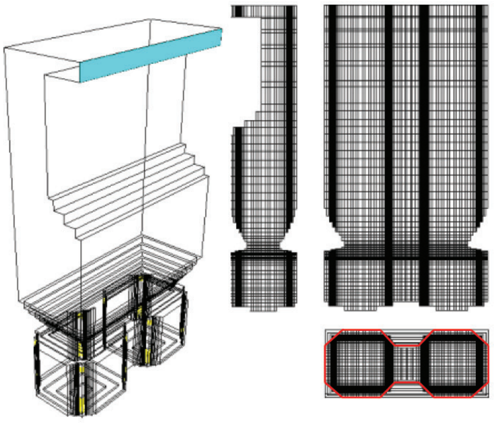

Figure 12 – Grid discretisation

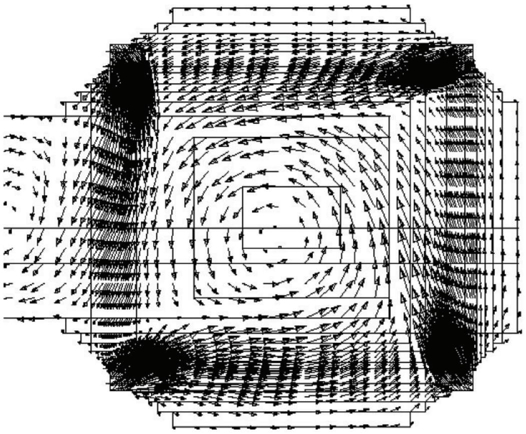

Figure 13 – Velocity vectors

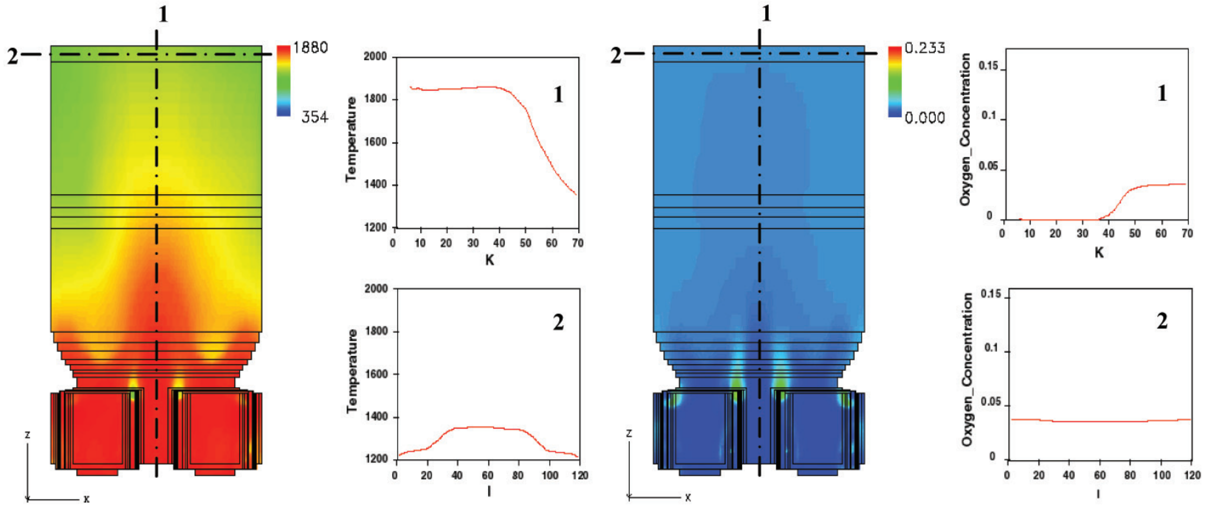

Figure 14 – Predicted temperature (K) and oxygen level (vol. fraction) contours and profiles for the conventional operational regime (centre line, exit of the furnace)

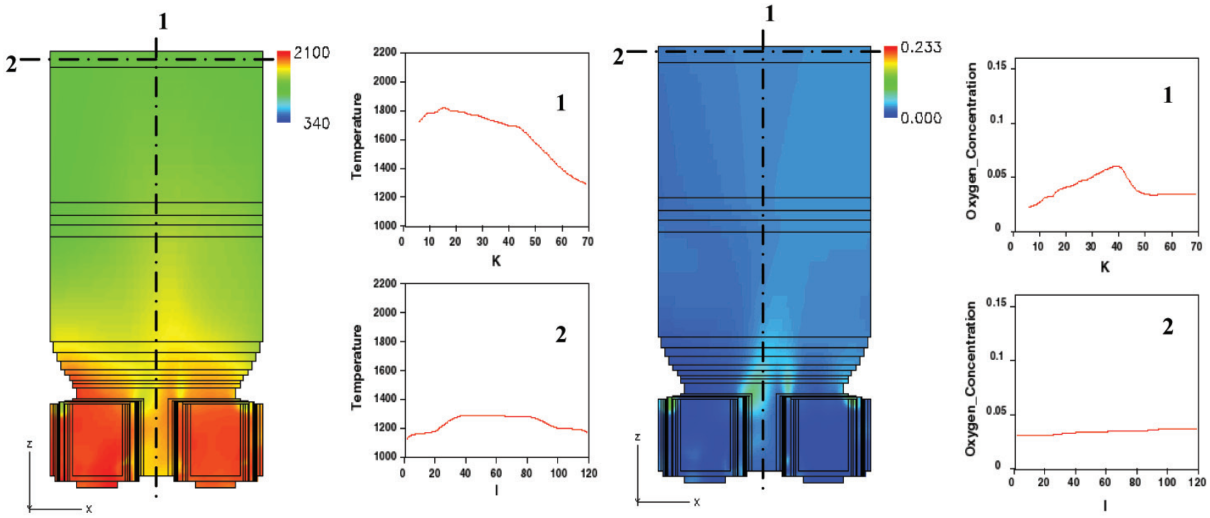

Figure 15 – Predicted temperature (K) and oxygen level (vol. fraction) contours and profiles for the plasma operational regime (centre line, exit of the furnace)

The predicted results of industrial boiler simulations in conventional and plasma operational mode show that operation of the plasma burners there creates favourable conditions which promote stable ignition of the pulverised fuel and its intensive burning within the combustion chamber.

Full-scale trials

The schematic of the plasma generators mounted directly onto direct flow pulverized coal burners is shown in Fig. 4. The use of different types of burners does not incur essential distinctions in the mechanism of thermo chemical preparation of pulverized coal for combustion.

The scheme of the boiler's furnace and its geometrical sizes are shown in Fig. 11. During the tests of oil-fuel-free boiler start-up, the main operating parameters were measured with the help of standard boiler measuring instruments. Also, samples of raw coal and volatile ash were taken at cer-tain time intervals depending on the increase of heat generation in the furnace and the temperatures of flue gas at the outlet. In addition, the flame temperature was periodically measured.

The full-scale trials of the boiler BKZ-640 (steam productivity 640 t/h) start-up and stabiliza-tion of coal-dust flame were fulfilled in correspondence with a specially constructed operating pro-gramme, ratified by the technical manager of Gusinoozersk TPP.

Plasma starting-up of the boiler was carried out from cold (non-operated) state in accordance with Instruction for the boiler exploitation and work program of the trials.

Temperature measuring was effected with the help of thermocouples and optical infrared py-rometers. Samples of gas and volatile ash for analyses were taken before electrical filter with the help of special ejector sampling tube in accordance with the method of SOUZTEKHENERGO [8].

The main results of the trials are gathered in Table 5.

In 1 hour and 35 minutes after starting of all four plasma generators and the supply of the pulverised coal to the plasma-fuel systems temperature of the exhaust gas in turning chamber was 300OC. After 4 hours and 10 minutes, the conditions for steam turbine activation were achieved. In 5 hours temperature of the exhaust gas in turning chamber achieved 370OC at that turbine speed achieved 3000 rpm. The temperature of the gas at the furnace outlet (height is 32.3 m) achieved 1030-1175 OC. The combustible matter in the ash was 15.8% while all the volatile matter evolved to the gas phase. This translates to an unburned carbon was about 3.2%. After an elapsed time of 6 hours and 55 minutes the power-generation was 10 MWe, and pulverised coal was supplied to four main boiler burners of the upper burner level above PFS when the power-generating unit load be-came 15 MWe.

When the temperature in the turning chamber was 380^{O}C (7 hours and 25 minutes from the start-up initiation) and for a power generation of 45 MWe, pulverised coal was supplied to all of the upper level main burners. Temperature of the gas inside the furnace on the outlet achieved 1050-1200 ^{O}C. After 10 hours from start-up, the power of power-generating unit achieved 120 MWe, the temperature inside the furnace (height is 32.3 m) was 1150-1300 ^{O}C, the temperature of the flue gas in turning chamber achieved 480OC and the flue gas temperature after electrostatic precipitator (ESP)

Table 5 – Main results of industrial trials of Gusinoozersk TPP boiler starting-up with the help of PFS

Day time of sampling	Number and type of the boiler	Gas temperatures in the furnace, turning chamber and exhaust gas			Characteristics of raw coal before the mill				Combustible and volatile matter content in dry dust loss before electrofilter		Combustible and volatile matter content in pulp after electrofilter	
hours-minutes		T_f, ^{O}C	T_{sc}, ^{O}C	T_{eff}, ^{O}C	W^W, %	A^d, %	V^{daf}, %	Q^W_I, kcal/kg	C_V, %	V^{daf}, %	C_{PULP}, %	V^{daf}, %
6-00	#2 BKZ-640-140	825-1025	200	61	26.0	28.4	45.0	3840	48.1	11.1	30.7	13.4
7-35		985-1040	300	80					23.1	8.7	27.6	7.0
11-00		1030-1175	370	83					15.8	4.4	16.5	3.8
13-25		1050-1200	380	85					30.2	7.0	20.2	6.6

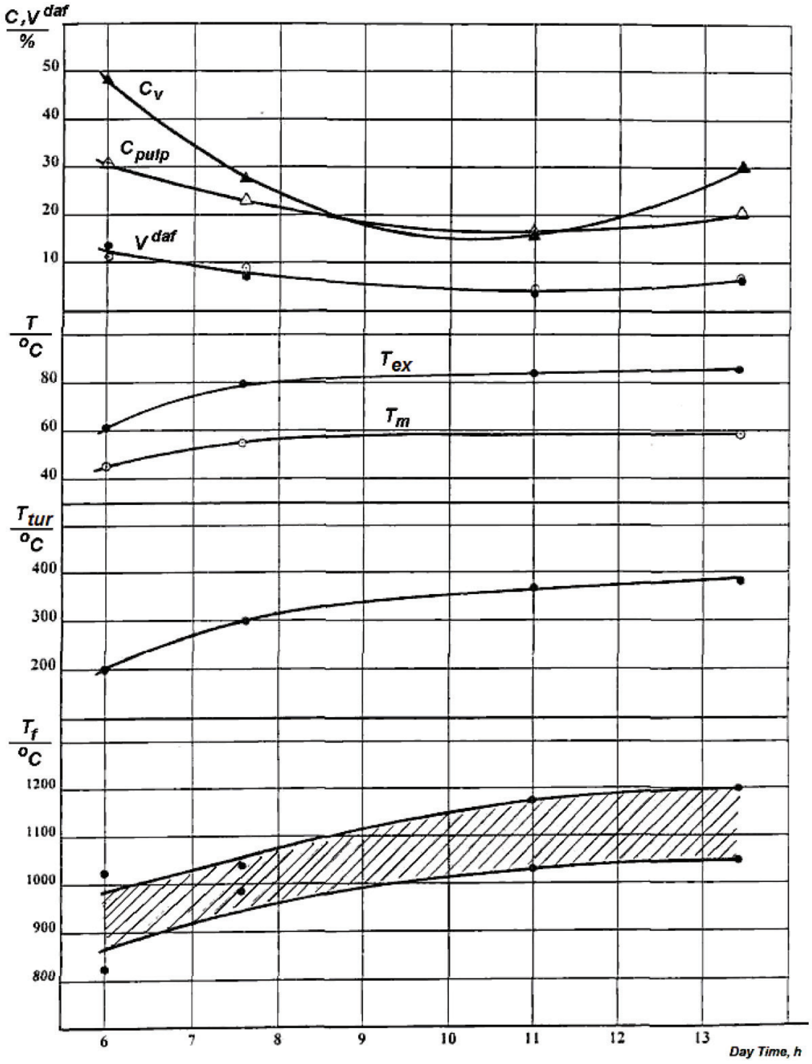

Figure 16 – Variation the main parameters of the trial with the duration of plasma starting-up of the boiler BKZ-640-140

was 90°C. Plasma-fuel systems are stopped after attaining these conditions. The burners equipped with plasma generators then operate as the main pulverised coal burners and the boiler itself operates in design mode without the need for further plasma stabilisation. Fig. 16 summarises the start-up period. As seen from the figure, the temperatures of exhaust gas, milling agent, gas in turning chamber and minimal and maximal temperatures in the furnace increase monotonously.

The curves for combustible and volatile matter content in the dry coal dust before the ESP and pulp (slurry) downstream of it have minima. Their subsequent rise can be explained the whole upper level of main burners not being equipped with PFS.

Further heating of the furnace decreases combustible and volatile matter content in dry dust be-fore the ESP and pulp after electric filter and brings to conformity with the boiler Operating Instruc-tion. Note, minimal temperature T*f* (Fig. 5) is temperature of the pulverised coal flame at the PFS outlet near the burner throat. The maximum flame temperature T*f* was measured by Infrared Pyrom-eter.

The following data were measured when the boiler power was 120 MW and the excess air factor was 1.24 the: concentration of oxygen (O_2) in exhaust gas was 6.1%, NOx was 700 mg/nm^3 (1431.5 ppm), unburned carbon was -0.8%, temperature in the body of flame was 1270°C and tem-perature in the furnace outlet was 1050°C. The concentration of carbon dioxide (CO_2) in exhaust gas calculated through O_2 concentration was 14%.

Comparison of the experimental data with the predictions (Fig. 15) shows satisfactory agree-ment. As we can see the difference in temperature of the combustion products inside the furnace is not more than 17% and at the furnace outlet it is about 6%. The difference in concentrations of oxy-gen in the exhaust gas is about 30%. A possible explanation of the discrepancy is the 60% boiler load factor during the period of the measurements.

CV is combustible matter content in dry dust loss before electrofilter; CPULP is combustible matter content in pulp after electric filter; Vdaf is volatile matter content; Tex is exhaust gas temperature; Tm is temperature of milling agent; Ttur is gas temperature in the turning chamber; Tf is gas temperatures in the furnace.

Conclusions

- Developed, investigated and industrially-tested plasma-fuel systems (PFS) improve coal com-bustion efficiency of, while decreasing harmful emission from, pulverized-coal-fired Thermal Power Plants.
- PFS eliminate the need for expense gas or oil fuels on start-up.
- PFS improve coal ignition and burnout without the need for such remedies as increasing the mill temperature, augmenting the excess air factor, or finer grinding.
- The application of different numerical modelling approaches of pulverised coal preparation for combustion within the plasma burner has shed new light on the possible chemical and physical mechanisms of the coal-plasma interaction.
- Although the combustion process of pulverised coal may not be in thermal equilibrium, the present thermal equilibrium calculations resulted in predictions close to the experimental data.
- Simulation of an industrial boiler in conventional and plasma operational modes reveal that dur-ing the operation of PFS results in stable ignition and intensive burning of the pf at reduced temperature, conditions which reduce the amount of nitrogen oxide formation.
- Prior to the wider implementation of PFS, additional data relating to further coal types and their blends are ideally required.

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