

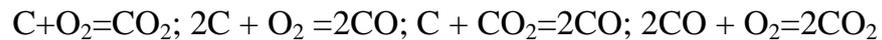
THE REGIMES OF POROUS CARBONIZED PARTICLE COMBUSTION

V. M. GREMYACHKIN

Head of the laboratory of the Institute for Problems in Mechanics,
Russian Academy of Sciences
(101, ave Vemadskii, Moscow 117526, Russia)

The process of the carbon particle combustion is a kinetic process up to rather high temperature [1-3]. Thus, the determination of the kinetics of the chemical reaction taking place in process of carbon particle combustion is the basis for the development of the theory of carbon particle combustion.

Four chemical reactions can take place in the process of carbon combustion:



The kinetics of gas-phase chemical reaction have been determined [4]:

$$\Phi_g = 1.057 \cdot 10^{-5} \exp(-27544/T) [CO][O_2]^{0.5} [H_2O]^{0.25} \quad (1)$$

where concentrations are determined in [mole/liter].

It may be considered that the kinetics of the heterogeneous chemical reaction of carbon interaction with carbon dioxide have been rather well determined too [5]:

$$\Phi_c = 740 \exp(-16748/T) [CO_2] \quad (2)$$

As regards, the kinetics of the heterogeneous chemical reactions of carbon interaction with oxygen that the results receiving in the different experiments are very contradictory. The absence of the kinetics of the heterogeneous chemical reaction of carbon with oxygen is the main hindrance for development of the theory of the porous carbonized particle combustion and gasification.

Let us consider the equations which determine the process of porous carbonized particle interaction with air in a furnace with wall heated. These conditions are the condition in what the experiments are as a rule realized. Such equations are first of all the equations of carbon atoms and oxygen atoms and heat conservation:

$$\text{div} \sum \frac{m_j I_j}{\mu_j} = \frac{\Phi S}{\mu_c} \quad (3)$$

$$\text{div} \sum \frac{n_j I_j}{\mu_j} = 0 \quad (4)$$

$$\text{div}(\sum I_j h_j + I_h) = \Phi S h_c - I_R \delta(r - R) \quad (5)$$

where $j = 1$ corresponds to CO_2 , 2 - CO , 3 - O_2 ; $I_R = \sigma(T_s^4 - T_w^4)$ is the heat flux by radiation from the particle surface to furnace wall; m_j and n_j are the numbers of the carbon and oxygen atoms in the molecular of the substance $C_{m_j} O_{n_j}$.

The expressions for fluxes of gaseous substances may be written in form

$$I_j - m z_j - \varepsilon p D \text{grad } z_j, \quad I_h = m c T - [\lambda_g \varepsilon + \lambda_c (1 - \varepsilon)] \text{grad } T$$

The next equations may be also considered:

$$\text{div } m = \Phi S \quad (6)$$

$$z_i + \sum z_j = 1 \quad (7)$$

$$\varepsilon u = -\frac{k}{\mu} \text{grad } P \quad (8)$$

The last equation is the equation for pressure alteration inside particle, as the flux of the products of the heterogeneous chemical reactions inside porous medium is connected with gradient pressure by Darcy's law.

For solution of the task it is necessary to consider the additional equation which includes the kinetics of the homogeneous and heterogeneous chemical reactions. Such equation may be the equation of oxygen diffusion

$$\text{div } I_3 = -\left(\frac{\mu_3}{\mu_c} \Phi_{o1} S + \frac{\mu_3}{2\mu_c} \Phi_{o2} S + \frac{\mu_3}{2\mu_1} \Phi_s\right) \quad (9)$$

where Φ_{o1} is the rate of carbon consumption in reaction with oxygen when the carbon dioxide is formed, and Φ_{o2} , when the carbon oxide is formed.

The system of the equations (3)-(9) must be solved with boundary conditions:

$$r = 0, u = 0, I_j = 0, I_h = 0; r = \infty, z_j = z_j^0, T = T_0 \quad (10)$$

if the kinetics of the all chemical reactions are known.

The kinetic regime of the particle combustion

In the kinetic regime of particle combustion the solution of the equations may be received in the gas phase above particle surface where the heterogeneous chemical reaction is absent. The solution received determines the distributions of the temperature and the concentrations on the coordinate in gas phase above particle surface and the dependence of the gas composition at the particle surface on the particle temperature and on the parameter $\eta_0 = m_g R / \rho D$, what determines the particle burning out rate.

The results of the experimental investigations of carbonized particle combustion are as a rule expressed in form of the dependence of particle burning out rate on the particle surface temperature and on the ambient oxygen concentration. The dependence most known and utilized in the last years is the dependence [6].

$$m_g = 7.0 \exp(-9908 / T_s) \sqrt{P \frac{\mu}{\mu_3} z_3^0} \quad (11)$$

If such dependence of the particle burning out rate on the particle temperature is taken into account that the dependence of the gas phase composition at the particle surface may be determined on the particle surface temperature only. In the experiments the alteration of the particle temperature was connected with alteration of the furnace wall temperature. For determination of the correlation between particle surface temperature and furnace wall temperature it is necessary to consider the processes inside porous particle what is impossible with kinetics of the reaction of carbon with oxygen unknown. Nevertheless, the solution of the task in gas phase may be only found for rather low furnace wall temperature T_w . It is first of all connected with equality of the oxygen concentration to zero at the particle surface and with the achievement of the rate of particle combustion the value near the rate of particle combustion in the diffusing regime ($\eta_0 = 0.1599$) [7].

Gas-phase regime of the particle combustion

On the further increasing of the furnace wall temperature the oxygen, which is

consumed in gas- phase reaction above particle surface, can not reach the particle surface and the heterogeneous chemical reaction of carbon with oxygen does not take place inside porous particle In this case the heterogeneous chemical reaction of carbon with carbon dioxide takes place only inside porous particle. This regime of particle combustion may be considered in the theory as the kinetics of the reaction of carbon with carbon dioxide is known.

At the integrating of the equations inside porous particle the next assumption had been made (1) heat flux in the solid porous medium of the particle is negligible in comparison with flux of the full enthalpy in gas, (2) the oxygen concentration inside porous particle is zero, (3) molecular regime of flow in the porous medium of the particle is realized and (4) the porosity and the internal surface of the porous medium inside particle do not depend on coordinate.

The solution of such task determines the rate of particle combustion, the particle temperature and the gas composition at the particle surface in dependence on furnace wall temperature for carbonized particle burning out in air. However, the solution of this task may be only received for rather high furnace wall temperature.

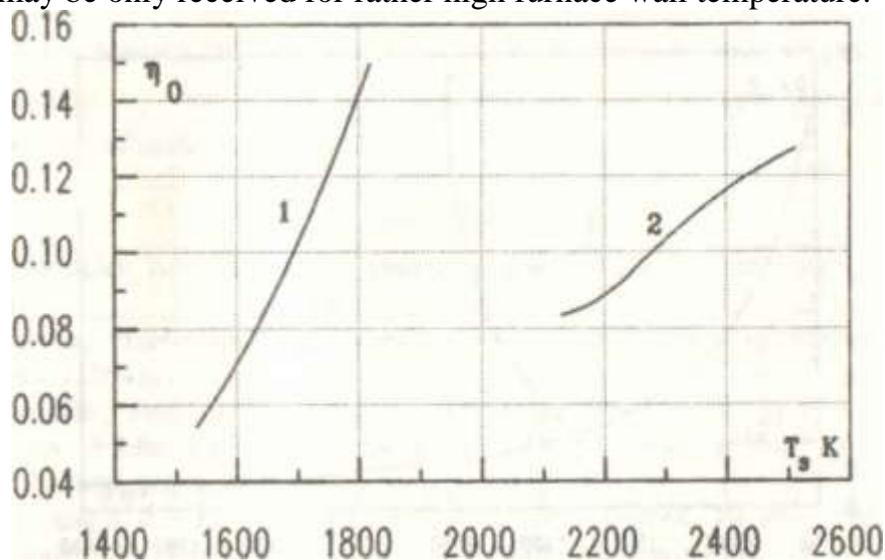


Fig.1. The dependence of the particle burning out rate on particle surface temperature for (1) kinetic regime and (2) gas-phase regime of the particle combustion for the particle having size about $100 \mu m$.

Results and Discussions

The dependence of the particle combustion rate on the particle temperature for particle diameter near $100 \mu m$ and burning out in air is shown in the Fig. 1. The curve 1 corresponds to kinetic regime of the particle combustion what is described by equation (11), but the curve 2 corresponds to gas- phase regime what is described by means of solution of the equations in gas-phase regime at high furnace wall temperature. It may be seen that the rate of the particle burning out is sharply increased in the kinetic regime of the particle combustion and that is approached to the maximum possible rate of the particle combustion in the diffusing regime ($\eta_0 = 0.1599$). In the gas-phase regime the rate of the particle burning out is smoothly increased and that reaches the maximum possible rate of the particle combustion at very high temperature. The minimum rate of the particle combustion in gas- phase regime is about half of the maximum possible rate of the particle combustion.

Thus the very sharply decreasing of the rate of the particle combustion must be

occurred when the particle temperature is increased. Such sharp decreasing of the rate of the particle combustion is connected with carbon consumption rate decreasing. In the kinetic regime the carbon is consumed as in the reaction of carbon with oxygen so in the reaction of carbon with carbon dioxide, but in the gas-phase regime the carbon is consumed in the chemical reaction of carbon with carbon dioxide only. It is necessary to mark that such sharp decreasing of the particle burning out rate was observed in the experiments where the dependence of time of the particle burning out on the particle size was investigated in the furnace with high temperature [8].

For determination the correlation between particle temperature and the furnace wall temperature in the kinetic regime and at the transition from the kinetic to the gas-phase regime it is necessary to consider the kinetics of the heterogeneous chemical reaction inside porous particle.

The domains in the space of the parameters: particle size - furnace wall temperature, in what (1) kinetic regime, (2) the gas-phase regime and (3) transition regime of the particle combustion take place, are shown in the Fig.2. As it is seen the transition regime of the particle combustion in what the particle burning out rate is sharply fallen down, takes place for particle size more than 70 μm approximately. For lower particle size the transition from the kinetic to gas-phase regime occurs smoothly without sharp alteration of the particle burning out rate.

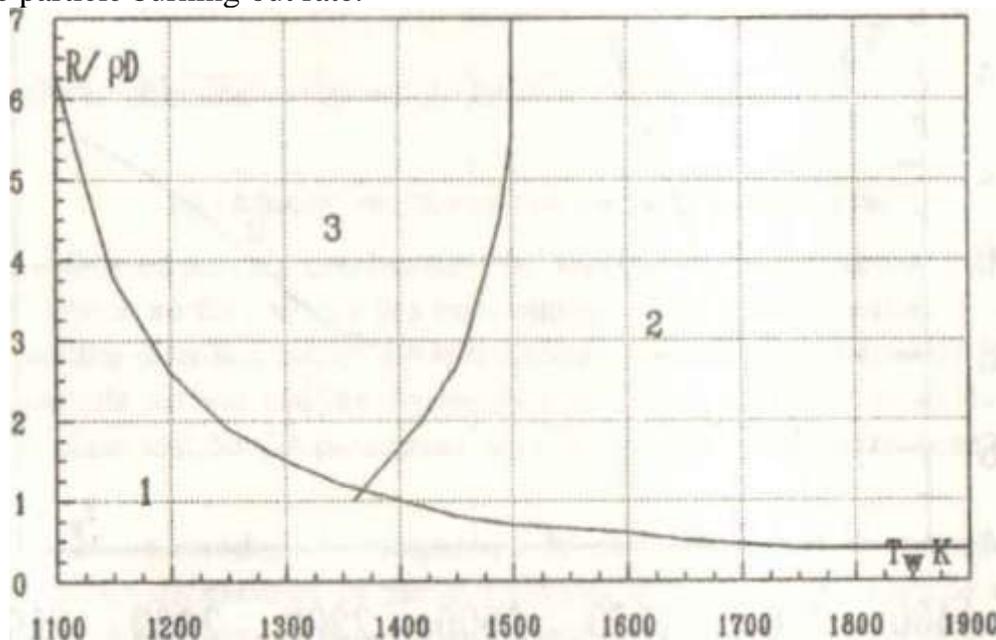


Fig. 2. The domains in space of parameter: $\xi = R/\rho D - T_w$, where (1) the kinetic regime and (2) the gas-phase regime and (3) transition regime of the particle combustion are existed

Conclusion

The model of porous carbonized particle combustion is considered. The model is based on the consideration of heat and mass transfer equations in the gas phase above the particle surface and inside porous particle.

Two regime of the particle combustion are considered: (1) the kinetic regime in what the heterogeneous chemical reactions of carbon interaction with oxygen and with carbon dioxide take place inside porous particle and (2) the gas-phase regime in what the heterogeneous chemical reaction of carbon with carbon dioxide takes place inside porous particle only and the oxygen is practically totally consumed in the homogeneous

chemical reaction above the particle surface.

The rate of the particle burning out is sharply increased in the kinetic regime and that reaches the value near the maximum possible rate of the particle combustion in diffusing regime. In the gas-phase regime of the particle combustion the rate of the particle burning out is smoothly increased and that reaches the maximum possible rate of the particle burning out at very high temperature of the furnace wall. The transition from the kinetic regime to gas-phase regime of the particle combustion occurs at the furnace wall temperature about 1300—1400 K for carbonized particle burning out in air and having size more then 70 - 80 μm

Thus the crisis of the rate of the particle combustion when the rate of the particle burning out is sharply fallen down, may be observed. The reason of the such phenomenon is the decreasing of the rate of the carbon consumption inside porous particle. In the kinetic regime the carbon consumes as in heterogeneous reaction of carbon with oxygen so with carbon dioxide but in the gas-phase regime the carbon consumes in the heterogeneous chemical reaction of carbon with carbon dioxide only.

Nomenclature

c - heat capacity of gas, D - gas diffusivity, I_j - fluxes of gaseous substances, I_h - heat flux, k - penetration of porous medium, m - mass flow of gas, m_g - mass flux of the gas at the particle surface, S - internal surface of particle porous medium, P - total pressure, T - temperature, T_s = temperature of the particle surface, T_w - temperature of furnace wall, u - gas velocity, z_j - mass concentrations, ε - porosity, μ - gas viscosity, $\bar{\eta}$ - mean molecular mass of gas, μ_j - molecular masses of substances, λ_g - heat transfer coefficient in gas, λ_c - heat transfer coefficient in solid, ρ - gas density, Φ - rate of carbon consumption,

References

1. AS.Predvoditelev, L.N.Khitrin, O.A Tsukhanova, et al. *Carbon combustion*, (in Russian), AS USSR, (1949).
2. E.S. Golovina, *High-temperature combustion and gasification of carbon*, (in Russian), Energoatomisdat, (1984).
3. N.M. Laurendau, *Progress in Energy and Combustion Sciences*, 4, 221 - 70, (1978).
4. N.V. Lavrov, E.I.Rosenfeld, G.N.Khaustovich, *The processes of fuel combustion and the defence of the ambient media*, (in Russian), Metallurgia, (1981).
5. S.Lee, J.C. Angus, R V Edwards, N.C. Gardner, *AIChE Journal*, 30, 583 - 593, (1984)
6. B.C.Young, I.W. Smith, *Eighteenth Symposium (International) on Combustion* The Combustion Institute, Pittsburgh, 1249 - 1255, (1981).
7. V.M.Gremyachkin, *Combustion, Explosion and Shock Waves*, 30,2-9,(1995)
8. V.I.Babiy, U.F.Kuvaev, *Coal dust combustion and the calculation of the coal-dust torch*, (in Russian), Energoatomisdat, (1986)