Coking Theory: Internal Stress in the Coal Batch

V. I. Sukhorukov

Eastern Coal-Chemistry Institute, Yekaterinburg, Russia

e-mail: vuhin@nexcom.ru

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Abstract—The development of local internal stress in the coal batch is analyzed on the basis of recent theoretical and experimental data. Its influence on coke quality is demonstrated. The influence of mineralized rock particles and large hard-to-crush particles of highly metamorphic coal (including petrographically uniform coal) is considered. The results of appropriate preparation of coal batch for coking are described.

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The main problems in coke production have been repeatedly discussed in this journal, but there has been little attention to their theoretical aspects. However, purely practical analysis of these problems is inadequate for subsequent improvement in the technology, since it does not reveal the theoretical principles responsible for the coal batch’s behavior. In fact, without a theoretical grasp of the processes, it is hardly possible to understand why a certain set of coal ranks is necessary to obtain strong coke and why certain conditions of batch preparation, coking, and coke treatment are required.

On the basis of experimental data, the primary aspects of coking theory at all stages of the process were first outlined in [1]. However, subsequent research gave rise to a theory of coking useful in the development of coking technology.

At the Eastern Coal-Chemistry Institute, theoretical concepts have been developed regarding the plastic state of the coal and also the gas-dynamic conditions in the charge, which determine the formation of vapor–gas product fluxes and determine the pressure at the furnace chamber wall in coking, as confirmed by semiindustrial and industrial research. A theory of local internal stress in the charge has been developed and used to develop new batch-preparation technologies, on the basis of crushing of the components (DK technology), differential crushing of the components (DDK technology), group crushing of the components (GDK technology), and selective crushing of the coal batch with pneumatic separation (ID PMS technology). However, this theory has not been completely formulated and requires further attention.

The basic coke-chemical principles regarding the influence of coking on the reliability and durability of the coke batteries’ refractory lining have been formulated. On that basis, a new operational strategy for coke furnaces may be developed, with raw-materials, technological, and repair aspects.

In the present work, we study the formation of internal stress, the elastic, strength, and physicochemical properties of the coke, and the influence of solid products of vapor–gas pyrolysis on the coke yield and strength.

Theoretical and industrial research permits the description of the basic aspects of industrial coking: the influence of the coking-chamber dimensions on the density and density distribution of the coal batch in practice.

On that basis, suggestions for the reconstruction, modernization, and improvement of Russian coke production may be outlined.

In this brief account, we focus on some new theoretical and scientific developments.

PLASTIC STATE OF COAL

On heating, coal is softened and clinkered as a result of the destruction of the primary macromolecular bonds, with severance of the oxygen-bearing groups, rupture of the ester and methylene bridges, and saturation of the resulting fragments with hydrogen, which is redistributed on pyrolysis [1]. The softened grains are deformed, and the contact surface area of the grains increases. Forces act between the molecules on the contacting surfaces, with the development of chemical bonds. These physical and chemical forces bind the residual coal grains into a single mass. In general outlines, this is the mechanism of coal clinking [1]. The quality of clinking may be judged from the viscosity of the plastic mass that forms, which is related to the resistance to gas motion (the gas permeability) [2]. The viscosity permits assessment of coal clinkering and is the initial parameter in analyzing the motion and pyrolysis of vapor–gas combustion products.

The transition of coal to the plastic state is similar to the flow of high-molecular compounds with a het-
erosicyclic structure of the primary chain. Softening of these materials is due to division of the chemical bonds into biradical clouds, which, on saturation, form low-molecular compounds or are recombined to create new molecular structures [3].

As for organic polymers, the pyrolysis of coal is associated with hydration and dehydration. The redistribution of hydrogen requires less activation energy than its addition from the gas phase and therefore is more likely [4]. Accordingly, the formation of free radicals and their saturation with hydrogen in the course of redistribution is the basic reason for the formation of the low-molecular plasticized materials that determine the coal’s transition to the plastic state [1].

The plastic mass of coal may be regarded as a heterogeneous system consisting of solid particles, non-volatile fluid components, and bubbles of light vapor-gas products continuously liberated from the system.

When coal passes to the plastic state in pyrolysis, lower resistance of the plastic mass to the gas pressure and hence higher gas permeability are associated with higher viscosity of the coal in the state of maximum softening [5]. This corresponds to the empirical formula

$$P = \frac{m}{\eta^n}$$  \hspace{1cm} (1)

where $P$ is the gas pressure; $\eta$ is the viscosity of the coal’s plastic mass; $m$ and $n$ are constants. This is radically different from the behavior of high-molecular thermoplastic materials and low-molecular liquids, whose gas permeability declines with increase in viscosity.

The gas permeability $\Gamma$ of the plastic mass is described by the equation [5]

$$\Gamma = -\frac{2}{9} \frac{R^2 \varphi}{1 - \varphi} \frac{\alpha e^{\frac{R}{\eta R}}}{\beta}.$$  \hspace{1cm} (2)

Here $R$ is the grain size of the coal; $\varphi$ is the porosity of the charge; $\eta$ is the viscosity; $\alpha$ is the surface tension; $K$ is the number of contacting grains; $\tau$ is the clinkering time.

We now calculate the gas permeability for different types of coal. We assume that

- for GZh26 coal $\eta = 0.6$ MPa s, $\tau = 2700$ s
- for K2 coal $\eta = 12.0$ MPa s, $\tau = 1200$ s

In these conditions, the gas permeability of the coal’s plastic mass is

- for GZh26 coal $\Gamma = 2.9 \times 10^{-4}$
- for K2 coal $\Gamma = 2.1 \times 10^{-3}$

As is evident, increase in the clinkering properties leads to sharp decrease (by an order of magnitude) in the gas permeability of its plastic mass. These data indicate that the clinkering properties are inversely proportional to the coking pressure (expansion pressure). In other words, the load on the furnace-chamber walls increases with increase in clinkering properties of the coal. However, this is a separate subject, which requires detailed consideration.

### INTERNAL STRESS IN COAL CHARGE

The theory of internal shrinkage stress has been developed in sufficient detail [1]. The basic formula takes the form

$$P = \frac{1}{3} \beta E_t \epsilon e^{-\frac{m \alpha \gamma}{b}} \phi(Bi) R_t,$$  \hspace{1cm} (3)

where $\phi(Bi) = A \sin \mu$. In bed coking, $A$ and $\mu$ are constants, in the range 1.0–1.25, while $A \sin \mu = 1$.

Thus, the internal shrinkage (bulk) stress in the charge is determined by the internal shrinkage $\beta$, the elastic modulus $E_t$, the ambient temperature $t_c$, the halfwidth of the coking chamber $b$, the thermal diffusivity $\alpha$, and the coking time $\tau$. In Eq. (3), $R_t$ is the relaxation coefficient. In other words, the stress declines with decrease in the shrinkage, the elastic modulus, the coking temperature, and the piece (bed) size and also with increase in the thermal diffusivity of the charge and the coking time.

Equation (3) characterizes the internal stress in coking and corresponds to the stress state of the material in coke formation as a function of the technological parameters.

However, the shrinkage stress is not the only type of stress in the charge. In the production of electrothermal coke, the addition of quartzite inclusions (5–10%) to the coal batch sharply reduces its strength [6]. However, the clinkering properties of the batch are unchanged. A method has been developed for calculating the local internal stress [7]. The following equations may be written

$$S = 1.5 \frac{P_{incl}^3}{r^3},$$  \hspace{1cm} (4)

$$P = \frac{a_{incl} + a_{co}}{1.5(1 + E_{incl})} (T - T_{co}) E_{co} E_{incl}$$  \hspace{1cm} (5)

or

$$S = \frac{a_{incl} + a_{co}}{1.5(1 + E_{incl})} (T - T_{co}) E_{co} E_{incl} r_{incl}^3$$  \hspace{1cm} (6)

Here $r_{incl}$ is the size of the quartzite inclusions, mm; $r$ is the distance from the center of the inclusion to the point at which the stress is determined; $P$ is the pressure created by the inclusion on the semicoke/coke mass; $a_{co}$ is the shrinkage coefficient of the semicoke on conversion to coke; $a_{incl}$ is the thermal-expansion coefficient of the inclusions; $T_{co}$ and $T$ are, respectively, the solidification temperature (the temperature of semicoke formation) and the final coking tempera-