Advances in Energy Research, *Vol. 3, No. 4 (2015) 195-203*
DOI: http://dx.doi.org/10.12989/eri.2015.3.4.195

Energy efficiency analyses of combined-cycle plant

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(Received June 24, 2015, Revised September 24, 2015, Accepted October 5, 2015)

Abstract. The authors consider the technique based on application of air heated in periodic regenerative ceramic heat exchangers by coal powder combustion products as a gas-turbine working medium to be rather promising for being studied. In this case the working medium can be heated to essentially higher temperatures than at coal combustion in the pressurized fluidized bed. Here only a small amount of ash contained in the coal combustion products settles in the ceramic heat exchanger and then penetrates into the heated air. It allows supporting high air temperature before the turbine at an acceptable level of ash concentration at gas turbine inlet. To substantiate the efficiency of this technique the authors have developed the technological scheme of coal-fired combined cycle plant with gas-turbine cycle working medium heated in periodic regenerative heat exchangers; the mathematical models of regenerative ceramic heat exchangers with cylindrical conduits and coal-fired combined cycle plant were developed. The paper introduces the results based on a detailed mathematical model of the optimization technical and economic studies of coal-fired combined cycle plant with gas-turbine cycle working medium heated in periodic regenerative heat exchangers.

Keywords: coal combined-cycle plant; ceramic heat exchanger; mathematical modeling; optimization studies

1. Introduction

Analysis of technologies for electricity production based on solid fuel shows that the optimal combination of reliability and energy and economic efficiency can be achieved through the use of gas-steam binary cycle in combination with coal combustion. However, the technology of coal combustion in the pressurized fluidized bed which is currently applied has considerable disadvantages that decrease greatly its competitiveness (Woodruff *et al*. 2005, Kirilillin *et al*. 2008, Alkov *et al*. 2002, Salamov 2009).

From our viewpoint a rather promising technology to be studied is the one based on the use of air as a gas-turbine working medium which is heated in periodic regenerative ceramic heat exchangers by the coal powder combustion products. In this case the working medium can be heated to essentially higher temperatures than at coal combustion in the pressurized fluidized bed.

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http://www.techno-press.org/?journal=eri&subpage=7 ISSN: 2287-6316 (Print), 2287-6324 (Online)

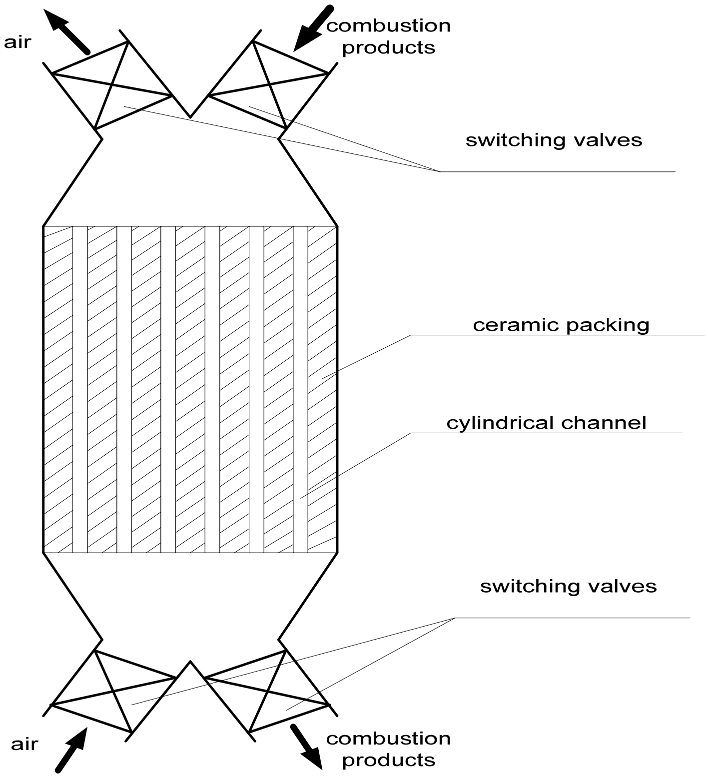

Fig. 1 Cyclic heat exchanger

Here only a small amount of ash contained in the coal combustion products settles in the ceramic heat exchanger and then penetrates into the heated air. This makes it possible to provide high air temperature before turbine (1200-1300^{o}C) at an acceptable level of ash concentration at gas turbine inlet (Kobayashi *et al.* 1999, Sunden 2005, Fend *et al.* 2011, Li *et al.* 2011, Ting *et al.* 2012, Moshida *et al.* 1999, Yamashita *et al.* 1999).

To substantiate the efficiency of this technology it is necessary to perform its optimization technical and economic studies by using the mathematical model of combined cycle unit with coal combustion and gas-turbine cycle working medium heated in regenerative heaters.

2. Mathematical modeling of a cyclic ceramic heat exchanger

The cyclic heat exchanger is presented in Fig. 1. The cycle consists of two equal periods of time: a period of ceramic packing heating and a period of cooling. The packing is heated by the coal combustion products and is cooled by air.

Combustion products and air travel according to the counter flow pattern. The channels are supposed to have a triangular arrangement when their centers are located at the vertexes of equilateral triangle with a side length equal to Sh. The cross-sectional area of packing that corresponds to each channel is equal to the area of hexahedron A presented in Fig. 2. It is easy to

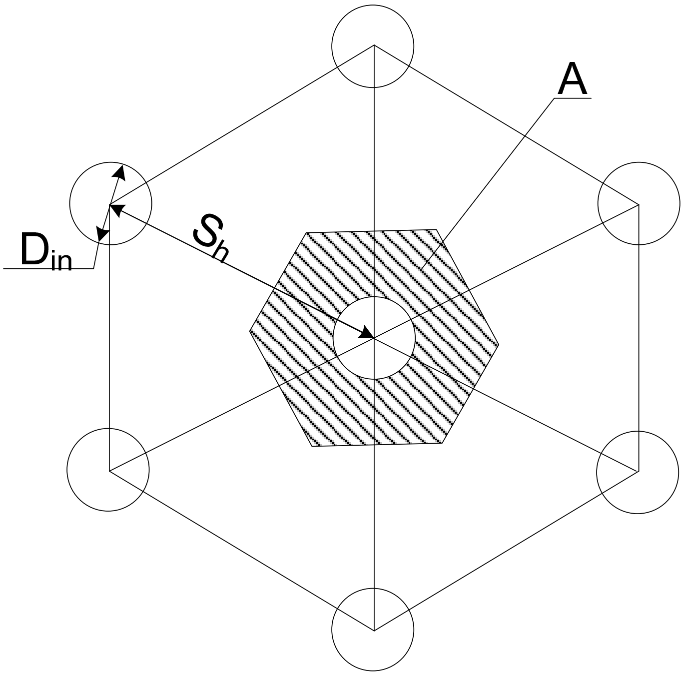

Fig. 2 Arrangement of channels

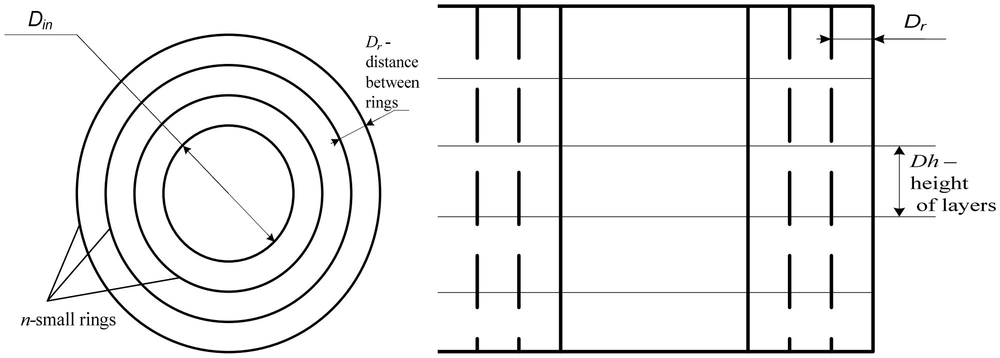

Fig. 3 Channel components in calculation of heat exchange

show that this area

$$S_A = \pi / 4 \cdot \left[(0.525 \cdot S_h)^2 - D_{in}^2\right] \tag{1}$$

Thus, when calculating heat exchange consideration is given to a ceramic ring with internal diameter equal to the diameter of channel (Din), and external diameter equal to 0,525Sh. This ring is divided into n small rings nested into each other. Besides, m layers are distinguished along the height (See Fig. 3). The external ring is assumed to have no heat exchange with the environment.

The total number of small rings in calculation of heat exchange is *n* • *m.* Account is taken of the heat received by the internal ring from gas or the heat transferred to the air, and heat exchange between the neighboring ceramic rings through their lateral surfaces and the ends.

The derivative of the ceramics temperature of the *i*-th small ring at time *t* is determined as

$$\frac{dT_{it}}{dt} = \frac{\sum_{j \in J_i} Q_{ij\,t} + \overline{Q}_{it}}{c_{(T_{it})} \cdot V_i \cdot \rho}, \; i = 1,\ldots, n \cdot m \tag{2}$$

where $Q_{ij\,t}$ - heat flow from the *j*-th ring adjacent to the *i*-th ring, J_i - set of numbers of rings adjacent to the *i*-th ring, $\overline{Q}_{it}$ - heat flow for the *i*-th ring at time *t* from gas or to air (if the *i*-th ring is not internal, then $\overline{Q}_{it} = 0$), *c* - specific heat capacity of ceramics, V_i - volume of the *i*-th ring, ρ - density of ceramics.

Solving a set of differential Eq. (2) by the Euler method for the period of heating and then for the period of cooling we determine the temperature of ceramics for all rings at the end of cycle, depending on the temperature at the beginning of cycle. The condition of stationarity implies equality between these temperatures. The condition is calculated by the Newton method. Here the discrepancies are represented by differences in ring temperatures at the beginning and at the end of cycle, and calculated parameters are represented by ceramics temperature at the beginning of cycle. For a group of ceramic heat exchangers we determine the temperatures resulting from mixing exhaust gases and air. These heat-transfer agents come from heat exchangers that are at different phases of cyclic process. It is sensible to assume that heat exchangers are divided into pairs and a shift in operation of heat exchangers in one pair makes up $\tau^{cycle}/2$, where τ^{cycle} -duration of cycle. Then the shift in operation of the *i*-th pair of heat exchangers (versus operation of the 1st pair) will make up

$$\Delta\tau_i = \frac{\tau^{cycle}}{2} \cdot \frac{i-1}{n_{pair}} \tag{3}$$

where n_{pair} -the number of pairs of heat exchangers.

Knowing the relationship between the temperature of combustion products and air, and time, it is easy to determine the temperature at the outlet of group of regenerative heat exchangers at each time instant, as well as average, maximum and minimum temperature over the entire cycle.

3. The mathematical model of coal-fired combined cycle plant

The studied plant is complex technical systems that contain a great number of various components connected by diverse process links. Technical studies of it were conducted on the constructed efficient mathematical models of the plant. This called for development of a coordinated system of mathematical models of energy and chemical-engineering components and subsystems of the plant. Besides, the problem of large dimensionality of the installation flow charts was solved at the stages of modelling the components, calculation of the flow charts and technical and economic studies.

The models were developed by the system of computer-aided program generation that was created at the Energy Systems Institute SB RAS. The system automatically generates a mathematical model of plant as a calculation subprogram in Fortran on the basis of information about mathematical models of individual components, process links among them and calculation

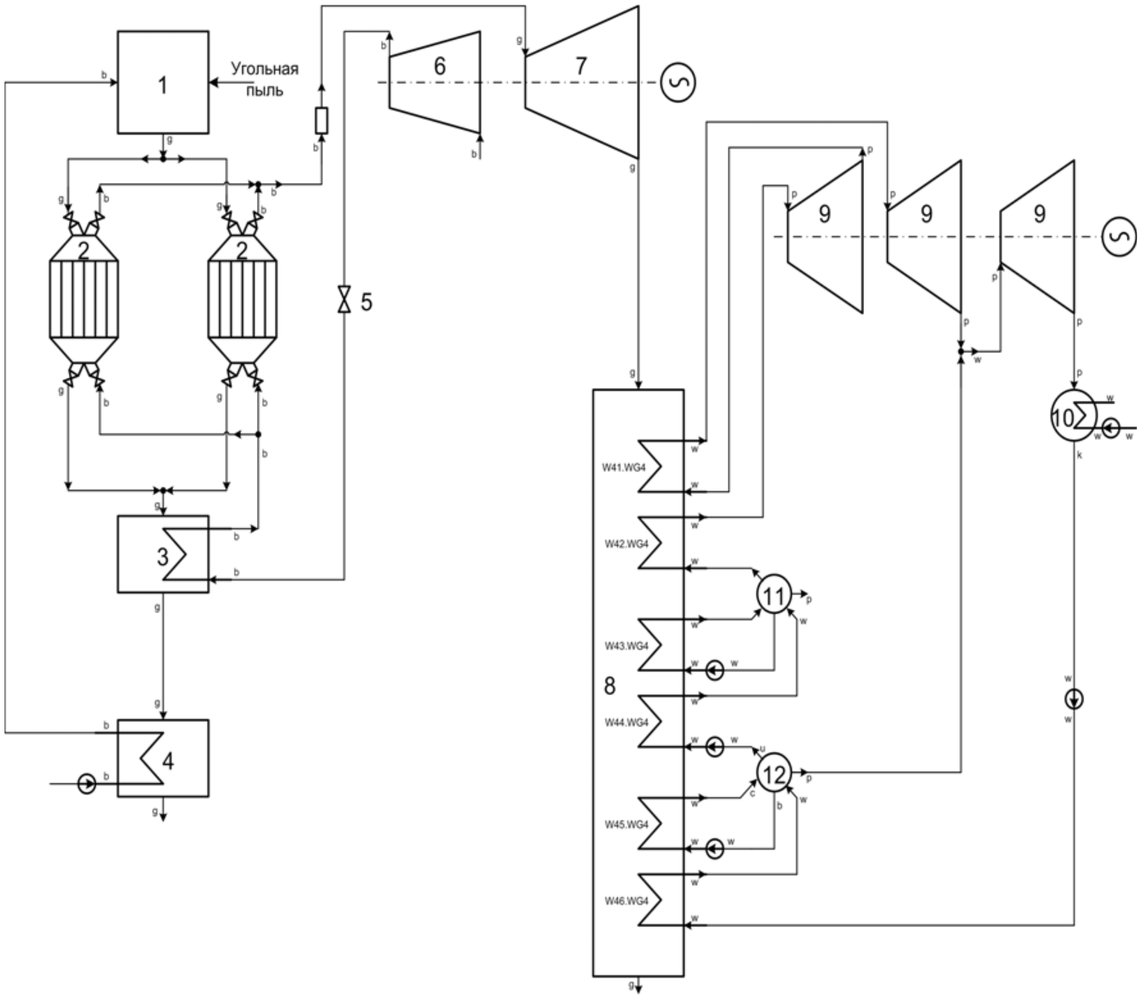

Fig. 4 A coal-fired combined cycle plant with regenerative cyclic air heaters: 1-combustion chamber, 2-a group of regenerative ceramic heat exchangers, 3-tubular heater of cycle air, 4-tubular heater of air coming for pulverized coal combustion, 5-control valve, 6-compressor, 7-gas turbine, 8-air waste-heat boiler, 9-steam turbine, 10-condenser, 11-high pressure drum separator, 12-low pressure drum separator, *b*-air, *g*- combustion products, *p*, *w*, *u*, *c*, *y*, *k* -steam, water, steam-water mixture

objectives. It should be noted that the mathematical models of the plant consist of hundreds of subsystems of algebraic, transcendent, differential equations and contain thousands of variables.

The mathematical models of groups of regenerative heat exchangers, air compressor, gas turbine, combustion chamber, air waste-heat boiler, steam turbine, etc. were used to develop the mathematical model of a coal-fired combined cycle plant. Its scheme is presented in Fig. 4. The model of the plant includes 556 input, 418 output and 7 iteratively specified parameters. The scheme is calculated by the Seidel iteration method.

The mathematical model of solid fuel combustion chamber is intended for determination of the combustion product composition and required air flow rate. The initial data here are flow rate, pressure and temperature of the fuel; temperature of combustion products at the combustion chamber outlet; excess air temperature and coefficient; and a share of heat loss due to chemical underburning.

The models of gas turbine and compressor serve to determine their capacity and outlet temperature of the working medium. The initial data are: working medium flow rate, component composition, inlet pressure and temperature, outlet pressure, adiabatic efficiency, working medium velocity at the turbomachine outlet. A simplified calculation of the expansion process (not considering the number of stages and their design characteristics) is made. The model of the main gas turbine takes into account decrease in thermal efficiency due to cooling of the air-gas channel by air. Besides, the mathematical model of gas turbine takes account of the constraint on the inlet temperature of gas and the model of compressor considers the constraint on the maximum admissible degree of compression.

The models of steam turbine compartments are used to determine the change in parameters of the working medium in the process of expansion as well as mechanical power generated during expansion. The models consider decrease in thermal efficiency during operation under wet steam conditions.

The mathematical model of steam turbine condenser that represents a steam-to-water surface heat exchanger is aimed at determining the value of heat-absorbing surface and cooling water flow rate. In doing so we set the thermodynamic parameters of steam and cooling water, steam flow rate, cooling water velocity and design characteristics. The condenser model is based on the technique of thermal calculation (Guidelines for thermal calculations 1982).

The mathematical models of heat exchangers of air waste - heat boiler include the equations of heat transfer and heat balance. The Seidel iterative method is applied to solve the set of equations. After the set of equations is solved we determine average and external calculated temperatures of tube metal, and the maximum permissible and effective stresses. Here we check whether or not the constraints on heat exchanger parameters including velocity of the heated heat-transfer agent at the inlet of tubes of heat-absorbing surface, tube metal temperature, etc. are met.

The subprograms based on the method of nodal points which employ dependences and tables of thermal properties of water and steam have been developed to determine thermodynamic and transportation water and steam parameters (enthalpy, entropy, specific volume, dryness, temperature, pressure, dynamic viscosity and heat conductivity) (Rivkin *et al.* 1980). The thermodynamic properties of gaseous mixes (enthalpy, heat conductivity and specific volume) are determined with the expressions applied to ideal gas mixes (Reid *et al.* 1977).

The mathematical model of the combined cycle plant is intended for engineering design of its components: heating surfaces of heat exchangers, ceramics mass, capacities of pumps, compressors, gas and steam turbines, etc.

4. The optimization studies of coal-fired combined cycle plant with regenerative cyclic air heaters

The mathematical model was applied to carry out optimization studies to determine optimal thermodynamic and discharge parameters of the plant by using the criterion of maximum electric efficiency in terms of physic-technical constraints on the plant parameters

$$\max \acute{\eta}(x,y) \tag{4}$$

subject to

Table 1 Optimal values of optimized parameters for the coal-fired combined cycle plant with periodic regenerative air heaters

Parameter, unit	Minimum value	Optimum value	Maximum value
Air pressure at inlet of ceramic heat exchangers, MPa	7.5	9.1	25.0
Air temperature at inlet of ceramic heat exchangers, *K*	300.0	983.2	1100.0
Air flow rate at inlet of ceramic heat exchangers, kg/s	200.0	471.7	600.0
Air temperature at outlet of tubular air heater, *K*	300.0	616.3	700.0
Enthalpy of high pressure steam, kJ/kg	2900.0	3392.7	3600.0
Steam pressure of reheat, MPa	10.0	56.6	60.0
Steam enthalpy of reheat, kJ/kg	2900.0	3545.8	3600.0
Pressure of low pressure steam, MPa	10.0	19.5	30.0
Pressure of high pressure steam, MPa	120.0	176.5	260.0
Gas pressure at gas turbine outlet, MPa	1.06	1.08	1.2
Water enthalpy at high pressure economizer outlet, kJ/kg	1200.0	2081.5	3000.0
Feed water flow rate, kg/s	100.0	222.5	300.0
Share of water flow rate in low pressure loop	0.1	0.85	0.99
Excess air ratio in combustion chamber	1.0	1.11	2.0
Consumption of pulverized coal, kg/s	50.0	74.2	150.0

Table 2 Main indices of coal-fired combined cycle plant with periodic regenerative air heaters

Index	Units	Value
Fuel consumption	thous. *t*/year	1736
Number of channels in group of ceramic heat exchangers	thous. pcs.	180
Area of heat exchange of channels in group of ceramic heat exchangers	thous. m^2	17
Ceramics mass in group of ceramic heat exchangers	*t*	1325
Temperature at gas turbine inlet	*K*	1730
Pressure at gas turbine inlet	MPa	9
Steam turbine capacity	MW	302
Gas turbine capacity	MW	312
Air compressor capacity	MW	286
Effective capacity	MW	610
Electric efficiency	%	47.8

$$H(x,y)=0 \tag{5}$$

$$G(x,y)\geq 0 \tag{6}$$

$$x_{\min}\leq x\leq x_{\max} \tag{7}$$

where x-vector of independent parameters to be optimized; y-vector of dependent parameters to be calculated; H-vector of equality constraints (equations of material and energy balances, heat transfer, etc.); G-vector of inequality constraints; $x_{\min}$, $x_{\max}$-vectors of boundary values of the parameters to be optimized.

The optimized parameters in the problem are pressures, temperatures, air flow rates, fuel consumption, enthalpies, pressures and flow rates of live steam, steam of high and low pressure, etc. In total 15 parameters of the flow sheet were optimized (Table 1).

A system of constraints (56 in all) includes conditions on non-negativity of the end temperature heads of heat exchangers, pressure differentials along the flow part of steam and gas turbines, constraints on the design temperatures and mechanical stresses of heat exchanger tubes, etc.

The combined cycle plant burns brown coal of the Mugunskoye deposit in Irkutsk region with the low heat of combustion 4130 kcal/kg. Its composition is (in %): carbon-0.46, hydrogen-0.036, sulfur-0.01, oxygen-0.1, nitrogen-0.01, humidity-0.19, ash content-0.19.

Table 2 presents optimal engineering parameters for variants of coal-fired combined cycle plant that were obtained in the studies.

5. Conclusions

The calculations performed indicate high energy efficiency of the considered flow sheet of the coal-fired combined cycle plant with periodic regenerative ceramic air heaters. This type of units is believed to be promising, since the optimized net efficiency obtained in these calculations for electricity production amounted to 48%.

Moreover, the use of air as a working medium in the gas turbine cycle affords an opportunity to extend the service life of the gas turbine and heating surfaces of the waste heat boiler, which will reduce the operating costs.

The goal of further research in this area is to optimize the combined cycle gas turbine unit parameters to meet the criterion of the minimum electricity price and to compare the efficiency of the studied combined cycle gas turbine unit with the other types of coal-fired power plants.

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