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BRIEF COMMUNICATIONS

Thermodynamics of Fuel Combustion at Tuyeres of a Blast Furnace

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Abstract—A thermodynamic analysis of fuel (carbon and methane) combustion at tuyeres of a blast furnace is made.

As is known [1], coal coke and natural gas are used as fuel in manufacture of cast iron. The combustion of coke and natural gas in the tuyere zone of a blast furnace strongly affects the entire run of a melting in a blast furnace and is highly important for control over the operation of a blast furnace. Methane, the main component of natural gas, virtually completely decomposes at temperatures exceeding 1273 K into carbon and hydrogen [2]:

$$CH_4 = C + 2H_2. \quad (1)$$

The reaction space at tuyeres of a blast furnace can be conventionally divided into two zones, oxidative and reductive. In combustion of carbon and methane in the oxidative zone, the following reactions are possible [3, 4]:

$$2C + O_2 = 2CO, \quad (2)$$

$$C + O_2 = CO_2, \quad (3)$$

$$2CO + O_2 = 2CO_2, \quad (4)$$

$$CH_4 + 3/2O_2 = CO + 2H_2O, \quad (5)$$

$$CH_4 + 2O_2 = CO_2 + 2H_2O, \quad (6)$$

$$CH_4 + 1/2O_2 = CO + 2H_2, \quad (7)$$

$$CH_4 + O_2 = CO_2 + 2H_2, \quad (8)$$

$$H_2 + 1/2O_2 = H_2O. \quad (9)$$

The combustion of carbon and methane in the reductive zone is accompanied by reactions of carbon and methane with carbon(IV) oxide and water in a gaseous state:

$$C + CO_2 = 2CO, \quad (10)$$

$$CH_4 + CO_2 = 2CO + 2H_2, \quad (11)$$

$$C + H_2O = CO + H_2, \quad (12)$$

$$CH_4 + H_2O = CO + 3H_2. \quad (13)$$

The forming carbon(II) oxide undergoes conversion:

$$CO + H_2O = CO_2 + H_2. \quad (14)$$

Here we made a comparative analysis of the standard Gibbs energies of the reactions of fuel combustion at tuyeres of a blast furnace. The standard Gibbs energies of the reactions were calculated per mole of atoms of the starting substances, as it was done in [5]. The input data for calculating the standard Gibbs energies of the reactions were taken from the reference book [6]. The results of the calculations are presented in Tables 1, 2 and Figs. 1, 2.

As seen in Fig. 1, the largest negative changes in the standard Gibbs energy in the oxidative zone at

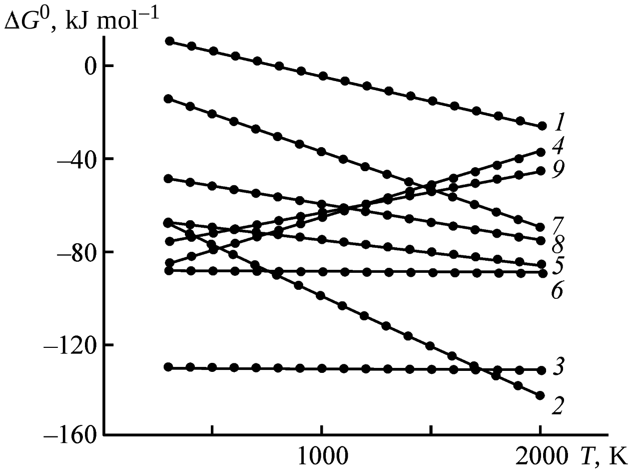

Fig. 1. Standard Gibbs energies ΔG^0 of reactions (1)–(9) vs. temperature T. Digits at curves are numbers of reactions; the same for Fig. 2.

Table 1. Standard Gibbs energies of reactions (1)–(9) in the temperature range 298–2000 K

T, K	ΔG^0, kJ mol^{-1}, for indicated reaction								
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
298	10.2	–68.6	–131.5	–85.8	–68.2	–89.2	–14.4	–49.1	–76.5
300	10.1	–68.7	–131.5	–85.7	–68.2	–89.2	–14.5	–49.1	–76.4
400	8.4	–73.2	–131.6	–82.8	–69.2	–89.1	–17.4	–50.4	–74.9
500	6.6	–77.8	–131.7	–79.9	–70.3	–89.1	–20.5	–51.8	–73.3
600	4.6	–82.3	–131.8	–77.0	–71.4	–89.1	–23.6	–53.2	–71.6
700	2.6	–86.8	–131.9	–74.0	–72.5	–89.1	–26.8	–54.7	–69.9
800	0.5	–91.3	–132.0	–71.1	–73.6	–89.1	–30.1	–56.2	–68.1
900	–1.7	–95.8	–132.0	–68.2	–74.7	–89.2	–33.3	–57.8	–66.3
1000	–3.8	–100.2	–132.1	–65.3	–75.8	–89.2	–36.6	–59.4	–64.5
1100	–6.0	–104.6	–132.1	–62.4	–76.9	–89.2	–39.9	–60.9	–62.6
1200	–8.3	–109.6	–132.1	–59.5	–78.0	–89.2	–43.2	–62.5	–60.8
1300	–10.5	–113.4	–132.1	–56.6	–79.1	–89.1	–46.5	–64.1	–58.9
1400	–12.7	–117.7	–132.2	–53.7	–80.1	–89.1	–49.8	–65.7	–57.0
1500	–14.9	–122.0	–132.2	–50.8	–81.1	–89.1	–53.1	–67.3	–55.1
1600	–17.2	–126.2	–132.1	–48.0	–82.2	–89.0	–56.4	–68.9	–53.2
1700	–19.4	–130.5	–132.1	–45.1	–83.2	–89.0	–59.7	–70.5	–51.2
1800	–21.6	–134.7	–132.1	–42.3	–84.2	–88.9	–62.9	–72.1	–49.3
1900	–23.9	–138.9	–132.1	–39.5	–85.2	–88.9	–66.2	–73.7	–47.4
2000	–26.1	–143.1	–132.1	–36.7	–86.2	–88.8	–69.5	–75.3	–45.4

high temperatures are characteristic of reactions (2) and (3). Straight line *2* [reaction (2)] intersects straight line *3* [reaction (3)] at 1750 K. To the right of the intersection point, straight line *2* runs lower than straight line *3*. This means that the chemical affinity of carbon for oxygen under the conditions of CO formation is the highest at high temperatures (above 1750 K). As temperature increases, the equilibria of reactions (4) and (9) are shifted toward formation of carbon(II) oxide and oxygen, and hydrogen and oxygen.

The standard Gibbs energy of the methane dissociation becomes negative at temperatures above 800 K, i.e., the equilibrium of reaction (1) increasingly shifts toward formation of carbon and hydrogen as temperature becomes higher. Of all the reactions of methane oxidation [reactions (5)–(8)], reaction (6), which yields carbon(IV) oxide and water, has the most negative values of the standard Gibbs energy. At low temperatures (< 700 K), the standard Gibbs energy of reaction (6) becomes even more negative than thate for reaction (2).

The results obtained in calculating the standard Gibbs energies of the reactions of carbon and methane combustion in the reductive zone of the furnace [reactions (10)–(13)] indicate that the values of ΔG^0 for

Table 2. Standard Gibbs energies of reactions (1)–(9) in the temperature range 298–2000 K

T, K	ΔG^0, kJ mol^{-1}, for indicated reaction				
	(10)	(11)	(12)	(13)	(14)
298	30.0	21.4	23.0	17.9	–5.6
300	30.0	21.3	23.0	17.8	–5.6
400	25.5	18.0	19.6	15.0	–4.8
500	21.0	14.6	16.1	12.1	–4.0
600	16.6	11.2	12.6	9.2	–3.2
700	12.1	7.7	9.0	6.1	–2.5
800	7.7	4.1	5.4	3.0	–1.8
900	3.2	0.6	1.9	–0.1	–1.1
1000	–1.2	–3.0	–1.7	–3.3	–0.5
1100	–5.5	–6.6	–5.3	–6.4	0.2
1200	–9.9	–10.1	–8.9	–9.6	0.8
1300	–14.2	–13.7	–12.5	–12.8	1.4
1400	–18.6	–17.2	–16.1	–16.0	2.0
1500	–22.9	–20.8	–19.7	–19.2	2.6
1600	–27.1	–24.3	–23.2	–22.4	3.1
1700	–31.4	–27.8	–26.8	–25.5	3.7
1800	–35.6	–31.3	–30.4	–28.7	4.2
1900	–39.8	–34.8	–33.9	–31.9	4.7
2000	–44.1	–38.3	–37.5	–35.1	5.3

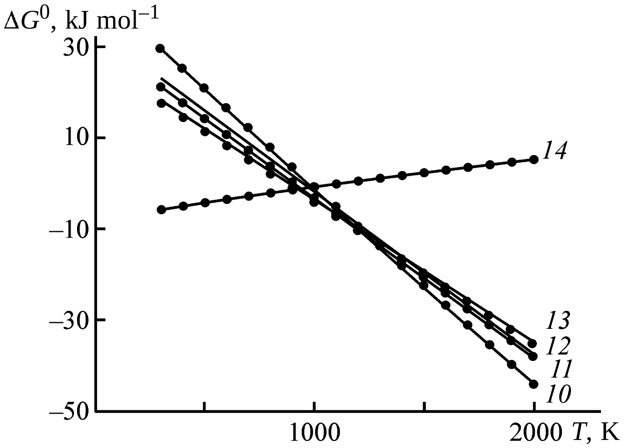

Fig. 2. Standard Gibbs energies ΔG^0 of reactions (10)–(14) vs. temperature T.

these reactions are close. At temperatures exceeding 1000 K, reactions (10)–(13) have negative standard Gibbs energies. As temperature becomes higher, the equilibria of these reactions increasingly shift toward formation of carbon(II) oxide and hydrogen. At high temperatures, reaction (14) of carbon(II) oxide conversion has positive standard Gibbs energy, i.e., gives a low yield of the reaction product [7].

Thus, thermodynamic analysis of fuel (carbon and methane) combustion at tuyeres of a blasting furnace shows that carbon(II) oxide and hydrogen must predominate in gases leaving the furnace. The experiments carried out in [8] confirm this conclusion. As a result of fuel combustion in the tuyere zone of the blasting furnace, the temperature of the gas reaches 2300 K. In this case, the content of methane and water vapor in the gas decreases nearly to zero. Carbon(II) oxide and hydrogen predominate in the reductive zone of the blasting furnace.

CONCLUSION

Thermodynamic analysis of fuel (carbon and methane) combustion at tuyeres of a blasting furnace and results of experimental studies show that carbon(II) oxide and hydrogen predominate in gases leaving the furnace.

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