ISSN 0040-6015, Thermal Engineering, 2021, Vol. 68, No. 3, pp. 209–220. © Pleiades Publishing, Inc., 2021.
Russian Text © The Author(s), 2021, published in Teploenergetika.

STEAM BOILERS, POWER-PLANT FUELS, BURNER UNITS, AND BOILER AUXILIARY EQUIPMENT

Coal Gasification: At the Crossroad. Technological Factors

S. P. Filippov[a, *] and A. V. Keiko[a]

[a]*Energy Research Institute, Russian Academy of Sciences, Moscow, 117186 Russia*

**e-mail: fil_sp@mail.ru*

Received June 16, 2020; revised July 13, 2020; accepted August 26, 2020

Abstract—The article presents results from analyzing the state of the art achieved in the coal gasification technologies developed around the world and the demand for them. It is shown that such technologies have presently arrived at a crossroad in their development. Their future will be determined by the development prospects of coal energy as a whole. Coal still continues to play the most important role in the world energy. In recent years, external factors have become extremely negative for the development of coal energy. Among other fuels, coal produces the largest specific emissions of CO_2 during its combustion, in view of which it may become the first victim of the unfolding energy decarbonization policy. Under such conditions, there is a need to diversify the coal utilization fields, primarily through manufacturing a wide range of chemical products with a high added value. This generates the need to develop the appropriate technologies, and, first of all, gasification technologies, the use of which opens the possibility of making almost the entire range of products from coal that are obtained from petroleum and natural gas. It has been determined that gasification technologies have already reached a high level of technical maturity, and a large number of gasifier designs have been proposed. It has been determined that the majority of operating coal gasification plants are presently used for manufacturing various chemical products, first of all, natural gas substitute (which is then forwarded to gas networks) and also methanol and ammonia. It is pointed out that only a few integrated gasification combined cycle plants have been implemented and planned for construction, which means that the private sector shows little interest in this technology. At the same time, such plants have quite a high potential for being used in low-carbon energy, of course, provided that the problem of disposing the captured CO_2 is solved. It is shown that a large number of gasifier equipment manufacturers are available around the world. However, gasifiers are produced in single units or in a small series, which unavoidably leads to the high cost of this equipment. For the further innovative development of the gasification technology, combined efforts should be taken by the private sector and the state.

Keywords: gasification, gasifier, integrated gasification combined cycle plant, synthesis gas, carbon dioxide, coal, thermochemical conversion efficiency, coal energy

DOI: 10.1134/S0040601521030046

The share of coal in the total consumption of primary energy around the world is presently larger than 27%. With respect to this indicator, coal is outgrossed only by petroleum (32%) but outrides natural gas (22%) [1]. It should be noted that the share of coal in the total consumption of primary energy around the world has not shown a decrease for the last half-century. In the early 1970s, it was equal to approximately 24%. Until recently, the production of coal increased steadily. For the last 50 years, it has increased by a factor of 2.5 and is now more than 7.5 billion t per annum, with China accounting for more than 46% (almost 3.6 billion t) of this amount. The structure of produced coals includes approximately 14% coking coals, 75% black coals, and 11% brown coals. A significant part of the produced coal (more than 17%) is delivered to the world coal market, the annual amount of which is now more than 1.3 billion t. A tendency toward decreasing the coal consumption in industrially developed countries and toward its growth in developing countries is observed [2]. This gives grounds to consider that coal is "a fuel for the poor," which, by the way, comprise two thirds of the global population.

Power plants are presently the largest consumers of coal around the world. They consume 68.9% of the produced coal, or approximately 5.2 billion t a year. The share of coal in the global generation of electricity is approximately 38% and has remained stable for the last 50 years. Approximately 1.43 billion t of coal per annum (18.9% of its total production) is forwarded as fuel to the sector of end users. Approximately 0.9 billion t (11.9%) of coal is used every year for coking purposes, and only 70 million t (0.3%) is subjected to other kinds of thermochemical processing, primarily, gasification.

It should be noted that coal remained the dominating kind of fuel for almost two centuries in the majority of industrially developed countries. In the 19th century, its share in the structure of organic fuels consumed around the world was more than 90% [3]. With the discovery of large hydrocarbon deposits and with a rapidly growing demand for petroleum products for internal combustion engines, by the mid 20th century, coal had been essentially driven back by petroleum and then also by natural gas. However, hydrocarbons were unable to fully push coal away from the global fuel and energy balance.

The popularity of coal is due to the following most important factors:

(1) Its resources are quite abundant.

(2) It is widely available over the globe.

(3) It is cheap.

(4) It is well amenable to transportation and convenient for storage.

(5) It has a fairly high heating value.

The share of coal in the structure of fossil organic fuel resources available in the world (including the potential-for-discovering deposits but without speculative resources of gas hydrates) is approximately 62%, and the coal reserves amount to more than 260 billion TJ [4]. Thus, the reserves of coal are sufficient for mankind for several centuries ahead. The cost of coal in the energy markets is approximately a factor of two cheaper than natural gas, which is coal's main competitor. In 2018, with the world average annual price for petroleum equal to $12/GJ ($68/bbl), the annual average price for power plant coal was equal to $1.8/GJ in the United States, $3.7/GJ in the European Union, and $4.4/GJ in Japan [2]. The annual average cost of natural gas in these countries in 2018 was equal to $3.0/GJ, $7.2/GJ, and $9.6/GJ, respectively. The black coal heating value (lower) is approximately 25 GJ/t, which is approximately a factor of 1.8 lower than the heating value of petroleum and natural gas. However, in contrast to petroleum and natural gas, a special and rather costly infrastructure is not required for coal transportation and storage. Black coal can be stored outdoors for a long period of time without essential loss of its quality.

At the same time, coal is inferior to natural gas and liquid hydrocarbons in consumer properties. Coal-fired power facilities are approximately a factor of 1.5 more costly than gas-fired ones and have lower efficiency (by a factor of 1.2–1.4 at boiler houses and by a factor of 1.3–1.5 at power plants). This difference is especially essential in small capacity facilities. In addition, coal has certain negative features owing to its component composition (the content of sulfur, nitrogen, transition metals, etc.), which has led to serious environmental problems in places of coal production and consumption. The negative features of coal manifested themselves to a full extent in the case of its large-scale use. First, this is pollution of the environment with the harmful substances generated during coal combustion in large amounts and in a wide range of them. Second, this is alienation of large areas for slag dumps and coal pits. Although these problems can be solved by applying certain process solutions, this will entail an essentially higher cost of energy generated from coal and, hence, make it less competitive.

In recent years, the external factors have become extremely negative for the development of the world coal energy [2]. Aggressive efforts are unfolding around the world for conservation of climate, and requirements are outspoken to reduce the atmospheric emissions of greenhouse gases, in particular, CO_2, which in fact are equivalent to the requirements to reduce the consumption of fossil organic fuels. Since it is particularly coal that produces the largest specific emissions, among fuels, during its combustion (approximately 96 kg CO_2/GJ vs. 73 kg CO_2/GJ for petroleum and 56 kg CO_2/GJ for natural gas [5]), coal energy can be expected to become the first victim of this policy. Attention should be paid to the fact that the fight for conservation of climate is combined with the continuing policy on environment conservation and sustainable development of the world's economy, which in itself exerted heavy pressure on coal energy.

It should be admitted that it is extremely difficult to adapt coal energy to the conducted "climatic policy" in view of the expensive technologies for capturing and subsequent disposal of CO_2. Under these conditions, the survivability of the coal industry will likely depend in many respects on how quickly efforts aimed at changing the role of coal in the economy by broadening its application fields will be met with success. Coal should be not only an energy source but also a raw material for manufacturing a wide range of chemical products with a high added value. Of course, coal might become a basis for the development of hydrogen energy if, first, it would be clear why hydrogen as an energy carrier is better for consumers than electricity and, second, large consumers of CO_2 were revealed or large capacity reservoirs were found for its reliable and cheap disposal for an extralong (several centuries) period of time. For solving all these problems, it will be necessary to develop appropriate technologies for deep coal processing. The previous experience gained from the development of such technologies will be of relevance in this respect.

DEMAND FOR COAL-GASIFICATION TECHNOLOGIES

The 1973 world oil crisis, which led to a four-fold growth in oil prices, and the fight for conserving the purity of the natural environment that began at that time resulted in that the problem of accelerated development of efficient technologies for converting coal into synthetic liquid and gaseous fuels became quite pressing [3]. Relevant programs were adopted in all leading countries around the world, and they enjoyed state and corporate financial support. Investigations were developed in all basic lines of thermochemical coal conversion, including the following:

(1) pyrolysis, i.e., thermal destruction of coal under the exclusion of air, which is usually performed at atmospheric pressure and temperature of 500–900°C;

(2) hydrogenation, i.e., thermochemical destruction of coal in hydrogen at high pressure (5–15 MPa) and moderate temperature (350–450°C), and

(3) gasification, i.e., thermochemical destruction of coal at high temperature (800–1200°C or higher) and moderate pressure (up to 4 MPa) with supplying a relatively small quantity of oxygen (pure or with the air), often with the addition of steam (and sometimes carbon dioxide). Steam is necessary to obtain a larger yield of hydrogen, and oxygen is necessary for supporting the endothermal reactions with energy.

Coke (semicoke in processing brown coals), tar, and a mixture of gases are the main pyrolysis products. The tar, which is obtained in relatively small quantities, can be processed into liquid fuel and various chemical compounds. The obtained gas has a quite high heating value and can be used as fuel. It should be noted that the replacement of expensive charcoal by cheap black coal coke led at one time to a revolution in metallurgy. Conversion of black coal tar into various chemical products became the basis of coal chemistry development.

Hydrogenation allows the coal organic mass to be converted almost completely into a mixture of liquid hydrocarbons consisting mainly of heavy fractions, which need additional processing to obtain liquid engine fuels. This technology involves certain problems, which stem from the need to maintain very high pressure and to supply a large quantity of hydrogen for the process. For producing hydrogen, the steam–oxygen coal gasification technology is being actively developed, as a result of which producer gas with a high content of CO and hydrogen is obtained, so-called synthesis gas. After purifying this gas with subsequently subjecting CO to steam conversion, sufficiently pure hydrogen is obtained. Synthesis gas itself can also serve as a raw material for producing synthetic liquid fuels. The relevant process was proposed in the early 1920s by F. Fischer and H. Tropsch and was called after them. Owing to mastering the coal hydrogenation and gasification technologies and the Fischer–Tropsch process, Germany succeeded in establishing the industry of producing engine fuels from coal before World War II. In the 1950s–1980s, synthetic liquid fuel from coal was produced on a commercial scale in the Republic of South Africa, the supplies of oil to which were embargoed by the UN decision for conducting the apartheid policy.

The coal pyrolysis and hydrogenation technologies have a fundamental drawback: their processes feature poor selectivity. The liquid products obtained from these processes are a mixture of many substances, mainly aromatic and heterocyclic ones. It is extremely difficult to control their composition and is only possible in its rather narrow range. In fact, the required products are separated from "what was obtained." Coal gasification taken in combination with Fischer–Tropsch synthesis is a very flexible and highly selective technology. By selecting the proper catalysts, this technology makes it possible to produce a wide range of chemical products, and primarily those "that are needed."

As a result of the revival of coal chemistry investigations in the 1970s–1990s, many new coal conversion technologies based on its pyrolysis, hydrogenation, and gasification processes were proposed. Many of them were tested on pilot facilities and prepared for commercial-grade implementation. However, the discoveries of large petroleum and gas deposits, conducting of energy saving policy, and development of nuclear energy along with the following broader use of renewable energy sources resulted in that the scarcity of high-grade liquid and gaseous fuels ceased to be a problem. The world prices for hydrocarbons became essentially more stable. As a result, both the private sector and governments lost interest in the development of deep coal processing technologies. At present, the need for these technologies has remained only in countries that have large coal deposits and small reserves of petroleum and gas, in particular, in China. The manufacture of products other than those for energy applications, e.g., nitrogenous fertilizers and methanol, has become the main field of using such technologies. Gasification is aimed at supporting these production processes with hydrogen obtained from coal processing.

In the early 1970s, gas turbine units (GTUs) and high-efficient combined cycle plants (CCPs) constructed on the basis of GTUs began to be put into use in the power industry on a mass scale. Liquid hydrocarbons and natural gas served as fuel for them. There also emerged an endeavor to introduce CCPs into coal energy. Prior to usage in CCPs, coal had to be gasified. The gasification products were supplied, after having been subjected to purification, to the GTU combustion chamber. The application of a low-temperature gas purification technology involved the need of cooling high-temperature producer gas, as a result of which large amounts of heat were generated. At the same time, steam had to be supplied to the gasifier. Therefore, proposals to integrate the coal gasification processes into the CCP cycle became quite logical. Many various CCP process arrangements with coal gasification integrated into the cycle were developed; they are known in the classification outside of Russia as an integrated gasification combined cycle (IGCC) [6, 7].

Russia is among the countries with the largest coal resources. According to the data of the World Energy Council (WEC), the coal resources in Russia are estimated at 4108 billion t (or 17.8% of the world's resources) [8]. Given the coal production amounts from 485 to 668 million t per annum, which are planned in the Energy Strategy of Russia by 2035 [9], the coal resources available in the country will be sufficient for a few thousand years. The specific feature of Russia's coal resources is that they have a large fraction of brown coals (33.6%), which are characterized by a high content of moisture, low heating value, and poor transportability and storageability. It is advisable to use such coals at their production place. Therefore, the development of coal technologies, including gasification, is of special interest for Russia.

In Russia, a large experience with development of gasifiers has been gained. In the 1950s, more than 350 gas producer plants were in operation in the Soviet Union, at which more than 2500 gasifiers of different designs were installed [3]. These were mainly small-capacity air-blown atmospheric-pressure gasifiers with a fixed coal bed. The annual production of gas in them reached 37 billion m^3 in 1958. After discovering large deposits of cheap natural gas in the country in the early 1960s, production of gas from coal turned out to be economically unprofitable and began to decrease rapidly. In 1978, only 1.5 billion m^3 of gas was produced from coal. This was mainly gas obtained using the underground coal gasification method.

In the post-Soviet time, investigations into the coal gasification field in Russia began to fade gradually. They were continued with progressively decreasing intensity on the experimental facilities at the All-Russia Thermal Engineering Institute (Moscow) (lumped coal gasification in the bed—the so-called "hearth method"), at the Central Boiler and Turbine Institute (St. Petersburg) (powdered coal gasification in oxidizer flow), and at Kompomash (Moscow) (coal-water slurry direct flow vortex gasification). Investigations were also carried out on small experimental facilities in some other organizations, in particular, at the Kutateladze Institute of Thermophysics, Siberian Branch (Russian Academy of Sciences, Novosibirsk) (plasma assisted gasification), and at the Ural Federal University (Yekaterinburg) (powdered coal gasification in oxidizer flow).

At present, the technologies for thermochemical coal destruction, including those for its gasification are carried out in Russia mainly by enthusiasts, without any significant support from the state and private sector. Many scientific teams broke up; the laboratory facilities were dismantled or reoriented at solving new problems. Many technologies seem to have become lost irretrievably. Under the present-day conditions, scientific and technological competence in the field of coal processing and coal chemistry in Russia can only be preserved and developed under support by the state. Otherwise, they can be lost very quickly, and, if a need arises to revive them, it will be extremely difficult to do so within foreseeable timeframes and at acceptable costs.

The more so, it cannot be excluded that the current climate protection campaign, with its stringent requirements for reducing CO_2 emissions, will not be a long-term one. The point is that there is still no unequivocal scientific explanation to the observed phenomenon of increasing atmosphere temperature in the planet. Nor is there a consensus among specialists whether or not to place the responsibility for its growth on the anthropogenic activity. Therefore, if the temperature of the Earth atmosphere becomes stabilized or if the tendency of its change turns to the opposite, coal energy will be exonerated.

Thus, the development of coal utilization technologies, including gasification technologies, is at a crossroad. Their future will be determined by the coal energy development prospects as a whole. The question that was raised 10 years ago in [10]: "Coal gasification: quo vadis?" is becoming still more topical. Therefore, the problem of improving its technologies to enhance the energy and economic efficiency remains important.

DEVELOPMENT OF GASIFICATION TECHNOLOGY

The coal gasification technologies proposed in different countries feature a great variety. The following gasification technologies are developed most actively:

(1) in a fixed coal bed with updraft or downdraft blow,

(2) in a fluidized bed of inert filler with or without circulation, and

(3) in an entrained flow with dry or liquid slag removal.

Some other technologies, e.g., in a plasma flow or in a slag or metal melt, are being developed. The characteristics of the obtained producer gas (its component composition and heating value) are mainly determined by the process arrangement, kind of initial fuel, gasifying agent (blow) composition, and gasifier temperature and pressure. Any kinds of solid or liquid fuel can be subjected to gasification: coal, biomass, oil shales, fuel oil, and also combustible waste (industrial and municipal). Air, oxygen, and steam taken in certain combinations are commonly used as blow (an also carbon dioxide, but in essentially more rare cases).

The choice of blowing type and gasification process depends on the purpose of gas to be obtained. Steam-oxygen blowing is used for producing gas with a high content of hydrogen and carbon monoxide. The obtained synthesis gas is widely used for its further processing: it serves as raw material for synthesizing various chemical products. Owing to the use of steam–air (air) blowing, it becomes possible to do without an expensive air separation unit and obtain cheaper gas (although having a lower calorific value). Such gas can be used in the industry and for energy generation purposes.

The development and application of coal gasifiers have a very wide geography. Therefore, even such authoritative source as the World Gasification Database [11] and known comprehensive reviews, e.g., [12]

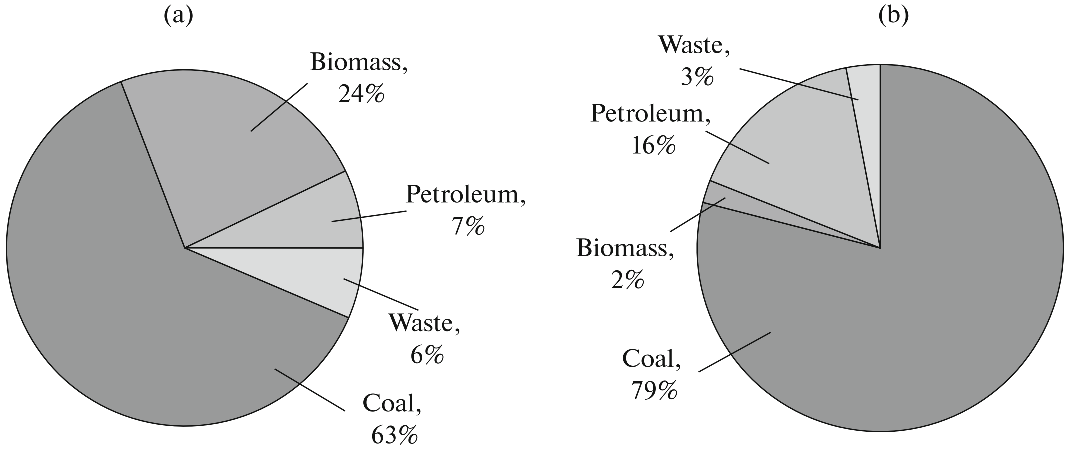

Fig. 1. Distribution of gasification units by solid fuel kinds (a) by the number of projects and (b) by installed capacity (with reference to the gasified fuel energy).

do not fully reflect the modern scales on which solid fuel gasification technologies are applied around the world. To the best of our knowledge, there have been approximately 900 gasification facilities included in the implemented, planned, and nonimplemented projects for the last quarter of a century. These facilities do not cover numerous small capacity gasifiers used in some Asian countries. Some of the facilities that were constructed have already been decommissioned.

Figure 1 shows the distribution of solid fuel gasification facilities by the types of initial fuel. It can be noted that the majority of solid fuel gasifiers around the world operate on coal. Their fraction makes approximately 63% in the total quantity of the available gasifier plants, and the energy produced by them makes 79% of the total energy of gasified fuel. The "waste" category is predominantly represented by fluidized bed gasification of fuel pellets made from waste, i.e., refuse derived fuel (RDF). This category does not include installations for staged incineration of solid municipal waste, which also use the pyrolysis and gasification processes as the first stage of their processing; their review is presented in [13]. The "petroleum" category includes petroleum coke, asphalt, and oil sands. Biomass occupies a significant portion in the total number of implemented projects (approximately 24%). However, in view of essentially smaller unit capacities of biomass firing facilities, its role in terms of energy units looks noticeably more moderate (only 2%).

As regards the application fields of coal gasification facilities, a judgement about them can be made from the data given in Fig. 2. It presents the gasification facilities that are presently available around the world (both operating and nonoperating) and those planned for implementation, the total number of which is 432 units. In analyzing information about the purpose of coal gasifiers, attention should be paid to the ratio of the number of planned (including those that are under construction), implemented, and terminated projects. The latter include nonimplemented (canceled), repurposed projects, and projects that stopped their operation before the end of their design service life. Quite a high percentage of planned projects testifies that the private sector had interest in this field until recently.

At present, the majority (more than 200) of operating coal gasification facilities are used for producing substitute natural gas (SNG), which is then supplied to gas networks, and it should be noted that more than 80% of such facilities are in China. The progress in synthesis gas methanation field[1] (the Sabatier reaction) has resulted in an essential growth of the total installed capacity of coal gasifiers around the world [14]. Coal gasification for producing SNG has become one of leading tendencies in the last decade in the field considered. It should be noted that the data in Fig. 2 do not take into account the Chinese coal-coking enterprises. At the same time, the methanation technology has recently been mastered on a mass scale in China, and more than 100 enterprises already deliver SNG to gas supply networks.

Obtaining of liquid chemical products, including ethanol, acetic acid, dimethyl ether, etc., remains the traditional synthesis gas application method. There is a growing interest in using the Fischer–Tropsch synthesis and obtaining olefins from coal. As of February 2020, nine projects of this sort involving gasifiers with a unit feed-in capacity ranging from 1500 to 3000 t/day and an enterprise total output from 10000 to 25000 t of

[1] From the technological point of view, methanation is quite a simple thermocatalytic process, which is inverse to the methane steam conversion process that goes on the same catalysts as methane gasification. The difference is that the Sabatier reaction requires comparatively moderate temperatures (250–450°C) and high pressure for running it, whereas steam conversion goes under the opposite conditions.

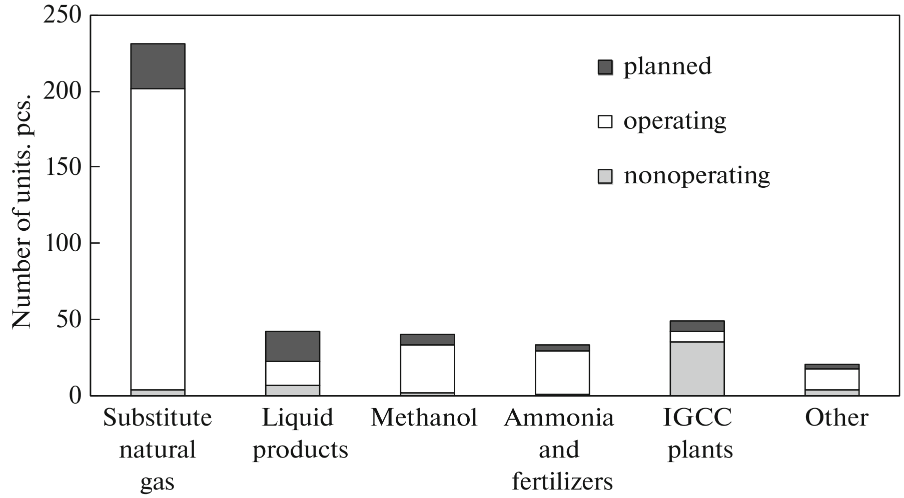

Fig. 2. Distribution of coal gasification units in application fields, pcs.

synthesis gas a day are at different planning and construction stages. At the same time, efforts for making Fischer–Tropsch installations essentially more compact are also observed. Their unit capacity indicated in the recently announced projects has decreased to 1–3 t/day in liquid fuel. The obtaining of chemical products and the Fischer–Tropsch synthesis are united in Fig. 2 into the "liquid products" category. Combining of the gasification and synthesis technologies opens the possibility to get from coal almost the entire range of products obtained from petroleum and natural gas with the use of petroleum- and gas-chemical technologies.

Methanol and ammonia, the markets of which are huge in volume, are produced in very large amounts from the synthesis gas obtained from coal. Methanol has a very wide range of industrial applications. The most noticeable part of it serves as raw material for producing methyl tert-butyl ether, an additive for high-octane gasolines. A significant part of methanol is used for obtaining olefins, which are subsequently converted into a wide range of highly demanded chemical products, which can make coal chemistry enterprises essentially more economically efficient. Ammonia is mainly converted into nitrogen fertilizers, the demand for which is traditionally high and shows a constant growth.

It can be seen in Fig. 2 that the use of IGCC plants looks rather weak against the background of successes achieved in the other coal gasification applications. During the last two decades, the number of implemented IGCC projects (outside of China) was as few as ten. By 2019, only seven of them had remained in operation. There are also only seven coal-based IGCC plants that are planned to be constructed around the world. It should be noted that the canceled projects are concentrated in the United States, Canada, and the United Kingdom, whereas the planned projects are in the countries of the Asia Pacific region. The few number of IGCC projects that are planned for implementation testifies that the private sector shows low interest in this technology.

The "Other" category, which is few in number (see Fig. 2), includes a few single projects aimed at obtaining heat, process steam, and hydrogen. This last circumstance should deserve special attention. It shows that, till recently, coal was not seen by the private sector as a large source of hydrogen intended for setting up hydrogen energy.

Figure 3 shows the distribution of gasifiers operating around the world by the process type and kind of design, which are associated with the developer companies. In the overwhelming majority (86%) of coal gasifiers, the entrained-flow gasification process is realized. The major part of entrained-flow gasifiers use oxygen conversion of coal-water slurry, and their minor part use steam-oxygen conversion of powdered coal.

The choice of the gasification technology (the gasification method and gasifier design) is governed, first, by the properties of the applied fuel (primarily of its mineral part) and, second, by the purpose of the gas produced.

For gasification in a fixed bed, lump coal (usually fractions no less than 10 mm in size) or coal briquettes are required. The obtained gas is enriched with methane, which makes it less suitable for synthesizing methanol or other liquid products. On the other hand, such gas has a higher heating value, which is favorable for using it in combined cycle plants. This gas also contains coal tar, which adds difficulty to and cost of its purification. The specific features of a fixed bed gasifier design ensure its high energy efficiency owing to heat recovery inside of the reactor and reduce the technology demand for oxygen, thus improving its economic indicators. However, the fact that the fuel

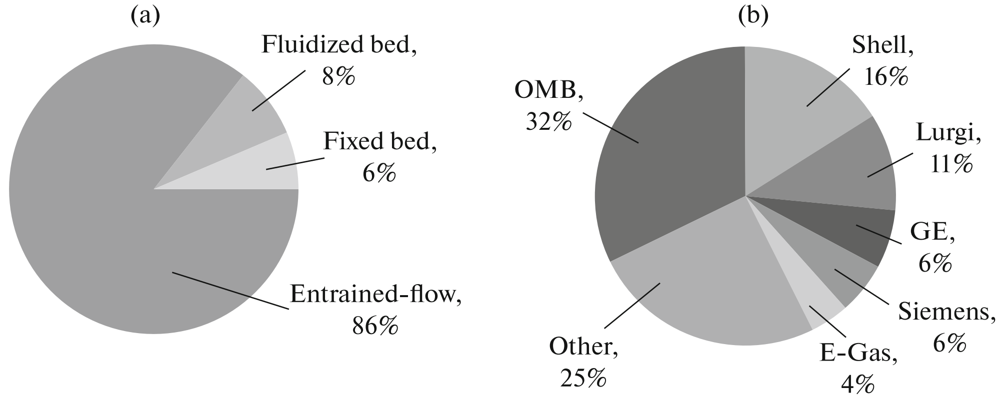

Fig. 3. Distribution of the number of coal gasifiers (a) by the process types and (b) by design types.

dwells in such reactors for a long period of time has an adverse effect on their throughput capacity and, hence, on their economic indicators. Fixed bed gasifiers are used for gasifying high-ash and low-grade coals and also various solid waste [15].

Fluidized bed gasifiers use fine-grained coal, usually with fractions not smaller than 1 mm and not larger than 10 mm in size. Fine dust is carried over from the reactor, and large pieces deposit on the bottom, thereby clogging the air distribution grate. Fluidized bed gasification carried out at a temperature of 800–950°C entails active slagging processes; therefore, highly reactive coals, in particular, brown and young black coals, are more suitable for such gasification. Reactors of this type have not received wide commercial use in view of the complexity of controlling the gasification process; relatively low coal conversion ratio; low calorific value of the obtained gas, which is often ballasted by fluidizing agent; and low throughput of the reactors caused by limitations on the blowing rate and on the draft distribution grate area.

For entrained-flow gasification, powdered coal is used, as a rule, with fractions not larger than 0.25 mm. The grinding of coal to particles of such sizes involves rather large energy expenditures. Entrained-flow gasification is usually carried out at a high temperature and requires large consumption of expensive oxygen. This process is often carried out at increased pressure. High temperature of the process, taken in combination with using powdered coal, predetermines the most important advantages of entrained-flow gasifiers. First of all, they have a high throughput, which is a consequence of a large reacting surface of fine coal particles and high rates of the chemical reactions. The coal particle dwelling time in the gasifier is a few seconds. The obtained gas does not contain tarry substances, which helps simplify its purification and reduce its cost. Owing to a high content of hydrogen and CO in the obtained gas, it is attractive for use to synthesize various chemical substances. To simplify the feeding of coal into the reactor, which operates at high pressure, coal-water slurry is used. This also helps enrich the gas with hydrogen. Entrained-flow gasifiers are characterized by a high coal conversion ratio. Liquid slag removal can quite easily be arranged in them. However, in view of increased energy loss with liquid slag, it is not advisable to process high-ash coals in such reactors. There are also limitations on using high-fusion-ash coals.

There were four leaders among the producers and developers of gasifiers 10 years ago:

(1) Shell (since 2019, Air Products) (high-temperature steam-oxygen entrained-flow powdered coal gasification with liquid slag removal);

(2) Texaco (since 2004, GE) (oxygen moving-flow coal-water slurry gasification);

(3) Lurgi (including its affiliates BGL, SASOL, ZVU and their replicas and modifications) (fluidized-bed air blown or steam-oxygen blown gasification); and

(4) ConocoPhillips (presently E-Gas) (two-stage oxygen blown coal-water slurry gasification with liquid slag removal).

At present, there are three leaders with the first place occupied by the Chinese OMB gasifiers designed at the Eastern China University of Science and Technologies (ECUST), the share of which is equal to 32% (see Fig. 3). They are followed with a large gap by the gasifiers of Shell (16%) and Lurgi (11%). The OMB gasifiers are hitherto only entering the world market; therefore, outside of China, the installations produced by GE, Siemens, and E-Gas still preserve their positions, although their market niche has shifted from the United States and European countries to China, India, and South Korea. Some companies offer commercial gasifiers that essentially copy Siemens' technology. Among them, the gasifiers Choren Coal Gasification produced by German company Choren, HT-L produced by Chinese company Hangtian, and Shenhua Gasifier produced by Chinese company Shenhua Ningxia Coal Group [15] are worthy of noting. Fixed/moving bed Lurgi-type gasifiers demonstrate unfailing stability in the market.

It should be pointed out that, among the gasification projects being implemented by Shell and GE, coal plays a progressively decreasing role, giving way to heavy oil refinery residues. In parallel with this, there is a growing need of petroleum refinery enterprises for hydrogen, which is obtained by subjecting petroleum residues to thermal conversion.

The developments of modern air-blown gasifies are very few in number. In this regard, the gasifier produced by Mitsubishi Heavy Industries (Japan) can be mentioned. This gasifier is intended for use in IGCC. Three projects of this sort have been implemented. The achieved power plant efficiency is 42%. With the air separation unit excluded from the gasification compartment process flow diagram, the capital outlays for the plant can be reduced by up to 25%.

According to the data of [10], the total capacity of coal gasification plants in synthesis gas around the world was 17.7 GW 10 years ago, of which 15.3 GW (more than 86%) were in China. Since that time, the growth in the capacity of gasifier plants was mainly due to those in the Asia region. In China, coal gasification is seen as the coal industry growth driver. The Chinese government has plans to bring the coal gasification amounts up to 1 billion t a year (30% of its production) [16]. Large-capacity gasifiers, which have the best technical and economic indicators, should become the technological basis for implementing these plans. Statistical information on the use of large-capacity coal gasifiers of different types in China is available [17]. Lurgi systems, up to 200 of which are in operation [18], remain the most widely used among fixed/moving bed gasifiers. Among entrained-flow gasifiers, ECUST plants in the OMB version dominate in China. There are a few alternative designs, in which coal-water slurry is also used, e.g., Jinhua [19]. The designs of the OMB and Jinhua gasifiers have much in common with the GSP gasifier, the principles of which were developed in Germany as far back as the 1930s.

The total number of large coal gasification plants in China with a unit capacity of above 700 t/day reaches 670 units, and their total installed capacity is larger than 350 million t/year. Of them, the GE gasifiers account for approximately 23%; Lurgi fixed/moving bed gasifiers for 19%, GSP for 7%, and Shell for 4%. The remaining approximately 47% are the gasifiers of Chinese designs, 34% of which are coal-water slurry gasification plants, with the OMB design being the absolute leader (15%).

In the overwhelming majority of cases, coal gasification is used in China for obtaining chemical products and synthetic fuel. In particular, Chinese company Shenhua Ningxia Coal Group operates five Siemens gasifiers each having a capacity of 2000 t of coal a day for reprocessing coal into polypropylene and 24 other similar gasifiers for reprocessing coal into synthetic liquid fuel [15]. A few new, large-capacity gasifiers are at the design and construction stage. Only five large gasifiers in China generate electricity as their main purpose, which account for less than 1% of the country's fleet of gasifiers.

A conclusion can be drawn from what was said above that the gasification technologies have already reached a high level of maturity. Many designs of gasifiers have been proposed, using which it is possible to perform efficient thermochemical conversion of coals with different properties to produce gas for various purposes. The gasification technologies have already been widely put into use in industrial production processes. Deep reprocessing of coal into various chemical products and synthetic methane, a natural gas substitute suitable for feeding it to the conventional gas supply network, has become their main application field.

DEVELOPMENT OF INTEGRATED GASIFICATION COMBINED CYCLE PLANTS

For the last 40 years, IGCC plants have passed all stages of the innovation cycle: the period of 1980–1990 saw their development stage, which was aimed at proving the technical effectiveness of the technology; the period of 1990–2000 saw their demonstration stage, which confirmed the possibility of their commercial use, and the period of 2000–2010 saw their deployment stage, during which experience with them was accumulated, and their specific cost was reduced. Finally, in 2010–2020, their technology should enter the stage of widely putting them into practical use, but this has not yet happened. Of the fifteen projects of coal-fired IGCC plants that were supposed to be commissioned in the 2010s, only five of them have been implemented. One of them operates unprofitably; the commissioning dates of three other projects were shifted, and another six projects were wound down or reoriented for natural gas already before commencing their operation or even construction. The commissioned plants are located in Japan, Korea, China, and India, and the terminated projects are in the United Kingdom, the United States, and Canada. Eight more projects were closed before the beginning of construction during the economic crisis of 2008–2009: seven in the United States and one in the United Kingdom. From the technical point of view, the implemented projects of coal-fired IGCC plants were quite satisfactory. However, the economic efficiency of these plants did not allow them to compete with the conventional coal- and gas-fired power plants.

In due time, the development of IGCC plants was motivated, first, by the endeavor to improve the coal utilization energy efficiency and, second, by the desire to bring the environmental indicators of coal-fired power plants in line with the relevant standards at lower costs. The efficiency of the developed IGCC plants was expected to reach 45–46%. At that time, the efficiency of coal-fired steam turbine units (STUs)

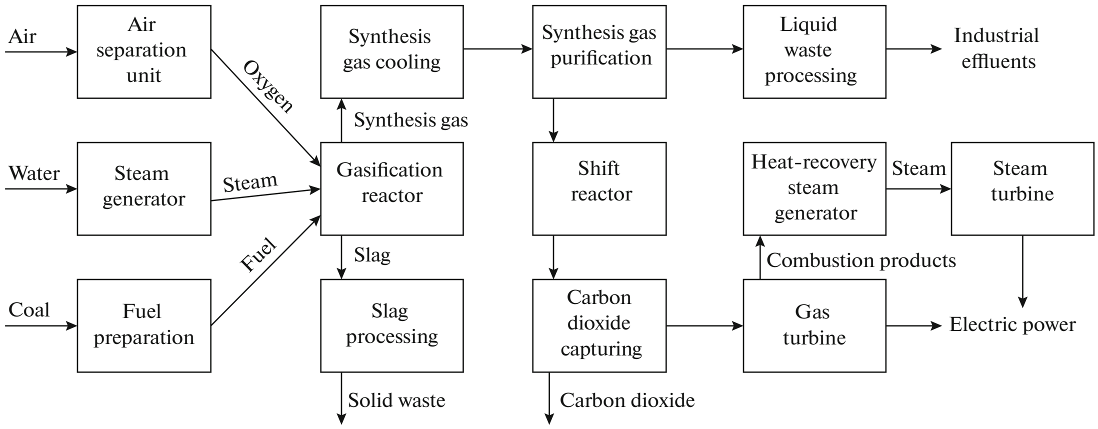

Fig. 4. Basic process flow diagram of an IGCC plant with CO_2 capture.

was not higher than 37–38% [3]. The world's leading manufacturers of gas turbine equipment developed turbines optimized for firing synthesis gas and hydrogen [20, 21].

However, the technical progress in electricity generation and accessibility of natural gas were factors that drastically changed the conditions for applying IGCC plants. Owing to increasing the parameters and optimizing the design of main equipment components, the efficiency of gas-fired CCPs was increased to 60% and higher, and that of coal-fired STUs to 43% and in individual cases even to 46%. Methods for purifying flue gases from coal-fired power plants with acceptable power performance and economic indicators have been mastered on a commercial scale. At the same time, the efficiency of IGCC plants that has presently been achieved does not exceed 43%. The fact that the construction of power-generating equipment for ultrahigh steam parameters (with a pressure of higher than 30 MPa and temperature of 650–700°C or higher) has been mastered allows a conclusion to be drawn that the efficiency of coal-fired power plants may exceed 50%. Achieving the IGCC plant efficiency higher than 45% is a hard-to-solve problem.

The specific feature of an IGCC plant is that its process flow diagram is essentially more complex in comparison with a coal-fired STU and a gas-fired CCP. It should also be noted that its significant part operates at high pressure (2–4 MPa). This entails an increase in the material intensity and specific cost of the plant, higher consumption of electricity for plant auxiliaries, less reliable operation of the equipment, and degradation of its maneuverability. Efficient operation of IGCC plants is only possible in the electric load schedule base part.

So-called "islands" can be identified in the IGCC plant process flow diagram:

(1) a "process" island, which includes a fuel preparation system, a gasifier, producer gas cooling and purification systems, liquid effluents purification system, and purifying agents regeneration system, and;

(2) a "power" island, the main components of which are a gas turbine unit, steam turbine plant, and heat-recovery steam generator.

To comply with the CO_2 capturing requirements posed to an IGCC plant, it becomes necessary to use oxygen or steam-oxygen blowing. This makes it possible to obtain producer gas without ballast nitrogen, the presence of which results in an increased volume of gases to be purified and increased purification cost. In that case, an air separation unit, a "shift" reactor, and a system for extracting CO_2 from the producer gas are added into the IGCC plant process flow diagram (Fig. 4). Expensive, high-capacity cryogenic installations are as a rule used for producing oxygen.

The "shift" reactor serves for catalytic conversion of the carbon monoxide contained on the producer gas into CO_2 and additional hydrogen, which is used in the GTU as fuel. This opens the possibilities for almost complete extraction of CO_2 from the IGCC plant's gaseous waste, which is not attainable for a coal-fired STU with acceptable expenditures.

To realize the shift reaction $CO + H_2O = CO_2 + H_2$, steam is additionally supplied to producer gas. To extract CO_2 from the producer gas composition, a few commercially mastered methods have been proposed, which are mainly based on chemical absorption in a wet scrubber. The use of a wet scrubber entails a decrease in the power plant thermal efficiency and generates the need for new CO_2 extraction and binding methods. The gas purification ratio from CO_2 in the projects of IGCC plants is, with taking the economic considerations into account, usually 90–95%. Within the economy decarbonization concept, this ratio should be further increased, which will entail essentially larger energy consumption and higher purification cost.

If stringent limitations are put into force on the CO_2 emissions, it is particularly this process flow diagram of an IGCC plant ensuring CO_2 capturing that may become needed, naturally, provided that the problem of disposing the captured CO_2 is solved. Extraction of CO_2 from producer gas is essentially more profitable than from flue gases of a coal-fired STU. This is because the producer gas is smaller in volume and has a higher content of CO_2.

The gasifier is the "process island" key component that determines the efficiency of the entire IGCC plant. Its performance efficiency can be characterized by different parameters, such as the carbon conversion ratio, specific yield of synthesis gas per kilogram of gasified fuel, and the H_2/CO ratio in synthesis gas. The coal thermochemical conversion efficiency (the gasification efficiency), which is equal to the ratio of total chemical energy of gaseous products obtained from gasifying 1 kg of coal to its heating value, can serve as the integral indicator. For the most widely used gasifier designs, this ratio varies from 70 to 85%. The lower value is typical for entrained-flow gasifiers, and the higher value is typical for fixed/moving bed gasifiers. As a rule, the higher the gasification temperature and the lower the producer gas heat recovery degree, the lower the fuel thermochemical conversion efficiency.

The need of carefully purifying producer gas prior to supplying it to the GTU combustion chamber is stemming from the following three main factors:

(1) Acid gas impurities are highly corrosive.

(2) Suspended particles have a destructive abrasive effect on the gas turbine components.

(3) Microdispersed carbon contained in producer gas has a poisoning effect on the shift reaction catalysts.

The commercially mastered purification processes take place at temperatures of approximately 400°C; this generates the need to cool producer gas, which has a negative effect on the plant's efficiency. In this connection, developments of new hot gas purification technologies are of importance.

The experience gained from the operation of IGCC plants has shown that degraded plant operation reliability is a consequence of complicating its process flow diagram. The availability factor of IGCC plants varies from 62 to 90% [22, 23]. Its high values (80–90%) are reached at IGCC plants operating on petroleum coke. For IGCC plants operating on coal, this indicator is usually in the range 77–82%. For comparison, the availability factor of modern coal-fired steam turbine power plants is 90–92%, and that of plants operating on natural gas is 94–96%. The best availability factor of the IGCC plant operating on coal equal to 85% was reached in Korea at the Taean power plant commissioned in 2016.

Approximately 70% of failures that occur during operation of IGCC plants are connected with malfunctions of the air separation unit, which are usually caused by failures of the main compressor. The gasifier itself accounts for approximately 14% failures in the operation of IGCC plants, and half of these failures are due to the planned gasification reactor shutdown for replacing the fuel feeders. Outages are also caused by slagging of the gasifier equipment, malfunctions in the fuel transportation system, and instability of the gasification and lighting up processes. In China, where gasification plants have noticeably lower availability indicators in comparison with those in the United States, the problem is solved by using a standby reactor (and sometimes even two). With the plant average availability factor equal to 77%, the use of one and two standby gasifiers increases the system availability factor up to 94.7 and 98.6%, respectively.

It is possible to do without using air separation, producer gas purification, and "shift" reactor, thereby reducing the cost, if the GTU is shifted to operate in a closed cycle. In this case, however, bulky heat exchangers will have to be included in the system, and CO_2 will have to be captured only after the fuel combustion. As a result, the cost of the CO_2 capturing operation will become approximately 2.5 times higher. The electrical efficiency of such process flow diagram will not be high in view of low GTU cycle parameters. The overall economic effect from implementing such arrangement will be negative. The closed cycle has therefore been recognized to be a dead end branch in the IGCC's evolution.

A so-called Allam cycle can be considered as a radical solution using which almost 100% of the generated CO_2 can be captured [24]. The use of steam-oxygen coal gasification and subsequent oxygen-enriched combustion of purified synthesis gas in the GTU combustion chamber results in that the gas after the GTU consists of CO_2 and steam with insignificant admixtures of other gases, mainly nitrogen. After moisture condensation, such gas becomes almost pure CO_2. By setting CO_2 to recirculate through the gasifier, it becomes possible to decrease the temperature in the gasifier and improve its energy efficiency. Recirculation of CO_2 can also be used for the GTU combustion chamber if there is a need to decrease the temperature in it. The Allam cycle has presently been approbated in the pilot plant in Texas, which uses natural gas as fuel, with the thermal capacity equal to 50 MW. In the future, the use of this cycle will make it possible to achieve the efficiency equal to 59 and 51% for operation on natural gas and coal, respectively.

For implementing the Allam cycle, pure oxygen is required, whereas the currently used oxygen gasifiers operate on air enriched with oxygen up to 95%. In view of this circumstance, there is a need to develop new air-separation technologies, in particular, those involving the use of molecular sieves. If it becomes possible to do away with cryogenic air separation units, better reliability and economic indicators of the power plant can be obtained. Approximately 16% of the generated electricity is consumed for air separation in the implemented IGCC projects. This is the largest consumer of power for plant auxiliaries, the total level of which at an IGCC plant is as high as 23%.

A compressor-free CCP setup with oxygen-enriched combustion of natural gas and complete capturing of CO_2 that is close to the Allam cycle is presented in [25]. It can also be transformed into the CCP setup with oxygen-enriched coal combustion and CO_2 capturing. It is advisable to use two-stage gasification processes in such process flow diagrams. At the first stage, volatiles are removed from coal. At the second stage, the remaining coke residue is subjected to oxygen gasification. The use of a pump for compressing liquid oxygen makes it possible to exclude the compressor from the GTU process flow diagram, thus saving on the compression work. The advantage of this diagram is that smaller expenditures are required for CO_2 capturing. As is well known, the furnishing of conventional IGCC plants with CO_2 capturing systems results in that the power plant efficiency drops by up to 7%, and its cost increases by 6–10%.

To decrease the energy consumption for plant auxiliaries, increased attention is now paid to peripheral systems in works on technological improvement of IGCC plants [26]. The developments of new methods for high-temperature purification of gases and air-separation methods [27, 28] and optimization of IGCC process flow diagrams aimed at better integration of functional units into their composition [29, 30], which were pointed out above in the article, have become the leading ones.

The developments of new IGCC plants are predominantly oriented at using petroleum coke and coal. The development of IGCC plants operating on biomass or treated solid municipal waste seems to be unprofitable in view of the objective contradiction between the economically justified low-grade fuel collection radius and gasifier plant unit capacity [31]. By economic considerations, the minimal level of the IGCC plant electrical capacity is, according to [31], in the range of 200–300 MW.

An efficient solution may be the integration of electricity generating plants into the process diagrams for obtaining chemical products from coal, e.g., methanol, which are based on the gasification and synthesis technologies. This opens the possibility to use combustible waste from the main production and excess heat for electricity generation.

CONCLUSIONS

(1) Coal still continues to play the most important role in the global energy. Thermal power plants, to which approximately 69% of the coal produced around the world is supplied, remain the largest coal consumers. The share of coal in the global generation of electricity makes approximately 38% and has remained at this level for already about half a century despite large gas and nuclear energy development scales.

(2) The development of gasification technologies has by now turned to be at a crossroad. Their future will be determined by the coal energy development prospects as a whole. Since, among organic fuels, coal produces the largest specific CO_2 emissions from its combustion, it may become the first victim of the energy decarbonization policy.

(3) It is extremely difficult to adapt coal energy to the currently conducted "climatic policy" because the technologies for capturing and subsequently storing CO_2 are rather expensive. Under such conditions, the coal energy survivability can be ensured by broadening the coal application fields, first of all, by obtaining a wide range of chemical products with a high added value, competitive with the products obtained from petroleum and natural gas.

(4) The coal gasification technologies have already reached a high level of technical maturity, and many designs of gasifiers have been proposed. The obtaining of various chemical products, in particular, substitute natural gas, methanol, and ammonia has become the main field of their application. However, gasifiers are manufactured in single units or in small series, which results in their high cost. In approximately 86% of coal gasifiers, the gasification is realized in entrained flow. This is mainly oxygen-enriched conversion of coal-water slurry and steam-oxygen conversion of powdered coal.

(5) The very small number of IGCC plant construction projects that have been implemented and planned to be implemented around the world testifies that the private sector shows little interest in this technology, although such plants have a sufficiently high potential for being used in low-carbon energy; of course, provided that the problem of disposing the captured CO_2 is solved.

(6) In the post-Soviet time, investigations into coal gasification began to gradually fade in Russia. Since Russia has huge coal reserves, it is advisable to support and develop the relevant scientific and technological competences in Russia; they must not be lost. This should become a joint concern of the state and private sector.

REFERENCES

1. *Key World Energy Statistics* (International Energy Agency, Vienna, 2019).
2. *World Energy Outlook. 2019* (International Energy Agency, Vienna, 2019).
3. B. M. Kaganovich, S. P. Filippov, and E. G. Antsiferov, *Efficiency of Energy Technologies: Thermodynamics, Economics, Forecasts* (Nauka, Novosibirsk, 1989) [in Russian].
4. L. S. Belyaev, O. V. Marchenko, S. P. Filippov, S. V. Solomin, T. B. Stepanova, and A. L. Kokorin, *World Energy and Transition to Sustainable Development* (Kluver, Dordrecht, 2002).

5. *Guidelines for National Greenhouse Gas Inventories*, Vol. 2: *Energy* (IPCC, 2006; MGEIK, 2006). https://www.ipcc-nggip.iges.or.jp/public/2006gl/
6. G. G. Ol'khovskii, "Solid fuel gasification in the global energy sector (a review)," Therm. Eng. **62**, 465–472 (2015). https://doi.org/10.1134/S0040601515070071
7. G. G. Ol'khovskii, "New projects for CCGTs with coal gasification (review)," Therm. Eng. **63**, 679–689 (2016). https://doi.org/10.1134/S0040601516100074
8. *World Energy Resources: 2016* (World Energy Council, 2016).
9. *Energy Strategy of the Russian Federation for the Period until 2035*, Approved by RF Government Decree No. 1523-r of June 9, 2020.
10. M. Gräbner and B. Meyer, "Coal gasification — Quo vadis?," World Min.: Surf. Underground **62**, 355–362 (2010).
11. https://www.globalsyngas.org/resources/map-of-gasification-facilities/. Accessed October 5, 2020.
12. A. V. Zaitsev, A. F. Ryzhkov, V. E. Silin, R. Sh. Zagrutdinov, A. V. Popov, and T. F. Bogatova, Ed. by A. F. Ryzhkov, *Gas Generator Technologies in Power Engineering* (UralORGRES, Yekaterinburg, 2010) [in Russian].
13. A. N. Tugov, "Modern technologies for thermal processing of municipal solid waste and prospects for their implementation in Russia (review)," Therm. Eng. **68**, 1–16 (2021).
14. J. Gorre, F. Ortloff, and C. van Leeuwen, "Production costs for synthetic methane in 2030 and 2050 of an optimized Power-to-Gas plant with intermediate hydrogen storage," Appl. Energy **253**, 113594 (2019). https://doi.org/10.1016/j.apenergy.2019.113594
15. *Assessment of Technical and Economic Potential of Deep Processing of Coal of "Karakanskii-Zapadnyi" Open Cast Mining Site* (Technische Univ. Bergakademie Freiberg, Inst. für Energieverfahrenstechnik und Chemieingenieurwesen, Freiberg, Germany, 2017) [in Russian]. http://www.karakan-invest.ru/investor/perspective/Otchet-FGA.pdf. Accessed March 21, 2020.
16. Y. Yueting, Y. Qiuhua, L. Weibin, Y. Gen, and P. Dengfeng, "Summary of the current application status of coal gasification technology and gasifiers," Chem. Eng. Des. Commun. **45** (1), 15–44 (2019).
17. Y. Ma and Q. Fang, "Application status and development trend of large-scale coal gasification technology in China," Nitrogen Fert. Syngas **47** (3), 1–3 (2019).
18. Z. Li, "Application of BGL pulverized coal slag gasification technology in domestic industrialization," Shandong Chem. Ind. **46** (8), 123–125 (2017).
19. Z. Li, X. Li, and C. Li, "Brief introduction to coal-water slurry gasification technology of Jinhua gasifier," Fert. Ind. **46** (1), 50–52 (2019).
20. I. Barnes, *Recent Operating Experience and Improvement of Commercial IGCC*, Report (IEA Clean Coal Centre, 2013).
21. S. C. Gülen, *Gas Turbine Combined Cycle Power Plants* (CRC, 2019).
22. *IGCC Puertollano. A Clean Coal Gasification Power Plant*, THERMIE Programme Report (ELCOGAS, 2001).
23. S. P. Filippov and A. V. Keiko, *Review of Breakthrough Technologies in Gas and Coal Energy and Recommendations for Their Implementation in Russia: Analytic Note* (Inst. Energ. Issled. Ross. Akad. Nauk, Moscow, 2011) [in Russian].
24. R. Allam, S. Martin, B. Forrest, J. Fetvedt, X. Lua, D. Freed, G. W. Brown, Jr., T. Sasakia, M. Itoh, and J. Manning, "Demonstration of the Allam cycle: An update on the development status of a high efficiency supercritical carbon dioxide power process employing full carbon capture," Energy Procedia **114**, 5948–5966 (2017). https://doi.org/10.1016/j.egypro.2017.03.1731
25. A. S. Kosoi, Yu. A. Zeigarnik, O. S. Popel', M. V. Sinkevich, S. P. Filippov, and V. Ya. Shterenberg, "The conceptual process arrangement of a steam–gas power plant with fully capturing carbon dioxide from combustion products," Therm. Eng. **65**, 597–605 (2018). https://doi.org/10.1134/S0040601518090045
26. *Analysis of Technological Solutions for Combined-Cycle Plants with Intracycle Coal Gasification*, Ed. by A. F. Ryzhkov (Ural. Gos. Univ., Yekaterinburg, 2016) [in Russian].
27. S. Bin, X. Wen, W. Wei, and K. Po-Chih, "Techno-economic analysis of oxy-fuel IGCC power plants using integrated intermittent chemical looping air separation," Energy Convers. Manage. **195**, 290–301 (2019). https://doi.org/10.1016/j.enconman.2019.05.006
28. C. L. Pozo, S. Cloete, J. H. Cloete Á. J. Álvaro, and Sh. Amini, "The oxygen production pre-combustion (OPPC) IGCC plant for efficient power production with CO_2 capture," Energy Convers. Manage. **201**, 112109 (2019). https://doi.org/10.1016/j.enconman.2019.112109
29. U. Ahmed, U. Zahid, and Y. Lee, "Process simulation and integration of IGCC systems for H_2/syngas/electricity generation with control on CO_2 emissions," Int. J. Hydrogen Energy **44**, 7137–7148 (2019). https://doi.org/10.1016/j.ijhydene.2019.01.276
30. N. M. A. Al Lagtah, S. A. Onaizi, A. B. Albadarin, F. A. Ghaith, and M. I. Noura, "Techno-economic analysis of the effects of heat integration and different carbon capture technologies on the performance of coal-based IGCC power plants," J. Environ. Chem. Eng. **7**, 103471 (2019). https://doi.org/10.1016/j.jece.2019.103471
31. A. V. Keiko, D. N. Svishchev, and A. N. Kozlov, *Gasification of Low-Grade Solid Fuel: The Level and Directions of Technology Development* (Inst. Sist. Energ. im. L. A. Melent'eva Sib. Otd. Ross. Akad. Nauk, Irkutsk, 2007) [in Russian].

Translated by V. Filatov