10. E. T. Brook-Levinson and A. V. Zakharov, "Statistical theory of vacancies in an equilibrium crystal," Dokl. Akad. Nauk BSSR, No. 6, 514-517 (1981).
11. E. T. Brook-Levinson and A. V. Zakharov, "Statistical thermodynamics of Shottky defects in molecular and ionic crystals," Inzh.-Fiz. Zh., 44, No. 2, 244-250 (1983).
12. V. V. Belov and E. T. Brook-Levinson, "Clusters of vacancies in crystals: Statistical description," Izv. Akad. Nauk BSSR, Ser. Fiz.-Mat. Nauk, No. 6, 91-97 (1983).
13. E. T. Brook-Levinson and O. D. Chernetsov, "Vacancy correlation factor and small clusters of vacancies in an equilibrium crystal," Phys. Lett., 91A, No. 4, 171-173 (1982).
14. E. T. Brook-Levinson and O. D. Chernetsov, "Statistical theory of vacancy interactions in heavy rare gas crystals," Fiz. Nizk. Temp., 10, No. 5, 576-584 (1984).
15. L. A. Rott, Statistical Theory of Molecular Systems [in Russian], Nauka, Moscow (1979).
16. Yu. L. Klimontovich, Statistical Physics [in Russian], Nauka, Moscow (1983).
17. E. T. Brook-Levinson, "Self-consistent statistical theory of vacancies in an equilibrium crystal without using the minimum condition on the thermodynamic potential," Dokl. Akad. Nauk BSSR, 25, No. 12, 1085-1088 (1981).
18. E. T. Brook-Levinson and V. V. Belov, Statistical Theory of Equilibrium Systems at Arbitrary Densities [in Russian], Minsk (1983) (Preprint No. 3, Inst. of Heat and Mass Transfer, Academy of Sciences of the BSSR).
19. V. V. Belov and E. T. Brook-Levinson, "A statistical-mechanical explanation of crystal line structure of the heavier rare gas solids," Phys. Lett., 80A, No. 4, 314-316 (1980).
20. E. T. Brook-Levinson and V. V. Belov, "Statistical theory of thermodynamic and structural properties of molecular crystals," Inzh.-Fiz. Zh., 40, No. 1, 126-133 (1980).
21. S. Glesston, K. Leider, and G. Airing, Theory of Absolute Reaction Rates [Russian translation], IL, Moscow (1948).
22. E. H. C. Parker, H. R. Glyde, and B. L. Smith, "Self-diffusion in solid argon," Phys. Rev., 176, No. 3, 1107-1110 (1968).
23. W. M. Yen and R. E. Norberg, "Nuclear magnetic resonance of Xe^{129} in solid and liquid xenon," Phys. Rev., 131, No. 1, 269-275 (1963).
24. A. Berne, G. Boato, and M. De Paz, "Experiments on solid argon," Nuovo Cimento, 46B, No. 2, 182-209 (1966).
25. A. Berne, G. Boato, and M. De Paz, "Self-diffusion coefficient in solid argon," Nuovo Cimento, 24, No. 6, 1179-1181 (1962).
26. D. G. Cowgill and R. E. Norberg, "Pulsed NMR studies of self-diffusion and defect structure in liquid and solid krypton," Phys. Rev. B, 13, No. 7, 2773-2781 (1976).
27. A. V. Chadwick and J. A. Morrison, "Self-diffusion in solid krypton," Phys. Rev. B, 1, No. 6, 2748-2753 (1970).

CARBON COMBUSTION IN CYLINDRICAL CHANNELS WITH EDDY WASHING OF THE WALL

I. P. Basina and A. F. Katsovich

UDC 662.61.612.3

The article presents the experimentally determined dependences of carbon combustion on the wall of a model of a cyclone chamber and of the air excess number at the outlet from the model on a number of design and regime factors.

It is known [1, 2] that the combustion process of a carbon channel is the most interesting problem (the so-called "internal" problem) in studying heterogeneous combustion of carbon; its importance does not only concern the development of the theory of this process, it also has a direct bearing on the operation of real heating and technological installations. Of special interest is the investigation of the regularities of the burning of carbon in a cylindrical channel with rotary (cyclone) motion of the stream. In this case there is full analogy with the process occurring in cyclone furnaces where part of the fuel is burned after separation on the chamber wall [3]. If we take into account the known features of the interaction of the separating particles with the slag film covering the furnace wall [4] and

---

Alma-Ata Institute of Architecture and Building Construction. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 48, No. 5, pp. 832-838, May, 1985. Original article submitted March 12, 1984.

0022-0841/85/4805-0609$09.50

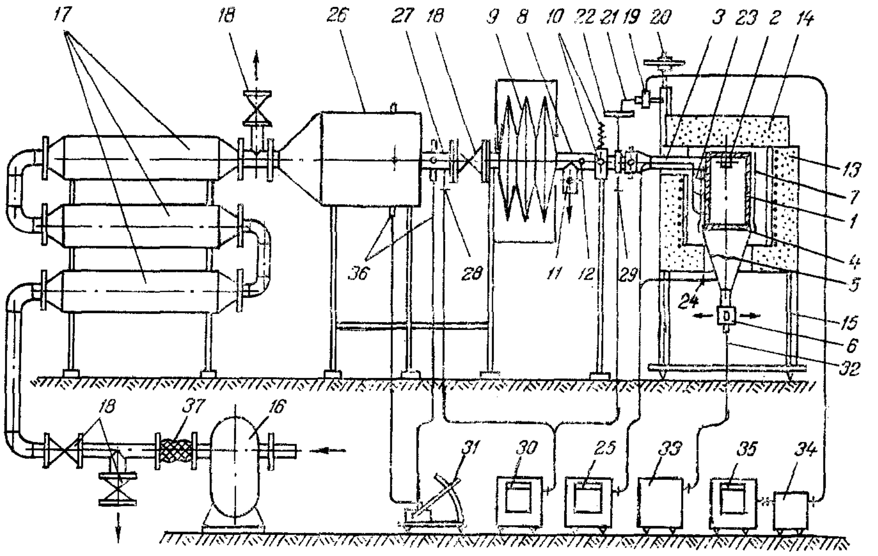

Fig. 1. Diagram of the experimental installation.

idealize the process, the combustion of carbon on the wall may be represented as burning of a cylindrical channel washed by a curving (cyclone) stream.

The present investigation was also carried out in accordance with such a model. The experimental method was based on the study of the combustion of carbon on the wall of a model of the cyclone chamber made of electrode carbon, with continuous automatic recording of small changes of the weight of the burning cylinder.

A diagram of the experimental installation is shown in Fig. 1. The basic element of the installation is the carbon cylinder 1, i.e., the model of a cyclone chamber covered on top by lid 2. The curving (cyclone) motion of the stream is ensured by the tangential feed of air through pipe 3 on which the carbon cylinder is mounted, and a flat fullering diaphragm at the outlet from the model.

In the lower part of the carbon cylinder there is the conical gas-discharge pipe 5 provided with the special annular slide valve 6. To prevent burning on the outside of the carbon cylinder, it is placed in a special course 7 made of thin heat-resistant steel sheet. The model of a cyclone thus assembled is mounted on pipe 8 of the elastic element 9, a bellows fixed at one end. To lower the level of the vibrations induced when the installation is in operation, the pipe of the elastic element 8 is extended by the damping springs 10. Mounted in pipe 8 are two slides 11 and 12 which make it possible to arrange either for air to be supplied to the model of the cyclone chamber or to discharge it into the environment. The model of the cyclone chamber is placed in the electric furnace 13 covered on top by lid 14. The design of the installation envisages the possibility of moving the furnace on special guides 15. Before the model of the cyclone chamber is mounted, the furnace is lowered on guides 15 to the extreme low position, then the model is mounted on pipe 8, the furnace is returned to its previous position and is closed by lid 14.

While the model of the cyclone chamber is mounted in the electric furnace, particular attention is given to the "free" placing of the cylinder in the pipe of the heater so that the system consisting of the air-supply pipe 3, the carbon cylinder 1, and the gas-discharge pipe 5 does not touch the inner surfaces of the furnace. The air is forced into the experimental installation by blower 16 connected through the soft insert 37, and it is heated by the electric air heater 17. The amount of draft air is controlled by valves 18; excess air is expelled into the atmosphere.

For the continuous recording of small changes of the mass of the burning cylinder, the design of the installation envisages a special measuring unit whose main element is the mechanotron 19 type 6MKh4S mounted on the raising and lowering mechanism 20. With its aid the needle of mechanotron 21 can be brought into contact with the mirror face 22 attached to pipe 8. The operating principle of the measuring unit consists in the following: under the effect of the weight of the model mounted on pipe 8, the bellows 9 assumes a certain initial deformation, after which the needle 21 of the mechanotron is brought into contact with the mirror face 22. During the experiment, in proportion to the burning out of the cylinder and the corresponding decrease of its weight, the deformation of the elastic element, the bellows, also decreases. This change of deformation is registered by the mechanotron 19.

The experiment consists of two stages: a) preliminary preparation and bringing the installation up to the specified regime; b) the experiment itself.

At the first stage the installation is brought up to the steady regime: the carbon cylinder is heated to 1273-1323°K, and the air is heated to the constant specified temperature (within the limits T_a = 473-623°K). At that time the slides 11 and 12 are put into such a position that the air, after having passed through bellows 9, is released into the atmosphere, avoiding the model of the cyclone chamber. In this case the structure of the bellows is heated to the temperature of the draft air; this eliminates any effect of the temperature factor on the nature of the deformation of the bellows under the effect of the weight of the model.

To eliminate the possibility of atmospheric air penetrating into the model of the cyclone chamber, the annular slide valve 6 was closed up to the beginning of the second stage of the experiment, and all the slits were stuffed up with fire-clay.

The second stage of the experiment starts with switching of the slides 11 and 12, after which the stream of hot air is directed into the model of the cyclone chamber. At that instant the combustion of carbon begins on the inner surface of the cylinder, and this leads to the corresponding decrease of the weight of the model, and as a consequence, to a change in the deformation of the elastic element — the bellows 9. This change in deformation is registered by the mechanotron 19 whose needle is brought into contact with the mirror face 22 at the instant the second stage of the experiment begins.

During the experiment we measured the following: the temperature of the wall of the carbon cylinder at six points and the temperature of the discharge gases with the thermocouples TPP-555 (items 23 and 24) connected to the potentiometer KSP-4 (item 25); the air temperature in the chamber of static pressure 26 and at the inlet to the model of the cyclone with the thermocouples TKhA (items 28 and 29) connected to the potentiometer KSP-4 (item 30); the flow rate, and consequently the speed of the air entering the cyclone according to the gradient of static pressures in chamber 26 and in the profile collector 27 with the micromanometer 31 via head meter 36; the composition of the combustion products collected through the gas sampling pipe 32 mounted in the gas discharge pipe 5, carried out on the gas analyzer GKhP-100 (item 33); the nature of the burning (change of weight) of the carbon cylinder during the experiment with the mechanotron 19 connected through the control instrument 34 to the potentiometer KSP-4 (item 35).

To reveal the effect of the principal geometric and regime factors in the design of the model and in the arrangement of the installation, the possibility of varying the following basic parameters is envisaged: the inner diameter of the model of the cyclone chamber D_c = 70, 80, 90, and 100 mm; the relative length of the model L/D_c = 1.25, 1.5, 1.75, and 2.0; the relative diameter of the diaphragm d/D_c = 0.3, 0.4, 0.5, and 0.6; the relative area of the nozzle for air intake $(F_{in}/F_c) \cdot 100$ = 2, 3, 4, and 6%; relative roughness k/D_c = 0.00254, 0.00223, 0.00198, and 0.00178; speed of air intake ω_{in} = 50, 70, 85, and 100 m/sec; temperature of the draft air T_{in} = 473, 523, 573, and 623°K.

Thus, the investigation is a very laborious multifactor experiment, and we therefore carried out its optimum mathematical planning by which we established the necessary sample size (determined the number of experiments), viz., 32 experiments.

The data obtained in one of the experiments, presented in Fig. 2, illustrate the qualitative pattern characteristic of all the experiments.

It can be seen from Fig. 2 that the temperature of the gases discharged from the cyclone and the temperature of the model wall increase monotonically during the experiment because the system is being heated by the combustion of the carbon. The stable composition of the discharge gases (Fig. 2b) indicates that the process is stable, and the linear change of weight of the cylinder in the course of the experiment (Fig. 2c) permits one to conclude that diffusion phenomena are of primary importance in the investigated process, i.e., the carbon combustion occurs in the intermediate region with a substantial shift toward the diffusion region.

By processing the data of the experimental investigation, carried out, as pointed out above, by the method of optimum mathematical planning, we obtained the generalized dependences

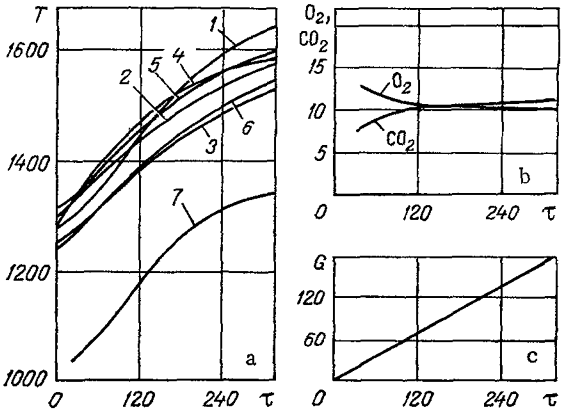

Fig. 2. Change of the temperature of the cylinder wall and of the discharged gases T (°K) (a), of the content of oxygen O_2 (%) and carbonic acid CO_2 (%) in the combustion products (b), and of the weight of the model G (g) (c) within time τ (sec): 1-6) wall temperature of the model at six points lying on diametrically opposed generatrices of the cylinder; 7) temperature of the discharged gases.

of the burning of carbon on the wall cylinder $\Delta G (\mathrm{kg/m^2 \cdot h})$ and of the air excess number α at the outlet from the model on the investigated geometric and regime factors:

$$\Delta G = \left(1{,}227 + 12{,}258\,\frac{F_{\mathrm{in}}}{F_{\mathrm{c}}}\,100\right)(0{,}0295 + 0{.}0128 w_{\mathrm{in}}) \times \left[0{,}726 + 0{,}844\,\frac{L}{D_{\mathrm{c}}} - 0{.}404\left(\frac{L}{D_{\mathrm{c}}}\right)^2\right]\left[1{,}322 - 1{,}085\,\frac{d}{D_{\mathrm{c}}} + 0{.}775\left(\frac{d}{D_{\mathrm{c}}}\right)^2\right]\left(0{,}673 + 153{,}46\,\frac{k}{D_{\mathrm{c}}}\right)(0{.}753 + 0{,}00045 T_{\mathrm{in}}) \tag{1}$$

and

$$\alpha = (7{,}262 - 0{,}0165 T_{\mathrm{in}} + 0{,}0000115 T_{\mathrm{in}}^2) \times \left(1{,}307 - 144{,}05\,\frac{k}{D_{\mathrm{c}}}\right)\left[0{,}99 - 0{,}431\,\frac{d}{D_{\mathrm{c}}} + 0{,}95\left(\frac{d}{D_{\mathrm{c}}}\right)^2\right]\left[2{,}256 - 1{.}456\,\frac{L}{D_{\mathrm{c}}} + 0{.}408\left(\frac{L}{D_{\mathrm{c}}}\right)^2\right]. \tag{2}$$

The obtained equations enabled us to establish the dependence of the intensity of the process of mass transfer (the process of carbon burning on the wall of a cylindrical channel) on the investigated parameters in the traditional criterial form:

$$\mathrm{Nu} = 0{,}00699\,\mathrm{Re}^{0{,}975}\,\mathrm{Pr}^{0{,}4}\left(\frac{T_{\mathrm{in}}}{273}\right)^{1{,}58}\left(\frac{F_{\mathrm{in}}}{F_{\mathrm{c}}}\,100\right)^{0{,}97} 10^{-0{,}00083\left(\frac{L}{D_{\mathrm{c}}}\right)^{7{,}545}}\left(\frac{d}{D_{\mathrm{c}}}\right)^{-0{,}22}\left(\frac{k}{D_{\mathrm{c}}}\right)^{0{,}389}. \tag{3}$$

As determining parameters we adopted the adiabatic combustion temperature, the tangential component of the speed of the gas stream, and the relative mean oxygen concentration in the space of the model.

The Nusselt diffusion criterion in Eq. (3) is determined in the form $\mathrm{Nu} = RD_{\mathrm{c}}\Delta G / 3600 D C \rho_{\mathrm{a}}$.

The Reynolds number (Re) and the Prandtl number (Pr) are determined as:

$$\mathrm{Re} = \frac{w_{\varphi} D_{\mathrm{c}}}{\nu_{\mathrm{a}}} \text{ and } \mathrm{Pr} = \frac{\nu_{\mathrm{a}}}{D}.$$

An analysis of the obtained dependences provides a notion of the nature and degree of the effect of the various factors on the intensity of burning of the carbon on the wall and the effectiveness of using oxygen in the model of a cyclone chamber.

As we assumed, it was found that the greater influence on the intensity of the combustion process on the wall was exerted by the "consumption" factors: the cross-sectional area of the nozzle F_{in} and the intake velocity of the air w_{in} (see Fig. 3a, b). The increasing burning of carbon on the wall with increasing air flow rate, in view of the linear nature of the burning of carbon in the course of the experiment and of the fairly high initial temperature to which the model is heated (1273-1323°K), confirm once more the prevalence of the diffusional nature of the burning of carbon.

The effect of the relative length of the model L/D_{c} on the burning of carbon is determined by the reduced intensity of burning on the wall when the length of the chamber increases (see Fig. 3c); this may be due to the poorer conditions for diffusion in consequence of the reduced curving of the flow.

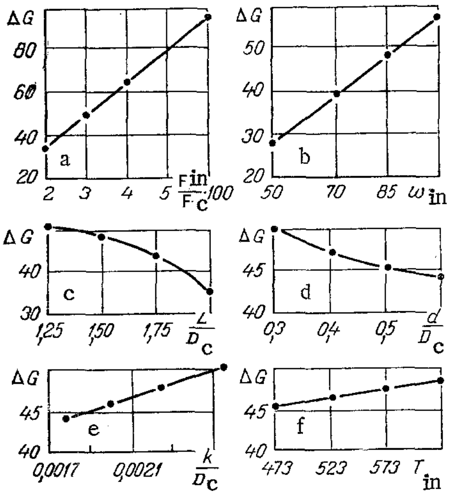

Fig. 3

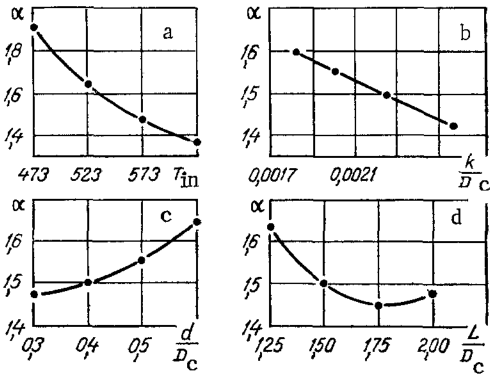

Fig. 4

Fig. 3. Dependence of specific burning of carbon ΔG (kg/m^2•h) on: a) the relative area of the intake nozzle $(F_{in}/F_c)\cdot 100$ (%); b) the inlet speed of the air w_{in} (m/sec); c) the relative length of the cylinder L/D_c; d) the relative diaphragm diameter d/D_c; e) the relative roughness of the wall k/D_c; f) the temperature of the draft air T_{in} (°K).

Fig. 4. Dependence of the air excess number α at the outlet from the model: a) on the temperature of the draft air T_{in} (°K); b) on the relative roughness of the wall k/D_c; c) on the relative diaphragm diameter d/D_c; d) on the relative length of the cylinder L/D_c.

An increase of the relative diaphragm diameter d/D_c leads to reduced intensity of burning (see Fig. 3d) because of the characteristic features of the aerodynamics of the diaphragm cyclone chamber [3], viz., the reduced curvature of the flow when the fullering diameter is increased.

It is known that increased roughness of the walls of cyclone chambers increases the overall reaction surface on the one hand; on the other hand it decreases the curvature of the eddy flow. The obtained increased intensity of burning of carbon with increased relative roughness of the model walls k/D_c (see Fig. 3e) is apparently due to the prevalent effect of the overall reaction surface under the given conditions; this is in agreement with the data of known investigations of heat and mass transfer in cyclone chambers [5].

The nature of the dependence of the intensity of carbon burning on the temperature of the air supplied to the model (see Fig. 3f) is determined by the mitigation of the deleterious effect of the nonisothermal conditions (the temperature of the air supplied to the model is lower than the initial temperature of the cylinder walls) when the temperature of the draft air rises.

The effectiveness of using oxygen in the model of the cyclone chamber is characterized by the air excess number α at the outlet from the model. An analysis of the experimental data showed that the effectiveness of using oxygen in the model of the cyclone chamber is influenced most strongly by the temperature of the draft air.

Lowering the air excess number and consequently increasing the effectiveness of the utilization of oxygen in the model coupled with the raising of the temperature of the draft air (see Fig. 4a) take effect because of the prevailing influence of the temperature factor on the intensity of diffusion of oxygen from the gas stream to the hot carbon surface: with increasing temperature of the draft air the diffusion coefficient increases.

The increased degree of utilization of oxygen (decreases of α) with increasing relative roughness k/D_c (Fig. 4b) is due to the prevailing effect of the increase of the overall reaction area in our case.

As pointed out before, an increase of the relative diaphragm diameter d/D_c leads to reduced intensity of burning of carbon on the wall of the model, and thereby the reduced degree of oxygen utilization (increased α) in the model of the cyclone chamber (Fig. 4c) is also determined.

The complex nature of the influence of the relative cylinder length L/D_c on the degree of utilization of oxygen (see Fig. 4d) is most probably due to the combined influence of two factors: increased reaction surface (length of the path and dwelling time of the gases in the model) with increasing L/D_c and the corresponding decrease in curvature of the flow. Thus, for relatively short cylinders ($L/D_c < 1.75$) the influence of the former factor was found to be decisive, and consequently an increase of L/D_c up to some known limits increases the degree of oxygen utilization (decrease of α). For long cylinders ($L/D_c > 1.75$) the decisive influence is that of the latter factor, and therefore an increase of L/D_c and the corresponding decrease in the curvature of the flow entail a decreased degree of oxygen utilization (increase of α).

NOTATION

Nu, Nusselt number; Re, Reynolds number; Pr, Prandtl number; D_c, inner diameter of the model of a cyclone chamber; L/D_c, relative length of the model; d/D_c, relative diaphragm diameter; F_{in}/F_c, relative area of the nozzle admitting air; k/D_c, relative roughness of the wall of the model; w_{in}, speed of air intake; T_{in}, temperature of the draft air; ΔG, specific burning of carbon on the wall of the model of the cyclone chamber; R, specific oxygen expenditure in the burning of carbon; D, effective diffusion coefficient; C, relative mean weight concentration of oxygen within the space of the model; α, air excess number; ρ_a, density of the gases within the space of the model at the adiabatic temperature of burning; w_φ, tangential component of the gas stream within the space of the model; ν_a, coefficient of kinematic viscosity of the gaseous medium in the model determined at the adiabatic temperature of burning; τ, time.

LITERATURE CITED

1. L. N. Khitrin, The Physics of Combustion and Explosion [in Russian], Moscow State Univ. (1957).
2. B. V. Kantorovich, Fundamentals of the Theory of Combustion and of the Gasification of Solid Fuel [in Russian], Izd. Akad. Nauk SSSR, Moscow (1958).
3. A. B. Reznyakov, I. P. Basina, S. V. Bukhman, et al., Combustion of Natural Solid Fuel [in Russian], Nauka, Alma-Ata (1968).
4. I. P. Basina and B. N. Korneev, "Interaction of fuel particles with a film of liquid slag (in connection with cyclone combustion chambers)," in: Collection of Materials of the Fourth All-Union Conference on "Combustion of Solid Fuel," Vol. 3, Nauka, Novosibirsk (1974), pp. 25-32.
5. A. V. Tonkonogii and V. V. Vyshenskii, "Investigation of convective heat exchange on models of cyclone chambers," in: Problems of Heat and Power Engineering and Applied Thermophysics [in Russian], Issue I, Izd. Akad. Nauk KazSSR, Alma-Ata (1964), pp. 183-205.