Emission of CO, NO and CO_2 during gas combustion

Introduction

The role of natural gas as a fuel in the global primary energy supply is increasing due to new resources of that fuel and beneficial environmental characteristics. Carbon dioxide emissions per unit of chemical energy of methane is the lowest among all the fossil fuels, resulting from a favorable C/H ratio of 0.25. Low sulfur content allows to cool the exhaust gases below the dew point and to avoid the corrosion of the installation. That is why the chimney's sensible enthalpy loss is very low for most of the natural gas appliances. A simple chemical structure of methane facilitates almost complete combustion and low carbon monoxide and hydrocarbons emissions even with excess air ratios close to 1. As a result of all the aforementioned advantages, natural gas is frequently considered as the best fuel available nowadays [1].

Individual gas heating systems are one of the natural gas applications. Gas boilers are characterized by a simple structure, high efficiency, low exhaust gases harmfulness, ease of automation, small space requirement, small thermal inertia and silent operation. One of the few disadvantages is the increased risk of explosion, which however can be minimized by appropriate metering and automation. Another disadvantage of natural gas is low emissivity of its flames, which leads to smaller radiative heat transfer surfaces in a gas boiler and a demand for much larger convective heat exchangers than required for high emissivity flame fuels [2].

The main parameter characterizing each boiler is its energy efficiency, which can be expressed as the ratio of the heat absorbed by the medium and the chemical energy of the fuel. In case of condensing boilers the energy efficiency, calculated based on the lower heating value (LHV) of the fuel, can exceed the value of 100 %. An important energy loss during gas boilers operation, when the combustion process runs properly, is the loss in sensible enthalpy of the flue gases. The heat losses to the surroundings are also of certain importance [3].

The aim of the exercise

The aim of this exercise is to conduct mass and energy balances of the gas boiler and to evaluate emission factors of noxious gases produced in the course of combustion.

Experimental rig

The main element of the test rig used in this exercise is the gas water heater. A schematic diagram of this boiler is presented in Fig. 1. Cold water flows into the coil heat exchanger and absorbs heat from flue gases by radiation, convection and conduction. The hot water is released to a sink. The amount of used water is measured by a water flow meter. The natural gas is supplied to a burner where it is combusted using air as oxidant. The amount of gas consumed is measured by a gas meter. The flue gases obtained in the process are cooled in the heat exchanger and then flow into the chimney. The composition and temperature of the gases are measured using a gas analyzer at the chimney's inlet.

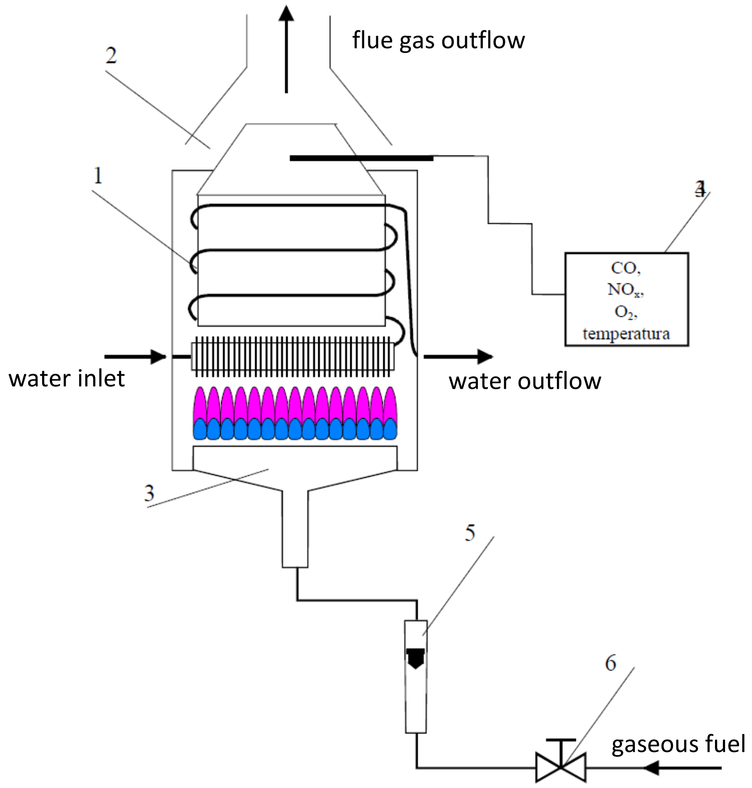

Fig. 1. Schematic diagram of the test rig. 1 - water coil, 2 – draught interrupter, 3 – injection type gas burner, 4 - flue gas analyzer, 5 – rotameter, 6 - control valve

The experimental procedure

Conduct the experiments following the steps below:

1) turn on the gas analyzer and wait for its readiness
2) open the water valve and set the flow so that the outlet water temperature does not exceed 50°C. The flow of water automatically starts the gas burner
3) wait until the displayed temperatures and measured gas compositions stabilize
4) start the stopwatch and note down current values of water and gas volumes
5) stop the stopwatch after the time specified by the supervisor and note down all the remaining measured quantities
6) calculate the flow rates of water and gas
7) repeat steps 3 to 6 for other values of the gas flows rates

Write down results of the measurements in Table 1.

Tab.1. Results of the measurements

No.	t_{ww} °C	t_{wd} °C	V_w $\mathrm{dm^3}$	τ s	V_g $\mathrm{dm^3}$	$[CO_2]$ %	$[CO]$ ppm	$[O_2]$ %	$[NO]$ ppm

Analysis of the results

For each of the combustion gas flow rates perform the calculations following the scheme below:

1. Formulate components balances:

carbon balance:

$$CH_4 = n''_{ss}([CO_2] + [CO]) \tag{1}$$

hydrogen balance:

$$2CH_4 = n''_{H_2O} \tag{2}$$

oxygen balance:

$$0.21n'_a = n''_{ss}\left([CO_2] + [O_2] + \frac{1}{2}[CO]\right) + \frac{1}{2}n''_{H_2O} \tag{3}$$

nitrogen balance:

$$0.79n'_a + N_2 = n''_{ss}(1 - [CO_2] - [CO] - [O_2]) \tag{4}$$

Assume that the natural gas used in the experiment consists of methane and nitrogen ($N_2 + CH_4 = 1$). If the gas analyzer does not allow measuring CO_2 concentration, assume that $CH_4 = 0.98$. The set of equations (1)-(4) can be easily solved numerically. The unknowns in the set are: $CH_4, N_2, n''_{ss}, n''_{H_2O}$ and n'_a. In order to determine the measurement uncertainties, the derivatives of the unknowns with respect to the measured quantities should be determined. For the needs of the current exercise, the derivatives can be calculated numerically in an approximate way, by substitution of a single measured quantity increased by 1 % to the set (1)-(4). The approximated derivative of the i-th unknown with respect to j-th measured quantity can be calculated as

$$\alpha_{ij} = \frac{n_i^j - n_i}{0.01p_j} \tag{5}$$

where:

n_i^j – the value of i-th unknown obtained from solution of the set (1)-(4) with an increased value of the j-th measured quantity by 1%

n_i – the value of i-th unknown obtained from solution of the set (1)-(4) with unchanged values of the measured quantities

p_j – the value of the j-th measured quantity

Uncertainty in the i-th computed quantity can be calculated using the uncertainty propagation formula

$$\Delta n_i = \sqrt{\sum_j \left(\alpha_{ij} \Delta p_j\right)^2} \tag{6}$$

where Δp_j is the uncertainty of the j-th measured quantity.

2. Calculate the minimum air requirement and its uncertainty:

$$n_{a,min} = \frac{2CH_4}{0.21} \tag{7}$$

$$\Delta n_{a,min} = \frac{2\Delta CH_4}{0.21} \tag{8}$$

3. Calculate the excess air ratio and its uncertainty:

$$\lambda = \frac{n'_a}{n_{a,min}} \tag{9}$$

$$\Delta\lambda = \sqrt{\left(\frac{\Delta n'_a}{n_{a,min}}\right)^2 + \left(\frac{n'_a}{n_{a,min}^2}\Delta n_{a,min}\right)^2} \tag{10}$$

4. Calculate the sensible enthalpy loss carried away with the flue gases:

$$\zeta_{fs} = \frac{n''_{ss}\left([CO_2](Mi)_{CO_2} + [CO](Mi)_{CO} + [N_2](Mi)_{N_2} + [O_2](Mi)_{O_2}\right) + n''_{H_2O}(Mi)_{H_2O}}{CH_4(MW_d)_{CH_4}} \tag{11}$$

5. Calculate loss due to incomplete combustion:

$$\zeta_{chs} = \frac{n''_{ss}[CO](MW_d)_{CO}}{CH4(MW_d)_{CH_4}} \tag{12}$$

While determining the uncertainties of ζ_{fs} and ζ_{chs}, assume that the uncertainty of temperature measurement was zero due to relatively high accuracy of temperature measurements and low accuracy of enthalpy approximation.

6. Determine the uncertainties of ζ_{fs} and ζ_{chs} by numerical differentiation.

7. Calculate the efficiency using the indirect method and determine its uncertainty:

$$\eta_e = 1 - \zeta_{fs} - \zeta_{chs} \tag{13}$$

$$\Delta\eta_e = \sqrt{\left(\Delta\zeta_{fs}\right)^2 + (\Delta\zeta_{chs})^2} \tag{14}$$

Then calculate the efficiency using the direct method.

8. Calculate the stream of water and its uncertainty:

$$\dot{m}_w = \frac{m_w}{\tau} \tag{15}$$

$$\Delta\dot{m}_w = \sqrt{\left(\frac{\Delta m_w}{\tau}\right)^2 + \left(\frac{m_w}{\tau^2}\Delta\tau\right)^2} \tag{16}$$

9. Calculate the heat flux absorbed by the water and its uncertainty:

$$\dot{Q}_u = m_w c_w (t_{ww} - t_{wd}) \tag{17}$$

$$\Delta\dot{Q}_u = \sqrt{\left(\Delta\dot{m}_w c_w (t_{ww} - t_{wd})\right)^2 + (\dot{m}_w c_w \Delta t_{ww})^2 + (\dot{m}_w c_w \Delta t_{wd})^2} \tag{18}$$

10. Calculate the chemical energy flux in the natural gas and its uncertainty:

$$\dot{E}_{ch} = CH_4 \frac{n_g}{\tau} (MW_d)_{CH_4} \tag{19}$$

$$\Delta\dot{E}_{ch} = \sqrt{\left(\Delta CH_4 \frac{n_g}{\tau}\right)^2 + \left(CH_4 \frac{\Delta n_g}{\tau}\right)^2 + \left(CH_4 \frac{n_g}{\tau^2}\Delta\tau\right)^2} \tag{20}$$

where

$$n_g = p_g V_g / (MR) T_g \tag{21}$$

Furthermore assume that

$$\Delta n_g = \sqrt{\left(\frac{p_g}{(MR)T_g}\Delta V_g\right)^2} \tag{22}$$

11. Calculate the efficiency using the direct method and its uncertainty:

$$\eta_e = \frac{\dot{Q}_u}{\dot{E}_{ch}} \tag{23}$$

$$\Delta\eta_e = \sqrt{\left(\frac{\Delta\dot{Q}_u}{\dot{E}_{ch}}\right)^2 + \left(\frac{\dot{Q}_u}{(\dot{E}_{ch})^2}\Delta\dot{E}_{ch}\right)^2} \tag{24}$$

12. Determine concentration of the noxious substances recalculated to the 3% of oxygen content:

$$[i]_{3\%} = [i]\frac{18}{21 - [O_2]} \tag{25}$$

Create plots of the calculated efficiency (direct and indirect), excess air ratio and emission of noxious substances with respect to the thermal power of the boiler. Formulate observations and draw conclusions.

Literature

[1] Wilk R.: Podstawy niskoemisyjnego spalania, PAN, Katowice, 2000

[2] Jarosiński J.: Techniki czystego spalania, WNT, Warszawa, 1996

[3] Szargut J.: Termodynamika techniczna, Wydawnictwo Politechniki Śląskiej, Gliwice, 2000

Appendix

Assume the following uncertainties of the measured quantities:

1. Uncertainty in concentration measurements:
   - O2: $\Delta[O_2] = \mp 0.2\%$
   - CO: $\Delta[CO] = \mp 0.5\ \mathrm{ppm}$
   - NO: $\Delta[NO] = \mp 5\ \mathrm{ppm}$
2. Uncertainty (relative) in gas volume measurement: $\mp 0.5\%$
3. Uncertainty (relative) in water volume measurement: $\mp 5\%$
4. Uncertainty in temperature measurement (thermocouple type K, class 1): $\Delta T = \mp 1.5\ ^\circ\mathrm{C}$
5. Uncertainty in time measurement:
   - Mechanical stopwatch: $\Delta\tau = \mp 0.5\ s$ (response time 0.3 s and accuracy of the stopwatch 0.2 s)
   - Electronic stopwatch: $\Delta\tau = \mp 0.3\ s$ (response time 0.3 s and accuracy of the stopwatch 0.01 s)