BOILERS

EXAMPLE No. 3

GAS COMBUSTION AND GENERATION OF EXHAUST COMBUSTION PRODUCTS

Combustion – rapid biogas exothermic oxidation reactions occurring at high heat emissions. Combustible materials shall be those which during the oxidation, the emitted heat is sufficient to support spontaneous combustions reactions.

Reactions involving an *oxidizer* and *fuel*.

Oxidizing agents are atmospheric oxygen in the air, and the *oxidized* – combustible fuel elements.

Fuel or its elements, air, oxygen, nitrogen and other components of the composition may be measured by mass or by volume units, e.g. kg or n. m^3.

Density is used during the conversion from one unit to another.

Drawing up the balance of the combustion process equality, the oxygen involved in the oxidation reaction is assessed as well as nitrogen, part of air composition. Air consists of nitrogen, oxygen, hydrogen, carbon dioxide and inert gases. Due to the theoretical calculations, hydrogen, carbon dioxide and inert gases (forming all together 1% in the air) refer to nitrogen which of 78% is in the air.

It can be stated that the air consists of 21% oxygen and 79% nitrogen.

Consequently, 1 m^3 of air requires 3,76 nitrogen volume (79/21 = 3,76) or 1 – st mole of oxygen requires 3,76 mole of nitrogen, this results air composition in the combustion reaction as follows:

$$O_2 + 3,76N_2$$

Solving practical workshop cases, it is necessary to know the amount of air required for one mass or volume unit combustion of combustible material and the percentage composition of the produced combustible products.

Practical workshop goal:

Calculations are necessary to determine how much oxygen and nitrogen in the atmospheric air needed in the combustion process, the amount and type of combustion products produced.

In this calculation example, the gas (which contains – in Table 1) is burnt in the combustion unit and the generated high-temperature gases are directed to the gas turbine; combustion products (Table 2) from the gas turbine are directed into the boiler – utilizer. Combusted gas lowest calorific value (LCV) 50.000 kJ / kg.

Table 1

Combusted gas composition, %			
CH_4	C_2H_6	C_3H_8	C_4H_{10}
98	1,9	0,5	0,4

The table is compiled according [B. 1]

Table 2

Exhaust gas composition, %				Exhaust products content, kg/h	Exhaust products temperature, °C
CO_2	H_2O	N_2	O_2	400,00	600
3,0	8,0	78,0	13,0		

The table is compiled according [B. 1]

1. Calculating the optimum ratio of fuel and oxidizer burning methane (CH_4); oxidizer – Oxygen (O_2).

Table 4

The molar mass of a molecule, g/mol				
H	C	O	CH_4	O_2
1,0	12	16	16	32

Combustion reaction – **methane / oxygen**:

For complete combustion of one methane molecule 2 oxygen molecules are required:

The molar mass of the gas is calculated:

$$\frac{m_{O2}}{m_{CH4}} = \frac{V_{O2} \times M_{O2}}{V_{CH4} \times M_{CH4}} = \frac{N_{O2} \times M_{O2}}{N_{CH4} \times M_{CH4}} = \frac{2 \times 32}{1 \times 16} = \mathbf{4,0}$$

N – Number of material structural units (molecules) needed in the combustion reaction.

In this case, the volume ratio of oxygen to methane volume is equal to 2, e.g. the combustion of 1 m^3 of methane requires 2 m^3 oxygen.

2. Air, containing oxygen is used for fuel combustion in the unit, not the oxygen. The percentage of O_2 content (mass) in the air is 23,2%.

The ratio of oxygen and air is determined:

$$\Delta = \frac{m_{O2}}{m_{oro}} = 0{,}232$$

If this ratio is multiplied by a combustible gas (index "dd") mass in order to burn, we get the following:

$$\Delta = \frac{a^{m}_{O2-dd}}{a^{m}_{air-dd}}$$

$$a_{air-dd}^{m} = \frac{a_{O2-dd}^{m}}{0,232}$$

$$a_{air-CH4}^{m} = 4,0$$

Then

$$a_{air-CH4}^{m} = \frac{4,0}{0,232} = 17,24$$

Conclusion:

17,24 kg of air required to burn 1 kg of methane; 9,512 m^3 of air required to burn 1m^3 of methane:

$$\frac{4,0}{0,232} \times \frac{16}{29} = 9,512$$

Air molar mass M_{air} = 29 g/mol.

3. Calculating the optimal fuel and oxidizer ratio (combustion reaction):

- methane combustion:

$$CH_4 + 2O_2 \rightarrow 2H_2O + CO_2 + \text{heat}$$

$$\frac{m_{O2}}{m_{CH4}} = \frac{2\times32}{16} = 4{,}0 \text{ kg O}_2$$

- **ethane combustion:**

$$2C_2H_6 + 70_2 \rightarrow 4CO_2 + 6H_2O$$

$$\frac{m_{O2}}{m_{C2H6}} = \frac{7\times32}{2\times30} = 3{,}733 \text{ kg } \mathrm{O_2}$$

- **propane combustion:**

$$\mathrm{C_3H_8} + 5\mathrm{O_2} \rightarrow 3\ CO_2 + 4H_2O$$

$$\frac{m_{O2}}{m_{C3H8}} = \frac{5\times32}{1\times44} = 3{,}636 \text{ kg } \mathrm{O_2}$$

- butane combustion:

$$C_4H_{10} + 6{,}5O_2 \rightarrow 4\,CO_2 + 5H_2O$$

$$\frac{m_{O2}}{m_{C4H10}} = \frac{6{,}5\times 32}{1\times 58} = 3{,}586 \text{ kg } O_2$$

4. The exhaust gas composition is converted into a form of volumetric to mass:

$$M = 0{,}03 \times 44 + 0{,}08 \times 18 + 0{,}78 \times 28 + 0{,}13 \times 32 = 28{,}76$$

Molecular gas composition is calculated :

$$CO_2 = 12 + 2 \times 16 = 44$$

$$H_2O = 1 \times 2 + 16 = 18$$

$$N_2 = 14 \times 2 = 28$$

$$O_2 = 16 \times 2 = 32$$

5. Proportion of the gaseous components in the exhaust gas:

$$CO_2 = 0{,}03 \times \frac{44}{28{,}76} = 0{,}046$$

$$H_2O = 0{,}08 \times \frac{18}{28{,}76} = 0{,}050$$

$$N_2 = 0{,}78 \times \frac{28}{28{,}76} = \ 0{,}759$$

$$O_2 = 0{,}13 \times \frac{32}{28{,}76} = 0{,}145$$

6. Combustion product enthalpy, kJ / kg at 600°C (Table 4):

$$h_d = 0{,}046 \times 146{,}4 + 0{,}050 \times 283 + 0{,}759 \times 151{,}6 + 0{,}145 \times 139 = 156{,}1 \times 4{,}187 = 653{,}61$$

Table 4

Exhaust gas enthalpy h, kcal/kg (× 4,187 kJ/kg)

Combustion products	Temperature, °C									
	100	200	300	400	500	600	700	800	900	1000
CO_2	18,0	40,8	65,2	91,1	118,2	146,4	175,5	205,4	235,9	267,0
H_2O	37,7	83,7	131,3	180,4	231,0	283,0	336,6	391,6	448,1	506,2
N_2	20,9	46,1	71,8	97,9	124,5	151,6	179,1	207,0	235,4	264,2
O_2	18,7	41,5	65,0	89,1	113,8	139,0	164,7	190,7	217,0	243,6
SO_2	13,0	29,5	47,0	65,3	54,5	104,2	124,5	145,1	166,1	187,2

The table is compiled according [B. 1, table F.11]

Passing exhaust gas *mass*, kg/h, to the combustion unit is calculated:

$$CO_2 = 0{,}046 \times 400{,}0 = 18{,}40$$

$$H_2O = 0{,}05 \times 400{,}0 = \ 20{,}00$$

$$N_2 = 0{,}759 \times 400{,}0 = 303{,}60$$

$O_2 = 0{,}145 \times 400{,}0 = \ 58{,}00$ (oxygen mass in the gas).

7. Fuel gas composition is converted from volumetric to mass:

$$MW_f = 0{,}98 \times 16 + 0{,}019 \times 30 + 0{,}005 \times 44 \ + 0{,}004 \times 58$$
$$= 16{,}70$$

Molecular composition :

$$CH_4 = 12 + 4 = 16$$
$$C_2H_6 = 12 \times 2 + 6 = 30$$

$$C_3H_8 = 12 \times 3 + 8 = 44$$

$$C_4H_{10} = 12 \times 4 + 10 = 58$$

O_2 = 0,145 x 400,0 = 58,00 kg/h (oxygen mass in the gas).

8. Proportion of the gaseous elements in the fuel, kg/h:

$$CH_4 = 0{,}98 \times \frac{16}{16{,}70} = 0{,}939 \times 32{,}08 = 3{,}006$$

$$C_2H_6 = \ 0{,}019 \times \frac{30}{16{,}70} = 0{,}036 \times 32{,}08 = 1{,}16$$

$$C_3H_8 = \ 0{,}005 \times \frac{44}{16{,}70} = 0{,}027 \times 32{,}08 = 0{,}866$$

$$C_4H_{10} = 0{,}004 \times \frac{58}{16{,}70} = 0{,}014 \times 32{,}08 = 0{,}446$$

9. 4,0 kg of oxygen is required to burn 1 kg of methane (CH_4). Oxygen content for the combustion of elements, kg/h, is calculated:

$$1\,kg\,CH_4 = 3{,}006 \times 4{,}0 = 12{,}02$$

$$1\text{ kg }C_2H_6 = 116 \times 3{,}733 = 4{,}33$$

$$1\text{ kg }C_3H_8 = 0{,}866 \times 3{,}636 = 3{,}15$$

$$1\text{ kg }C_4H_{10} = 0{,}446 \times 3{,}586 = 1{,}60$$

However, the oxygen in the exhaust gas after combustion falls, kg/h:

$$58{,}0 – 12{,}02 – 4{,}33 – 3{,}15 - 1{,}60 = 36{,}90$$

During the combustion of *methane*, molar mass ratio of evolved carbon dioxide (CO_2) is calculated:

$$M_{CO2}/M_{CH4} = 12 + 32/12 + 4 = 2{,}75$$

Combustion of *ethane:*

$$M_{CO2}/M_{C2H6} = 4\,(12+32)/2(24+6) = 3{,}20$$

Combustion of *propane:*

$$M_{CO2}/M_{C3H8} = 3 \times 48/44 = 3{,}272$$

Combustion of *butane :*

$$M_{CO2}/M_{C4H10} = 3{,}310$$

After combustion of *methane*, $\mathrm{CO_2}$ is produced:

$$3{,}006 \times 2{,}75 + 1{,}16 \times 3{,}20 + 0{,}866 \times 3{,}272 + 0{,}446 \times 3{,}310 = 14{,}22$$

CO_2, kg/h, after combustion:

18,40 + 14,22= 32,62

After combustion of methane, H_2O is produced, kg/h:

$$M_{H2O}/M_{CH4} = 2 \times 18/12 + 4 = 2{,}25$$

After combustion of *ethane*

$$M_{H2O}/M_{C2H6} = 6 \times 18/2 \times 30 = 1{,}80$$

After combustion of *propane*

$$M_{H2O}/M_{C3H8} = 4 \times 18/44 = 1{,}636$$

After combustion of *butane*

$$M_{H2O}/M_{C4H10} = 1{,}552$$

After combustion of methane, H_2O is produced:

$$3{,}006 \times 2{,}25 + 1{,}16 \times 1{,}80 + 0{,}866 \times 1{,}636 + 0{,}446 \times 1{,}552 + \mathbf{20{,}00} = 30{,}96$$

Thus, the composition products, kg/h, contain:

$$CO_2 = 18{,}40 + 14{,}22 = 32{,}62$$

$$H_2O = 30{,}96$$

$$N_2 = 303{,}6$$

$$O_2 = 36{,}90$$

$$O_2 + H_2O + N_2 + O_2 = \ 32{,}62 + \ 30{,}96 + \ 303{,}6 + \ 36{,}90$$
$$= 404{,}08$$

Converting into mass parts:

$$CO_2 = \frac{32{,}62}{404{,}08} = 0{,}0807$$

$$H_2O = \frac{30{,}96}{404{,}08} = 0{,}0766$$

$$N_2 = \frac{303,6}{404,08} = 0,7513$$

$$O_2 = \frac{36,90}{404,08} = 0,0913$$

References

1. Ganapathy, V. *Steam Generators and Waste Heat Boilers: For Process and Plant Engineers*. 2014.
2. Kleinert, E. *HVAC and Refrigeration Preventive Maitenance*. 2015.
3. Martinaitis, V., Lukoševičius, V. *Šilumos gamyba deginant kurą (Heat production burning fuel).*Vilnius: Technika, 2014.
4. Švenčianas, P., Adomavičius, A. *Engineering Thermodynamics*. Kaunas: Technologija, 2011.
5. Villu Vares, Ulo Kask and other. *Biokuro naudotojo žinynas (Biofuel user's manual)*. Vilnius: Žara, 2007.

Virginija Urbonienė

Vilnius College of Technologies and Design

EN	This project has been funded with support from the European Commission. This publication [communication] reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.
PL	Publikacja została zrealizowana przy wsparciu finansowym Komisji Europejskiej. Publikacja odzwierciedla jedynie stanowisko jej autorów i Komisja Europejska oraz Narodowa Agencja Programu Erasmus+ nie ponoszą odpowiedzialności za jej zawartość merytoryczną.
ES	El presente proyecto ha sido financiado con el apoyo de la Comisión Europea. Esta publicación (comunicación) es responsabilidad exclusiva de su autor. La Comisión no es responsable del uso que pueda hacerse de la información aquí difundida.
LT	Šis projektas finansuojamas remiant Europos Komisijai. Šis leidinys [pranešimas] atspindi tik autoriaus požiūrį, todėl Komisija negali būti laikoma atsakinga už bet kokį jame pateikiamos informacijos naudojimą.