Perspective technologies for conversion of Siberian coals into synthetic fuels and electricity with carbon dioxide removal systems

A.M. Kler, E.A. Tyurina, A.S. Mednikov, V.V. Stepanov

***Abstract* - Consideration is given to the perspective technologies for combined production of synthetic fuel (SF) and electricity. The mathematical models of plant for co-production of synfuel and electricity (PCSE) intended for combined production of electricity and synthesis of methanol and dimethyl ether (DME) or membrane-based hydrogen production from coal were developed. They were used in the optimization studies on the installations. As a result of the studies the design characteristics for the plant elements, the relationships between the synthetic fuel and electricity productions, etc. were determined. These data were used to identify the ranges of synthetic fuel price for various prices of fuel, electricity and equipment, and estimate the profitability of synthetic fuel production.**

Special attention is paid to modeling of CO_2 removal system as part of PCSE and studies on PCSE optimization. The account is taken of additional capital investments and power consumption in the systems.

***Index Terms*- mathematical modeling, plant for co-production of synfuel and electricity, hydrogen, methanol, dimethyl ether, CO_2 removal system.**

1. INTRODUCTION

Signing and implementing the Framework Convention on Climate Change and the Kyoto Protocol foster the creation of both greenhouse gas emission quota markets and markets of alternative energy directly related to fulfillment of these agreements. The damage to the environment caused by coal energy can be decreased by using environmentally cleaner fuels of coal origin.

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Specialists consider methanol, dimethyl ether and hydrogen as most perspective for use kinds of synthetic fuels. This is explained by a number of circumstances. Methanol, one of the main products of large-scale chemistry, is widely used for production of a great variety of valuable chemical substances. World methanol production has reached 35 million t yearly and the demand for methanol is constantly growing, which is related to its use in the new fields, for example production of high-octane additives to motor fuel, as a fuel for power plants equipped with highly efficient combined cycle installations, etc. Currently the attention of the world science is caught by a new perspective energy carrier – dimethyl ether. DME is characterized by complete combustion and high cetane number, its combustion products practically do not produce harmful emissions and it can be used as a diesel fuel. Hydrogen is undoubtedly one of the most promising environmentally clean energy carriers. Its chemical energy can be efficiently converted to electric and mechanic energy without producing greenhouse gases.

Development of economically efficient technologies for synthetic fuel production from coal is an urgent problem. The studies on SF production technologies that have been conducted at ESI SB RAS show that it is feasible to combine the large scale SF production from coal with electricity production. This makes it possible to utilize a considerable quantity of thermal energy and combustible waste of SF production. The energy efficiency and economic efficiency of the combined production appear to be essentially higher than those of separate productions. The mathematical models of energy technology installations for combined production of electricity and synthesis of methanol or DME and for production of electricity and membrane hydrogen production from coal were developed. They were used in the optimization studies on the installations. As a result of the studies the constructive characteristics for the elements of the installations, the relationships between the synthetic fuel and electricity productions, etc. were determined. These data were used to determine the ranges of synthetic fuel prices for various prices of fuel, electricity, equipment and the profitability of synthetic fuel production [1, 2, 6].

One of the major issues arising from the study of technologies for SF production in the light of the Kyoto agreements on reduction of greenhouse gas emissions is associated with the calculation of costs required to remove CO_2. Despite the fact that the world puts a great emphasis on the projects dealing with removal and disposal of CO_2 (Norway, Canada, Algeria), to date, the question remains open.

Therefore, special attention is paid to modeling of CO_2 removal system as part of PCSE and studies on PCSE optimization. The account is taken of additional capital investments and power consumption in the systems.

Note that great attention in the world and Russia is paid to the integrated processing of solid fuels into synthetic high-grade fuels with CO_2 removal [3, 4, 5]. In the paper the authors place an emphasis on the comprehensive technical and economic analysis of such technologies and plants based on them. The analysis rests on the same methods and approaches to their mathematical modeling and nonlinear optimization of their parameters. Besides, the analysis is made for identical operation conditions of the considered plants (cost of the initial fuel, electricity price, specific capital investments in components and subsystems, specified profitability, etc.).

2. MODELING OF PCSE FOR SYNTHETIC FUEL PRODUCTION

The studies conducted in this work are based on the mathematical models of PCSE. These models have three aggregated modules (Figure1): the module of synthesis gas production (I), the module of synthetic fuel production (II), energy module (III) and CO_2 removal module (IV). In the first module the solid fuel is gasified and the mix of hydrogen and carbon monoxide (synthesis gas) is produced. Besides, here the synthesis gas is cooled in the heat exchangers of gas generator and the compounds of ash, sulfur and excessive CO_2 are removed.

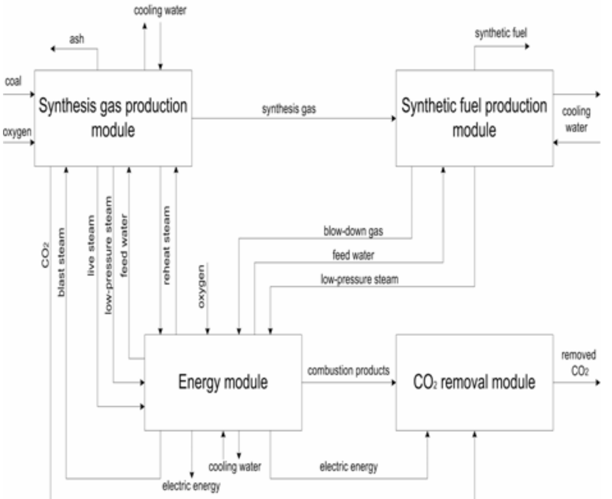

Figure 1. A simplified scheme of material flows in PCSE.

The heat produced during gas cooling is used for steam generation. The steam is supplied to steam turbine of the energy module to produce electricity. In the second module catalytic synthesis of methyl alcohol or dimethyl ether is performed and the low pressure steam is generated in the intermediate synthesis reactors, that are intended for extraction of reaction heat (or hydrogen production using palladium membranes with low pressure steam generation in CO converters). This steam goes to the low pressure section of steam turbine. The blowdown gas goes from the SF production module to the combustion chamber of module III, the combustion products from this chamber are used for electricity production in gas turbines. The waste heat boiler of this module generates high and low pressure steam that is supplied to the steam turbine.

Figure 2 presents a simplified flow diagram of PCSE for coal-based DME synthesis. It should be noted that the flow diagrams of PCSE for synthesis of DME and methanol differ. The PCSE for DME synthesis has a module for separation of DME, methanol and water. Besides, methanol produced by DME synthesis is recirculated through reactor.

Figure 3 presents a more detailed flow diagram of PCSE for production of hydrogen and electricity from coal.

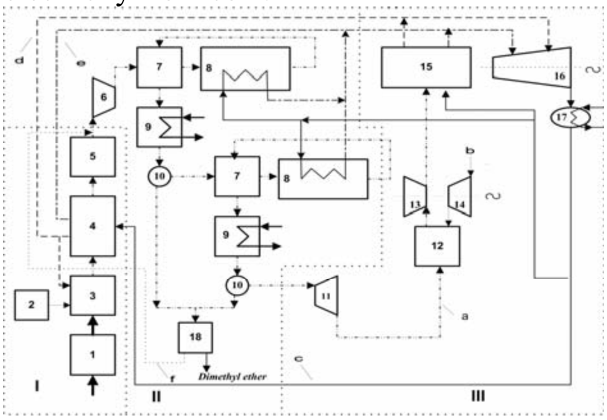

Figure 2. A flow diagram of PCSE for DME synthesis from coal: a – gas flows, b – air flows, c – feed water flows, d – low pressure steam flows, e – high pressure steam flows, f - methanol recirculation; module I - synthesis gas production, module II - DME synthesis, module III – energy; 1-fuel preparation system, 2- air separation system, 3- gas generator, 4 – synthesis gas cooling system, 5- synthesis gas treatment system, 6- synthesis gas compressor, 7- regenerative gas-gas heat exchanger, 8-catalytic reactors of DME synthesis, 9- refrigerator-condenser, 10- DME separator, 11- expanding pipe, 12- blowdown gas combustion chamber, 13-primary gas turbine, 14- air compressor, 15-waste heat boiler, 16-steam turbine, 17-steam turbine condenser, 18-module for water, methanol and DE separation.

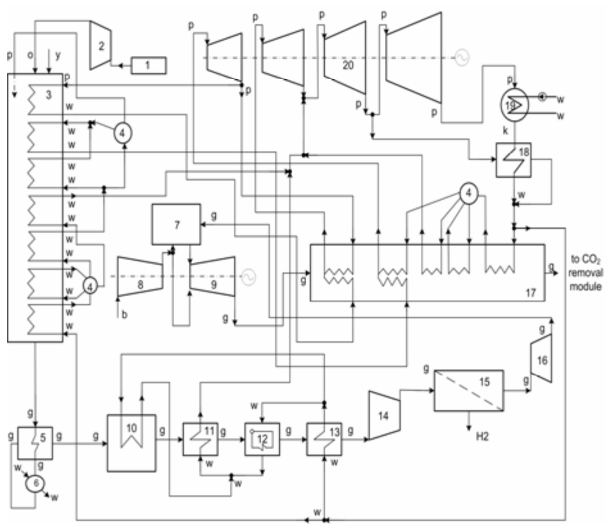

Figure 3. A design diagram of PCSE for production of hydrogen and electricity: 1– a module for oxygen production, 2– oxygen compressor, 3 – gas generator, 4 – drum – separator, 5 – dry ash collector, 6 – regenerative gas-gas heat exchanger, 7 – system for deep purification of gasification products, 8 – combustion chamber of gas turbine, 9 – air compressor, 10 – primary gas turbine, 11 – reactor of CO conversion, 12–14 – convective heat exchanger on gasification products, 15 – compressor of conversion products, 16 – installation for membrane separation of conversion products, 17 – gas turbine, 18 – waste heat boiler, 19 – low pressure regenerative heater, 20 – steam turbine condenser, 21 – steam turbine, w – water, p – steam, k – condensate, g – gas, z – ash, y – coal, o – oxygen.

Developing the flow diagram of PCSE for combined electricity and hydrogen production we envisaged perspective solutions on the technological arrangement of processes used in PCSE. Fuel is gasified in gas generators with fluidized bed and dry bottom ash handling with an oxygen-steam draught under the pressure of 2 MPa. The gas generator is the analogue of the Winkler gas generator, a rather well studied generator implemented on a commercial scale. Hydrogen production is based on the principles of membrane separation of gaseous mixtures. The modules on the basis of palladium membranes are taken as membrane modules which allow high temperature and pressure operation. High selectivity of the membranes makes it possible to produce high purity hydrogen. The flow diagram envisages meeting the main requirement of palladium membranes, i.e. there should not be considerable amounts of carbon and sulfur oxides in separated gas since they can form stable chemical compounds with palladium and, thus, decrease the diffusion rate. The CO concentration in the gasification products is decreased in reactors for CO conversion and sulfur compounds are removed in the system for deep purification of gasification products. Energy module includes the combined cycle which is most perspective for energy plants.

The studied plants are complex technical systems that contain a great number of various components connected by diverse process links. Technical and economic studies of the PCSE were conducted on the constructed efficient mathematical models of the plants. This called for development of a coordinated system of mathematical models of energy and chemical- engineering components and subsystems of the plants. Besides, the problem of large dimensionality of the PCSE flow charts was solved at the stages of modeling 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 Institute. The system automatically generates a mathematical model

TABLE 1. THE KEY TECHNICAL AND ECONOMIC INDICES FOR THE OPTIMAL VARIANTS OF PCSES FOR SF AND ELECTRICITY PRODUCTION FROM COAL.

Indices	Variants of PCSEs for		
	hydrogen production	DME synthesis	methanol synthesis
Annual natural fuel consumption, thousand t		4500	
Annual standard fuel consumption, thousand tce		2500	
Annual SF production:			
- in standard fuel, thousand tce	655	1600	1350
- in natural fuel, thousand t	165	1625	1880
Capacity, MW:			
-steam turbine,	351	240	270
- gas turbine,	349	110	145
- auxiliaries,	57	189	185
- useful.	642	150	225
Annual electricity supply, million kWh	4500	1060	1560
Total investments in installation, million dol.	890	1350	1150
Exergy efficiency of SF production, %	45.3	59.2	61.7
Price of electricity supplied, cent/kWh		5	
Price of SF production, dol./tce	198	288	270
Total cost of PCSE products, million dol./ year	354.7	513.8	442.5

of PCSE as a calculation subprogram in Fortran on the basis of information about mathematical models of individual components, process links among them and calculation objectives. It should be noted that the mathematical models of the plants consist of hundreds of subsystems of algebraic, transcendent, differential equations and contain thousands of variables.

The mathematical model of coal gasification module includes the models of reaction gas generator chambers, radiation and convective heat exchangers, in which gasification products are cooled by water or steam, and systems of synthesis gas cleaning. The mathematical model of synthetic fuel production module contains the models of synthesis gas compressors, catalytic reactors, regenerative gas-gas heat exchangers and condensers, membrane system for hydrogen extraction, etc. The mathematical models of energy module includes the models of gas turbines, air compressor, blowdown gas combustion chamber, steam turbine and waste-heat boiler. A detailed description of the applied models is given in [1, 2, 6].

The PCSE models are aimed at engineering design of the installation elements, i.e. the models are intended to determine the heating areas of heat exchangers, the catalyst volume in reactors for methanol or DME synthesis, the required area of membrane surfaces, capacities of pump drive and compressors, capacities of gas and steam turbines, thermodynamic parameters, gasification product flow rates, CO conversion products, combustion products, water and steam at different points of the diagram, etc.

Table 1 presents basic technical and economic indices of the optimal variants of PCSEs for methanol and DME synthesis and PCSE for hydrogen production from coal that were obtained in optimization studies on mathematical models of installations without inclusion of costs for the CO_2 removal system. The options of methanol and DME production are seen to essentially differ in the ratio of product output (SLF and electricity). The installations for DME synthesis, for example, are characterized by a higher level of SLF production (in the energy terms) in comparison with the installations for methanol synthesis. PCSEs for methanol synthesis produce much more electricity (by a factor of 1.5-2.0 subject to the kind of fuel used). This is explained by the fact that virtually all the amount of CO is used in synthesis reactors for DME production. In PCSEs for methanol synthesis a large volume of CO arrives after synthesis at the combustion chamber of the gas turbine.

Production of gaseous hydrogen requires lower investments and correspondingly has lower prices. It should be noted here that the use of gaseous hydrogen as an energy carrier in the future gives rise to development of effective methods for its storage and transportation. As a result its final cost for consumers will increase sizably as against SLF, since the costs for storage and transportation of liquid fuels are much lower than for gaseous ones.

3. MODELING OF CO_2 REMOVAL SYSTEMS WITHIN PCSE

In the light of the Kyoto agreements on emissions of greenhouse gases into the environment it is important to determine the cost of PCSE products, i.e. synthetic fuel and electricity, taking into account the costs of CO_2 removal.

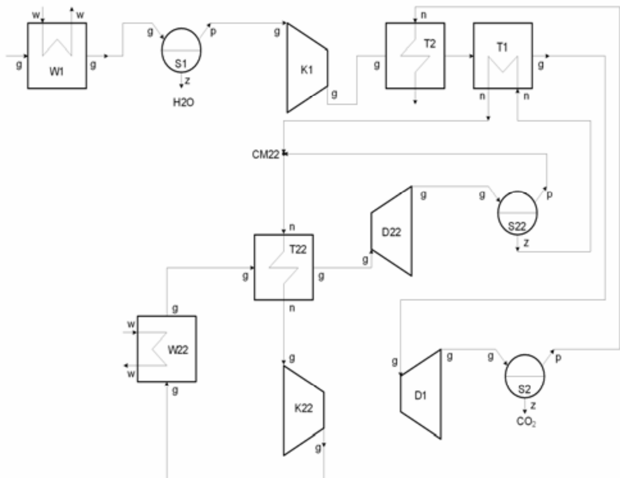

Figure 4. System for CO_2 removal: W1, W22 – gas-water heat exchanger, K1 – compressor of combustion products, K22 – compressor of nitrogen refrigerating cycle, S1, S2, S22 – liquid phase separators, T1 – a group of regenerative coolers, T2 – a group of coolers using external cooling agent, T22 – a group of coolers in the nitrogen cooling cycle, D1, D22 – turbine expanders.

The CO_2 removal in the system is based on the cryogenic method. This method seems to be more efficient for removal of carbon dioxide on large scale, since based on the tentative estimations requires lower costs as compared to other methods of purification (absorption, adsorption, membrane and others). We employ the expansion type system with external cooling circuit that uses liquid nitrogen as a cooling agent and with regeneration of cold from the last stages of cooling. A simplified flow diagram of the system for CO_2 removal from the combustion products is presented in Figure 4.

Constructing the mathematical model of CO_2 removal system we used the models of elements the system consists of: coolers, regenerative heat exchangers, turbine expanders, compressors, separators, gas-water heat exchangers, etc.

In calculations of the systems for carbon dioxide removal by cryogenic methods it becomes necessary to determine the thermodynamically equilibrium composition of multi-component liquid-vapor mixtures. The accuracy and rate of finding such a composition determines to a greater extent the accuracy and rate of calculations of the considered systems. To make the above calculations we use an efficient method of determining thermodynamic equilibrium composition of multi-component liquid-vapor mixture that was developed at ESI SB RAS [2]. The method reduces essentially the time of calculating the PCSE elements and is highly accurate. Mathematically the calculation of the equilibrium phase state of the multi-component liquid-vapor systems reduces to minimization of Gibbs function taking into account equalities constraints on material and energy balances and inequalities constraints that require non-negativity of masses of individual phases and logic conditions that determine the area in which the solution is sought (pre-critical, supercritical with possible parallel existence of liquid and vapor phases, etc.). The method is based on a two-stage iterative calculation of the equilibrium composition of the mixture. At each stage the problems of one-dimensional minimization of Gibbs function are solved. The suggested method is a basic method for modeling most of the elements in the considered systems. The developed mathematical model of the CO_2 removal module is included into PCSE to carry out optimization studies of the indicated installations taking into account the costs of CO_2 removal.

4. OPTIMIZATION STUDIES ON PCSES WITH CO_2 REMOVAL SYSTEMS

The studies performed on mathematical models of PCSEs for SF and electricity production from coal aim to determine optimal thermodynamic and flow characteristics of installations and variation of their technical and economic indices as a function of operation conditions (prices of fuel, equipment, products).

The optimal PCSE variants were determined by solving nonlinear mathematical programming problems that involved calculation of the installation parameters (mix of blast to the gas generators, catalyst volume in the synthesis reactors, areas of the membrane surfaces, temperatures and pressures of the working media of the combined cycle plant, etc.) to provide a minimum price of SF produced at the set levels of internal rate of return (IRR), prices of fuel consumed and electricity supply based on the physical and technical constraints on installation parameters and costs of CO_2 removal.

Mathematically the problem is stated as follows

$$\min C_{SF}(x, y, k_m, \Delta K_{CO_2}, N_{ap}^{\Sigma})$$

subject to

$$H(x,y)=0,$$
$$G(x,y)\geq 0,$$
$$x_{\min}\leq x\leq x_{\max},$$
$$IRR=IRR_z,$$
$$N_{ap}^{\Sigma}=N_{ap}^{ETI}+N_{ap}^{CO_2},$$

where x – vector of independent optimized parameters; y – vector of dependent calculated parameters; H – vector of equality constraints (the equations of material, energy balances, heat transfer, etc.); G – vector of inequality constraints; $x_{\min}$, $x_{\max}$ – vectors of the boundary values of the optimized parameters; C_{SF} – SF cost; k_m – specific cost of membranes; ΔK_{CO_2} – investments in the CO_2 removal system; IRR, IRR_z – calculated and set internal rate of investment return, respectively; N_{ap}^{Σ} – auxiliary power supply of PCSE with the CO_2 removal system; N_{ap}^{ETI} – auxiliary power supply of PCSE without the CO_2 removal system; N_{ap}^{CO2} – auxiliary power supply of the CO_2 removal system.

Enthalpies, pressures and flow rates of the live steam, temperature of the conversion process and the total area of the palladium membranes in PCSE for hydrogen production, catalyst volume at PCSE for methanol or DME synthesis, pressure drops in the expanders, liquid nitrogen flow rate in the combustion product cooling circuits in the CO_2 removal systems, etc. were taken as optimized parameters. The system of constraints incorporates conditions of nonnegativity of the end temperature drops of heat exchangers, pressure differentials along the flow-through part of steam, gas turbines and expanders, the calculated temperatures and mechanical stresses of heat exchanger pipes, the minimum and maximum temperature of gasification and CO conversion, etc. The initial technical and economic information is taken from the earlier conducted studies at Energy Systems Institute on technologies of solid fuel conversion to synthetic liquid and gaseous fuels and the analysis of cost estimates of production and energy enterprises [2, 3]. The coal price is assumed to be $20/tce. The internal rate of return makes up 15%, which corresponds to the world practice of studies on large-scale projects.

Table 2 presents optimal parameters of the major elements of the CO_2 removal systems in different kinds of PCSEs, the flow rates of combustion product components at the vapor and liquid phases are given by separator in Table 3.

Tables 2, 3 illustrate distribution of CO_2 liquefaction parameters (temperatures, pressures, flow rates of working media and heat carriers in vapor and liquid) for primary elements. The flow rate of exhaust gases arriving at the CO_2 removal system in PCSE for hydrogen production (1376 kg/s) is much higher than in PCSE for methanol (696 kg/s) or DME (418 kg/s) synthesis, which is caused by large volumes of electricity production by

PCSE for hydrogen production. Depending on the PCSE variant the cooled flow temperature decreases by 120-130 K in the system of heat exchangers of stage 1 T1, by 15-20 K at stage 2 T2. The cooling effect of the turbine expander D1 is 30-35 K. Thus, the highest effect of combustion product cooling is achieved in the turbine expander D1 and the system of heat exchangers of stage 1 through cold regeneration of the last cooling stage.

Table 4 presents basic technical and economic indices of the optimal variants of PCSE for SF and electricity production from coal, considering costs of CO_2 removal (in this case costs of CO_2 utilization were not taken into account). Energy consumption for carbon dioxide removal from combustion products is characterized by the nonlinear dependence and the essential growth with the decreasing partial pressure of CO_2 in combustion products. For this reason CO_2 is extracted incompletely and its small amount is found in the exhaust gases. Note that part of CO_2 is removed from synthesis gas in the gasification module of the considered PCSEs. Electricity consumption and capital investments in CO_2 removal in the gasification module are taken into consideration to calculate PCSE indices without CO_2 removal systems.

TABLE 2. OPTIMAL PARAMETERS OF CO_2 REMOVAL SYSTEMS IN PCSES FOR SF AND ELECTRICITY PRODUCTION FROM COAL.

<table>
<tr><th rowspan="2">Element</th><th rowspan="2" colspan="2">Index</th><th colspan="3">PCSE for</th></tr>
<tr><th>hydrogen production</th><th>DME synthesis</th><th>methanol synthesis</th></tr>
<tr><td>1</td><td colspan="2">2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td rowspan="8">T1</td><td rowspan="2">Cooled flow temperature, K</td><td>inlet</td><td colspan="3">303.2</td></tr>
<tr><td>outlet</td><td>172.8</td><td>180.8</td><td>174.6</td></tr>
<tr><td rowspan="2">Cooling flow temperature, K</td><td>inlet</td><td>119.4</td><td>129.0</td><td>130.1</td></tr>
<tr><td>outlet</td><td>278.1</td><td>293.5</td><td>293.8</td></tr>
<tr><td colspan="2">Cooling flow pressure, MPa</td><td colspan="3">0.1</td></tr>
<tr><td colspan="2">Cooled flow pressure, MPa</td><td colspan="3">0.4</td></tr>
<tr><td colspan="2">Total area of heat exchangers, m^2</td><td>37686.0</td><td>13865.0</td><td>27913.0</td></tr>
<tr><td colspan="2">Pipe weight, t</td><td>301.3</td><td>110.9</td><td>223.2</td></tr>
<tr><td rowspan="8">T2</td><td rowspan="2">Cooled flow temperature, K</td><td>inlet</td><td>172.8</td><td>180.8</td><td>174.6</td></tr>
<tr><td>outlet</td><td>155.7</td><td>158.0</td><td>159.2</td></tr>
<tr><td rowspan="2">External nitrogen temperature, K</td><td>inlet</td><td colspan="3">83,8</td></tr>
<tr><td>outlet</td><td>154.1</td><td>167.8</td><td>162.2</td></tr>
<tr><td colspan="2">External nitrogen pressure, MPa</td><td colspan="3">0.2</td></tr>
<tr><td colspan="2">Cooled flow pressure, MPa</td><td colspan="3">0.4</td></tr>
<tr><td colspan="2">Total area of heat exchangers, m^2</td><td>22636.0</td><td>12792.9</td><td>6576.7</td></tr>
<tr><td colspan="2">Pipe weight, t</td><td>181.0</td><td>102.3</td><td>52.6</td></tr>
<tr><td rowspan="9">T22</td><td rowspan="2">Cooled flow temperature, K</td><td>inlet</td><td colspan="3">303.2</td></tr>
<tr><td>outlet</td><td>183.6</td><td>189.3</td><td>186.7</td></tr>
<tr><td rowspan="2">Cooling flow temperature, K</td><td>inlet</td><td>119.2</td><td>130.5</td><td>127.5</td></tr>
<tr><td>outlet</td><td>290.5</td><td>291.4</td><td>293.0</td></tr>
<tr><td colspan="2">Cooling flow pressure, MPa</td><td colspan="3">0.2</td></tr>
<tr><td colspan="2">Cooled flow pressure, MPa</td><td>15.5</td><td>18.0</td><td>17.8</td></tr>
<tr><td colspan="2">External nitrogen flow rate, kg/s</td><td>395.7</td><td>181.1</td><td>197.7</td></tr>
<tr><td colspan="2">Total area of heat exchangers, m^2</td><td>46638.1</td><td>44414.7</td><td>44181.3</td></tr>
<tr><td colspan="2">Pipe weight, t</td><td>384.0</td><td>365.7</td><td>363.8</td></tr>
<tr><td rowspan="4">W1</td><td rowspan="2">Cooled flow temperature, K</td><td>inlet</td><td>338.6</td><td>340.5</td><td>387.8</td></tr>
<tr><td>outlet</td><td colspan="3">298.2</td></tr>
<tr><td rowspan="2">Cooling water temperature, K</td><td>inlet</td><td colspan="3">293.2</td></tr>
<tr><td>outlet</td><td colspan="3">303.2</td></tr>
</table>

END OF TABLE 2

1	2		3	4	5
	Cooling water pressure, *MPa*			0.5	
	Cooled flow pressure, *MPa*			0.3	
	Cooling water flow rate, *kg/s*		6112.2	1876.8	2808.9
	Total area of heat exchangers, m^2		1396.7	671.1	472.85
	Pipe weight, *t*		10.4	5.0	3.5
Д1	Flow pressure, *MPa*	inlet		0.4	
		outlet		0.1	
	Flow temperature, *K*	inlet	155.7	158.0	159.2
		outlet	119.3	128.8	129.9
	Generated power, *MW*		42.4	9.5	17.4
Д22	Nitrogen pressure, *MPa*	inlet	15.5	18.0	17.8
		outlet		0,2	
	Nitrogen temperature, *K*	inlet	183.6	189.3	186.7
		outlet		83.9	
	Generated power, *MW*		52.2	26.5	28.2
K1	Combustion product pressure, *MPa*	inlet		0.2	
		outlet		0.4	
	Combustion product temperature, *K*	inlet	297.9	298.2	297.0
		outlet		303.2	
	Consumed power, *MW*		49.9	11.8	19.8
	Total area of built-in gas-water heat exchangers, m^2		1449.0	862.0	1001.0
	Pipe weight of built-in heat exchangers, *t*		11.0	7.1	8.0

TABLE 3. PHASE STATE OF COMBUSTION PRODUCT COMPONENTS BY SEPARATOR

Element	Flow rate (kg/s)	Pressure (MPa)	Temperature (K)	Phase state	Components of vapor-gas mixture		
					CO_2	N_2	O_2
PCSE for hydrogen production							
S2	1375.5	0.1	119.4	vapor	1.9	1015.0	201.9
				liquid	156.7	0.0	0.0
S22	395.7	0.2	84.2	vapor	-	196.7	-
				liquid	-	199.0	-
PCSE for DME synthesis							
S2	418.4	0.1	129.4	vapor	2.3	280.0	54.0
				liquid	82.1	0.0	0.0
S22	181.1	0.2	84.2	vapor	-	79.5	-
				liquid	-	101.6	-
PCSE for methanol synthesis							
S2	696.2	0.1	130.1	vapor	4.7	480.2	108.4
				liquid	102.9	0.0	0.0
S22	197.7	0.2	84.2	vapor	-	86.5	
				liquid	-	111.2	

TABLE 4. BASIC TECHNICAL AND ECONOMIC INDICES OF PCSE FOR SF AND ELECTRICITY PRODUCTION IN TERMS OF ENERGY CONSUMPTION AND INVESTMENTS IN CO_2 REMOVAL SYSTEMS

Indices	PCSE variants for		
	hydrogen production	DME synthesis	methanol synthesis
1	2	3	4
CO_2 content in exhaust gases, thousand t/year	4000.0	2127.0	2700.0
CO_2 extraction, thousand t/year	3950.0	2070.0	2592.0

END OF TABLE 4

1	2	3	4
CO_2 emission after extraction, thousand t/year	50.0	57.0	108.0
CO_2 emission in combustion products of SF, thousand t/year	0.0	3100.0	2585.0
Total emission of CO_2 at SF production and combustion, thousand t/year	**50.0**	**3157.0**	**2693.0**
Capacity in CO_2 removal system of, MW: - combustion product compressors,	50.1	11.8	19.8
- nitrogen compressors in the nitrogen refrigerating unit,	182.7	91.1	99.5
- expanders of combustion products,	42.4	9.5	17.4
- expanders of nitrogen refrigerating unit,	52.2	26.5	28.2
- total auxiliaries.	138.0	67.0	75.0
Annual electricity supply by PCSE considering consumption in CO_2 removal system, million kWh	3334.0	592.0	1045.0
Investments in CO_2 removal systems, million dol.	128.0	86.0	93.0
Investments in PCSE with CO_2 removal systems, million dol.	1018.0	1436.0	1243.0
Price of electricity supplied, cent/kWh		5.0	
SF price with costs for CO_2 removal systems, dol./tce	356.0	325.0	312.0
Total cost of PCSE products with costs for CO_2 removal systems, million dol./year	400.0	549.6	473.5
Rise in cost of PCSE products considering costs for CO_2 removal systems, %	11.3	7.0	6.5

5. CONCLUSION

The CO_2 removal systems are characterized by sizable investments and electricity consumption for auxiliaries, leading to an essential rise in cost of synthetic fuels produced. Depending on the mix of combustion products the specific investments in the CO_2 removal systems account for 35 - 40 dol./ t CO_2 per year. The major portion of electricity for auxiliaries of PCSEs for SF and electricity production is used in compressors of combustion products and nitrogen in the nitrogen refrigeration cycle. The net electricity generation in expanders of the CO_2 removal system in PCSE does not cover this energy consumption. Additional costs of the CO_2 removal systems in PCSEs result in rise of cost of PCSE products by 11.3%, 7% and 6.5% for PCSEs for hydrogen production, DME synthesis and methanol synthesis respectively, in comparison with installations without the CO_2 removal systems.

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