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Heat-Transfer Coefficient for a Single Coke Piece

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Abstract—The heat-transfer coefficient for a single coke piece is determined experimentally, in the case of convective heat transfer with coolant gas. The experimental method and apparatus are described. A mechanism is proposed for the convective heat transfer of the coke piece with inert gas. The heat-transfer coefficient in the coke bed is considerably increased on account of additional turbulization of the flux.

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The heat-transfer coefficient is a fundamental characteristic of processes accompanied by heat transfer between a solid and a liquid. It largely determines the development and rate of these processes. For the heat transfer of a coke bed with inert gases, a large number of methods have been proposed for calculating the heat-transfer coefficient, on the basis of data regarding heat transfer in ideal (laboratory) conditions [1]. These methods give very different results, on account of the complexity of formulating an experiment for a coke bed, even in laboratory conditions, and the application to coke of formulas derived for other materials. In industrial conditions, extensive research on heat transfer has been conducted by Starovoit and his colleagues [2].

As yet, there has been no assessment of how mutual obstruction of the surfaces of complex coke pieces and variable size of the channels through which the cooling gas flows affect the motion of the heat carrier, the heat-transfer mechanism, and the rate of heat transfer in the coke bed. Likewise, there have been no experiments on the internal thermal stress of actual coke pieces, with their complex shape.

These topics may be addressed by studying the heat transfer of a single coke piece in ideal conditions. On that basis, we may identify means of intensifying the convective heat transfer in the coke bed.

In experiments on convective heat transfer, attention focuses on the heat-transfer coefficient, which is determined on the basis of steady and unsteady heat fluxes. Among methods based on unsteady heat fluxes, we may note the method of regular thermal conditions [3, pp. 167, 168].

In investigating the heat transfer of a single coke piece, we may employ the method of regular thermal conditions of the first kind, which has the following advantages. Experiments by this method proceed rapidly, as a rule, without the need for prolonged preliminary holding of the samples at a specified temperature. These experiments permit investigation with continuous variation in temperature to a specified value. Only one quantity is measured in the experiments: the cooling rate. There is no need to measure the body's surface temperature. This is especially expedient when studying coke pieces, which have a complex geometric outline. A major benefit of the method of regular thermal conditions of the first kind is the possibility of measuring the temperature at any point of the body. This is especially important in studying the heat transfer of coke pieces, whose shape and size differ considerably.

A downside of the method is the need for compliance with the theoretical boundary conditions in the experiments.

The mean heat-transfer coefficient for regular thermal conditions of the first kind is given by the formula [3, p. 68]

$$\bar{\alpha} = \Psi\frac{mC}{F}, \quad (1)$$

where the coefficient Ψ characterizes the nonuniformity of the body's temperature distribution; m is the cooling rate; C is the specific heat of the body; and F is the surface area of the body.

The cooling rate characterizes the relative rate of temperature variation of the body over time. At the regular stage, the dependence $\ln v = f(\tau)$ is a straight line; here($v = t - t_c$ is the excess temperature and τ is the time. Geometrically, the cooling rate is the slope of this straight line.

This formula may be used with the following boundary conditions: the ambient temperature is constant (t_c = const); and the Fourier number (dimensionless time) is

$$\mathrm{Fo} = \frac{a\tau}{R_{equ}^2} \geq 0.55,$$

where a is the thermal diffusivity; τ is the time elapsed since the beginning of the process; and R_{equ} is the body's equivalent linear dimension.

The coefficient Ψ is the ratio of the surface-mean excess temperature to the bulk-mean excess temperature of the body and is calculated as

$$\Psi = \frac{M}{\mathrm{Bi}_v} = \frac{1}{\sqrt{1 + n\mathrm{Bi}_v + \mathrm{Bi}_v^2}}.$$

Here $M = m/m_\infty$ is a dimensionless coefficient; $\mathrm{Bi}_v = \bar{\alpha} R_{equ}/\lambda$ is the Biot number; λ is the thermal conductivity; $R_{equ} = KF/V$ is the body's equivalent linear dimension; K is the form factor; F is the body's surface area; V is the body's volume; n depends on the form factor; m is the cooling rate as the Biot number tends to infinity ($\mathrm{Bi}_v \longrightarrow \infty$).

For bodies that are geometrically different—a sphere, a cylinder, a parallelepiped, etc.—n has similar values. For example, n is 1.633, 1.414, and 1.437 for a plate, a cylinder, and a sphere, respectively. Therefore, the whole set of n values may be replaced by the mean value $n_{me} = 1.437$ [4, p. 268]. We use that value in our calculations. The use of a mean n value is particularly justified for coke pieces, which have a complex geometric outline.

For bodies with a simple geometric outline, K may be calculated from the formula in [3, p. 79]. If calculation of K is impossible, a preliminary experiment is conducted with a solid sample of specified geometry, made of material with known thermophysical properties, and then an experiment is conducted with a sample of the same size and shape made from the material under investigation. Because the coke pieces have a complex geometric outline, which differs significantly from piece to piece, the use of preliminary experiments to determine K is not feasible. In that case, we try to identify the shape best corresponding to the actual coke piece. In the present work, we assume that the coke piece corresponds to a right-angled parallelepiped with sides R_1, R_2, and R_3 [5, p. 27]. The form factor is then calculated from the formula [3, p. 79]

$$K = \left[\pi^2\left(\frac{1}{R_1^2} + \frac{1}{R_2^2} + \frac{1}{R_3^2}\right)\right]^{-1} \mathrm{m}^2. \quad (2)$$

The requirements of similarity theory are satisfied in formulating the experiment and analyzing the results. The experimental dependence takes the form

$$\mathrm{Nu} \approx A\mathrm{Re}^n.$$

Here $\mathrm{Re} = \frac{wd_e\rho}{\mu} = \frac{wd_e}{\nu}$ is the Reynolds number; w is the speed of the coolant gas; d_e is the equivalent diameter of the coke piece; ρ is the density of the coolant gas; μ is the dynamic viscosity of the coolant gas; $\nu = \mu/\rho$ is the kinematic viscosity of the coolant gas; $\mathrm{Nu} = \alpha d_e/\lambda_g$ is the Nusselt number; α is the heat-transfer coefficients; and λ_g is the thermal conductivity of the coolant gas.

In the experiment, the requirements imposed by the method of regular thermal conditions are satisfied: specifically, constant ambient temperature and constant heat-transfer coefficient. We use massive apparatus, whose total specific heat is considerably greater than that of the sample. The experimental apparatus is not heated. (Only the sample is heated.) Considerable coolant flow rate is specified, so as to ensure large total specific heat of the coolant passing through the apparatus each second, which is 10–20 times the total specific heat of the coke piece. The heat-transfer coefficient is constant, because there is no change in the physical properties of the heat carrier and its linear velocity is constant (after recalculation for the free cross section).

The working chamber of the experimental apparatus corresponds to an aerodynamic tube of open type. There is a uniform distribution of the heat-carrier flow rates at entry to the apparatus. The proportion of the cross section occupied by a coke piece of maximum size is no more than 0.6%. Coke pieces of very different size and shape are selected, so as to determine the influence of the piece's shape on the heat transfer and to obtain a mean formula for the heat-transfer coefficient.

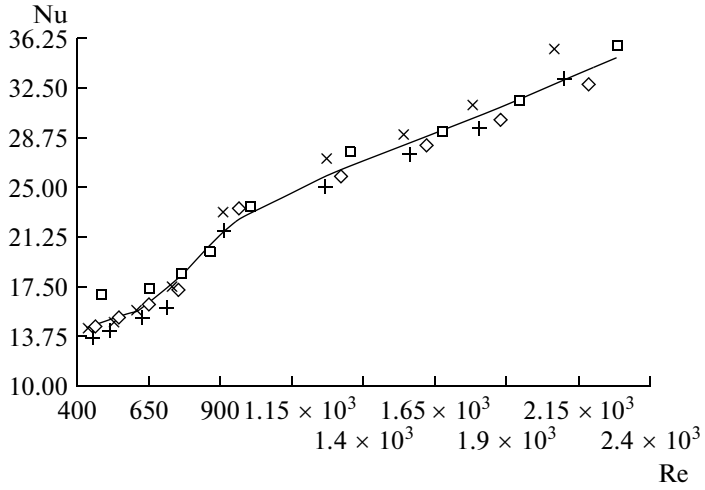
The sample sizes required for analysis of the experimental data are determined as follows. First, the shape of the coke piece is estimated. Then, the lengths of the parallelepiped's sides are measured and, after averaging the results, their ratio is determined. Knowing the volume of the coke piece and the ratio of its dimensions, the linear dimensions may be analytically calculated for subsequent calculations.

Experiments are conducted for four coke pieces (linear dimensions 10–40 mm), with the following ratios of their sides: (1) 1 : 1 : 1.6; (2) 1 : 2.58 : 3; (3) 1 : 1.27 : 3.17; (4) 1 : 1.85 : 2.32.

The total consumption of heat carrier is determined by means of a measuring diaphragm designed and positioned in accordance with [6].

The coke temperature is measured by a Chromel–Alumel thermocouple (wire diameter 0.2 mm). A hole (diameter 1.2 mm, depth 9–15 mm) is made in the coke piece to accommodate the thermocouple. No protective equipment is used in inserting the thermocouple. Electrical insulation is provided by coating the thermocouple wire with epoxy resin, which may operate satisfactorily up to 300°C. The thermocouple is fixed in the coke piece by epoxy resin, which is preliminarily solidified to a semifluid state so as to prevent steeping of the coke. The final solidification occurs in the hole. The volume of epoxy resin is no more than 0.01 ml. In the analysis of the results, a correction is introduced for the change in total specific heat of the sample on account of the hole, the wire and the thermocouple's hot junction, and the epoxy resin in the piece; this correction is no more than 0.2%.

The presence even of traces of water in the coke would lead to considerable error in determining the total specific heat of the sample. Therefore, the coke sample is dried at 160–180°C for complete moisture



Experimental results for sample 1 (+), sample 2 (×), sample 3 (□), and sample 4 (◇).

removal before each series of experiments. The drying time required is determined in preliminary experiments for each piece; the end of drying is signaled by the lack of mass variation after 30-min holding at 160°C. The sample is also held at 160–190°C for 5 min before each experiment.

After heating in a furnace, the sample is placed at the axis of the working chamber in a heat-carrier (air) flux at a certain flow rate. The sample is suspended in the chamber on the thermocouple wire, to which it is firmly attached by epoxy resin. An adjustable plate permits regulation of the sample's position in the chamber; a measuring instrument corresponding to accuracy class 1.5 is employed.

The temperature variation over time is then recorded. Preliminary calculations determine the onset of regular thermal conditions for each coke piece. A long time interval with 20–30°C temperature variation is selected; this corresponds to small change in the thermophysical properties of the coke piece. For the selected section, a straight line is plotted in the coordinates $\ln \nu = f(\tau)$ on the basis of the experimental points, by the least-squares method. The cooling rate is determined from the slope of this straight line.

In the analysis of the experimental data, we use mean data for the thermophysical parameter at the beginning and end of the temperature range. The thermal conductivity and specific heat of the coke are taken from [7]; the ash content, apparent density, and final coking temperature are taken into account here.

The linear dimension R_{equ}, which is required for calculations on the basis of Eq. (1), reflects the influence of the body's dimensions on the heat transfer within the coke piece but not on the hydrodynamic structure of the heat-carrier flow around the body. Therefore, in determining the Reynolds number, we use the mean linear dimension of the coke piece as the equivalent diameter d_e.

The increment in speed variation is chosen so that the change in Re on passing to the next experimental point is around 20% of the previous change. At each point, six experiments are conducted for each coke piece. From the set of cooling-rate values for the experiments at the given point, we determine the mean, mean-square deviation, and confidence interval.

The results are shown in the figure. As we see, the dimensions and the ratio of linear dimensions of the coke pieces have little influence on the rate of heat transfer at fixed Re (in the same hydrodynamic conditions): the experimental points for different coke pieces lie close together.

A curve is plotted through the experimental points by means of Mathcad software. The curve consists of three different sections: a shallow initial section (Re = 430–650); a convex middle section (Re = 650–1400); and a near-linear final section (Re > 1400). This form of the curve may be explained in terms of the convective heat transfer of a cylinder and a sphere.

When gas flow arrives at a cylinder, two regions with different hydrodynamic characteristics may be distinguished: a frontal zone; and a zone behind the cylinder [9, pp. 101, 102]. Over a broad range of Re—up to $Re = (1–4) \times 10^5$ [9, p. 101]—the frontal part of the cylinder is in a stable laminar boundary layer, in the absence of artificial turbulization. The motion of the flow behind the cylinder undergoes a series of transformations. Up to $Re \approx 0.5–1.5$, uninterrupted flow around the cylinder is observed; then the flow breaks away from the surface, and an eddy zone is formed behind the cylinder. There is no turbulization of the boundary layer. For the laminar boundary layer of a cylinder, a sphere, or irregular particles, $Re \approx 0.5$ [8, 10]. Beginning at $Re \approx 30–50$, the surface-area ratio between the frontal section and the rear section is more or less constant: ~45% of the total cylinder surface in the frontal section and ~55% in the rear section. At a certain Re value, determined by the turbu-

lence of the incoming flow, the state of the surface, and the angle of attack, a turbulent boundary layer is formed at the rear of the cylinder. With complete turbulization of the boundary layer at a cylinder (sphere), Re ~ 0.82 [8]. Similar gas flow is observed for a sphere.

The following formulas, obtained by analysis of copious experimental data, have been recommended for calculating the mean heat-transfer coefficient over the perimeter of a cylindrical pipe [9, p. 104]

$$\begin{aligned} \overline{\mathrm{Nu}} &= 0.49\mathrm{Re}^{0.50}, \quad \mathrm{Re} < 1000; \\ \overline{\mathrm{Nu}} &= 0.245\mathrm{Re}^{0.60}, \quad \mathrm{Re} > 1000. \end{aligned} \tag{3}$$

For a coke piece, the $\mathrm{Nu} = f(\mathrm{Re})$ curve depends on the heat transfer in the rear of the piece, since the front section is characterized by a stable laminar layer with an invariant heat-transfer mechanism at all the experimental Re values.

The initial section of the curve corresponds to laminar layer over the whole surface of the coke piece. The stable laminar boundary layer exists over a much larger range for a coke piece than for a sphere. This may be due to the surface roughness and inhomogeneity of the coke piece, which is associated with better adhesion and greater thickness of the boundary layer and correspondingly with greater thermal resistance.

The second section of the curve corresponds to flow breakaway and the development of an eddy zone behind the coke piece. On account of the surface inhomogeneity—the presence of numerous projections and depressions—this process must be accompanied by turbulization of the boundary layer at local sections (in the region of the projections).

The third section of the curve corresponds to a turbulent boundary layer at the rear of the piece. For this region, we obtain the following dependence by the least-squares method

$$\mathrm{Nu} = 0.351\mathrm{Re}^{0.596}. \tag{4}$$

As we see, the exponent in Eq. (4) is practically the same as in Eq. (3). This indicates identical development of the process and hence similar physical mechanisms of heat transfer. However, the absolute value of the heat-transfer coefficient is 1.43 times greater for the coke piece than for a cylindrical pipe, at the same Re. This may be attributed to the difference in shape and surface conditions of the coke piece and cylindrical pipe. Turbulization is more pronounced at surface projections.

Hence, we conclude that, for a single coke piece resembling a right-angled parallelepiped (a reasonable approximation in practice), the convective heat transfer resembles that for a cylinder or a sphere. The differences are mainly due to the surface state of the coke piece.

The results agree with the model for calculating the heat transfer in a coke bed that may be described by an array of cylindrical bodies in transverse flow [11, pp. 85–87].

For the mean hydrodynamic conditions of an industrial dry-slaking chamber, the heat-transfer coefficient in the coke bed is 128 $\mathrm{W/m^2}$ deg, according to the Giprokoks method [1]. For these conditions, the heat-transfer coefficient given by Eq. (4) is smaller by a factor of ~3.4. This may be attributed to turbulization of the flow in the bed on account of the sharp constrictions and turns, as well as the numerous contact points between the pieces and repeated flow breakaway [10]. For these reasons, the whole boundary layer at the surface of the coke piece involved in heat transfer is turbulized, rather than simply the rear section of the boundary layer. At fixed Re, the degree of turbulization is greater than for the rear section of a single coke piece.

Thus, the heat transfer in a coke bed is considerably intensified. This compensates for the decrease in heat transfer due to the formation of dead zones between the pieces and mutual obstruction of their surfaces.

REFERENCES

1. Grebenyuk, A.F., Golubev, A.V., and Kovalenko, D.A., 1 Analysis of Experimental Data Regarding Heat Transfer in Dry-Slaking Systems, *Uglekhim. Zh.*, 2006, no. 3/4, pp. 48–54.
2. Starovoit, A.G., Anisimov, V.A., and Goncharov, V.F., Kinetics and Cooling of Coke in a Dry-Slaking Chamber, *Koks Khim.*, 1990, no. 3, pp. 9–10.
3. Osipova, V.A., *Eksperimental'noe issledovanie protsessov teploobmena: ucheb. posobie dlya vuzov* (Experimental Study of Heat Transfer: A University Textbook), Moscow: Energiya, 1979.
4. Lykov, A.V., *Teoriya teploprovodnosti* (Theory of Heat Conduction), Moscow: Vysshaya Shkola, 1967.
5. Eidel'man, E.Ya., *Osnovy tekhnologii koksovaniya uglei* (Principles of Coking Technology), Kiev–Donetsk: Vishcha Shkola, Golovnoe Izd., 1985.
6. *Pravila izmereniya raskhoda gazov i zhidkostei standartnymi suzhayushchimi ustroistvami RD-50-2/3-80* (Rules for Measuring Gas and Liquid Flow Rates by Standard Tapered Instruments: Reference Documents RD-50-2/3–80), Moscow: Izd. Standartov, 1982.
7. Agroskin, A.A. and Gleibman, V.B., *Teplofizika tverdogo topliva* (Thermal Physics of Solid Fuel), Moscow: Nedra, 19890.
8. Chukhanov, Z.F., Heat Transfer of a Cylindrical Pipe and Sphere in a Gas Flow, *Dokl. Akad. Nauk SSSR*, 1946, vol. 52, no. 8, pp. 685–688.
9. Mikheev, M.A. and Mikheeva, I.M., *Osnovy teploperedachi* (Principles of Heat Transfer), Moscow: Energiya, 1977.
10. Chukhanov, Z.F., High-Speed Methods of Intensifying Convective Heat and Mass Transfer, *Izv. Akad. Nauk SSSR, Otd. Tekhn. Nauk*, 1947, no. 10, pp. 1341–1356.
11. Muchnik, D.A. and Postol'nik, Yu.S., *Teoriya i tekhnika okhlazhdeniya koksa* (Theory and Technology of Coke Cooling), Kiev–Donetsk: Vishcha Shkola, Golovnoe Izd., 1979.

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