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STEAM BOILERS, POWER-PLANT FUEL, BURNER ARRANGEMENTS, AND AUXILIARY BOILER EQUIPMENT

Solid Fuel Gasification in the Global Energy Sector (a Review)

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Abstract—In the review of the Conference on Gasification of Solid Fuels, which was held on October 2013 by the United States, the commercial use of the most advanced coal gasification systems in the chemical and power industry is considered. Data on the projects of integrated solid fuel gasification combined-cycle plants, either being developed or exploited in the United States, as well as the nature and results performed in specialized organizations to improve the existing gasification equipment and systems, are presented.

Keywords: coal, gasification, combined cycle plants, synthetic gas, gas purification, refractory materials, modeling

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In 1999, the National Energy Technology Laboratory of the U.S. Department of Energy and the Gasification Technologies Council designed a database, which now covers 747 projects, and 1741 gasifiers, including 393 active and commercially exploited ones with the thermal performance of 104.7 GW (t). Another 1370 gasifiers with the thermal performance of 147.4 GW (t) are planned to be constructed. Distribution of their total thermal performance over the period of 1950–2018 is shown in Fig. 1, that among world regions in Fig. 2, that according to the purpose of the produced synthetic gas in Fig. 3, that by the efficiency and number of gasifiers operating on various raw materials in Fig. 4, and various gasification technologies in Fig. 5.

Data on the ten most powerful gasification projects are given in Table 1, including the number of operating (first term) and reserve (second term) gasifiers. Here, data on the largest operating gasification plants can be also found. They produce 25% of the world's ammonia and 35% of the world's methanol. The construction of megaplants promotes a rapid increase in the total capacity of plants (see Fig. 1). China's coal and chemistry industry evolves most intensively [1].

MODERN CCPS WITH COAL GASIFICATION IN THE UNITED STATES

The largest combined cycle plant (CCP) with coal gasification (net power is 618 MW) came online in the power grid of Duke Energy (United States). It may be fueled by synthetic gas, natural gas, or a mixture of both. The estimated availability of such TPP (defined by us as utilization factor) is 75% during the first 15 months after the commissioning and 85% during the project life cycle.

The TPP project was approved in March 2008, the construction started in May of the same year and ended mainly in December 2011. The initial pilot launch of the CCP fueled by synthetic gas took place in October 2012. The commercial exploitation started in June 2013.

The combined cycle plant follows a 2 + 1 scheme. It includes two 7FB GTPs produced by General Electric, each with the capacity of 236 MW when fueled by synthetic gas, and a steam turbine of the same company with the capacity of 322 MW. The recovery boilers were provided by the Doosan Company (South Korea).

In accordance with the number of GTP in the CCP, there are two gasification lines with respect to the technology developed by General Electric (formerly Texaco). The air separation plant was provided by the Air Products Company.

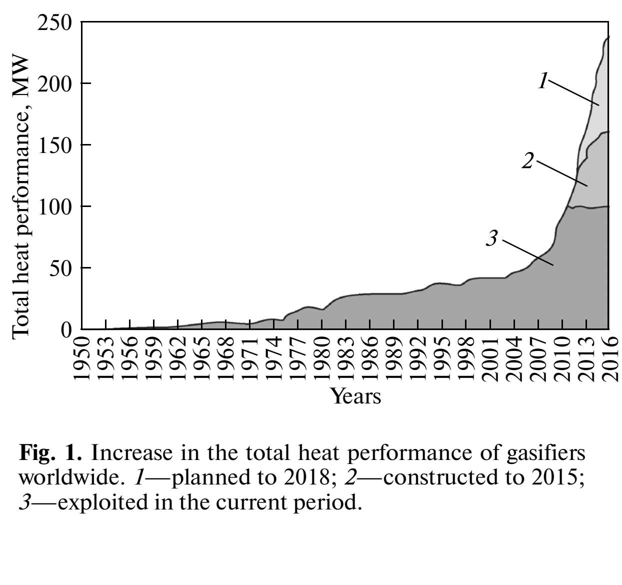

Fig. 1. Increase in the total heat performance of gasifiers worldwide. *1*—planned to 2018; *2*—constructed to 2015; *3*—exploited in the current period.

Table 1. Largest gasification companies

Company	Country	Technology	Number of gasifiers	Thermal performance, MW (t)	Launch year	Raw materials	Product
Pearl GTL	Qatar	"Shell"	18 + 0	10936	2011	NG	LF
Yinchuan GTL	China	"Siemens"	22 + 2	9300	2016*	Coal	LF
Datang Ningxia SNG	China	SEDIN	45 + 3	7125	2015*	Lignite	SNG
Sasol Synfuels West	RSA	"FBOB Lugri"	40 + 0	7048	1977	Coal	LF
Sasol Synfuels East	RSA	"FBOB Lugri"	40 + 0	7048	1982	Coal	LF
CHNG Xinjang SNG	China	TPRI	7 + 1	6450	2014*	Coal	SNG
Jamnagar Gasification, first stage	India	E-Gas	6 + 2	5000	2015*	OC	EE
Jazan IGCC	Saudi Arabia	"Shell"	16 + 0	4465	2016*	OR	EE
Yankunag Yulin GTL	China	OMB	8 + 0	3733	2015*	Coal	LF
Yulin Methanîl Plant	China	"General Electric"	10 + 4	3383	2015*	Coal	Methanol
Iuner Mongolia Chemical Plant	China	"Shell"	3 + 0	3373	2011	Lignite	Methanol
Shenhua Ningxia, first stage	China	"Siemens"	5 + 0	1912	2011	Coal	Methanol
Great Plains Synfuels Plant	United States	"FBOB Lugri"	12 + 2	1900	1984	Lignite	SNG
Shenxua Baotou	China	"General Electric"	5 + 2	1750	2011	Coal	Methanol
Hexigten SNG	China	SEDIN	12 + 2	1670	2012	Coal	SNG
SARLUX IGCC	Italy	"General Electric"	3 + 0	1271	2000	OR	EE
ISAB Energy IGCC	Italy	"General Electric"	2 + 0	1203	1999	OR	EE
Sanwei Neimenggu	China	"General Electric"	4 + 2	1167	2011	Coal	Methanol
Edwardsport IGCC	United States	"General Electric"	2 + 0	1150	2012	Coal	EE

NG—natural gas; SNG—synthetic natural gas; LF—liquid fuel; OC—oil coke; OR—oil residues; EE—electric energy. * Plant is being constructed.

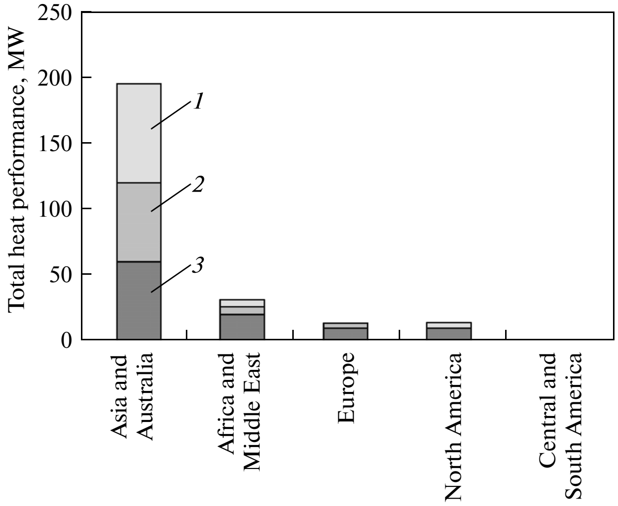

Fig. 2. Distribution of gasifiers along world regions. Designations as in Fig. 1.

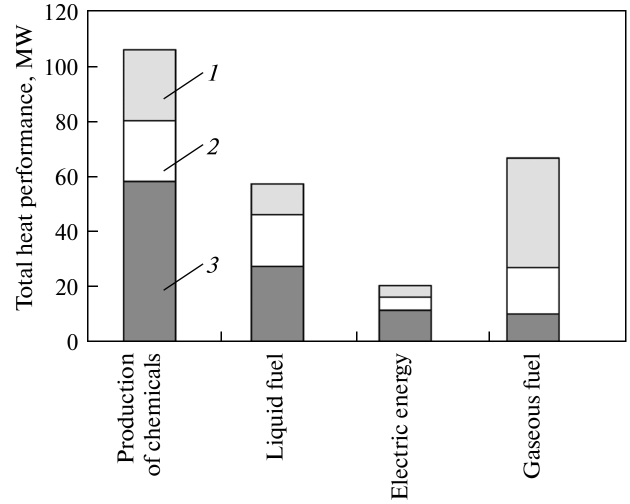

Fig. 3. Distribution of the total thermal performance of gasifiers based on the areas in which the obtained synthetic gas is used. Designations as in Fig. 1.

The total thermal energy of synthetic gas generated during the commissioning and testing on the TPP in 2012 amounted to 339000 GJ, 1170000 GJ in 2013, and 2717000 GJ after the commercial exploitation [2].

In Kemper County (Mississippi, United States), a CCP with TRIG[1] gasification was constructed. It uses two SGT6-5000F GTPs produced by the Siemens Company and a steam turbine produced by the Toshiba Company. The peak CCP power will be 582 MW and 524 MW when fueled by synthetic gas. Gasification of lignite obtained through open-pit mining with humidity over 40% is performed in two transport reactors. H_2S and CO_2 are removed using the Selexol technology with further processing into liquid sulfuric acid and 65% CO_2 removal.

The mean combustion value of lignite is 12.3 MJ/kg (variation range from 11.1 to 13.6 MJ/kg), moisture content 45.5% (variation range from 42 to 50%), and sulfur content 1.0% (variation range from 0.35 to 1.70%). The production of sulfuric acid will be approximately 135 000 t/year, 20000 t/year of ammonia, and the amount of CO_2 that will be used to maintain the formation pressure in oil production will be approximately 3 million t/year.

In October 2013, the power line of approximately 115 km was launched and electric energy was applied to the TPP site, natural gas (approximately 8 km) and CO_2 (approximately 95 km) pipeline construction was finished, pipeline to divert final effluents (approximately 50 km) was built, and open-pit coal mine (125 km^2) was laid out.

[1] TRIG is an integrated transport reactor.

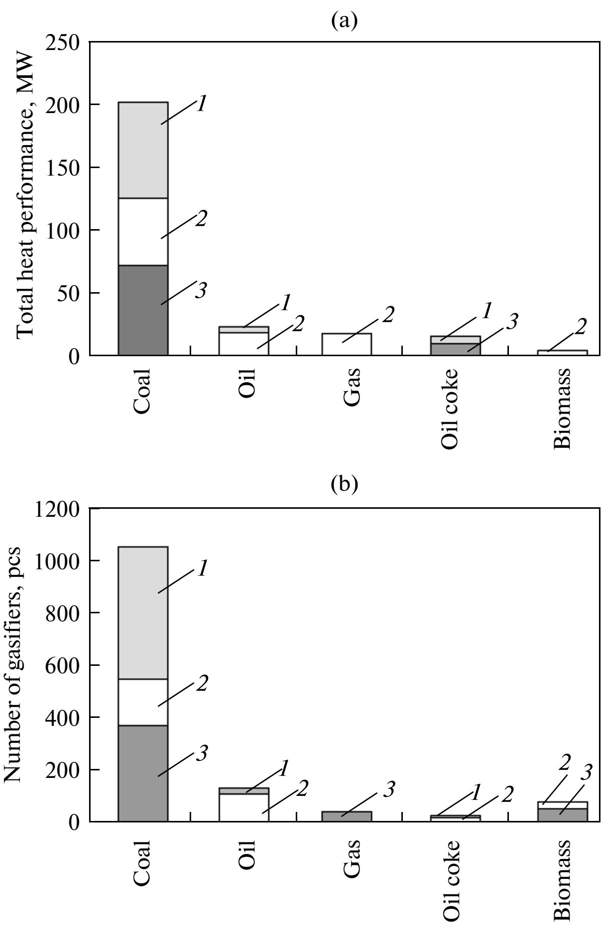

Fig. 4. Distribution of the (a) total heat performance and (b) number of gasifiers based on various types of the initial raw materials for production of synthetic gas. The notation is the same as in Fig. 1.

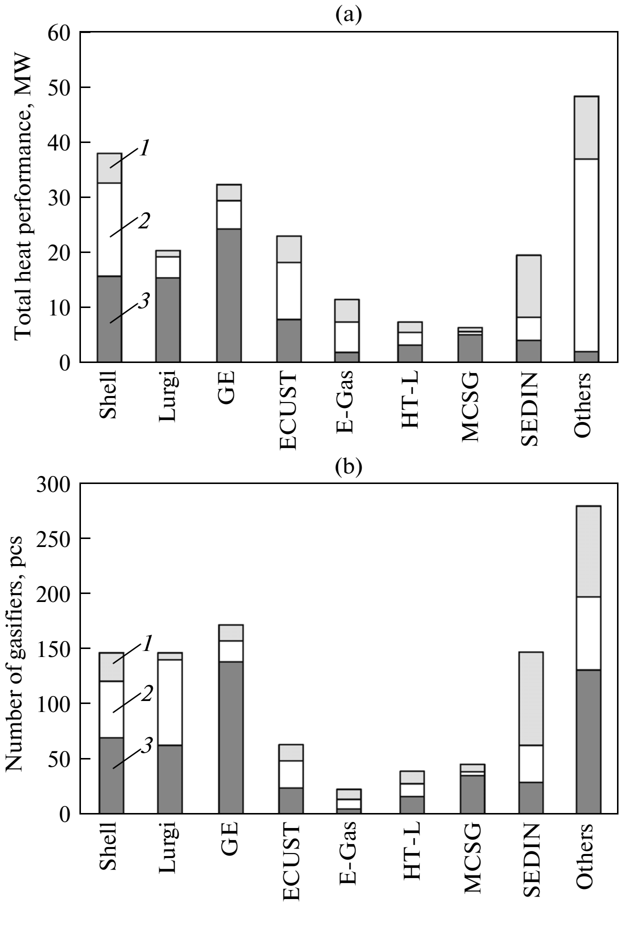

Fig. 5. Distribution of the (a) total heat performance and (b) number of gasifiers based on gasification technologies. The notation is the same as in Fig. 1.

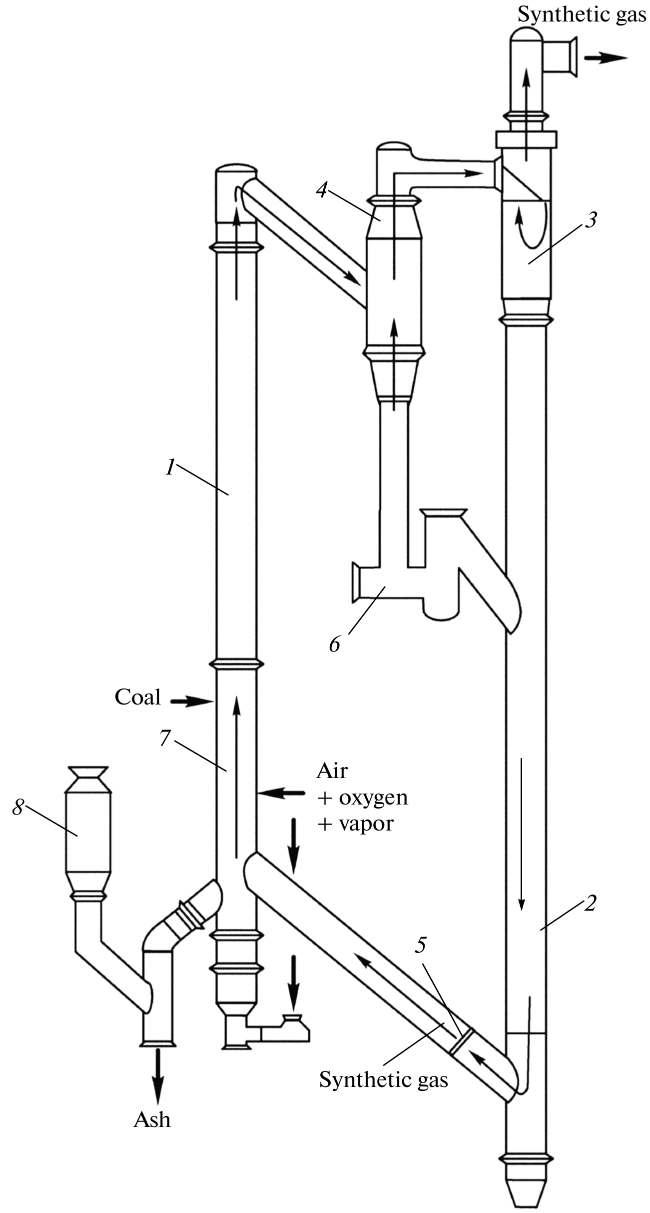

Fig. 6. Scheme of transport coal gasifier. *1*—Lifting pipe; *2*—riser; *3*—cyclone riser; *4*—the first cyclone stage; *5*—J-shaped wheel; *6*—ealing ring; *7*—mixing zone; *8*—start-up burner.

In late August 2013, the first warm starts of both TPPs were performed. By that moment, 74% of all work was completed.

The scheme of TRIG transport gasifier is shown in Fig. 6. It is simple and has been applied for a long time. When using this gasifier, it is possible to perform gasification of low-rank coals, which come into the reactor as dried dust. In order to generate synthetic gas for further combustion in the TPP, air blasting is used. Oxygen injection is applied to produce chemicals and liquid fuels. The reactor operates without ash melting, which is removed in the solid state without the formation of polluted effluents.

The performance of TRIG gasifier can be increased up to 5000 t of coal/day. The power of CCP, which was built as the two-boiler single-turbine unit with two such gasifiers, will be 800 MW with the efficiency of over 43% with a lower heat value of coal [3, 4].

In recent years, the following reliability rates of the Wabash River TPP fueled by oil coke were obtained during the operation of the CCP system with E-Gas gasification (262 MW) launched in 1995 (Table 2).

APPLICATION AND DEVELOPMENT OF COAL GASIFICATION SYSTEMS IN CHINA

Siemens has designed and manufactured dry coal dust gasification systems based on oxygen blowing (formerly GSP) with the performance of 500 t/day, where gasification occurs at temperatures of 1350–1750°C; 38 devices, mainly for chemical plants, were ordered. More than 30 such systems are being implemented or exploited in the chemical industry of China. They reached carbon degasification of 99%, $H_2 + CO$ of more than 91% in dry gas, CH_4 of less than 0.1% O_2 at the flow rate of less than 310 m^3 per 1000 m^3

Table 2. Reliability rates, %, of E-Gas gasification system*

Unit or system of gasification plant	2011	2012	August 2013
Synthetic gas cooler	99.9	98.1	100.0
Gasifier	94.3	99.4	98.8
Suspension preparation and supply	100.0	99.9	99.9
Particle removal	99.8	100.0	96.2
Slag removal and treatment	98.7	100.0	99.9
Hot-gas-path	99.2	100.0	100.0
Gasifier system in general	92.1	97.4	94.9
Coupled systems:			
sulfur recovery unit	98.2	99.7	100.0
low-temperature heat exchangers	97.5	99.8	99.3
sour gas removal unit	99.8	100.0	100.0
air separation unit	99.8	83.0	96.5

* Estimations of nonplanned standings based on their duration [5].

Table 3. Performance characteristics of ECUST gasifiers

Characteristic	Plant no.				
	1	2	3	4	5
Number of devices: operating + reserve	1 + 1	2 + 1	2 + 1	2 + 1	1 + 0
Performance, t/day	2000	1500	1200	1150	1150
Availability, %	97.0	97.2	88.4	94.7	86.1
Reliability, %	99.7	99.1	96.2	98.2	99.4
Running time, h	8520	8546	7764	8319	7561
Longest time of continuous operation, h	2040	5834	2568	2703	2120
Time of scheduled outages, h	240	164	720	312	1180
Time of unscheduled outages, h	24	74	300	153	43
Reasons for unscheduled outages (equipment with defects)	Network	ASU*	One outageæ network; two outages—ASU	ASU, network	Drains

* ASU—air separation unit.

(under normal conditions). The longest continuous operation was 90 days. Several projects of such systems are being developed for the United States and other countries [6].

China has developed and produced its own coal gasification systems and equipment for such systems. In the projects of the East China University of Science and Technology (ECUST) [7], coal-water suspension gasification (there are also projects with dry coal dust) is performed by oxygen injection in the vertical in-line unit with a downward motion of the medium.

China has executed 33 projects with 90 gasifiers having total performance of more than 110 000 t/coal per day. They are intended mainly for chemical plants. The highest performance of the device is 3000 t/day. A total of 12 companies with 29 gasifiers have been exploited. The gasifier with the capacity of 2200 t/day and working pressure of 4 MPa was launched in March 2013. It has been exploited with the nominal load of 95–100%; continuous campaigns is 80 days or more and carbon yield is higher than 98%.

The data on five installations that have been in operation during the entire 2012 are given in Table 3.

WAYS OF IMPROVING GASIFIERS AND THEIR SYSTEMS

During the Conference on Gasification Technologies, directions and results of some investigations performed by the National Energy Technology Laboratory (NETL) of the U.S. Department of Energy to enhance the efficiency of gasifiers, reduce capital and operating costs, reduce the cost of electricity, and provide efficiency of vehicles operating on different coals, including low-grade coals of the United States, were presented.

The investigations were also meant for development of reliable gasifier models and increasing their readiness by 10%. The directions are choice of refrac-

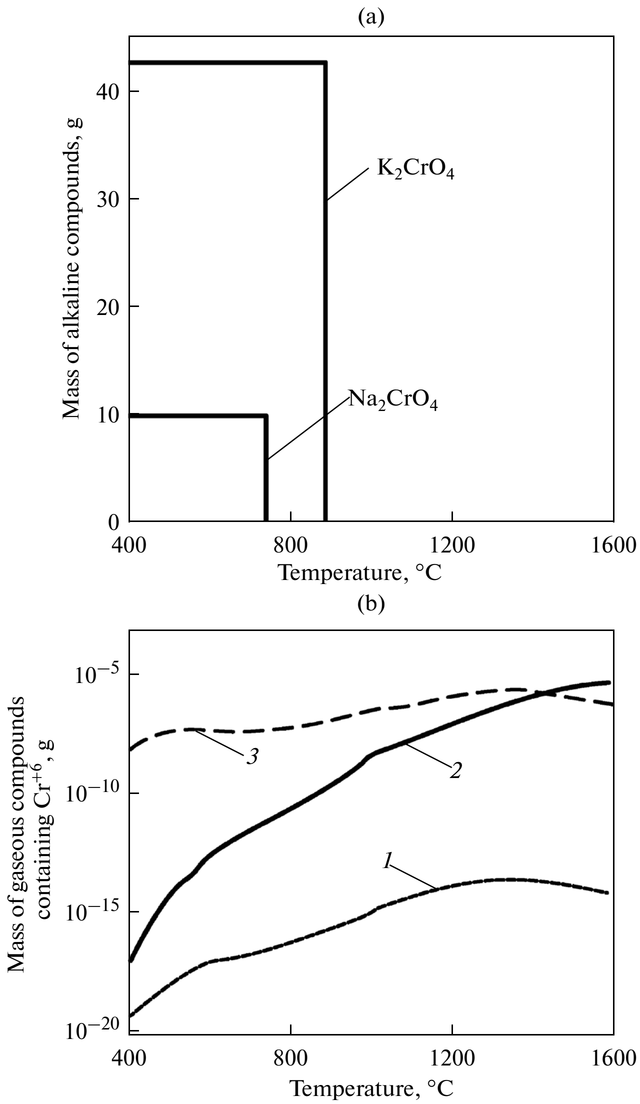

Fig. 7. Dependence of the (a) amount of alkaline and (b) gaseous compounds with Cr^{+6} on temperature. *1*—$CrO(OH)_4$; *2*—$CrO(OH)_2$; *3*—CrO_3.

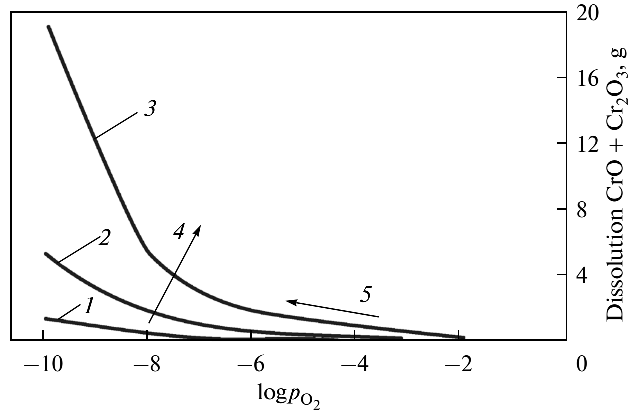

Fig. 8. Influence of partial pressure and temperature on dissolution of $CrO + Cr_2O_3$ out of the mixture of 90% Cr_2O_3 and 10% Al_2O_3. Temperature, °C: *1*—1400; *2*—1500; *3*—1600; *4*—temperature increase; *5*—decrease in the partial pressure of O_2.

tory materials for the manufacture of gasifier equipment, modeling of gasification processes, and reduction of harmful emissions [8].

Refractory materials are studied by three companies engaged in industrial gasification, seven research organizations, three commercial companies, and three government agencies from Europe, the United States, Canada, and Japan.

Studies on lining materials were carried out in order to improve the reliability, readiness, and maintainability of gasifiers, as well as to reduce their standing time. For this purpose, melted ash phases, slag viscosity at high temperatures and effects of additives on its properties, interaction between slag and lining, and wearing and damage of the material from which it is made were studied. Refractory materials with improved properties and sensors to monitor the temperature of gasification were developed. The processes described in the text below were studied.

Modeling of gasifiers was performed with physical identification of computational models based on the kinetic programs and experimental data obtained by the gasification of raw coal material and with the introduction of applicable scientific results. The result of such modeling will be a user-friendly interface between the kinetic characteristics and reacting multiphase CFD-models, by means of which it would be possible to perform calculations with high reliability and accuracy, as well as modeling properties of coals for selecting a suitable raw material for gasification.

The requirements for purification of crude synthetic gas, which are necessary to comply with the EPA's requirements on harmful emissions and efficiency of processes for its purification, were developed.

In industrial plants, NETL specialists and partners will study methods for removing lead, mercury, arsenic, selenium, and sulfur from hot synthetic gas with estimating the amount of removed materials and the cost of processes. In addition, alternative methods and materials for the selective capture of these substances will be explored.

Presently, the causes of damage to the lining are corrosion and delamination. The studied samples had internal cracks from lining formation, areas with overheating, cracking angles as a result of crimp stress, penetration of molten slag in cracks and pores from the inside, initial signs of surface corrosion under the effect of slag, horizontal cracks caused by thermal fatigue and creeping, crack binding, formation of internal voids starting from delamination, signs of creeping in areas of slag penetration and corrosion at the hot side, and detachment of the damaged layer from the hot side.

To improve the performance and reliability of the gasification process with liquid slag removal, a refractory material on the basis of Cr_2O_3 containing phosphates was developed by the specialists from the NETL laboratory. It has been assimilated and put into production under the name Aurex 95P. When tested in the industrial gasifier during 237 days, its layer thickness reduced by 1/3, whereas the same thickness of generally used lining decreased initially by 2/3. After three years of operation, the outer surface of the new lining was smooth in contrast to the traditional one, which suffered from numerous projections and depressions over the same period. Some characteristics of the refractory materials are shown in Figs. 7 and 8.

To investigate the effect of slag, a model was developed, which allowed:

(1) to reveal its characteristics (melting point, viscosity, phases (solid, liquid, and vapor);

(2) to predict and adjust them using additives linking the corresponding gas phases in slag;

(3) to organize interaction between lining and slags; and

(4) to influence viscosity and corrosion aggressiveness of slag by additives.

The calculations were performed with different types of fuel (coal of various quality, oil coke) biomass, their chemical composition, amount of ash, as well as conditions in the gasifier (temperature and gas composition). The model was created according to the thermodynamic laws, literature data, and results of the bench tests. The main purposes of this modeling were reduction of lining corrosion, ensuring of slag output of in the gasifier, and gas cooler pollution prevention.

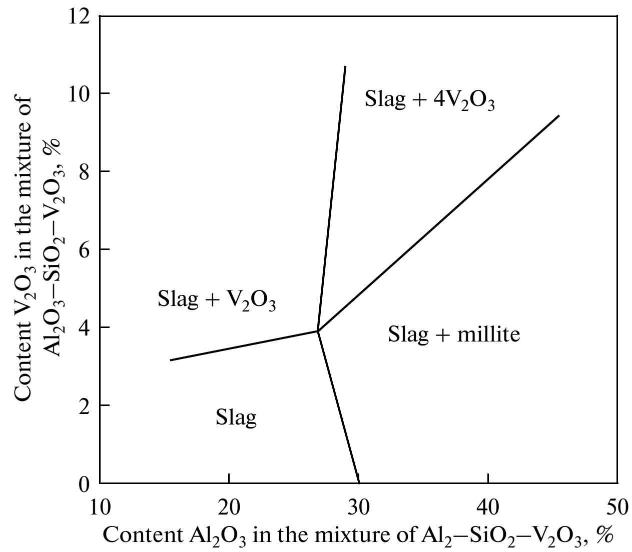

Fig. 9. Phase diagram of slag.

Figure 9 shows the phase diagram corresponding to 1500°C, oxygen partial pressure of 0.001 Pa, and CaO and FeO contents in the slag of 7 and 13.5% (by weight) [8].

The budget of the RTI International Research Association (Research Triangle Institute International), in which, as well as in the NETL, gasification processes and equipment for their implementation are investigated, is 730 million dollars. RTI employs 3800 special-

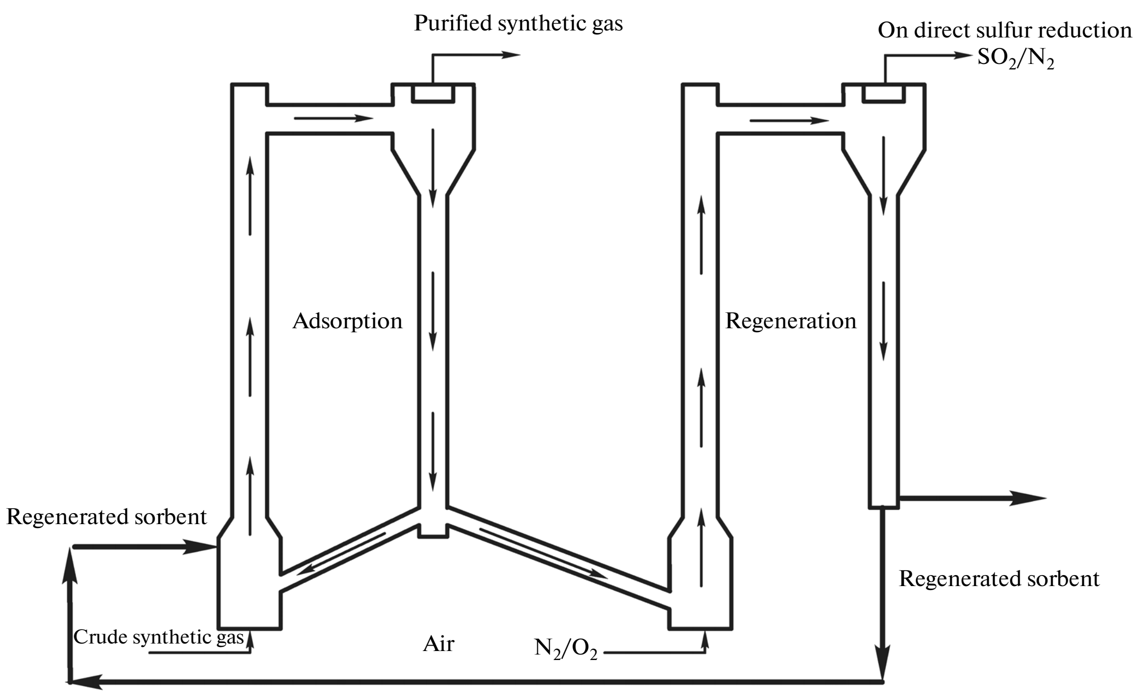

Fig. 10. Scheme of hot desulfurization in transport reactor.

Table 4. Comparison of technologies for synthetic gas purification

Technology characteristics	Purification technology		
	Rectisol	Selexol	RTI
During desulfurization			
Pressure effect	Yes	Yes	No
Need for COS hydrolysis	No	*	No
Process temperature, °C	From –60 to –40	0–40	More than 315
Final sulfur content, $million^{-1}$	Less than 0.1	1–20	Less than 0.1
During CO_2 removal			
Removal effectiveness, %	97–99	90–99	More than 97
Relative capital costs	1.0–1.2	1.0	0.8
Relative GTP efficiency	Less than 1.0	1.0	To 1.03

* Depending on the conditions of application.

ists, who work on more than 1800 projects. In the Energy Technologies Association, promising processes for further use in the energy sector, in particular for coal gasification, are being developed.

RTI specialists develop materials, model processes (discussed later), design, perform laboratory and bench research, and test processes in pilot plants and industrial sites [9].

At the moment, the following technologies are being developed:

(1) synthetic gas purification at high temperatures, which allows more than 20% reduction in capital investments and efficiency increase of CCPs with coal gasification by more than 3%;

(2) advanced methanation processes to reduce capital investments in the production of methane from coal by 45%;

(3) catalytic pyrolysis of the biomass for subsequent distillation and production of liquid fuels; and

(4) CO_2 capture with 40% decrease in energy consumption.

Small modular systems for production light oil fuels (aviation kerosine and diesel fuel) and advanced water treatment systems for the industry with a reduction of the water cost by 20–50% and energy consumption for its production by 90% are also being developed.

The technology of hot desulfurization of synthetic gas was proposed in 2001. The pilot plant based on this technology was tested for 3000 h at a chemical plant of the Eastman Company in 2006–2008, which provided 99.9% H_2S removal and COS removal to a residual sulfur of less than 5 $million^{-1}$ at 315°C and pressure above 4.2 MPa. Demonstration tests of the plant for hot desulfurization with the plant for CO2 emission located serially started in 2010 and were planned up to 2015 on the CCP with coal gasification installed on the Tampa TPP in Florida (United States). They are held at the plant for hot desulphurization with the electrical capacity of 50 MW supplied with approximately 20% of synthetic gas produced in the gasification system. Table 4 shows comparison of the technology for hot desulfurization with alternative systems for synthetic gas treatment.

Desulfurization is carried out in the same transport reactor as the commercial one, whose scheme is shown in Fig. 10. Sulfur is bound by the solid sorbent, i.e., by zinc oxide at above 315°C, which is regenerated with air at 650–760°C (Fig. 10, right side). The regeneration product is chemically absorbed by methyldiethanolamine.

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