

ENERGETIC, PHYSICAL AND CHEMICAL PROPERTIES OF GASEOUS FUELS

Alina POPA, Sorin SOFRONIE, Alexandru DIMA

UNIVERSITY OF CRAIOVA – ROMANIA

Abstract. Gaseous fuels are mixtures of combustible gases, oxygen, nitrogen and water vapor. They may be natural or homemade. The first category includes natural gas and petroleum gases. Coke oven gas, blast furnace gas, refinery gases, gas of gas producer, hydrogen etc. are considered artificial fuels. The gas exploitation is associated with the oil operation. In terms of energy, natural gas is a clean fuel, easily extracted, transported and stored, burned almost completely with high calorific value. Romania extracts significant quantities of natural gas, but also imports for industrial and household consumption needs.

Key words: gaseous fuel, calorific power

1. COMPOSITION OF GASEOUS FUELS

It is important to know the composition of gaseous fuels for the distribution networks calculation - with or without slopes or condensing rates- or with the formation of compounds such as cryohydrates. It is recommended not to use high physicochemical magnitudes shown by appropriate tables and to resort to laboratory tests in order to determine the real size for each case.

Natural gaseous fuels extracted in Romania contain mostly methane, CH₄. For the transport network calculations and for sizing the combustion plants, the composition is reported in percent for 1 m³_N + (CH₄):

$$(\text{CO}_2) + (\text{CO}) + (\text{H}_2) + (\text{H}_2\text{S}) + (\sum \text{C}_m\text{H}_n) + (\text{N}_2) + (\text{O}_2) + (\text{H}_2\text{O}) = 100\% \quad (1)$$

The expression is in volumetric participations. In most cases the composition is expressed relative to the anhydrous state.

$$(\text{CO}_2)_{\text{anh}} + (\text{CO})_{\text{anh}} + (\text{H}_2)_{\text{anh}} + (\text{H}_2\text{S})_{\text{anh}} + (\sum \text{C}_m\text{H}_n)_{\text{anh}} + (\text{N}_2)_{\text{anh}} + (\text{O}_2)_{\text{anh}} + \dots = 100\% \quad (2)$$

Humidity is expressed in g/m³_{NC.g.anh} (normal m³ of anhydrous fuel). Calculations are performed for the composition reported to the wet state:

$$(\text{CO}_2)_{\text{nm}} + (\text{CO})_{\text{n}} + (\text{H}_2)_{\text{nm}} + (\text{H}_2\text{S})_{\text{nm}} + (\sum \text{C}_m\text{H}_n)_{\text{nm}} + (\text{N}_2)_{\text{nm}} + (\text{O}_2)_{\text{nm}} + \dots + (\text{Wt})_{\text{nm}} = 100\% \quad (3)$$

where:

$$(\text{Wt})_{\text{nm}} = 0,1244(d)100(100 + 0,1244(d)) \quad (4)$$

d = gas humidity (in g / (m³_{NC.g.anh}))

The transition from one state to another is done by multiplying the participation of each component with the conversion factor corresponding to each state.

It may be noticed the high percentage of methane and the very low content of non-combustible gas (CO₂). The fields of Transylvania with remarkable composition are important for the petrochemical industry.

2. CALORIFIC POWER

The calorific power at constant pressure is defined as the heat produced by the complete combustion of 1 m³_N of that gas so that the fuel, the combustion air and gases are at the same temperature and pressure.

Table 1

The composition of some gas wells from Romania

Gas	Composition in % by volume						
	Methane CH ₄	Ethan C ₂ H ₆	Propane C ₃ H ₈	Butane C ₄ H ₁₀	Pentane C ₅ H ₁₂	Hexane C ₆ H ₁₄	Carbon dioxide (CO ₂)
Rich gas from Prahova Boldești	78	9.24	6.23	3.46	1.10	1.77	0.20
Poor gas from Moinesti, Gura Ocnitei	95.13	1.19	1.35	0.73	0.45	0.34	-
Poor gas from Manesti, Vladeni	99.80	-	-	-	-	-	0.20
Poor gas from Aricesti	95	2	-	-	-	-	3

Table 2

Composition of reservoirs from Transylvania

Deposit	CH ₄	C ₂ H ₆	C ₃ H ₈	C ₄ H ₆	C ₅₊	Other compounds
Basin no. 1	99.92	0.06	0.02	-	-	-
Basin no. 2	99.72	0.08	0.02	-	-	0.18
Basin no.3	99.57	0.06	0.06	-	-	0.20
Sub-Carpathians area	95.26	0.79	0.79	0.53	1.69	-

Table 3

Composition of some refinery gases

Source of gas	Density (kg/m ³ N)	Composition in % by volume									
		Hydrogen H ₂	Methane CH ₄	Ethylene C ₂ H ₄	Ethane C ₂ H ₆	Propylene C ₃ H ₆	Propane C ₃ H ₈	Butylenes C ₄ H ₈	Butane C ₄ H ₁₀	Pentane C ₅ H ₁₂	Hexane C ₆ H ₁₄
Crude oil tanks	1.10	-	46.8	10.5	6.0	-	18.8	-	12.1	4.3	1.5
Petrol tanks	1.64	-	7.2	4.2	11.0	-	34.7	-	34.0	7.3	1.6
Rich cracked gas (1)	1.21	-	34.8	1.7	21.6	4.7	17.4	3.0	7.5	5.8	3.5
Rich cracked gas (2)	1.40	-	-	38.4	1.5	-	17.8	-	22.9	19.4	-
Rich cracked gas (3)	1.22	-	30.3	2.8	19.6	7.4	17.0	6.3	9.4	5.5	1.7
Rich cracked gas (4)	1.08	3.0	38.0	10.2	14.0	-	18.7	2.2	9.7	4.2	-
Poor cracked gas (1)	0.88	-	44.4	18.2	22.6	12.0	2.8	-	-	-	-
Poor cracked gas (2)	0.74	-	66.0	7.6	20.7	2.5	2.8	-	0.4	-	-
Cracked gas in the vapor phase (1)	1.26	-	25.0	-	34.9	-	21.9	-	9.8	5.3	3.1
Cracked gas in the vapor phase (2)	1.27	9.0	28.0	20.0	14.0	15.0	3.0	8.5	1.0	-	-
Cracked gas from the liquid-vapor phase (1)	-	3.0	50.0	2.0	17.0	9.0	10.0	4.0	5.0	-	-
Rich gas, crude oil stabilization (1)	0.67	-	82.5	-	10.6	-	5.1	-	1.8	-	-
Rich gas, crude oil stabilization (2)	0.61	-	93.3	-	3.8	-	2.2	-	0.7	-	-

Calorific power is determined experimentally or by calculation based on the elementary composition. For the combustion plants the lower calorific power is important and is determined using the relationship:

$$Q_i = 1/100(\sum r_i Q_{i,i} - 2,5W_t \cdot \rho_{H_2O}) \quad (5)$$

where: 2.5 MJ / kg is the water latent heat of vaporization in normal conditions; $Q_{i,i}$ – the lower calorific power of the fuel gas in MJ/m³N; W_t – the total water content in %; r_i – the volume participation of component i .

Lower calorific power of some elementary fuels is given in Table 4.

For hydrogen, the upper calorific power is: $Q_s = 143846$ kJ / m³N.

3. DENSITY

Fuel gas density for normal state is calculated using the expression:

$$\rho_c = 1/100\sum r_i \rho_i \quad [\text{kg/m}^3\text{N}] \quad (6)$$

where: r_i – volumetric participation of component i ; ρ_i – density of component i in [kg/m³N].

Table 4

Lower calorific power of some elementary fuels

Name	Chemical formula	Lower calorific power	
		kJ / m ³ N	kcal / m ³ N
Hydrogen	H ₂	10760	2570
Carbon dioxide	CO	12635	3018
Hydrogen sulfide	H ₂ S	23381	5585
Methane	CH ₄	35707	8529
Ethane	C ₂ H ₆	63 572	15185
Propane	C ₃ H ₈	91023	21742
Butane	C ₄ H ₁₀	118 339	28281
Pentane	C ₅ H ₁₂	145787	34818
Ethylene	C ₂ H ₄	59 461	14203
Propylene	C ₃ H ₆	86402	20638
Butylenes	C ₄ H ₈	113706	27160
		kJ / kg	kcal / kg
Carbon	C	37800	8100
Sulfur	S	10450	2500
Hydrogen	H	121226	29000

For other thermodynamic state, defined by temperature T [°C] and pressure p [bar, 10^5 Pa] fuel density is determined by the relationship:

$$\rho = \rho_c \cdot 273,15 / (273,15 + t) p / 1,01325 \text{ [kg/m}^3\text{N]} \quad (7)$$

For a mixture of combustible gases, weighted average relative to the anhydrous state is calculated using the expression:

$$\begin{aligned} \rho^{anh} = & \sum_{i=1}^n r_i \rho_i = 0,01964(\text{CO}_2)^{anh} + \\ & + 0,0152(\text{H}_2\text{S})^{anh} + 0,01427(\text{O}_2)^{anh} + \\ & + 0,1251(\text{N}_2)^{anh} + 0,0125(\text{CO})^{anh} + \\ & + 0,0009(\text{H}_2)^{anh} + 0,00716(\text{CH}_4)^{anh} + \end{aligned} \quad (8)$$

$$+ 0,0134(\text{C}_4\text{H}_6)^{anh} + \dots \quad \left[\text{kJ/m}^3\text{c.g.anh} \right]$$

Table 5 shows values of the density relative to anhydrous state for several artificial gaseous fuels.

4. SPECIFIC HEAT

It represents the average value at constant pressure relative to normal cubic meter, in the temperature range $(0 - t)^\circ\text{C}$.

$$c_c = \frac{1}{100} \sum_{i=1}^n r_i c_i \quad [\text{kJ}/(\text{kg}\cdot\text{K})] \quad (9)$$

where c_c is the average specific heat of component i at constant pressure, in the temperature range $(0-t)^\circ\text{C}$

Table 5

Density relative to anhydrous state for artificial gaseous fuels

Name of gases	Composition in % by volume								Density of dry gas, ρ_{anh} [kg/m ³ N]
	CO	H ₂	CH ₄	C _m H _n	H ₂ S	CO ₂	O ₂	N ₂	
1. Gas-producer									
Large pieces of Donetsk anthracite	27.5	13.5	0.5	-	0.2	5.5	0.2	52.6	1.135
Charcoal from Moscow Basin	25	14	2.2	0.3	1.2	6.5	0.2	50.6	1.130
Celeabinsk charcoal	30	113	2	0.2	0.2	5	0.2	49.4	1.128
Hydro-peat pieces	24.5	15	2.5	0.4	0.1	8.5	0.2	45.8	1.127
Peat pieces in machined shapes	28	15	3	0.4	0.1	8	0.2	45.3	1.121
Kindling wood	29	14	3	0.4	-	6.5	0.2	46.9	1.122
Gas-producing with fluidized bed of small coal pieces (0-6 mm) from Moscow Basin	21.7	7.1	1.1	-	0.4	6.9	0.2	62.2	1.217
Milled peat	20.3	10.9	1.9	0.7	-	9.8	0.2	56.2	1.188
2. Water gaz:									
Coke	37	50	0.5	-	0.3	6.5	0.2	5.5	0.715
Anthracite	38.5	48	0.5	-	0.5	6	0.2	6.3	0.736
3. Water gaz	27	46	7.5	0.7	15	15	3.5	-	1.1499
4. Air gaz	32.5	0.7	-	-	1	1	-	65	-
5. Underground gasification gas									
Charcoal from Moscow Basin	10	14.5	1.8	-	0.6	9.5	-	63.6	1.146
Coal	18.4	11.1	1.8	-	0.6	10.3	0.2	57.6	1.191
6. Gas of low-temperature carbonization									
Peat	16	20	19.5	1.7	41.3	41.3	-	1.5	-
Charcoal from Moscow Basin	7.8	9	28	3.5	50	50	-	1.7	-
Coal from Jidova-Pescareasca	13.7	9	17	2.6	46	47.5	-	3.9	-
Glossy brown coal from Comanesti	10.2	12.1	26.1	3.3	5.5	37.9	-	5	-
Gas coal from Lupeni	5.6	13.3	48.8	6.3	3.6	13.6	-	5.7	-
7. Gas of coking									
Impure	6.8	57	22.3	2.73	0.4	2.3	0.8	7.7	0.507
8. Mixed gas (of mixture)									
Jiu Valley coal	26.5	13.5	1.8	0.3	1	6	0.2	50	-
Brown coal from Comanesti and lignite	27.5	14.5	1.8	0.2	1	5.5	0.2	49	-
Anthracite or coke	26.5	13.5	0.5	-	0.2	5.5	0.2	52	-

Table 5 (continued)

Name of gases	Composition in % by volume								Density of dry gas ρ_{anh} [kg/m ³ N]
	CO	H ₂	CH ₄	C _m H _n	H ₂ S	CO ₂	O ₂	N ₂	
9. Blast furnace gas									
Coke	28	2.7	0.3	-	0.3	10.5	-	58.5	1.296
Charcoal	27	8	1.6	-	-	12	-	51.4	1.238
10. Gas of oil pyrolysis	0.8	14	41	4.3	-	0.5	-	0.2	0.996

Table 6

Specific heat relative to anhydrous state of gaseous fuels combustible components

t(°C)	C _{H2}	C _{H2S}	C _{CH4}	C _{C2H6}	C _{C3H8}	C _{C4H10}	C _{C5H12}	C _{CO}
0	1,276	1,506	1,548	2,210	3,047	4,127	5,12	1,299
100	1,289	1,532	1,640	2,494	3,507	4,705	5,83	1,302
200	1,297	1,561	1,758	2,775	3,946	5,253	6,41	1,307
300	1,297	1,595	1,883	3,043	4,370	5,772	7,13	1,317
400	1,297	1,632	2,017	3,306	4,759	6,266	7,73	1,329
500	1,306	1,670	2,139	3,953	5,094	6,689	8,25	1,343
600	1,306	1,707	2,260	3,775	5,429	7,112	8,78	1,357
700	1,310	1,745	2,377	3,985	5,722	7,484	9,23	1,372
800	1,314	1,783	2,494	4,181	5,985	7,806	9,62	1,386
900	1,322	1,816	2,603	4,361	6,228	8,112	9,98	1,400
1000	1,326	1,850	2,699	4,529	6,458	8,401	10,34	1,413

Specific heat relative to the initial state is calculated with the relationship:

$$c^i = \left(c^{anh} + 0,001244d \cdot c_{H_2O} \right) \frac{100}{100 + 0,1244d} \quad \left[\text{kJ} / (\text{m}^3_N c \cdot g_{um} \cdot \text{K}) \right] \quad (10)$$

where:

$$c^{anh} = \sum_{i=1}^n r_i c_i^{anh} \quad (11)$$

Specific heat data relative to anhydrous state of gaseous fuels components are shown in Table 6.

5. THERMAL CONDUCTIVITY

Its values were experimentally determined and are shown in Table 7.

6. KINEMATIC VISCOSITY

It is used for the flow section and the equivalent diameter calculation. Reynolds criterion for the flow hydrodynamic regime estimation is calculated using the expression:

$$Re = w \cdot d_{ech} / \nu \quad (12)$$

where: w is the flow speed (m/s); d_{ech} – the equivalent hydraulic diameter (m); ν is the kinematic viscosity, in (m²/s).

The equivalent hydraulic diameter is calculated using the expression:

$$d_{ech} = 4 \cdot S / P \quad (\text{m}) \quad (13)$$

where: S is the sectional area through which the gas flows (m²); P – wetted perimeter (m).

In Table 8 there are given the kinematic viscosity values for some gases.

Table 7

Thermal conductivity $\lambda \cdot 10^2$ [W/(m.K)]

Gaseous fuel	Temperature [°C]										
	0	100	200	300	400	500	600	700	800	900	1000
Thermal conductivity $\lambda \cdot 10^2$ [W/(m.K)]											
Blast furnace gas	2,13	2,77	3,39	3,99	4,57	5,14	5,70	6,25	6,79	7,32	7,84
Coke oven gas											
Pure	6,85	8,95	11,0	12,9	14,8	16,7	18,6	20,4	22,2	24,0	25,7
Crude	6,83	8,93	10,9	12,8	14,7	16,6	18,5	20,3	22,1	23,9	25,6
Pipeline Natural Gas											
Saratov - Moscova	2,38	3,43	4,52	5,67	6,84	8,05	9,29	10,6	11,9	13,2	14,5
Daşava - Kiev	2,51	3,62	4,77	5,98	7,21	8,49	9,79	11,1	12,4	13,8	15,2

Table 8

Kinematic viscosity											
Temperature [°C]											
Gaseous fuel	0	100	200	300	400	500	600	700	800	900	1000
Kinematic viscosity $\nu \cdot 10^6$, (m ² /s)											
Blast furnace gas	12,7	21,7	32,9	45,8	60,0	76,7	94,2	113	135	157	181
Coke oven gas											
Pure	25,9	44,2	66,7	92,9	122	156	193	233	273	319	368
Crude	24,6	41,6	64,1	89,2	117	149	185	223	264	307	353
Pipeline Natural Gas											
Saratov - Moscova	12,2	21,1	32,3	45,0	60,2	77,0	95,7	117	138	161	186
Daşava - Kiev	14,3	24,6	37,7	52,6	70,3	90,0	112	136	161	188	217

7. PRANDTL CRITERION

It is used to calculate the coefficient of heat transfer by convection. Pr is the ratio of kinematic viscosity and thermal diffusivity:

$$Pr = \nu/a \quad (14)$$

Its values are dependent on the nature of the fuel as follows:

- Carbon monoxide: CO + air: 650°C;
- Methane: CH₄ + air: 800°C;
- Ethane: C₂H₆ + air: 550°C;
- Propane: C₃H₈ + air: 550°C;
- Acetylene: C₂H₂ + air: 350°C.

8. AUTO-IGNITION TEMPERATURE OF THE AIR-FUEL MIXTURE

Self-ignition temperature is the temperature of ignition of the mixture of the enthalpy of the air-fuel mixture.

As natural gas in Transylvania comprises 98 and 99% CH₄, being the purest fuel in the world, its physical and chemical characteristics are closed to those of pure methane as shown in Table 10.

Table 9

Prandtl criterion											
Temperature [°C]											
Gaseous fuel	0	100	200	300	400	500	600	700	800	900	1000
Prandtl criterion Pr											
Blast furnace gas	0.682	0.672	0.668	0.665	0.668	0.673	0.678	0.682	0.686	0.690	0.693
Coke oven gas											
Pure	0.425	0.430	0.440	0.454	0.465	0.475	0.483	0.493	0.500	0.507	0.514
Crude	0.420	0.429	0.440	0.455	0.467	0.477	0.486	0.495	0.503	0.510	0.517
Pipeline natural Gas											
Saratov - Moscova	0.709	0.708	0.738	0.768	0.792	0.816	0.832	0.842	0.849	0.856	0.863
Daşava - Kiev	0.735	0.734	0.763	0.797	0.836	0.862	0.886	0.904	0.917	0.925	0.928

Table 10

Characteristics of pure methane and natural gas from Transylvania

Characteristics	Pure methane	Natural gas from Transylvania
Molar mass	16,04	16,13
Density under normal conditions [kg/m ³ _N]	0,716	0,716
Density at 15 °C and 0.1 MPa [kg/m ³]	0,678	0,678
Relative density	0,554	0,554
The gas constant, R [kJ/m ³ /kgK]	59,2	59,2
Kinematic viscosity under normal conditions [cm ² /s]	14,49*10 ⁻⁶	-
Viscosity at 20°C [cm ² /s]	16,57*10 ⁻⁶	-
Specific heat, c_p , at $p = 0.1$ MPa and $T = 0^\circ\text{C}$ [kJ/m ³ _N grd]	1,545	-
Specific heat c_v [kJ/kg grd]	1,633	-
The Ratio c_p/c_v	1,319	1,315
Solidification temperature [°C]	-184	-184
Boiling temperature [°C]	-165	-165
Thermal conductivity [kJ/m h grd]	0,1084	-

Table 10 (continued)

Characteristics	Pure methane	Natural gas from Transylvania
Critical temperature [°C]	-82	-
Critical pressure [MPa]	5,6	4,5
High calorific pressure [kJ/m ³ _N]	39808	39871
Lower calorific pressure [kJ/m ³ _N]	35764	35772
Ignition temperature at 0.1 MPa, when it is mixed with air [°C]	650-750	-
Theoretical volume of air needed for combustion [m ³ _N / m ³ _N]	9,52	-
Burning rate [m/s]	0,39	-
Water resulting from the burning [kg/m ³ _N]	1,6	-
Limits of explosion, in [%] of methane in air (in volume)	5...15	5...15,4
Explosion wave speed [m/s]	2300	-
Explosion temperature [°C]	1445	-
Theoretical combustion temperature [°C]	2050	-

9. CONCLUSIONS

The fuel energy properties have to be known in order to design a gaseous fuel combustion plant. Their determination is made using laboratory equipment with performance of high precision. A high performance combustion plant is projected knowing all the characteristics of the fuel which will be used. Combustible gas distributors assume the responsibility for the gaseous fuels delivered to consumers.

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