

BLAST FURNACE GAS AS A PRODUCT OF PIG IRON PRODUCTION

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Abstract

One of the products of pig iron production is blast furnace gas. Its pressure energy can be used, among other things, by including an expansion turbine with subsequent production of electricity. The contribution discusses the possibilities of calculating the thermodynamic quantities of blast furnace gas as a mixture of gases. The state equation of an ideal gas does not apply accurately enough over a wide range of temperatures and pressures. The inaccuracy of the ideal gas state equation generally increases with decreasing temperature and increasing pressure. To verify the dependence of gas thermodynamic quantities on pressure and to calculate state quantities under normal conditions, I present the so-called Benedict-Webb-Rubin equation, which can be easily derivable, so that from the pressure formula it is possible very easily to obtain formulas for other thermodynamic variables, is sufficiently precise and the values of constants are set for a large number of gases.

Keywords: Pig iron, blast furnace gas, state equation, thermodynamic quantities

1. INTRODUCTION

In the case of blast furnace gas as one of the products of pig iron production, it is necessary to know its composition, temperature and pressure in order to be able to objectively assess its other possible uses. It is known that thermodynamic quantities also depend on pressure. In this paper, this dependence is examined and the aim is to determine the conclusion whether it is necessary to seriously consider this dependence or not.

2. COMPOSITION OF BLAST FURNACE GAS

The concentrations of the blast furnace gas individual components take on the following values as standard, see **Table 1**.

Table 1 Standard composition of blast furnace gas

Component	Volume part (1)	Weight part (1)
CO	0.225	0.209224807
CO ₂	0.18	0.262985863
H ₂	0.025	0.001673118
N ₂ (N ₂ +Ar)	0.56	0.520790282
CH ₄	0.01	0.005325930

From the above table it is clear that the largest part in the blast furnace gas is occupied by nitrogen. In fact, it is a mixture of nitrogen and argon from the supplied air. A small part of the CO₂ in the air is already contained in the measured proportion of CO₂ in the blast furnace gas.

The following dry air composition is considered for the calculation, see **Table 2**.

Table 2 Standard composition of dry air

Component	Volume part (1)	Weight part (1)
O ₂	0.2095	0.231450008
N ₂	0.7809	0.755267378
Ar	0.0093	0.012826775
CO ₂	0.0003	0.000455839

The other components (H₂, O₃ and inert gases Ne, He, Kr, Xe) do not need to be taken into account at all, as there are only slight traces of these gases in the air. Atmospheric nitrogen N_{2atm}, as a mixture of gases in air other than oxygen, is then assumed in the following standard composition, see **Table 3**.

Table 3 Standard composition of atmospheric nitrogen

Component	Volume part (1)	Weight part (1)
N ₂	0.987855787	0.982717306
Ar	0.011764706	0.016689578
CO ₂	0.000379507	0.000593116

As can be seen from **Table 3**, atmospheric nitrogen contains a certain amount of CO₂. It is now clear that in the case of the calculation taking into account atmospheric nitrogen, it is necessary to recalculate the share of CO₂ in the blast furnace gas to a new value, see **Table 4**. This will be smaller than the measured value of CO₂ by the part that is already part of atmospheric nitrogen.

Table 4 Recalculated composition of blast furnace gas

Component	Volume part (1)	Weight part (1)
CO	0.225	0.208679889
CO ₂	0.1797874	0.261991113
H ₂	0.025	0.001668761
N _{2atm}	0.5602126	0.52234817
CH ₄	0.01	0.005312058

3. REAL BEHAVIOR OF GASES

The state equation of an ideal gas does not apply accurately enough over a wide range of temperatures and pressures, large deviations are especially noticeable in the critical point area. The inaccuracy of the equation of state of an ideal gas generally increases with decreasing temperature and increasing pressure.

There are a number of equations of state that describe with some degree of accuracy the real behavior of gases. In this paper, I used the so-called Benedict-Webb-Rubin equation (BWR equation) to verify the dependence of thermodynamic quantities of blast furnace gas on pressure and to calculate state quantities under normal conditions.

The equations (1) to (7) can be written with a small modification according to [1,2], e.g. in the form:

$$p = \frac{RT}{v_m} + \frac{B_0RT - A_0 - \frac{C_0}{T^2}}{v_m^2} + \frac{bRT - a}{v_m^3} + \frac{\alpha a}{v_m^6} + \frac{c}{T^2 v_m^3} \cdot \left(1 + \frac{\gamma}{v_m^2}\right) \cdot e^{\frac{-\gamma}{v_m^2}} \quad (1)$$

$$u_m = u_m^0 - \frac{A_0 + \frac{3C_0}{T^2}}{v_m} - \frac{a}{2v_m^2} + \frac{\alpha a}{5v_m^5} + \frac{3c}{T^2 v_m^2} \cdot \left(\frac{1 - e^{\frac{-\gamma}{v_m^2}}}{\gamma} \cdot v_m^2 - \frac{1}{2} \cdot e^{\frac{-\gamma}{v_m^2}}\right) \quad (2)$$

$$i_m = i_m^0 + \frac{B_0RT - 2A_0 - \frac{4C_0}{T^2}}{v_m} + \frac{2bRT - 3a}{2v_m^2} + \frac{6\alpha a}{5v_m^5} + \frac{c}{T^2 v_m^2} \cdot \left[3 \cdot \frac{1 - e^{\frac{-\gamma}{v_m^2}}}{\gamma} \cdot v_m^2 + \left(\frac{\gamma}{v_m^2} - \frac{1}{2}\right) \cdot e^{\frac{-\gamma}{v_m^2}}\right] \quad (3)$$

$$s_m = s_m^0 + R \ln \frac{v_m}{RT} - \frac{B_0R + \frac{2C_0}{T^3}}{v_m} - \frac{Rb}{2v_m^2} + \frac{2c}{T^3 v_m^2} \cdot \left(\frac{1 - e^{\frac{-\gamma}{v_m^2}}}{\gamma} \cdot v_m^2 - \frac{1}{2} \cdot e^{\frac{-\gamma}{v_m^2}}\right) \quad (4)$$

$$c_{vm} = c_{vm}^0 + \frac{6C_0}{T^3 v_m} - \frac{3c}{T^3 v_m^2} \cdot \left(2 \cdot \frac{1 - e^{\frac{-\gamma}{v_m^2}}}{\gamma} \cdot v_m^2 - e^{\frac{-\gamma}{v_m^2}}\right) \quad (5)$$

$$c_{pm} = c_{vm} + R \cdot \left[1 + \frac{B_0 + \frac{2C_0}{RT^3}}{v_m} + \frac{b}{v_m^2} - \frac{2c}{RT^3 v_m^2} \cdot \left(1 + \frac{\gamma}{v_m^2}\right) \cdot e^{\frac{-\gamma}{v_m^2}}\right]^2 \cdot Q \quad (6)$$

$$Q = \left[1 + 2 \cdot \frac{B_0 - \frac{A_0}{RT} - \frac{C_0}{RT^3}}{v_m} + 3 \cdot \frac{b - \frac{a}{RT}}{v_m^2} + \frac{6\alpha a}{RT v_m^5} + \frac{c}{RT^3 v_m^2} \cdot \left(3 + \frac{3\gamma}{v_m^2} - \frac{2\gamma^2}{v_m^4}\right) \cdot e^{\frac{-\gamma}{v_m^2}}\right]^{-1} \quad (7)$$

where:

p - the pressure (MPa)

u_m - the molar internal energy of gas (kJ.kmol⁻¹)

i_m - the molar enthalpy of gas (kJ.kmol⁻¹)

s_m - the molar entropy of gas (kJ.kmol⁻¹.K⁻¹)

c_{vm} - the molar specific heat capacity of a gas at a constant volume (kJ.kmol⁻¹.K⁻¹)

c_{pm} - the molar specific heat capacity of a gas at a constant pressure (kJ.kmol⁻¹.K⁻¹)

Q - the coefficient of BWR equation (-)

Table 5 Values of gases state quantities at their critical point [3,4]

Gas	Temperature (°C)	Pressure (MPa)	Density (kg.m ⁻³)	Specific volume (m ³ .kmol ⁻¹)
CO	-140.2	3.491167	301	0.093058306
CO ₂	31	7.351065	463.9	0.094869476
H ₂	-239.9	1.294478	31	0.065030323
N ₂	-147.1	3.393101	311	0.090075241
CH ₄	-82.5	4.628739	162	0.099031049
Ar	-122.4	4.864098	531	0.075231638

A_0 , B_0 , C_0 , a , b , c , α , γ are the constants of the BWR equation characteristic for a given gas. The value of the constants together with the scope of validity are shown in **Table 6**.

The condition of temperature range and maximum pressure is met in the case of blast furnace gas expansion and for the condition of maximum reduced density, which is the ratio of density under the monitored conditions and density at the critical point, follows from **Table 5** and **Table 8**, that it is also met.

Table 6 BWR equation constants for individual blast furnace gas components [1,2]

Constant	CO	CO ₂	H ₂	N ₂	CH ₄	Ar
A_0	1.03115	2.7634	0.155164	1.1925	1.855	0.823417
B_0	0.04	0.045628	2.08463E-05	0.0458	0.0426	0.02228259
C_0	11,240	113,330	395.164	5,889.07	22,570	13,141.25
a	0.03665	0.051689	-0.0016321	0.0149	0.0494	0.0288358
b	0.0026316	0.0030819	0.000338337	0.00198154	0.00338004	0.0215829
c	1,040	7,067.2	7.26997	548.064	2,545	798.2437
α	0.000135	0.00011271	-0.000121488	0.000291545	0.000124359	3.5589E-05
γ	0.006	0.00494	0.0035073	0.0075	0.006	0.002338271

Table 7 Area of constants validity (t - temperature, max. d_r - maximum reduced density, max. p - maximum pressure) [1,2]

	CO	CO ₂	H ₂	N ₂	CH ₄	Ar
t (°C)	-25 to 200	0 to 275	-150 to 50	-163 to 200	-140 to 200	-111 to 327
max. d_r (-)	0.2	2.1		1.25	1.8	2.25
max. p (MPa)	10	70	14	85	40	80

Using the BWR equation (area of constants validity is shown in **Table 7**), the values of state quantities of the blast furnace gas individual components under normal conditions were determined - see **Table 8**. These are needed to convert volume flow to mass flow.

I verified the dependence of the thermodynamic quantities of the blast furnace gas on the pressure using the BWR equation for different temperatures in the monitored range. The following **Table 9** can serve as an example.

Table 8 Values of gases state quantities under normal conditions [5]

Gas	Temperature (°C)	Pressure (Pa)	Density (kg.m ⁻³)	Specific volume (m ³ .kmol ⁻¹)
CO	0	101,325	1.250417971	22.40095
CO ₂			1.976425283	22.267449
H ₂			0.089971256	22.406489
N ₂			1.250444471	22.402754
CH ₄			0.717489672	22.359946
Ar			1.784013627	22.392206

Table 9 Dependence of specific heat capacity c_p on pressure

Pressure (MPa)	C_p for $t=0^\circ\text{C}$ ($\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)	C_p for $t=50^\circ\text{C}$ ($\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$)
0.10	0.999494	1.009306
0.12	0.999593	1.009367
0.14	0.999692	1.009428
0.16	0.999792	1.009490
0.18	0.999891	1.009551
0.20	0.999990	1.009612
0.22	1.000089	1.009673
0.24	1.000188	1.009734

4. CONCLUSION

Calculations and mathematical modeling have confirmed that the dependence of thermodynamic quantities on pressure is negligible and does not need to be considered for common practical calculations.

Further calculations can be used to accurately determine the course of blast furnace gas expansion in the individual stages of the expansion turbine [6] and then the power of the electric generator. This is decisive for determining the return on investment for the possible use of an expansion turbine [7].

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