

PECULIARITIES OF USING SLURRY FUELS IN THERMAL POWER PLANTS

by

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The study regards the issues of increasing the thermodynamic efficiency of a typical condensing thermal power plant using coal-water and organic coal-water fuels as the main source. The attention is paid to the use of the phase transition heat of the water vapor of the flue gas. We have shown that it is possible to increase the power plant efficiency by about 3.7% (gross) relative to the base value (in the case of using pulverized coal). We propose to use the flue-gas desulfurization technology for creating fuel slurries in which a liquid incombustible base will be replaced, for example, with aqueous solutions of Ca(OH)₂. This will create a closed water cycle, improve the efficiency of SO_x flue gas purification and improve the performance of scrubbers.

Key words: power plant; efficiency; coal-water fuel; organic coal-water fuel; gas cleaning; condensation

Introduction

Improving the energy and environmental efficiency of traditional industrial power plants is a foreground task in many countries [1, 2]. This is especially relevant for the countries, where electrical energy is produced mainly through the combustion of solid fuels: China, India, Australia, Germany, and others [3, 4]. The problems associated with the emission of solid waste in the form of ash and slag [5] as well as dangerous emissions of CO₂, NO_x, SO_x, Hg and other substances are usually considered.

At present, the issues of thermal impact of hot flue gases emitted into the atmosphere on the environment are almost not considered. The temperature of these gases reaches 140-160 °C depending on the combustion efficiency [6] and boiler design. To increase the overall efficiency of the power plant, it is necessary to lower the temperature of flue gases emitted into the atmosphere. When solving the issue of increasing the thermodynamic efficiency of traditional thermal power plants, the transition to more efficient methods of utilizing the flue gases heat can be considered as one of the possible approaches [7]. The simplest method is installation of additional heat exchanging surfaces with a decrease in gases temperature to ensure a stable process of phase transition at water vapor condensation. It will also be necessary to solve the main problem of such a technical solution, which consists in the formation of dilute acids (nitric and sulfuric). In this re-

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gard, the number of basic components for the formation of these acids (sulfur and NO_x ; CO_2 to a much lesser extent, but it is also important from the point of GHG emissions) is important. Formation of NO_x and SO_x is affected not only by the boiler operating parameters but also by the fuel type. The largest share in world energy production is provided by coal combustion [1, 2]. The resulting gas emissions contain a significant amount of SO_x and NO_x . Essentially (sometimes multiple), they can be reduced by switching to burning coal-water fuel (CWF) and organic coal-water fuel (OCWF) instead of traditional pulverized-coal fuel (PCF) [8].

In most cases, the efficiency of large boilers is quite high (about 90%) regardless of the fuel type (coal dust or slurry). At the same time, in the case of a slurry fuel with humidity of about 35-50%, there are huge losses of thermal energy by the unused heat of the water vapor of the outgoing flue gases. Utilization of this heat by switching to a condensation mode will significantly increase the efficiency of not only the boiler but also the thermal power plant in relation to the flue gas. Together with modern methods of flue gas purification, this direction can provide a basis for energy-efficient and environmentally safe production of heat and electric energy during CWF and OCWF combustion and can become a competitor to traditional coal-fired power plants.

Due to this approach, it seems possible to consider the following proposals for improving the thermodynamic efficiency of boiler plants. When CWF and OCWF combustion, it is necessary to ensure the water condensation in the flue gas with heat recovery and simultaneous processing of acid bases by their treatment with alkaline solutions or other methods. Water vapor condensate after cleaning should be used for the preparation of CWF, thus implementing a closed water-rotation cycle.

The aim of this work is to present the concept of increasing the thermodynamic efficiency of traditional power plants using CWF or OCWF as the main fuel for utilization of flue gases heat.

Materials

An increase in thermodynamic efficiency of the power plant will be considered by the example of burning fuel obtained from coal processing waste. Such wastes are the so-called filter-cakes obtained at dehydration of high-ash flotation products. In this study we use filter-cake of coking coal, tab.1. Filter-cakes can be used by the unconventional technologies for their processing, that is, in the case of combustion in the form of CWF or OCWF [9].

Table 1. Proximate and ultimate analysis results for filter-cake of coking coal

Proximate analysis				Ultimate analysis [%]				
W_r [%]	A^d [%]	V^{daf} [%]	Q_s^d [MJ/kg]	C^{daf}	H^{daf}	N^{daf}	S_r^d	O^{daf}
43.5	26.46	23.08	24.8	79.79	1.84	1.84	0.868	12.70

Research methodology

An increase in efficiency of CWF combustion should be considered in three aspects: utilization of heat of flue gases by reducing their temperature below the temperature of water vapor phase transition; purification of flue gases from sulfur and NO_x ; involvement of condensate of water vapors from flue gases into preparation of CWF by creating a closed water circulation.

Utilization of flue gas heat

Let us consider the classical scheme of the power plant (fig. 1) as an example. This is a condensing power plant (CPP), using CWF or OCWF as a fuel.

A special technology of preparation, storage, transport, and combustion of CWF is typical of such an energy plant. All these questions have been worked out theoretically and experimentally to a certain extent [10]. In addition, when considering the use of various filter-cakes as the main component of slurry fuel, it is necessary to take into account their increased ash content in comparison with ordinary coal and significant water content. This circumstance significantly influences the boiler combustion efficiency, as well as operation efficiency of slag-ash disposal systems when transferring boiler plants to incineration of non-standard fuel. There are studies that show the possibility of successful combustion of various high-ash fuels [11].

Theoretical evaluation of thermal efficiency of CPP, using PCF, CWF or OCWF as the main fuel, shows the following results. The CPP efficiency consists of the efficiency of its three components: boiler unit, turbine installation and pipelines connecting boiler and turbine installation:

$$\eta_{ps} = \eta_p \eta_{sb} \eta_t \quad (1)$$

In the CPP, the boiler and turbine are located in close proximity to each other. Therefore, the efficiency of thermal energy transporting in pipelines is quite high. Parameters of water vapor at the boiler output and turbine inlet are almost identical, which makes it possible to ensure a value of η_p of not less than 98-99%. Maximal heat losses are observed in the boiler and turbine units.

The heat balance of CPP boiler unit, fig. 1, can be described by the following known equation:

$$Q_r = Q_1 + Q_2 + Q_3 + Q_4 + Q_5 + Q_6 \quad (2)$$

Among these heat losses, the losses with outgoing flue gases play the main role since they have a sufficiently high heat content with respect to environmental parameters:

$$Q_2 = (i_{fg} - \alpha_{fg} i_a) (100 - Q_4) / Q_r \quad (3)$$

With a decrease in enthalpy difference between flue gases and air eq. 3 used for initial fuel combustion, the loss of heat with outgoing flue gases can be reduced. For example, assuming that the heat capacity of flue gas is constant in the range of 100-150 °C and burnout degree of CWF particle is more than 95% [12], a significant reduction in heat losses with flue gases can be

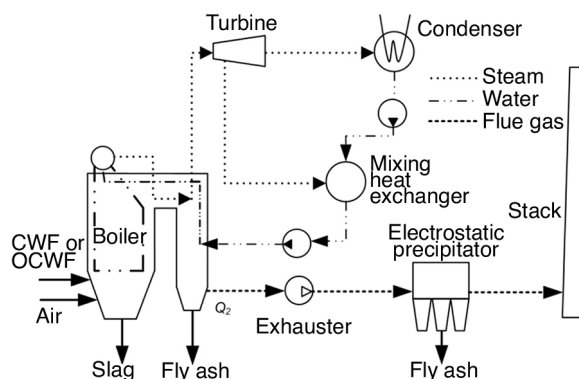


Figure 1. Scheme of the condensation thermal power plant: the compositions of CWS and CWSP for analysis of the scheme and calculations are given in tab. 2. The main components of slurries: filter cake of coking coal (tab. 1) and waste turbine oil (tab. 6)

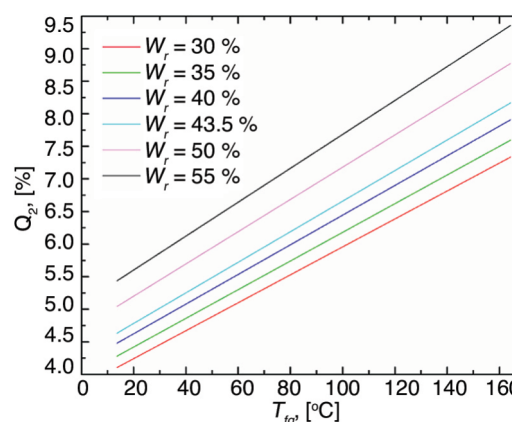


Figure 2. Theoretical losses Q_2 at the example of CWF (based on filter-cake) depending on gas temperature (T_{fg}) and moisture content of fuel

obtained, fig. 2. If we take into account the further decrease of the flue gas temperature to about 30-40 °C (limited by the driving force of heat transfer in the heat exchanging equipment), it can be noted that there is much more unused heat contained in the water vapor of flue gases.

According to fig. 2, with an increase in the fuel humidity, heat losses with flue gases increase at the same temperature. A significant share of losses relates to unused condensation heat. At present, the heat of phase transition and cooling of this water quantity is not used; as a result, there are significant heat losses with flue gases. The value of these losses in comparison with combustion of PCF can be sufficiently high.

For CWF and OCWF the relative heat content of water vapor for 1 kg of fuel in the working state can be determined by expression:

$$Q_{\text{H}_2\text{O}} = \frac{X_w (i_{fg} - i_w)}{Q_i G_f} = \frac{(G_f W_r / 100 + H_2O^H \eta + B^{aw}) (i_{fg} - i_w)}{Q_i G_f} \quad (4)$$

The use of heat of condensation of water vapor from the flue gas leads to a general increase in thermodynamic efficiency of the entire power plant. The studies [13] show that with a decrease in the temperature of flue gases for every 4.5 °C, there is an increase in the plant thermal efficiency by approximately 0.1%. The values presented correspond to combustion of coal dust with humidity about 10-15%. Nowadays the real thermodynamic efficiency of most power plants is up to 40-45%. These data do not reflect the results for the prospective power plants with supercritical and ultra-supercritical steam parameters with thermodynamic efficiency up to 50% [14]. The efficiency of modern boilers is quite high. Thermal efficiency of coal-fired boilers is up to 95% when using the design fuel at nominal operation mode.

To determine the prospects for increasing the power plant thermodynamic efficiency, we made an estimate for three fuel types - PCF, CWF and OCWF, tab. 2.

Table 2. Characteristics of fuels taken for calculations

Characteristics	Type of fuel		
	PCF	CWF	OCWF
Content of solid combustible components [%]	87	56.5	51
Working moisture content [%]	13	43.5	39
Content of liquid combustible organic substances in fuel composition [%]	0	0	10
Low heat value, Q_i [MJ/kg]	18.1	11.58	14.6

A typical boiler (fig. 1) was taken for calculations. This boiler provides a superheated steam with the temperature of 550 °C and pressure of 13.8 MPa. Slag from the boiler is removed in the liquid form [15]. This boiler can work in conjunction with turbines of various types, in particular, the condensation ones. Taking into account fuel characteristics, accepted for calculation, tab. 2, the percentage of boiler heat losses are as follows, tab. 3.

The value of Q_2 was calculated by eq. (3) for the flue gas temperature of 150 °C and air excess coefficient of 1.39 behind the tail heat exchange surface. In the integrated calculation, Q_3 losses can be taken as 0 since they are practically absent for large boilers. Q_4 losses can be taken as 0.4%, and this corresponds to the pilot operation of considered boiler using non-projected fuel. Heat losses through the elements of boiler surface for high-performance plants (more than 75 t/h of vapor) can be taken of 0.8%. The value of Q_6 is calculated by:

Table 3. Boiler heat losses

Type of fuel	Q_2 [%]	Q_3 [%]	Q_4 [%]	Q_5 [%]	Q_6 [%]
PCF	6.48	0	0.5	0.4	1.5
CWF	8.14	0	0.5	0.4	1.3
OCWF	7.65	0	0.5	0.4	0.8

$$Q_6 = a_{sl} C_{sl} t_{sl} \frac{A^r X_w (i_{fg} - i_w)}{100 Q_i G_f} \quad (5)$$

The maximal decrease of thermal efficiency relative to the pipelines and boiler caused by large losses in the cold source (phase transitions in the condenser) occurs in the turbine. The absolute turbine electrical efficiency depends mainly on its thermal efficiency. Now, in the world, a large group of turbines operates with steam temperatures at the inlet to the turbine of about 550-560 °C and pressures of up to 14-16 MPa. At the turbine outlet (condenser inlet) the pressure of steam is about 3-5 kPa.

The turbine thermal efficiency (gross) in an ideal thermodynamic cycle can be calculated:

$$\eta_t = (i_0 - i_{cond}) / (i_0 - i_{cw}) \quad (6)$$

The design value of the turbine efficiency eq. (6) is taken without consideration of losses in generator, bearings and individual elements of turbine (internal relative efficiency). In addition, the obtained value of turbine efficiency does not take into account steam extraction for heating delivery water. If we take into account the technological need of taking steam from the turbine to heat water circulating in the system (fig. 1), the thermal efficiency of turbine should be calculated with consideration of these steam extraction. For the considered boiler, the feed water temperature should be 230 °C according to the pilot operation results. In this case, when using the mixing heat exchangers at CPP for feed water heating, the thermal efficiency of turbine is determined:

$$\eta_t = \frac{(i_0 - i_{ks}) + 1 - \sum_{i=1}^n \alpha_i y_i}{i_0 - i_w} \quad (7)$$

where i_0 , i_{ks} , i_w [kJ/kg] are the enthalpy of superheated steam entering the turbine inlet, the enthalpy of steam at the turbine outlet and at the condenser inlet, respectively, the enthalpy of water entering the boiler at 230 °C, α_i – the share of the steam from the turbine extraction entering the direct-contact heat exchanger.

The coefficients α_i and y_i can be determined by the following expressions:

$$\alpha_i = (i_w - i_{cw}) / (i_{ex} - i_{cw}) \quad (8)$$

$$y_i = (i_{ex} - i_c) / (i_0 - i_c) \quad (9)$$

where i_{ex} , i_c [kJ/kg] are enthalpy of steam taken from the turbine, enthalpy of steam at the entrance to the condenser taking into account the internal relative efficiency of the turbine (85% accepted for calculations).

Depending on the fuel type (tab. 2), the amount of condensate that can be used to heat delivery water at return to the cycle is differing significantly. This amount is mainly determined by the moisture and hydrogen content of fuel eq. (2). The amount of moisture supplied with air for fuel combustion in the boiler can be ignored since its share in the total moisture content of water vapors is extremely small.

Specific heat consumption for electricity production can be determined as $q_t = 3600 / \eta_t$. Specific fuel consumption can be determined as $b = 3600 / Q_i \eta_{ps}$.

Cleaning flue gases from sulfur and nitrogen oxides

Traditionally, several methods for flue gas cleaning from harmful impurities are being considered. These include both the catalytic and non-catalytic methods [16]. This separation exists because of the need to dispose the components with significantly different properties. Among all components, sulfur and nitrogen oxides in the flue gas composition attract the greatest attention throughout the world. Gas purification from these components is prevalent in most

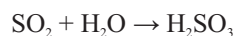
scientific studies and it is documented in strategies of environmental burden reduction of different countries [17]. However, there are the studies focused on flue gas cleaning from other substances (mercury and compounds of various metals), but they attract less attention [18].

In the flue gas, NO and SO₂ play the main role [19]. Concentration of NO₂ and SO₃ is actually less than 5% (practically much less), and this corresponds to the literature data [19] and results of experimental studies, tab. 4. This allows us to make the assumption that NO and SO₂ predominate in the flue gases.

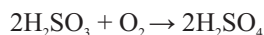
Table 4. Flue gas composition at different temperatures in the boiler furnace at combustion of CWF based on filter-cake [20]

	CO ₂ [%]	O ₂ [%]	CO [ppm]	H ₂ [ppm]	NO [ppm]	NO ₂ [ppm]	ΣNO _x [ppm]	SO ₂ [ppm]	T _{fg} [°C]	T _{fg} [°C]
Experiment 1	7.38	13.4	65	9	85	0	85	97	282.1	1152
Experiment 2	9.69	11.04	220	39	104	0.4	104.4	154	281	1412

An important characteristic for the gaseous combustion products is the possibility of their dissolution and interaction with water, which affects formation of acids. NO dissolves in water, but does not interact with it, while SO₂ dissolves and reacts with water with sulfurous acid formation:



Sulfurous acid is an unstable compound and, with increasing temperature, equilibrium of reaction shifts towards formation of initial substances. However, with an access of air (oxygen), it is oxidized to form sulfuric acid:



In the flue gas, there is always a certain amount of oxygen, not involved into oxidation of combustible substances, since the oxidizer supply is more than necessary for stoichiometric combustion. This affects formation of sulfuric acid during condensation of water vapors of the flue gas.

Thus, to clean flue gas, it is necessary to consider different technologies for utilizing harmful substances, when the temperature of the vapor-gas mixture is lower than the temperature of phase transition of water vapors. It is expedient to trap the sulfur compounds from aqueous solutions, and the nitrogen oxide from the gas mixture.

Now the studies on simultaneous utilization of sulfur oxides from nitrogen by various absorbers [21] are carried out. Substances based on alkali metals are the most widespread absorbers. Simultaneous cleaning allows simplification of the technological processes. The efficiency of SO_x and NO_x absorption is of great importance. According to [21], when using calcium hydroxide as an absorber, the degree of SO₂ absorption averages 90%, and absorption of nitrogen oxides is about 5%. The presented results can be considered acceptable, with respect to concentrations of these substances in the flue gases at CWF combustion.

Results and discussion

Utilization of flue gas heat

When comparing three options of using fuel prepared on the basis of coal processing, the following results can be obtained tab. 5.

Table 5 shows that thermal power plants operating with slurry fuel have a significant potential for additional thermal energy if the heat of water vapor of flue gas is utilized. When the water vapor is condensed, the overall efficiency of CPP can be significantly increased. In considered conditions, the improvement was about 3.7%. Specific of heat (natural fuel)

consumption for the electrical energy generation is reduced by about 8%. Specific fuel consumption when using slurry fuels with condensation of water vapor can be reduced by about 8%. It should be noted that the given values for increasing the plant efficiency are obtained without taking into account the auxiliary power consumption (gross). This means that during the actual operation of a thermal power plant, the increase in the production of electrical energy will be slightly less due to the presence of additional pumping equipment for moving condensate of flue gas water vapor.

Table 5. Comparison of thermal efficiency of CPP with different fuels

Parameter	Measurement units	PCF	SWF	OCWT
Without condensation of flue gas water vapor				
N_n thermal power of CPP	MW	404	404	404
Q_i	MJ/kg	18.1	11.58	14.6
η_p	%	98	98	98
η_i	%	48.5	48.5	48.5
η_{sb}	%	91.12	89.66	90.65
η_{ps} (gross)	%	43.31	42.61	43.08
G_f fuel consumption	kg/s	17.317	27.424	21.490
N_e electric power of plant (gross)	MW	112.807	112.807	112.807
q_i specific heat consumption for electricity production	MJ/kWh	7.42	7.42	7.42
b specific fuel consumption for electricity production	g/kWh	459.23	729.6	572.37
Without condensation of flue gas water vapor				
η_i	%	–	52.7	52.7
η_{ps} (gross)	%	–	46.3	46.8
N_e electric power of plant (with steam extraction for feed water heating) - gross	MW	–	122.7	122.7
q_i specific heat consumption for electricity production	MJ/kWh	–	6.83	6.83
b specific fuel consumption for electricity production	g/kWh	–	671.45	526.87

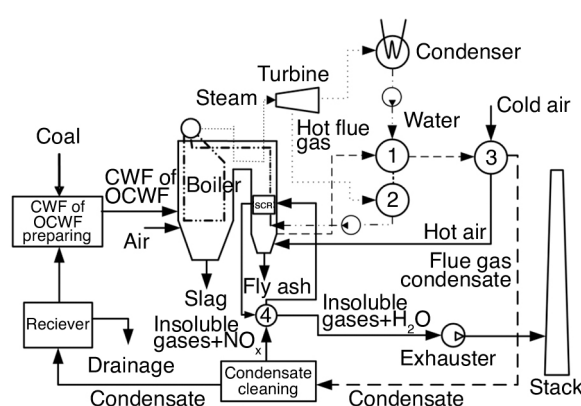


Figure 3. Scheme of thermal power plant with condensation of water vapor of flue gases (heat exchangers: 1, 3, 4 – recuperative, 2 – mixing)

It should be noted that with the water vapor condensation, a smaller part of their heat content goes to the feed water heating, while a significant amount of low-potential heat remains. This heat can be used for the power station needs or for outside consumer. The low-potential heat of the condensate can be used, for example, to heat the air entering the tail surface of the boiler air heater to temperatures that exclude the phenomenon of condensate precipitation in the convective part.

As a result of the obtained calculations (tab. 5) and analysis of the main elements of the CPP, shown in fig. 1, the diagram can be shown in a modified form fig. 3.

Figure 3 is a schematic diagram of a condensation power plant with flue gas heat recovery. This scheme is characterized by the presence of two recuperative heat exchangers – 1 and 3. In the first heat exchanger, the condensate emerging from the turbine is heated by hot flue gases to the water vapor condensation temperature. This allows significantly increasing the temperature of the feed water and reducing the selection of superheated steam from the turbine entering the mixing heat exchanger – 2. In the heat exchanger – 3, additional heating of the air can occur, which enters the air heater located in the convective part of the boiler. It also allows additionally improving the efficiency of the boiler and the overall efficiency of thermal power plant. The presence of the heat exchanger – 4 is necessary for the efficient neutralization of NO_x using the SCR technology. According to [22], the temperature in the zone of neutralization reaction of NO_x should be about 450 °C. In this case, the catalytic element is usually located in the convective part of the boiler. The heat exchanger – 4 allows partial heating of nitrogen oxides and other non-condensable gases entering the catalytic element, and partially returning heat to the boiler after catalytic neutralization.

One of the essential aspects of the proposed method of the flue gas heat utilizing is to consider the problem of condensation of water vapor on the surface of a heat exchanger in the presence of non-condensable gases. This task was not considered in the present work, but it is very important for the implementation of the proposed solutions. For the scheme presented in fig.3, we performed the thermal calculation for the main elements. The results of the thermal calculation are presented in tab. 6. The calculation is made for the example of using OCWF as the main fuel.

Table 6. Heat balance of the main elements of the scheme (fig. 3)

Part of the scheme	Material [kgs ⁻¹]	Power [MW]	Material [kgs ⁻¹]	Power [MW]
	Inlet		Outlet	
Steam boiler	OCWF–21.49 Air (400°C)–257.5 Water (230°C)–116.6	OCWF– 1271.9 Air–176.8 Water–115.8	Superheated steam (550°C)–116.6 Flue gas (150°C)–176.86	Superheated steam –404 Flue gas–147.5
Turbine	Superheated steam (550°C)–116.6	Superheated steam –404	Steam (≈33°C)–95.6 Superheated steam (230°C)–21	Steam–212.5 Superheated steam –6.2
Condenser	Steam (≈33°C)–95.6 Circulating water (20°C) –4226.3	Superheated steam –212.5 Circulating water–354.6	Water (≈33°C)–95.6 Circulating water–4226.3	Water–13.1 Circulating water –553.9
Heat exchanger 1	Water (33°C)–95.6 Flue gas (150°C)– without condensation of flue gas water vap o	Water–13.1 Flue gas–147.5	Flue gas condensate (≈99)–14.14 Water (130°C)–95.6 Flue gas (≈99°C)–162.72	Flue gas condensate–5.9 Water–52.2 Flue gas–16.1
Heat exchanger 2	Superheated steam (230°C)–21 Water (130°C)–95.6	Superheated steam –63.6 Water–52.2	Water (230°C)–116.6	Water–115.8

When analyzing the obtained results, it can be seen that the amount of water vapor condensate of the flue gas at the exit of the heat exchanger 1 is about 14 kg/s. With a known OCWF consumption of 21.49 kg/s, the amount of this condensate is enough to replenish the slurry fuel at a thermal power plant. At the same time, a significant part of water remains and its heat content is quite high. The amount of low-grade heat that can be obtained from the flue gas condensate and non-condensable gases (at the outlet of the heat exchanger –1) is a fairly large amount. In the structure of the thermal power plant of the condensation type, the use of this heat should first of all be used to heat the air entering the boiler.

Cleaning flue gases from sulfur and nitrogen oxides

Based on presented results of experimental and theoretical studies, a basic scheme for flue gas purification with simultaneous heat utilization is proposed figs. 3 and 4.

Main features of the suggested scheme: using $\text{Ca}(\text{OH})_2$ as an absorber of sulfur oxides; return of water to the cycle of CWF and OCWF preparation (section *Utilization of flue gas heat*); production of additional substances.

Interaction of flue gas components with alkaline solutions allows efficient absorption of sulfur oxides. The use of calcium hydroxide is an effective tool, while the products of interaction with sulfur oxides are the marketable products, for example, gypsum (CaSO_4).

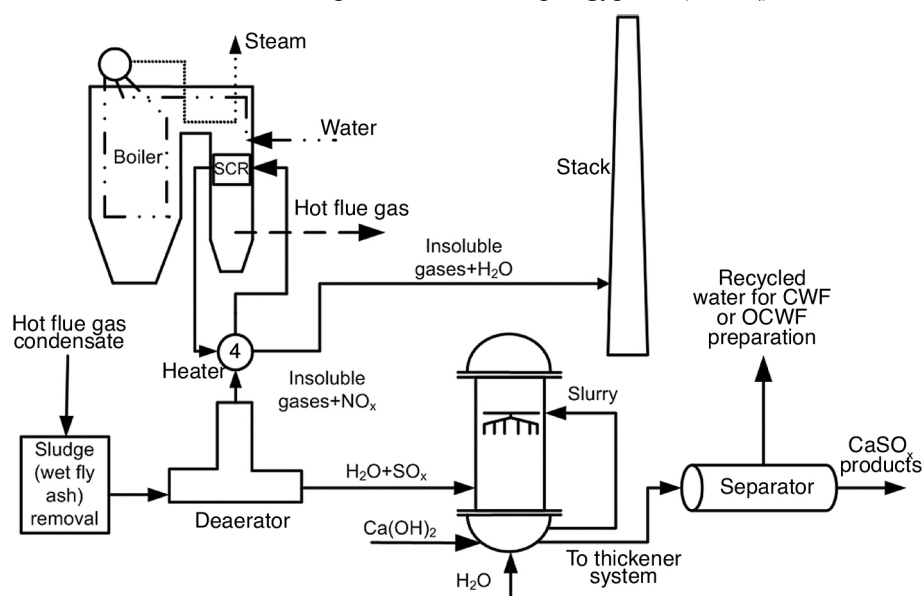
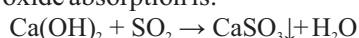
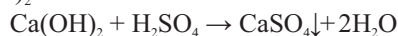


Figure 4. Scheme of flue gas purification

The reaction of sulfur oxide absorption is:



Interaction of $\text{Ca}(\text{OH})_2$ with sulfuric acid occurs:



According to the Le Chatelier principle, an increase in concentration of the initial substances will contribute to a shift of reaction equilibrium towards formation of products of this reaction. In this regard, more complete capture of sulfur oxides from the flue gas requires the supply of an alkali solution with $\text{Ca}(\text{OH})_2$ content higher than it is required theoretically. This leads to the fact that at the stage of separation of water and precipitated salts of sulfuric acid, an insignificant content of alkali is available in the liquid phase. With the further use of this water with $\text{pH} > 7$, the calcium salts will act as sulfur-absorbing substances at CWF and OCWF combustion in the boiler furnace. Thus, the content of harmful impurities in gas will be reduced relative to the overall reduction in emissions, when using the slurry fuel.

The primary experimental results to confirm this assumption were obtained by burning OCWF under laboratory conditions. We prepared a fuel composition based on filter-cake (tab. 1) and waste turbine oil (tab. 7). Mass fractions of the components were as follows: 50% dry filter-

cake, 40% water, 10% waste turbine oil. The composition was burned in a muffle furnace at a temperature of 750 °C. The fuel was portionwise fed into the combustion chamber. The one-time charge of the fuel mixture was about 150 ml. As a result of combustion, a flue gas containing a significant amount of water vapor was formed. Condensate was collected after deep cooling of water vapor. Further, we divided the condensate into two parts. The first part was used for preparing OCWF in which the water is replaced by a condensate (tab. 8). The dry alkali $\text{Ca}(\text{OH})_2$ was added to the second part of the condensate. The weight of added alkali was taken from the expected sulfur content in the resulting condensate (based on the calculation of the main sulfur oxidation reactions and stoichiometric ratios, as well as the elemental analysis of the filter-cake). Based on the results of the experimental results, the amount of alkali was about 4.5 g per 1 kg of the slurry.

Table 7. Liquid combustible component of OCWF

Sample	ρ_{20} [kgm ⁻³]	A^d [%]	T_f [°C]	T_{ign} [°C]	Q_s [MJkg ⁻¹]	T_b [°C]	Q_v [MJkg ⁻¹]
Waste turbine oil	869	0.03	217	245	45.1	315	0.167–0.209

Table 8. Concentration of sulfur compounds in the flue gas condensate

OCWF	OCWF based on condensate	OCWF based on condensate with $\text{Ca}(\text{OH})_2$ addition
0.308 g/l	0.269 g/l	0.313 g/l

Two additional OCWF were prepared. The first was prepared on the basis of the flue gas condensate, and the other was based on the flue gas condensate with the alkali addition. After combustion of the fuels we selected the appropriate samples of liquid condensed products. We founded that the condensation of water vapor of the flue gas makes it possible to reduce the concentration of harmful sulfur compounds emitted into the atmosphere. The use of condensate with additives of sulfur absorbing substances for the OCWF production has significant prospects under conditions of preliminary treatment with alkali $\text{Ca}(\text{OH})_2$. When this approach is implemented on an industrial scale, the salts of the sulfur-containing compounds can be removed from the boiler together with the ash, as they are stable solid water-insoluble substances.

Involvement of condensate into CWF preparation

The issue of the water source for preparation of slurry fuels is hardly considered in publications on CWF and OCWF combustion [9, 10]. Condensate, obtained by chemical treatment of condensed water vapors of flue gases, can be considered as a water source for CWF and OCWF preparation. The problem of high salinity (increased content of calcium hydroxide) in water is not a significant limitation for its use. In the process of CWF combustion, most of salts dissolved in water will convert into slag and come out with the ash. In addition, an increased content of alkali metal salts will contribute to binding SO_x and NO_x formed during combustion and, accordingly, a decrease in the emission of harmful substances into the atmosphere.

For scheme of condensate involving into the cycle CWF and OCWF production, fig. 3, two fundamentally important points should be noted. The first is the wet flue gas, which is free of fly ash and harmful gas impurities in the form of SO_x and NO_x figs. 3 and 4. Such wet flue gas contains less hazardous gases (as compared to technologies without condensation and flue gas cleaning), which can be dispersed in the environment without a significant impact on humans and nature. The second point is that when flue gas condensate is used to prepare CWF and OCWF, it is characterized by elevated alkali content. This should favorably affect the absorption of harmful

gas substances in the boiler furnaces at such fuel combustion. However, along with this, it is necessary to take into account the possible increased wear of pipelines and equipment, when designing and reconstructing CPP.

Conclusion

The use of CWF and OCWF in boiler units of the modern CHP should be accompanied by condensation of water vapors contained in the flue gas. This will significantly increase the overall efficiency of the plants and give additional low-potential thermal energy for the own needs or transfer to the third-party consumers.

The technology for processing harmful components of flue gases should be implemented depending on the type of neutralized component: NO_x from the gas phase and SO_x from liquid solutions. Condensate water vapors of the flue gas can be purified by alkaline solutions, which form insoluble compounds of commercial products, for instance, gypsum. Flue gas cleaning from nitrogen oxide can be carried out using the known technologies, for example, SCR. Due to SO_x absorption by alkaline solutions, process water with $\text{pH} > 7$ will be formed, which should be used for preparation of suspension fuels.

Flue gas desulfurization technology can be used not only for flue gas purification but also for the production of CWF and OCWF when replacing water of fuel slurries with alkaline aqueous solutions obtained by isolating insoluble compounds of sulfites and sulfates of calcium. The use of such fuel slurries will allow to catch a part of sulfur oxides in the boiler gas path and to remove them together with ash, for example, in the form of CaSO_4 . The conducted primary experimental studies show the prospects of this direction. The NO_x can be removed using known techniques, for example SCR.

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Nomenclature

A^d – ash content of dry fuel, [%]	i_{cond} – enthalpy of water vapor in condenser, [kJkg^{-1}]
A' – fuel ash content per as-received basis, [%]	i_{cw} – enthalpy of water condensate at corresponding pressure in condenser and supercooling absence, [kJkg^{-1}]
a_{sl} – portion of fuel ash in slag, [–]	i_{fg} – enthalpy of flue gases, [kJkg^{-1}]
b – specific fuel consumption for electricity production, [$\text{gkW}^{-1}\text{h}^{-1}$]	i_w – enthalpy of condensate at corresponding temperature, [kJkg^{-1}]
B^{av} – moisture content in air supplied into furnace for fuel combustion, [kg]	N^{daf} – content of nitrogen in fuel in terms of dry ash-free state, [%]
C^{daf} – carbon content in fuel in dry ash-free state, [%]	N_e – electric power of plant, [MW]
C_{sl} – slag heat capacity, [kJkg^{-1}]	N_h – heat power of CPP, [MW]
G_f – fuel consumption per as-received basis, [kg]	O^{daf} – content of oxygen in fuel in terms of dry ash-free state, [%]
H_2O^{hr} – amount of water generated when burning hydrogen with as-received fuel, [kg]	q_t – specific heat consumption for electricity production, [$\text{MJkW}^{-1}\text{h}^{-1}$]
H^{daf} – hydrogen content in fuel in dry ash-free state, [%]	Q_1 – usefully utilized heat (enthalpy of hot water or steam), [kJkg^{-1}]
i_0 – enthalpy of fresh vapor fed to turbine, [kJkg^{-1}]	Q_{2s}, Q_{3s} – heat losses through flue gases, chemically incomplete combustion, mechanical under burning, boiler insulation and physical heat of slag (not utilized usually), respectively, [Jkg^{-1}]
i_{ex} – enthalpy of steam from turbine extraction, [kJkg^{-1}]	Q_s^a – high heat value of fuel in analytical state, [MJkg^{-1}]
i_{ks} – enthalpy of steam at turbine outlet, [kJkg^{-1}]	Q_s^l – low heat value of fuel, [kcalkg^{-1}]
i_c – steam enthalpy at the condenser inlet, taking into account the turbine internal relative efficiency, [kJkg^{-1}]	Q_r – available heat, [Jkg^{-1}]
i_a – enthalpy of air fed to boiler, [kJkg^{-1}]	

Q_l – low heat value of fuel, [kcal kg^{-1}]	t_{sl} – slag temperature, [°C]
Q_r – available heat, [J kg^{-1}]	V^{daf} – amount of volatiles in terms of ash-free state, [%]
Q_v – heat of vaporization, [MJ kg^{-1}]	W_r – fuel moisture content per as-received basis, [%]
Q_{fg} – heat content of water vapors of flue gas, [MW]	W_{wfg} – share of heat in water vapors of flue gas used for feed water heating, [%]
S_t^d – content of sulfur in fuel in terms of dry state, [%]	X_w – relative amount of water, [kg]
T_b – boiling temperature, [°C]	<i>Greek symbols</i>
T_{fg} – temperature of flue gases leaving boiler, [°C]	α_{fg} – total coefficient of air excess, [m^3m^{-3}]
T_{ign} – ignition temperature, [°C]	η_p – efficiency of heat transport via pipelines, [–]
T_{ft} – temperature of flue gases in the boiler furnace, [°C]	η_t – efficiency of turbo-installation, [–]
T_f – flash temperature, [°C]	η_{sb} – efficiency of boiler, [–]
	η – degree of fuel particle burnout, [–]
	ρ_{20} – density at 20 °C, [kgm^{-3}]

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