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Innovations in World Cokemaking Technologies: A Report on the ESTAD 2019 Steel Conference

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Abstract—New developments in coke production are reviewed on the basis of papers presented at ESTAD 2019. Examples of new designs for coke batteries and ancillary equipment are presented, noting improvements in performance.

Keywords: coke, coal blend, blend components, coke batteries, coking pressure, bricklaying repair

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ESTAD 2019 (the Fourth European Steel Technology and Application Days) was held in Düsseldorf, Germany, on June 24–28, 2019, in parallel with the METEC trade fair. The organizer was the Steel Institute VDEh. Partners in conference organizations were the Austrian Society for Metallurgy and Materials (ASMET), the Swedish Steel Producers' Association (Jernkontoret), and the Italian Association for Metallurgy (AIM).

Specialists from many countries attended ESTAD 2019. In all 670 papers were presented at 150 sessions, on the following themes:

— iron production;

— steel production;

— rolling and forging of metals;

— steel materials and their use, coating application, additional machining of metals;

— Industry 4.0;

— energy considerations and environmental protection.

The presentations at ESTAD 2019 are of great interest for the development of European and world metallurgy.

In the sessions on iron production, the following topics were considered:

— Industry 4.0 and iron casting;

— coke production;

— sinter and pellet production;

— blast-furnace production;

— direct reduction of iron (DRI) and reduction by melting.

In the sessions on coke production, 17 papers were presented, on topics such as the following:

— experience in coal blend preparation for coking; fundamentals of coke production;

— the latest technological developments;

— coke plant operation;

— processing and use of coke-oven gas, use of coking byproducts.

We now briefly review the papers on coke production.

EXPERIENCE IN COAL BLEND PREPARATION FOR COKING, ANALYSIS OF COKING COAL, COKE QUALITY

1. Hyundai Steel (South Korea) presented a paper regarding a new approach to assessing the effect of oxidized high-fluidity coal on the coke's CSR value [1].

To decrease the cost of the coke, less expensive coal may be introduced in the coal blend. The blend of clinkering coal and poorly clinkering coal must ensure the required coke quality. The rheological properties of the coal blend are critical here: specifically, the fluidity, dilation, and plasticity. The prediction of coke strength may be based primarily on the fluidity. It also indicates the degree of oxidation of the coal.

Coal deteriorates under the action of the atmosphere; this is known as weathering. For highly oxidized coal, the reflection coefficient is high. However, this does not imply the formation of an anisotropic structure such that coke strength is increased.

In the South Korean paper, *CSR* prediction is based on the suitability of the coal for use in the coal blend (coal blend readiness B_o) and the reflectivity distribution index (RDI). The reliability of the method is confirmed by practical predictions of *CSR* in the period 2015–2018. On the basis of this approach, the influence of weathering on *CSR* may also be analyzed in quantitative terms, by means of actual *CSR* data,

Fluidity data for 14 coal ranks obtained by means of a Gieseler plastometer were used to calculate B_o. The chemical reaction is assessed for pairs of coal samples; in each pair, sample 1 is more fluid. The coal characteristics (fluidity, ddpm; dilation, %; reflectivity, %; and total reactivity) were tabulated; and the influence of the coals on the decrease in fluidity of coal 1 was plotted. An equation was derived for the predicted *CSR* value.

The combination of B_o and *RDI* is known as the New Index *NI* and characterizes the mean *CSR* for a single coal blend. Graphs of *CSR* (%) against *NI* permit selection of the best possible coal blend on the basis of the specified coal samples. Many factors affect the oxidation of the coal: the characteristics of the coal, the conditions in the coal store, the weather conditions, etc. The influence on the degree of oxidation increases with deterioration of the initial coal quality. Low-quality coal with a high content of volatiles is more susceptible to oxidation and self-ignition than high-quality coal.

The variation in fluidity in the course of coal storage was analyzed for two coals with a high content of volatiles (hard coking coal and semicoking coal). In both cases, oxidation occurs by the same process. The fluidity declines significantly here: slowly for the first 80 days of storage; and rapidly thereafter. The oxidation products are more stable and relatively inert. Therefore, the oxidized coal is less active in coking and results in lower *CSR*.

To guarantee the required coke quality, the maximum permissible storage time for hard coking coal is regarded as 80 days. If coal stored for longer than 80 days is added to the coal blend, coke quality will decline (>2% decrease in *CSR*). That is equivalent to the use of low-quality hard coking coal in the coal blend. Measurements must be taken to minimize the loss in coke quality, by means of *NI*. With higher *NI*, coke quality may be improved, and the influence of oxidized coal on *CSR* may be eliminated. Prediction of *CSR* by means of *NI* shows that it is useful in quantitative assessment and also in practical coal blend formulation.

2. A consortium of Canadian companies presented a paper regarding the determination of coal dilation in terms of the ISO/TS27 standard and the importance of correcting experimental dilation data [2].

Dilation is used in characterizing coking coal and also in formulating models of coal blend and predicting coke strength. Dilation must be determined in strict accordance with the relevant standards; the tests must be stringently monitored. The paper outlines the results of recent interlaboratory studies (ILS) on the determination of coal dilation according to the ISO/TS27 standard (for hard coal). The goal was to demonstrate that laboratory data on dilation obtained with reference to a standard coal mass of 2.5 g (% SD 2.5) entails elimination of the discrepancy in determining dilation by the Audibert–Arnu and Ruhr methods.[1]

The Audibert–Arnu method (ISO 349 standard for hard coal) is used, for example, in North America, Australia, China, France, Russia, Ukraine, and Poland. The Ruhr method (ISO 8264 standard for hard coal) is used in Europe. These two methods, employing different equipment and procedures, give different dilation values. In the interlaboratory studies, eight coal samples of different rank from Australia, Canada, China, Poland, South Africa, and the United States (with $R_o = 0.65–1.54$) are prepared and distributed between the laboratories and tested by different methods.

Statistical analysis of the experimental results with reference to a fixed coal mass of 2.5 g (standard mass) indicates that the discrepancy between the laboratory data falls outside the limits established by the ISO 23873 standard.

The dilation is used in delivery specifications and contracts; it is of great importance. Correction of the results with respect to a standard coal mass of 2.5 g (% SD 2.5) eliminates the discrepancy between the results.

The authors conclude that the results of the interlaboratory studies provide the basis for the review of three standards regarding the method of determining the dilation (ISO 349, ISO 8264, and ISO 23873). Correction with respect to a standard coal mass of 2.5 g is of great importance.

3. ArcelorMittal Dofasco (Canada) presented a paper regarding a practical approach to the rheology of coal [3].

In determining the clinkering and coking properties of coals, rheological data are gathered. According to the ASTM standard, the coal is tested by means of a Gieseler plastometer and a dilatometer. The fluidity and dilation may be used to determine the freshness of coal and to monitor its aging on storage. At ArcelorMittal Dofasco, coal may be stored for up to four months under cover. Therefore, its rheological properties are measured every week so as to promptly detect signs of aging.

The aim of the paper was to propose practical approaches to matching rheological tests with indus-

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[1] In 1993, on the basis of research by Canmet and CCRA, the concept of the specific dilation (*SD*) of coal (% SD 2.5) was introduced. It is the percentage dilation based on a coal pencil of height 60 mm for tests of an air-dried 2.5-g sample.

trial conditions and thereby to assist plant operators in understanding and applying the test results. The importance of temperature limits for the tests was noted. The conditions of coal supply and storage were described, and the rheological measurement procedure was presented. Test results were reported, with appropriate commentary and recommendations regarding the test procedure.

4. China Steel Corporation (Taiwan) presented a paper regarding the microstructure and microtexture of Indonesian coal briquets [4].

Indonesia plays an important role in the coal market, since it produces coal with low ash and sulfur content. It has a favorable geographical position and at present Asian coal consumers are very interested in the analysis of Indonesian metallurgical coal.

The Taiwanese researchers applied petrographic methods to Indonesian coal and coke so as to compare their characteristics. Many Indonesian coal samples have high vitrinite content. Therefore, many reactive maceral components are seen in the coke. The microstructure of the coke also indicates the presence of thin walls and the absence of inert maceral components. To determine the influence of these features on the coke quality and to increase the packing density of the coal samples, briquets are employed. The samples are investigated in a 15-lb pilot coke oven. To determine why the coke reactivity changes, the coal briquets and coke pieces are subjected to microtextural and microstructural analysis.

Like Japan, Taiwan lacks coal for coking and relies on imports. Indonesian coal is appearing in an Asian market previously dominated by Australia. Japanese experience indicates that it is expedient to improve the coking properties of the coal by briquetting. The China Steel Corporation believes that briquetting of the coal will permit more flexibility in its acquisition and coking and will decrease costs. Therefore, in the studies, the coal is in briquet form.

Indonesian coal is relatively young and has a high content of volatiles. It gives rise to coke of lower strength. The coal blend from which the briquets are formed contains two ranks of Indonesian coal (75%) and three ranks of coal with a lower content of volatiles (25%). The cold coal blend is briquetted without binder in a roller press. The goal is to determine the maximum quantity of Indonesian coal that may be used in the coal blend to which the briquets are added. The mechanical strength M_{30} of the coke and its CSR value are determined so as to permit selection of the coals employed.

The results indicate that, in order to obtain coke of satisfactory quality, no more than 10% of Indonesian coal must be present in the blend with coal that has a lower content of volatiles. Briquetting increases CSR by 4.3–10.6%. The tests are conducted in accordance with the following standards: ISO Micum drum and ISO 556.

5. Thyssen Krupp Steel Europe (Germany) presented a paper regarding improvement in the results obtained by means of a 10-kg carbonization retort [5].

Since 2015, the company has used a 60-kg pilot oven with a movable wall and a 10-kg carbonization retort within an electrically heated furnace for tests in its Duisburg laboratory. The coking properties of both individual coal samples and blends are verified. The retort operates with short coking periods; small samples are required for one-off tests. In contrast to the furnace with a movable wall, the retort does not permit measurement of the coking pressure on the furnace wall or the cold strength in accordance with the ISO standard, on account of the small quantity of coke produced. To expand the range of the retort and overcome its design limitations, it was decided to test the deposits formed on coking in the retort and also to determine the coke's cold strength.

To ensure specified cold strength, the coke is investigated by different methods so as to select the best. Coal samples of different ranks, from different regions, are tested. The results are compared with their maceral composition.

To determine the quantity of carbon deposits formed, a 50 × 40 × 20 mm refractory sample is placed in the free space of the retort under the carbon sample. After carbonization of the coal, the increase in sample mass due to the formation of a carbon deposit is measured, so as to determine the consequences of the deposits and provide useful information for the Schwelgern coke plant. To that end, the tests are conducted with coal and carbon-bearing materials of different types. The results permit comparison of the coke quality in the furnace with a movable wall and in the retort.

The quantity of carbon deposits on coking in the retort is determined by weighing the sample and calculating the difference between the mass before the test m_0 and the mass afterward m_1. The degree of carburization $\acute{m}$ is calculated from a formula taking account of the test duration and the surface area A of the sample

$$\acute{m} = (m_1 - m_0)/tA.$$

Two main factors are responsible for the deposit: 1) the quality of volatile material, which is related to the volume of gas formed on carbonization and hence to the quantity of hydrocarbons decomposing under the coal layer; 2) the temperature.

The small quantity of coke formed in the retort and its granulometric composition do not permit the use of standard 140/Micum methods in determining the cold strength of the coke. Therefore, the specifics of the coke produced in the retort are taken into account in adapting the method. Coke of the >20 mm class is selected, since the yield of the >40 mm class is small. A 6-kg sample of the >20 mm class is loaded in the

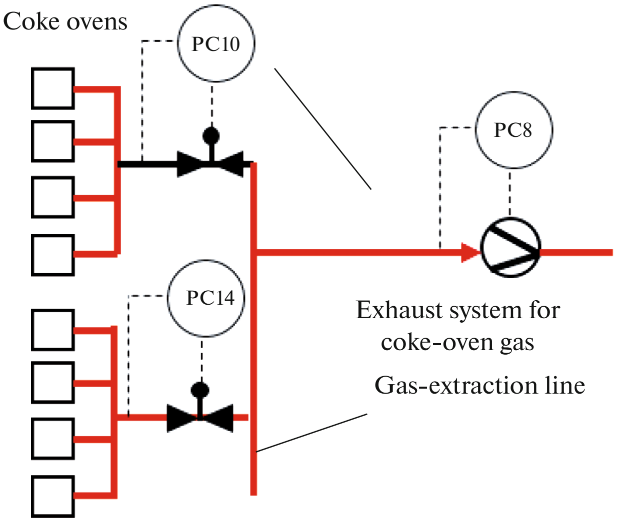

Fig. 1. Gas-exhaust lines and measuring instruments for coke ovens.

Micum drum. The paper describes the test procedure in detail.

The conclusion is that coking in the 10-kg retort provides a distinctive method of determining the characteristics of coal of single ranks and coal blends and so expands the potential for coal analysis and assessment. The authors establish the range within which the retort may be used to obtain results supplemental to experiments on the furnace with a movable wall.

6. JFE Corporation (Japan) presented a paper regarding the influence of aromatic amine on coal fluidity and coal strength [6].

The fluidity of the coal plays an important role in the preparation of the coal blend for coking since it greatly affects the coke characteristics. On the other hand, the quantity of coal with high fluidity has declined lately. In this context, coal blend additives for increasing the fluidity have been introduced. In the future, the supply of high-fluidity coal is expected to be problematic, and so it is important to find more effective additives.

In the Japanese research, the influence of 11 polyaromatic hydrocarbons on coal fluidity was studied. Attention focused, in particular, on the influence of chemical compounds containing oxygen, sulfur, and nitrogen, so as to find the most effective chemical components. The additives were introduced in coal of low fluidity, with measurements by a Gieseler plastometer. Additives containing oxygen decreased the fluidity, whereas aromatic amines improved it.

The coal fluidity increased with increase in molecular weight of the aromatic amine. The most effective amine proved to be *N*,*N*'-di-2-naphthyl-1,4-phenylenediamine (DNPD).

To establish the influence of DNPD on coke quality, an electrically heated furnace was used for the experimental coking of coal. The strength of a drum sample of coke was significantly increased on adding only 1 wt % of DNPD to the coal blend. This may be regarded as the key to finding more effective additives that improve the clinkering properties of coal.

RECENT TECHNOLOGICAL DEVELOPMENTS

1. Dutch specialists presented a paper regarding methods of decreasing fluctuations in the coking pressure [7].

The paper outlines new methods of controlling the coking pressure. They are used in coke plant 2 at Tata Steel’s Ijmuiden plant. The system for measuring the pressure of the coke-oven gas controls the shops gas-extraction and exhaust equipment. The maintenance of stable positive pressure in the coking chamber prevents air suction into the furnace and gas leakage.

The standard method of regulation the pressure P in the coke chamber is the proportional–integral (PI) method. At the Tata Steel plant, research was undertaken to improve this method. In Fig. 1, we show the gas-exhaust lines and the measuring instruments for coke ovens with PI control.

The pipelines and pump systems for gas extraction from the coke ovens are controlled by means of signals from the pressure-monitoring system, so as to keep the process within specified limits (for example, control point PC8).

The paper describes the process; the process model used to control the algorithm (a black box); the pressure factors and the instigating factors; and improvements made on the basis of the model. The results are outlined.

The model is developed by means of DotX PID Tuner software. The dependence of the pressure P on certain variables is mathematically expressed. The values of the variables are represented in the control system by the position of the corresponding valves. The pressure fluctuations in the coke oven are recorded by means of the instruments as a function of the fluctuations in the gas flow and its physical properties (temperature, density, and chemical composition), the ambient pressure, etc.

Improvements made over the course of twelve months as a result of the research are described. The improvement may be seen in terms of the time (%) for which the pressure is no more than 0.4 mbar from the specified value, which was 30–90% (mean 80%) before any improvements but reached 85% after fine tuning of the PID controller (and eventually ~90%).

By this means, the pressure fluctuations were reduced by more than 50%. Further decrease is possible by more careful adjustment of the controller, with automatic verification of the signals from the closed loop of the control chain.

2. FIB Services International (Luxemburg) presented a paper regarding the RPR SL method for the

treatment of microcracks in the refractory lining of coke ovens [8].

For the past twenty years, coke-plant managers have been required not only to solve the day-to-day problems of plant operation but also to curtail harmful atmospheric emissions. To that end, engineering companies have offered various clean solutions (on the basis of filters, hoods, dry coke quenching, individual monitoring of oven pressure, gas-tight doors, etc.).

Coke-battery chimneys are also sources of toxic emissions. Besides its environmental impact, the emission of chimney gases indicates unsatisfactory condition of the refractory lining in the ovens (cracks or open seams in the heating-wall lining) and also factors such as disruption of the heating conditions and imperfect regulation of the oven pressure. The resulting suction of coke-oven gas and small particles into the chimneys usually produces dark smoke.

Environmental protection forms the subject of numerous regulatory documents (the Kyoto protocol, the Paris accords, the Clean Air Act, European Community directives, etc.). Many measures have been taken to comply with those documents. The paper by FIB Services considered emissions of category 3: chimney emissions.

One important component of such emissions consists of particles smaller than 10 μm that are drawn into the heating system in charging and discharging or represent residues of refractories, mortar, and other repair materials. The small particles are evacuated from the coke ovens to the chimney. The large particles are deposited in the heating channels, in the gas and air channels, in the nozzles, or in the upper part of the regenerators.

Operating crews use the following methods of identifying leaks:

— visual inspection (through observation windows) and monitoring of the heating-wall surface on the coke-oven side;

— instrumental measurements of gas samples from the chimney (by means of endoscopes and gas analyzers or in terms of the opacity).

Repair methods used in practice for the refractory lining include relining of the end flues and other wall segments, modular replacement, ceramic welding, and guniting. Sealing microcracks is more challenging. At present, a common technique is to apply special coatings by means of compressed air.

FIB Services International has developed and patented a method of sealing microcracks with the material RPR SL. This method is simple and effective. Its goal is to seal numerous microcracks in the coke oven's wall and roof lining by means of a single operation. The RPR SL is supplied to the coke oven in liquid form by compressed air, through the charging hole.

In the coke oven, it breaks down and burns to form a large quantity of gas (CO_2 and water vapor), as well as a silica mist, which is distributed over the whole coke oven and penetrates the microcracks. Some very small silica particles break down on the inner surface of the microcrack forming a silica layer (SL), hence giving rise to the name.

Usually, two operators are required to apply RPR SL. The operation requires 3 L of RPR SL and takes 5–10 min. The paper presents the results of industrial tests at three plants, indicating that the new technology is more efficient than traditional methods.

3. Thyssen Krupp Steel Europe (tk SE) presented a paper regarding industrial and laboratory measurement of the internal gas pressure in coke ovens [9].

Coal blend must meet a set of criteria requiring quality and operation. One important consideration is cost.

In an effort to cut costs, the range of coal employed has been expanded. However, resorting to new operators in place of traditional partners may cause problems. In addition to loss of coke quality, the new varieties of coal may damage the battery lining on account of excess internal gas pressure (IGP). The oven wall pressure OWP in coking is regarded as an important parameter in terms of stable and reliable coke-battery operation. It cannot be measured directly in an industrial coke oven.

In practice, IGP must not exceed 20 kPa, since higher pressure may lead to critical OWP values. That may disrupt heating-wall operation and lead to obstructed motion of the coke cake and clogging of the coke. Therefore, the introduction of new types of coal in the coal blend should be preceded by a comprehensive program of laboratory and small-scale industrial tests.

As a rule, tk SE measures IGP once every eight days on a probe of a coal blend weighing 80 tons used on two coke oven batteries of the Schwelgern coke plant. IGP measurements are additionally carried out with variation in the conditions of coal blend preparation (granulometric composition, greasing, etc.). The measurements are made by means of a thermocouple and a special probe in a guide tube, which is introduced in the coal charge through a hole in the coke-oven door. A detector head on the probe transmits the information to a receiver. In normal conditions, all the operations take 15 min and are conducted 10 min after charging of the coke oven.

The thermocouple measures the temperature in the charge. All the data are transmitted wirelessly to the operator desk. In addition, the shrinking of the charge and the temperature in the standpipe are recorded at each furnace. To obtain more information, it is possible to take a small portion ($0.0672\ m^3$) of coal blend before charging in the coke oven and to test it in a coking furnace with a movable wall. The probe is used once and removed from the furnace an hour before coke pushing. The measurements are made at the Schwelgern coke plant.

Table 1. Design features of coke battery 2 before and after reconstruction

	Before	After
Construction date	1967–1975	2015
Designer	CarlStill (Germany)	IHI–PW Italia (Italy)
Heating system	Horizontal channel in coke-oven roof, six-stage combustion	Twin flues; two-stage combustion; recirculation
	Fuel: coke-oven gas or a mixture	Supporting structure at the coke-oven roof
Structural design	Buckstays, transverse tie rods	Buckstays and thermally shielded springs at transverse tie rods; springs over buckstays height

Table 2. Characteristics of reconstructed coke battery 2

Characteristic	Planned value	Mean
Coke-oven pushings per day	123	118
Time efficiency, %	143	140
NO_x in combustion products, ppm	170	151

The paper presents detailed information regarding the research at the industrial coke oven and also the improvements in the procedure for IGP measurement. Besides measurements at the Schwelgern plant, the coal blend is investigated at DMT (Essen) in a 600-kg furnace with a movable wall.

The measurements at the plant and in the laboratory are compared, and the factors affecting IGP are identified. Regular monitoring of IGP and its relation to OWP assists the operator in optimizing battery operation and extending coke-oven life. A precise correlation between industrial and laboratory measurements of IGP has been developed at tk SE.

4. JFE Steel (Japan) presented a paper regarding the reconstruction of coke battery 2 at the Kurashiki plant [10].

Most JFE Steel coke batteries are more than 40 years old. Therefore, an orderly updating plan is in place. This situation is typical of Japanese coke plants—in particular, those with batteries built in the 1960s and 1970s.

In the past decade, JFE Steel has replaced or reconstructed only 25% of its coke batteries. Reconstruction of the others continues.

Coke battery 2 was shut down in June 2015 and resumed operation after reconstruction in March 2017. Reconstruction took 21.7 months. In reconstruction, the most important requirement is operation with low NO_x emissions and high oven utilization (in terms of the proportion of existing coke ovens that are in use).

Table 1 presents a comparison of the design features of coke battery 2 before reconstruction (Carl Still design) and after reconstruction (IHI–Paul Wurth design).

Table 2 presents the performance of coke battery 2 after reconstruction.

5. Nippon Steel Engineering (NSE) of Japan presented a paper regarding improvements in the dry quenching of Coke [11].

Dry quenching of coke is of growing interest as a thermally efficient method that produces high-quality coke and so improves blast-furnace efficiency. After the introduction of the first dry-quenching system in Japan in the 1970s, NSE proposed important improvements. In 2009, the company developed the world's largest dry-quenching system, processing coke at a rate of 280 t/h. The paper describes in detail NSE's technology.

Significant NSE modifications of dry quenching include the introduction of a cyclone dust-catching unit and the creation of an automatic control system.

In the standard dry-quenching system, coke dust is removed from the circulating coolant gas in two stages: in a dust-settling bunker ahead of the boiler; and in cyclones ahead of the smoke fan. The operational efficiency of the dust-settling bunker is low (~20%). Therefore, measures are required to protect the heating surface of the waste-heat boiler from abrasive wear and to remove fine dust from the circulating gas in multiple cyclones ahead of the smoke fan. The presence of a complex two-stage dust-removal system greatly increases the cost of dry quenching.

NSE has developed a new design for the dust-removal system, with a single cyclone unit in place of both the dust-settling bunker and the multiple cyclones. This single-stage system is shown in Fig. 2, in comparison with the standard design.

The new design is based on numerical modeling of the process and tests of a small-scale physical model. This design removes 90 wt % of the dust, is more effi-

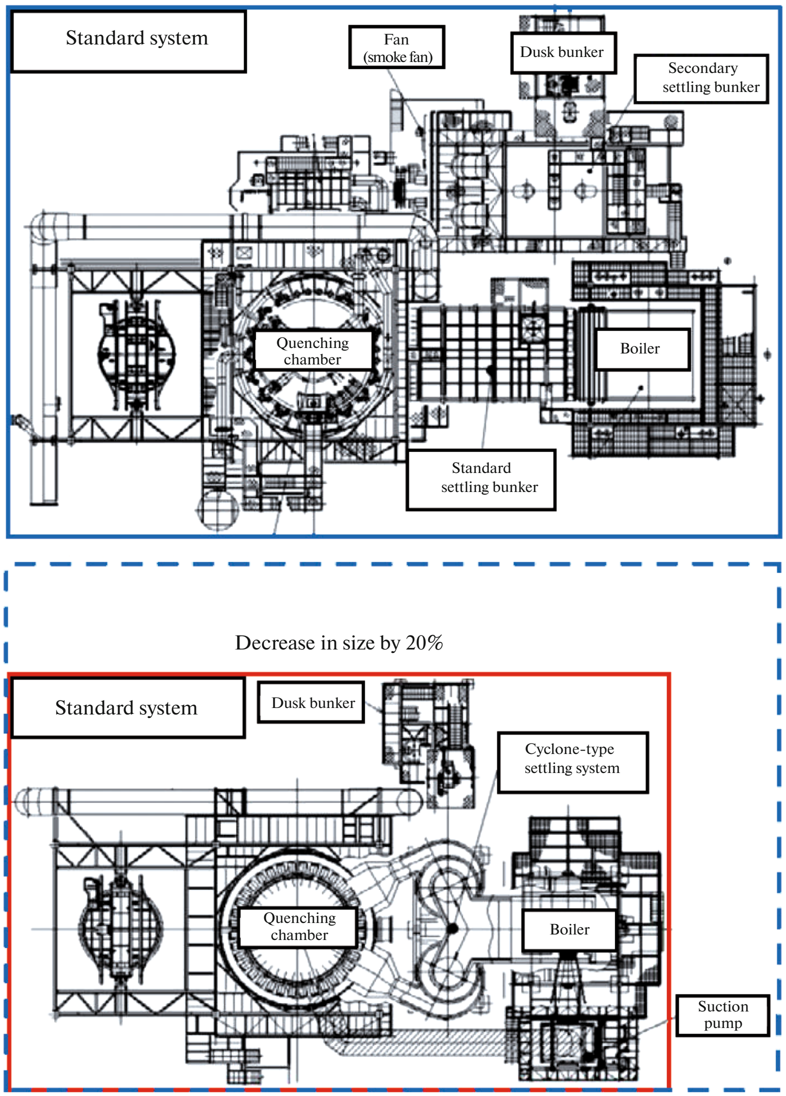

Fig. 2. Single-stage cyclone dust-removal system and standard system.

cient, and has the benefits in Table 3, according to NSE.

The first of these systems went into operation in 2017 at the Shanxi Guangda plant (operated by Coking Air Source Co., China). Tests show that it performs well, with ~96% efficiency. Inspection of the system after a year of operation reveals no marked damage.

Automatic Control System

To ensure safe and effective dry quenching of steel, NSE supplies not only the hardware but also appropriate software, including an automatic control system. For purchasers whose operators have limited experience, the company has developed an instruction

Table 3. Benefits of the new NSE dust-removal system

Characteristic	Benefit
Manufacturing cost of boiler and dust traps with ancillary equipment	About 25% lower than for standard system (16% less if the total initial cost of the dry-quenching system is taken into account)
Area required	About 25% lower than for standard dry-quenching system
Working life of boiler pipes	Longer than for traditional system by a factor of 1.5
Operating costs	Lower power costs thanks to lower input temperature

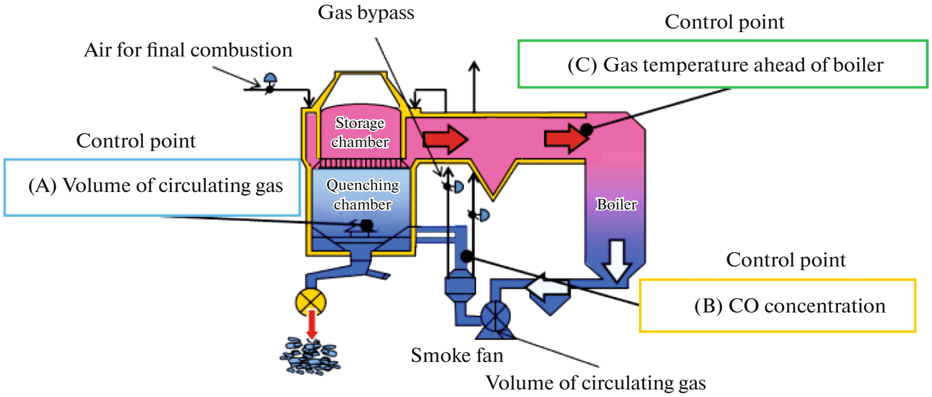

Fig. 3. Automatic control system for NSE dry-quenching system: (A) automatic control of the circulating-gas volume in accordance with the coke charge; (B) automatic control of the air supply to the quenching chamber so as to maintain the CO level in the circulating gas, %; (C) automatic control of the volume of circulating gas in the bypass line so as to maintain the boiler temperature below 980°C.

booklet regarding the automatic control system. This system is shown in Fig. 3.

The automatic control system is currently employed at all NSE dry-quenching systems.

6. Tata Steel (India) presented a paper regarding the influence of the operational parameters and the coal quality on coke production [12].

Requirements on the quality and granulometric composition of the coke are of particular importance as larger blast furnaces are employed and diverse reducing agents are introduced in the working volume. The quality of blast-furnace coke is determined by the properties of the coal blend and the coking parameters. The results also depend on the testing method.

The paper presents the following main aspects of Tata Steel's extensive research in this area:

— maintenance of coal blend characteristics and coal blend testing to permit optimization of the coking parameters at an integrated steel mill;

— the role of the coking process in ensuring coke quality and the influence of operational parameters (including the coking period, the battery temperature, the duration of stamp charging, etc.);

— the influence of the coal characteristics—in particular, fluidity and dilation—on coke quality.

The main conclusions are as follows.

1. The operational parameters of the coke battery—such as the increase in coking period and the coke's holding time—greatly affect the coke quality. For example, they may lead to greater piece size.

2. Increase in coking temperature may increase the cracking of the coal and decrease the mean piece size.

3. The duration of stamp charging greatly affects the mean piece size of the coke: increase in the time decreases the piece size, and vice versa.

4. If the coking properties of individual coal blend components worsen, the properties of the whole coal blend may be impaired, with consequent loss of coke quality.

COKE PLANT OPERATION

1. Severstal (Russia) and Paul Wurth (Luxemburg) presented a paper regarding a new production complex for coke in Russia [13].

At the beginning of 2018, Severstal and Paul Wurth (PW) signed a contract for the construction of a new production complex consisting of two sets of 56 coke ovens at Cherepovets Steel Works. Each set is of total capacity 1.4 million t/yr; stamp charging is employed. PW supplied the technology and engineering for the two sets of 56 coke ovens, a three-chamber dry-quenching system; two sets of coke machines; additional equipment for the coke plant and for coke screening; and mechanical clarification units for byproduct capture shop 2.

The main characteristics of the coke ovens are as follows: useful length 16.25 m; height 6.25 m; width 0.5 m; center-to-center distance 1.5 m; useful volume 43.7 m^3; and coking period 23 h.

The heating system, for the coke ovens employs coke-oven gas only. It is equipped with combustion-product analyzers so as to determine the quantity of NO_x and assess the temperature distribution. The refractory lining is designed by means of a 3D dynamic model of the flow; FLUENT modeling software is employed.

The PW design for the two sets of coke ovens is completed at the levels of basic and detailed engineering. The lining structure is confirmed by means of VAP (virtual assembly program) software. The structural design employs BAN software. The calculation method employed is useful for operational verification of the battery design.

The battery design is intended for operation at low winter temperatures. The monitoring instruments permit connection to a nitrogen supply network. (The basic valves, standpipes, flares, and SOPRECO® components may be monitored.) PW decided to use the SOPRECO® single-oven pressure-control system for the coke batteries. This is regarded as a best available technique (BAT).

The dry-quenching system (coke capacity 160 t/h) consists of three chambers of net productivity 55–82 t/h. (Two of the chambers operate, while the third is a backup.) The quenching chamber and prechamber measure 500 and 311 m^3, respectively. The quenching chamber is served by two hoists. In normal conditions, the productivity of the chamber–boiler module is 55 t/h for coke and 58 t/h for steam. The dry-quenching system incorporates designs by PW and IHI (Japan).

The paper presents information regarding the parameters of the dry-quenching system and the structure of the coke machines. The door-maintenance system is designed by PW in cooperation with VeCon and Schalke (Germany). Note that much of the working documentation for the construction of the new complex was developed by Giprokoks.

Finally, the paper noted that the new complex is characterized by high performance, is easy to repair, includes environmental-protection measures, and is based on best available techniques.

2. Dillinger Huettenweke, Zentralkokereii Saar, and the German Steel Institute VDEh presented a paper regarding new processes for high-quality coke production in Germany [14].

Despite problems in decreasing CO_2 emissions, the production system consisting of a blast furnace and an oxygen converter will remain the basis of Germany's steel industry, and there will continue to be a demand for high-quality blast-furnace coke.

At present, there are five coke works in Germany: Schwelgern, Huttenwerke Krupp Mannesman (HKM), Zentralkokerei Saar (ZKS), Salzgitter, and Prosper. Four of these are part of steel plants. Arcellor Mittal's Prosper plant (Bremen) is independent. German coke production fell from 28 million t/yr in 1980 to 9 million t/yr in 2015. This may be attributed to falling blast-furnace demand for coke (in connection with improvement in the process and increasing use of pulverized-coal injection) and to structural changes in the German steel industry and coal mining. Since 1993, Germany's demand for coke has exceeded its production; the gap is filled with imports.

To decrease imports, existing German coke batteries are being modernized (or replaced), and new ones are being built. For example, the ZKS plant, a subsidiary of Dillinger Huttenwerke, has signed a contract with PW Italia for the construction of the new B3 battery with 50 furnaces on a new site, as well as the dismantling of the existing B1 battery and its replacement by a new B1 battery with 40 coke ovens. Stamp charging is used in both cases.

In March 2014, HKM inaugurated the new coke battery 2 with gravitational charging, according to a design by TK Industruial Solutions (Uhde). Thus, gravitational coal blend charging and stamp charging have been successfully employed at German plants.

New thermal monitoring systems for coke batteries—in particular, temperature sensors—have been developed and introduced in production. On the basis of the measurements, high-tech control systems (expert systems) have been developed and introduced: for example, the Fuzzy system at the ZKS plant, which permits regulation of the coking temperature and time in accordance with specifications. The heat supply for coking is regulated by adjusting the gas flow rate and the interval between heating sessions.

As we know, the first pressure system for an individual coking chamber (the PROVEN® system) was introduced at the Schwelgern coke plant. The SOPRECO® pressure control system is employed at the new battery B3 in the ZKS plant. This system has also been installed at the new battery B1. The SOPRECO® system significantly reduces emissions on charging at ZKS. The system for extraction of the charging gases and their transfer to adjacent coke ovens has been improved.

Control of the coke machines has been significantly upgraded. The machines in the quenching cycle are controlled absolutely automatically, with no operator invention. The charging machines, the coke-dislodgment devices, and the gas-bypass operate semiautomatically. The positional precision of the machines is improved. Further improvements are underway.

Systems for coal sampling and coal blend formulation using experimental coke ovens have been developed and introduced. Such systems are created with the participation of researchers, operators, and commercial agencies. As a result, the *CSR* and *CRI* values for the coke have improved (increase in *CSR* from 55 to 77% over the past three years); rates of pulverized-fuel injection have increased (from 140–150 to 200–210 kg/t of hot metal); and the consumption of reducing agents in the blast furnace has fallen below 500 kg/t of hot metal.

The development and introduction of new automatic systems continues within the Industry 4.0 framework.

3. SDM (China) and PW Italia presented a paper regarding the first Jumbo coke batteries with top loading constructed in China by Paul Wurth [15].

In October 2010, SDM of Shandong, China, and PW Italia signed a contract to collaborate on the supply of top-loading coke batteries (height exceeding 7.2 m) to the Chinese market.

In November 2018, SDM obtained an order from Shandong Steel Group Rizhao for the construction of four 58-oven coke batteries at the Shandong Rizhao (SR) steel plant. The first two batteries were successfully introduced in 2018; the third and fourth followed in February and July, 2019, respectively. At the customer's wishes, the Jumbo battery developed by PW for the PT Krakatau POSCO coke plant (Indonesia) was modified and adapted in length and height for installation at the SR plant.

PW was responsible for the basic engineering of all the main components and the detailed engineering for the batteries' refractory lining, while also supplying the SOPRECO® system and the level-2 COKEXPERT® automation system.

The basic characteristics of the coke plant are as follows:

— capacity 3390000 t/yr; four batteries (2 + 2); 58 coke ovens per battery;

— center-to-center distance 1650 mm; coke ovens of useful length 18.85 m and height 7.326 m; effective height 6.916 m; width 550 mm; taper 70 mm;

— useful volume 71.7 m^3; coking period 24.5 h; 114 pushings per day; interval between coke pushings 12.7 min;

— three machine sets (2 + 1); two quenching chambers; one processing shop for coke-oven gas. (These components are not supplied by PW.)

The paper presents information regarding the PW technology with Jumbo ovens and describes in detail the coke ovens' heating system, the structural design, the ovens' outlet for the coke-oven gas, the SOPRECO® system, the COKEXPERT® system, etc. The advantages of the Jumbo coke ovens with respect to the smaller traditional ovens include decreased toxic emissions; improved operating conditions; and gains in coke quality. This is associated with the longer coking period. The distinguishing feature of the PW coke ovens is that air and lean gas are supplied on one side (the machine side), while the combustion products are removed on the other (the coke side).

Operation of the Jumbo furnaces at the PT Krakatau POSCO coke plant confirms the improvement in coke quality: coke with $CSR = 69\%$ and $CRI = 20\%$ is obtained. Practically all of the expected benefits of the Jumbo coke ovens are confirmed by 3D simulation of the gas flows using FLUENT software (including the position of the holes for the supply of air or mixed gas in the base of the heating channels, the levels of the air-supply stages over the height of the heating channels, and the degree of recirculation of the combustion products).

In collaboration, PW and SDM have developed high-tech coke batteries with large coke ovens for sale in the Chinese and international markets.

PROCESSING AND USE OF COKE-OVEN GAS AND USE OF COKING BYPRODUCTS

1. Tata Steel (India) presented a paper regarding improvement in sulfur recovery by means of Aspen Plus simulation [16].

Coke-oven gas is an important coking byproduct. It contains both valuable components and undesirable impurities. Corrosive sulfur-bearing compounds (H_2S, CS_2, and COS) must be removed to prevent corrosion of the equipment and to prevent toxic environmental emissions.

The most common method of removing hydrogen sulfide from coke-oven gas is the modified Klaus process, which removes 95–98% of the H_2S and yields sulfur of high quality. Research at Tata Steel aims at improving the efficiency of the Klaus systems at the Jamshedpur plant. To that end, the process is modeled by means of Aspen Plus software (v. 8.8), with a view to maximizing sulfur removal. The reliability of the model is verified by comparing the results with industrial data. By sensitive analysis, the optimal operational parameters are determined.

Maximum sulfur removal is obtained when the ratio of sour gas to hydrogen (mole/mole) is 0.754–0.759; the H_2S concentration in the input flow of sour gas is 12.8–13.2; and the temperature of the incoming gas at the first Klaus reactor is 240–258°C. These values correspond to the actual working conditions at the plant.

The paper describes in detail the research on the thermal and catalytic stages of the process; the equations of the reactions are presented. The experimental methodology is outlined, the system for sulfur removal is described, with the appropriate parameters (temperature and pressure) in the components (Klaus reactor, gas heater, sulfur condensation unit, etc.). The researchers study the influence of the molar ratio of the sour gas and the air in the gas flow on sulfur capture and the H_2S/SO_2 ratio in the gas tailings; the influence of the H_2S concentration in the sour gases on the sulfur capture and the ratio in the gas tailings; and the influence of the temperatures at the stages of gas combustion on these characteristics. The results are illustrated by corresponding numerical data.

2. Thyssen Krupp Steel Europe (Germany) and Schwelgern coke plant presented a paper regarding the optical reflection characteristics and utilization of carbon formed in the targeted decomposition of methane [17].

The use of carbon formed in methane pyrolysis (TCA carbon) as a replacement for green petroleum coke is considered. In the production of blast-furnace coke, such additives to the coal blend decrease the cost of the coke and increase its yield. The internal gas pressure (IGP) and the oven wall pressure (OWP) are decreased. The paper describes the formation of pyrolytic carbon (TCA carbon) and its properties and also provides information regarding the coking of coal blend containing such carbon in comparison with standard coal blend. Attention focuses on the dilation, IPG, and OWP. The final section considers the influence of various coal blend additives on the physical properties (cold strength I_{40} and hot strength *CSR*) and chemical properties (*CRI*) of the coke produced with different additives. The conclusion is that adding TCA carbon improves IPG and OWP. However, that also impairs the cold and hot strength. Microscopic analysis shows that TCA carbon is poorly introduced in the coke matrix. Therefore, its use as a coal blend additive is problematic, since critical coke quality is not ensured.

CONCLUSIONS

Iron production in the blast furnace will remain the basis of the steel industry, and there will continue to be demand for high-quality blast-furnace coke.

Coke producers always search for ways of improving its quality and decreasing its cost in an era when quality coal is becoming scarcer. That increases the importance of applied research by coke-plant operators and scientific researchers to improve the preparation and storage of coal used in coking.

Testing methods for coal continue to be improved, so that they more closely resemble production conditions. Likewise, efforts continue to improve coke production, in part to extend the working life of the equipment employed.

Coke batteries are being renovated and replaced. New coke batteries with large ovens are going online. Dry-quenching systems are improving and are being more widely adopted.

Researchers are also focused on improving the processing of coke-oven gas and decreasing workplace pollution and the coke plant's broader environmental impact in terms of atmospheric emissions.

REFERENCES

1. Ko, K., et al., A noval approach to quantify the effect of oxidized high fluidity coal on coke strength after reaction (CSR), *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
2. Giroux, L., et al., Findings of interlaboratory study on coal dilatation under ISO/TC27 and importance of correcting experimental dilatation results to a reference coal mass, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
3. Todoschuk, T., et al., Coal rheology: a practical approach for industry, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
4. Chen, Y., An application of coke microstructure and microtexture to Indonesian coal briquette, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
5. Grimm, M., et al., Enlargement of the analysis output from a 10-kg carbonization retort, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
6. Otsuka, H., et al., Upgrading effect of aromatic amine on coal fluidity and coke strength, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
7. Schuurmans, J., et al., Control methods to reduce coke oven pressure variations, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
8. Leheut, M., et al., RPR SL Application for the treatment of microcracks in the refractory lining of coke ovens, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
9. Schulten, M., et al., Comparison between industrial and laboratory IGP measurement, Ibid.
10. Imai, D., Reconstruction of Kurashiki no. 2 coke oven batteries, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
11. Kofaro, I., The latest technology of CDQ (Coke Dry Quenching) system, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
12. Kumar, D., et al., Influence of operating parameters and raw material quality in coke making, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
13. Filippov, A., et al., New coke making complex in Russia, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
14. Lin, R., et al., Advanced coke-making process to produce coke with high quality in Germany, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
15. Li, Q., et al., First top charging Jumbo batteries erected in China by Paul Worth, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
16. Roy, A., et al., Improving the efficiency of sulfur recovery unit using aspen plus simulation, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.
17. Liszio, H., et al., Optical characterization of carbon deposits formed during targeted methane decomposition and their incorporation in the coke structure, *Proc. 4th European Steel Technology and Application Days (ESTAD) Conf., June 24–28, 2019*, Düsseldorf, 2019.

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