

Paraschiv, Lizica Simona; Serban, Alexandru; Paraschiv, Spiru

Article

Calculation of combustion air required for burning solid fuels (coal/biomass/solid waste) and analysis of flue gas composition

Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Paraschiv, Lizica Simona; Serban, Alexandru; Paraschiv, Spiru (2020) : Calculation of combustion air required for burning solid fuels (coal/biomass/solid waste) and analysis of flue gas composition, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 3, pp. 36-45, <https://doi.org/10.1016/j.egy.2019.10.016>

This Version is available at:

<https://hdl.handle.net/10419/243977>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by-nc-nd/4.0/>

Tmrees, EURACA, 04 to 06 September 2019, Athens, Greece

Calculation of combustion air required for burning solid fuels (coal / biomass / solid waste) and analysis of flue gas composition

Lizica Simona Paraschiv^{a,*}, Alexandru Serban^b, Spiru Paraschiv^{a,*}

^a “Dunarea de Jos” University of Galati, Domneasca St. 47, Galati, 800008, Romania

^b Politehnica University of Bucharest, Splaiul Independentei St. 313, Bucharest 060042, Romania

Received 20 September 2019; accepted 18 October 2019

Available online 2 November 2019

Abstract

In power plants or any combustion systems, for a maximum efficiency of combustion, an operational safety procedure (reduction of CO emissions) and environmental pollution reduction, it is highly important to determine and monitor the flue gas composition resulting from burning of solid fuels in combustion chambers. The paper presents the development of a web application, which can prove extremely useful for thermo-energetic engineers and researchers who wish to perform combustion calculations of the solid fuels (coal / biomass / solid waste materials). The application allows users to enter the data on the elemental composition of the analyzed fuel, excess air and fuel flow rate to determine volume of oxygen and air necessary for fuel combustion and flue gas volume. This web application can be also successfully used both in designing stage of the combustion equipment and in the operating stage since the chemical composition of solid fuels is extremely variable (particularly in the case of waste materials) consequently it is highly important to know the optimum quantity of air required for a maximum efficiency of combustion. Proper control of the combustion process will lead both to the optimum functioning of the equipment and to less polluting combustion gasses and will also reduce thermal losses.

© 2019 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the scientific committee of the Tmrees, EURACA, 2019.

Keywords: Coal; Biomass and solid waste combustion; Combustion air; Flue gases; Combustion emissions analysis; Solid fuel combustion

1. Introduction

Combustion, is defined as a chemical reaction during which the fuel combustible elements are rapidly oxidized and a large quantity of energy is released. From a thermodynamic perspective, combustion is analyzed globally in that it focuses neither on the mechanism of combustion, called kinetics of combustion, which is an extremely complex chemical phenomenon, nor on the intermediate products of combustion.

The purpose of burning organic fuels in combustion plants is to obtain hot combustion gases which are the primary heating agent in the boiler, Kitto and Stultz [1]. Combustion of organic fuels is an exothermic process in which fuel and combustion air are consumed, generating combustion gases and solid products (ash/slag).

* Corresponding authors.

E-mail addresses: scraciun@ugal.ro (L.S. Paraschiv), sparaschiv@ugal.ro (S. Paraschiv).

Fuels are defined as substances that produce significant amounts of heat by combustion, and in order to be considered as fuel, a substance must meet the following criteria: to react exothermically with oxygen, at high speed and high temperatures; the resulting combustion products must be non-toxic; it should be widespread in nature, therefore it must be cost-effective with no other cheaper alternative uses; the resulting combustion products should not be corrosive in contact with any exposed surface, etc.

It is difficult to achieve an exact mass analysis for solid fuel, but in general coal, biomass, solid waste or other kind of solid fuel contains varying amounts of carbon, oxygen, hydrogen, nitrogen, sulphur, moisture and ash. The chemical composition of fuels can be established globally by designating the part that actually participates to combustion process, called combustible mass, and of the part that does not participate to burning, called ballast, that can be found among the resulting combustion products such as ash/slag. This way of defining the chemical composition of fuels further highlights the humidity, the amount of water present in fuels and it is called technical analysis.

Practical aspects related to the computation of combustion require a thorough analysis of the two components of fuels via elementary chemical analysis of primary chemical elements or stable compounds which are present in fuel composition.

The elementary chemical composition is expressed in units of mass for solid and liquid fuels [kg component/ kg fuel]. The chemical composition of solid and liquid fuels includes combustible elements as: carbon (C^i), hydrogen (H^i) and sulphur (S^i). The mass participation of chemical elements are indicated in parentheses.

Of these elements, sulfur is an unwanted presence, as it reacts with the moisture in the flue gas, resulting in sulfuric acid, which is extremely corrosive to the metal elements of the combustion plant. Other elements involved in the combustion process are: oxygen (O^i) bound, therefore present in fuel, nitrogen (N^i) (considered as inert in this case and therefore does not react with other elements, but in reality nitrogen oxides, NO_x are formed in the combustion process when fuels are burned at high temperatures, most often being the result of industrial activities, road traffic and electricity production, Spuru et al. [2], Spuru and Lizica-Simona [3]), and fuel moisture (W^i). Mineral mass or ballast, has the mass participation noted by (A^i). The sum of mass participations highlighted by the elementary analysis, must satisfy the Eq. (1).

We consider the burning of one kilogram solid fuel, with the following elemental analysis:

$$C^i + H^i + N^i + O^i + S^i + M^i + W_t^i = 100\% \text{ or } 1 \text{ kg of fuel} \quad (1)$$

Combustion is widely used for energy production both in industry and in household applications.

The combustion conditions in the household stoves have a crucial influence on the emissions, according to Lai et al. [4]. The traditional stove for cooking has a very low energy efficiency of 10%–15% and high emissions, while the traditional stoves used for space heating in rural areas have an energy efficiency of 25%–30%, Sun et al. [5,6] and Wei et al. [7].

Extremely low combustion efficiencies resulting in high energy wastage and high pollutant emissions are mainly due to insufficient air supply (inadequate air ratio) and poor mixing between air and fuel, Sun et al. [5,6].

In industrial boilers, the area where the combustion of fuels takes place is called the combustion chamber. Here the two elements present in any combustion process are introduced, namely the fuel, i.e. the component which is to be burned and the oxidant, the component which contains the oxygen needed for burning, Russell and George [8]. In the usual combustion process, air is the most common oxidant as it is free and easy to get, less often, the high-purity oxygen is used in metallurgy or in special combustion installations, Sang et al. [9]. Oxy-fuel combustion technologies where air is replaced by a mixture of pure oxygen and recirculated combustion gases is one of the most promising techniques for CO₂ capture and CO₂ emission reduction, Baskar and Senthilkumar [10], Zhang et al. [11], Jang et al. [12], Myrrha et al. [13], and Berrin and Hüsünü [14].

During combustion new chemical substances (called combustion gases) emerge as a result of combining the fuel and the oxidant. During a combustion process, the elements that exist prior to reactions are called reactants and components that exist after the reaction is completed are called products.

According to Fig. 1, depending on the type of combustion (excess air coefficient), the combustion gases may contain:

- for incomplete combustion ($\lambda < 1$): CO, CO₂, SO₂, H₂O, N₂
- for theoretical or stoichiometric combustion ($\lambda = 1$): CO₂, SO₂, H₂O, N₂
- for excedentary combustion ($\lambda > 1$): CO₂, SO₂, H₂O, N₂, O₂

Therefore, optimum combustion, requires oxygen, a good turbulence and a sufficient time for complete combustion of all the elements, Çengel and Michael [15].

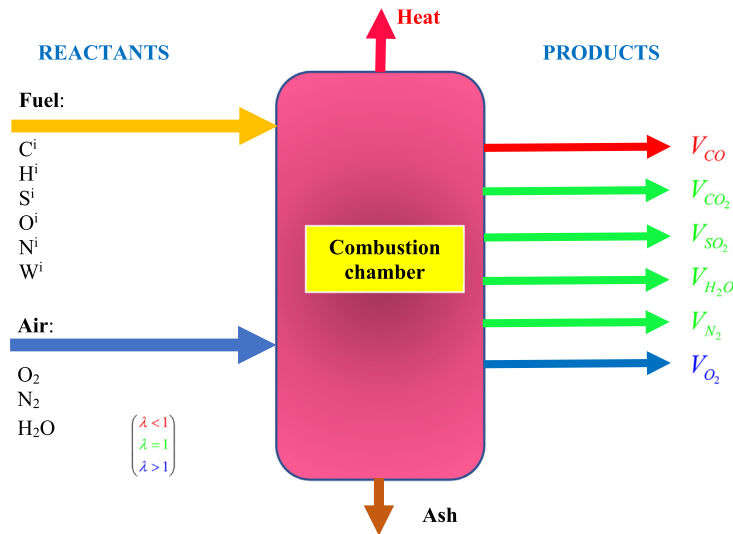


Fig. 1. The solid fuel combustion.

2. Theoretical combustion processes

The minimum amount of air necessary for the complete combustion of a fuel is called stoichiometric or theoretical air and when a fuel is completely burnt with theoretical air, there is no uncombined oxygen in the flue gas. A combustion process with less air than the theoretical one is incomplete and one with more air than the theoretical one is surplus. The ideal combustion process in which a fuel is completely burned with the minimum quantity of air is called stoichiometric or theoretical combustion. Incomplete combustion occurs when oxygen is insufficient, or may occur even in the presence of an oxygen excess, but the degree of its mixing with the fuel is insufficient.

Stoichiometry is a branch of chemistry which evaluates the quantitative balancing between elements, in combinations or chemical reactions. The gasses resulting from combustion are mainly made up of carbon dioxide (CO_2), nitrogen (N_2), water vapor (H_2O), carbon monoxide (CO), sulfur dioxide (SO_2), etc. In case of solid fuels, the soot (unburned carbon particles), can be present in combustion gasses. The perfect combustion, also called the theoretical combustion is characterized by the fact that combustion gases do not contain any combustible chemical elements (such as soot or carbon monoxide).

Mechanically incomplete combustion is characterized by the presence of combustible elements (such as C) in combustion gases, while chemically incomplete combustion is characterized by the presence of combustible gases in flue gases (such as CO).

The calculation of the combustion process is performed based on the chemical reactions of the combusting elements and aims to: determine the resulting thermal energy; determine the air quantity required for these reactions; determine the flue gas volume resulting from combustion. The quantity of air needed for combustion is very important, because if will not ensure a sufficient quantity of oxygen (air) the combustion will be incomplete, and on the other hand, if too much air is introduced, the combustion temperature decreases because the excess air takes over some of the heat and increases the resulting flue gases volume Maurice and Waldner Helen Gablinger [16]. Also the quantity of flue gases resulting from combustion is extremely important for proper sizing of the exhaust pipes, proper sizing of the chimney and the heat recovery systems.

Combustion results in combustion gases, with a varying composition depending on the oxidant and fuel type, ash or slag due to the fuel ballast, thermal energy, representing the useful effect which depends on the combustion conditions and on the quantity of air (oxidant) introduced in the system. For complete combustion of combustible elements a minimum quantity of oxygen contained in a minimum amount of air is required.

By combustion, the chemical energy of fuels is converted into heat, called the heating value. Another term which is commonly used to designate heat release is the calorific value of fuels. The quality of a fuel can be determined by taking into account the heating value released by combustion (this aspect represents one of the main criteria in

assessing the quality of fuels). The heating value is the amount of heat released under normal physical conditions ($p_0 = 1.013$ bar; $t = 0^\circ\text{C}$) and can be defined more simply as the heat released by the complete combustion of the fuel mass unit.

The heating value for solid and liquid fuels is measured in [kJ/kg]. Since water vapor (H_2O) is present in combustion gases as a result of hydrogen oxidation, the fuel moisture and the combustion air moisture, two types of heating values can be defined, depending on aggregation state of water, as a final product of combustion.

If the water resulting from combustion is converted into vapors, the latent heat of water vaporization is contained in combustion gases. If the water resulting from combustion is found as liquid, the heat of water vaporization is contained in the heating value. The higher heating value (HHV) is the reaction heat which contains the heat of water vaporization (water is a combustion product in the liquid state and all combustion products are obtained under normal conditions of temperature and pressure corresponding to normal physical state — the initial state of fuel and oxidizer before combustion). The lower heating value (LHV) is the reaction heat which does not contain water vaporization heat, as it can be found in combustion gases (water is a combustion product, in the vapor state, and all combustion products are obtained under conditions of temperature and pressure corresponding to the combustion process).

Volume of combustion air and the resulting flue gas volumes, are determined in N m^3 and refer to the unit mass of burning fuel. The calculations are made on assumption that combustion is complete and perfect and calculations are performed by stoichiometric relations, without treating the complex chemical reactions of exothermic oxidation of fuels.

3. Conservation of mass

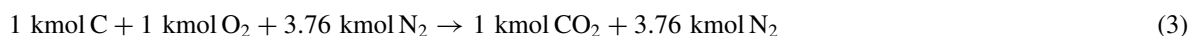
In combustion reactions, according to mass conservation law, total mass of the products must be equal to total mass of reactants, and also, total mass of each chemical element was preserved during the process.

Dry air composition can be approximated as 21% of O_2 and 79% of N_2 . Thus, to each kmol of O_2 introduced into the furnace, corresponds 3.76 kmol of N_2 ($0.79/0.21$).

Now consider the simple reaction of carbon with dry air to form carbon dioxide and nitrogen as given by:

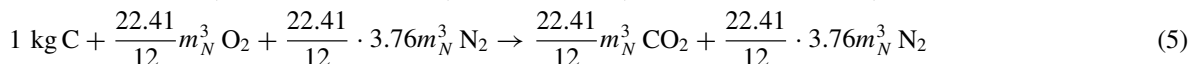
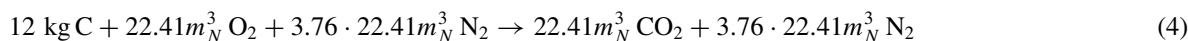


One can also consider Eq. (2) on a molar basis, as follows:



The kmol is the substance quantity whose mass expressed in kilograms is numerically equal to molecular mass M of the substance. According to Avogadro's law, at normal state (pressure of 760 Torr and temperature of 0°C), the volume occupied by one kmol of ideal gas is $22.41 \text{ N m}^3 / \text{kmol}$.

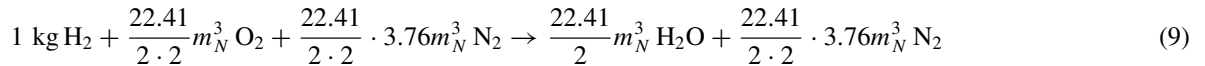
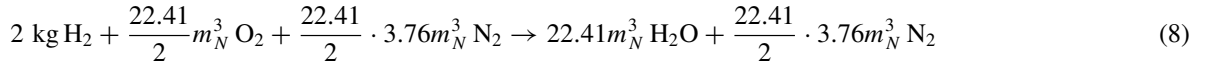
Since the mass of each element is given by its molecular mass and all ideal gases occupy equal volumes per kmole at the same pressure and temperature, Eq. (3) can also be expressed as:



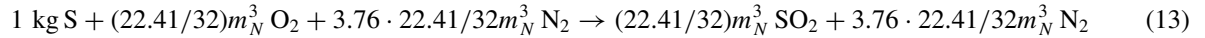
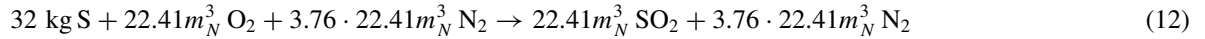
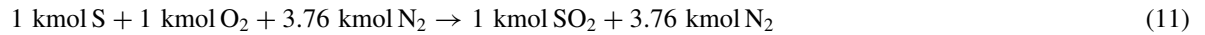
Here C and O_2 are the reactants since they exist before combustion, and CO_2 is the product since it exists after combustion, but N_2 appear both as a reactant and as a product, but he does not react chemically in the combustion chamber (inert gas). Chemical equations are balanced on the basis of the conservation of mass principle: The total mass of each element is conserved during a chemical reaction, but total number of moles is not conserved during a chemical reaction.

Hydrogen combustion:





Sulfur combustion:



4. Stoichiometric combustion air

The stoichiometric volume of oxygen required for complete combustion of fuel mass unit is obtained by summing volumes of oxygen required for combustion of fuel components, from the preceding equations. It can be noticed the presence of oxygen in fuel composition, having a mass participation of (O^i) and this quantity should be no longer introduced from the outside into the furnace.

The stoichiometric volume of oxygen required for combustion is:

$$V_{\text{O}_2}^0 = \frac{22.41}{100} \left(\frac{C^i}{12} + \frac{H^i}{4} + \frac{S^i - O^i}{32} \right) \left[\frac{m_N^3 \text{ O}_2}{\text{kg fuel}} \right] \quad (14)$$

The oxygen flow rate:

$$\dot{V}_{\text{O}_2}^0 = B \cdot V_{\text{O}_2}^0 \left[\frac{m_N^3 \text{ O}_2}{h} \right] \quad (15)$$

where B is the fuel flow rate, [kg fuel/h].

However, the boiler furnace uses atmospheric air and not oxygen. Oxygen has a volume participation in air by 21%. The stoichiometric volume of dry air required to burn one kilogram of fuel will be in these conditions:

$$V_a^o = V_{\text{O}_2}^o / 0.21 [m_N^3 \text{ air/kg fuel}] \quad (16)$$

The air flow rate:

$$\dot{V}_a^o = B \cdot V_a^o \quad [m_N^3 \text{ air/h}] \quad (17)$$

Previous calculations are valid if the combustion air is dry. However, if the air introduced into the furnace is moist, the stoichiometric air volume is higher, $V_{\text{aw}} > V_a$, due to the water vapor content. To take into account the absolute humidity x [kg H₂O/kg dry air] of the air, its temperature, t_a [°C] and its relative humidity, φ_a [%] need be known. With the known values for t_a and φ_a , use the Molliere diagram for moist air and the abscissa corresponding to intersection of your isotherm with isohigra φ_a , gives precisely the value of absolute humidity x [kg H₂O/kg dry air].

The usual value considered in the calculations is $x = 10$ g H₂O/kg, and it corresponds to the air parameters: $t_a = 25$ °C and $\varphi_a = 50\%$. If we want more accurate results, we can use the following computation relation that gives the value of x :

$$x = 0,622 \varphi_a p_s / (p_b - \varphi_a p_s) [\text{kg H}_2\text{O/kg dry air}] \quad (18)$$

The volume of water vapor in moist air is:

$$V_{\text{H}_2\text{O}}^o = x \rho_a V_a^o / \rho_{\text{H}_2\text{O}} \quad [m_N^3 \text{ H}_2\text{O/kg fuel}] \quad (19)$$

where: ρ_a [kg/N m³], density of air, normal state, $\rho_a = 1.2925$ kg/N m³;

$\rho_{\text{H}_2\text{O}}$ [kg/N m³], density of water vapor, normal state, $\rho_{\text{H}_2\text{O}} = 0.804$ kg/N m³.

The stoichiometric volume of wet air is:

$$\begin{aligned} V_{\text{aw}}^o &= V_a^o + x \rho_a V_a^o / \rho_{\text{H}_2\text{O}} = (1 + x \rho_a / \rho_{\text{H}_2\text{O}}) V_a^o \\ &= (1 + 1,61x) V_a^o \quad [m_N^3 / \text{kg fuel}] \end{aligned} \quad (20)$$

5. Stoichiometric combustion products

Volume of carbon dioxide:

$$V_{\text{CO}_2} = \frac{22,41}{12} \cdot \frac{C^i}{100} \left[\frac{m_N^3 \text{CO}_2}{\text{kg fuel}} \right] \quad (21)$$

The humidity of the combustion air and water vapor that was formed during hydrogen combustion, are treated as an inert gas, such as nitrogen. It is important to determine the water vapor content of the flue gases in order to determine their dew point temperature when the flue gases are cooled. Water vapor in the flue gases has two sources, with their corresponding volumes.

- Volume of water vapor from combustion of hydrogen:

$$V_{\text{H}_2\text{O}}^0 = \frac{22,41}{100} \left(\frac{H^i}{2} + \frac{W^i}{18} \right) \left[\frac{m_N^3 \text{H}_2\text{O}}{\text{kg fuel}} \right] \quad (22)$$

- Volume of water vapor due to the combustion air humidity:

$$V_{\text{H}_2\text{O}}'' = 1,61 \cdot x \cdot V_a^0 \quad [m_N^3 \text{H}_2\text{O}/\text{kg fuel}] \quad (23)$$

By summing the two components, we get the total volume of water vapor from the flue gas:

$$V_{\text{H}_2\text{O}}^o = V_{\text{H}_2\text{O}}' + V_{\text{H}_2\text{O}}'' = \frac{22,41}{100} \left(\frac{H^i}{2} + \frac{W^i}{18} \right) + 1,61 \cdot x \cdot V_a^0 \quad [m_N^3 \text{H}_2\text{O}/\text{kg fuel}] \quad (24)$$

Volume of sulfur dioxide:

$$V_{\text{SO}_2} = \frac{22,41}{32} \cdot \frac{S^i}{100} \left[\frac{m_N^3 \text{SO}_2}{\text{kg fuel}} \right] \quad (25)$$

The nitrogen presence in the combustion air greatly influences the efficiency of a combustion process, reducing the flame temperature and increasing the heat loss through the sensible heat of the flue gases exhausted at the stack, as it is introduced into the combustion chamber in large quantities and at with low temperatures and it is discharged with a higher temperature. In the flue gases, nitrogen comes from the fuel composition and from the combustion air, consisting of 79% of the nitrogen. Nitrogen volume:

$$V_{\text{N}_2}^0 = \frac{22,41}{28} \cdot \frac{N^i}{100} + 0,79 \cdot V_a^0 \left[\frac{m_N^3 \text{N}_2}{\text{kg fuel}} \right] \quad (26)$$

Total stoichiometric volume of dry flue gas will be:

$$V_{\text{gu}}^o = V_{\text{CO}_2} + V_{\text{SO}_2} + V_{\text{N}_2}^o = \frac{22,41}{100} \left(\frac{C^i}{12} + \frac{S^i}{32} + \frac{N^i}{28} \right) + 0,79V_a^o \quad [m_N^3 \text{dry flue gas}/\text{kg fuel}] \quad (27)$$

If combustion takes place under stoichiometric conditions, i.e. using the minimum quantity of air required for combustion ($\lambda = 1$), then the minimum volume of combustion gases will be obtained.

Eq. (28), gives the total volume of combustion gases, including water vapor content.

$$V_{\text{ga}}^o = V_{\text{gu}}^o + V_{\text{H}_2\text{O}}^o \quad [m_N^3 \text{flue gas}/\text{kg fuel}] \quad (28)$$

6. Combustion processes with excess air

Due to burners and furnaces imperfection, homogeneous mixtures between fuel and oxidant cannot be made, and so the probability of fuel element atoms to meet the oxygen atoms, is subunit. For this reason, in real combustion processes, it is common practice to use more air than the stoichiometric quantity to increase the chances of complete combustion or to control the temperature of the combustion chamber, in which case we say that the combustion was carried out with supplement air or with excess air, Ionita [17]. The ratio between the real air volume introduced into the burning chamber, V_a and the stoichiometric air volume, V_a^o is the air ratio or excess air coefficient and noted by λ .

$$\lambda = V_a / V_a^o \quad (29)$$

The values of the excess air coefficient, λ depend on a number of factors, of which the most important are the fuel properties, combustion mode and the furnace construction. For the furnace it is noted with λ_f and has values between 1.05 and 1.7. The volume of combustion air for combustion with excess air:

$$V_a = \lambda_f V_a^o \quad (30)$$

Not all combustion products are influenced by the air supplement λ_f , they depend only on the elemental composition of the fuel, such as CO₂ and SO₂. If we consider the humidity of the combustion air, in the case of excess air combustion, the relation for water vapor will change. It becomes:

$$V_{\text{H}_2\text{O}}'' = 1,61 \cdot \lambda \cdot x \cdot V_a^o \quad [m_N^3 \text{H}_2\text{O}/\text{kg fuel}] \quad (31)$$

and also modify relation that gives the total volume of water vapor from the flue gas:

$$V_{\text{H}_2\text{O}} = \frac{22,41}{100} \left(\frac{H^i}{2} + \frac{W^i}{18} \right) + 1,61 \cdot \lambda \cdot x \cdot V_a^o \quad [m_N^3 \text{H}_2\text{O}/\text{kg fuel}] \quad (32)$$

Compared with stoichiometric combustion, due to supplement of air, in the flue gas appears a new component, namely the volume of free oxygen introduced in excess, V_{O_2} :

$$V_{\text{O}_2} = 0,21(\lambda_f - 1)V_a^o \quad [m_N^3 \text{O}_2/\text{kg fuel}] \quad (33)$$

Another component whose volume changes is nitrogen, V_{N_2} :

$$V_{\text{N}_2} = \frac{22,41}{28} \frac{N}{100} + 0,79\lambda_f V_a^o \quad [m_N^3 \text{N}_2/\text{kg fuel}] \quad (34)$$

Volume of dry flue gas become:

$$V_{\text{gu}} = 22,41/100[(C/12) + (S_c/32) + (N/28)] + (\lambda_f - 0,21)V_a^o \quad [m_N^3 \text{dry flue gas}/\text{kg fuel}] \quad (35)$$

Total volume of wet flue gas for combustion with excess air is:

$$V_{\text{ga}} = \underbrace{\frac{22,41}{100} \frac{C}{12}}_{V_{\text{CO}_2}} + \underbrace{\frac{22,41}{100} \frac{S}{32}}_{V_{\text{SO}_2}} + \underbrace{\frac{22,41}{100} \frac{N^i}{28}}_{V_{\text{N}_2}} + \underbrace{0,79 \cdot \lambda \cdot V_a^o}_{V_{\text{N}_2}} + \underbrace{\frac{22,41}{100} \left(\frac{H^i}{2} + \frac{W^i}{18} \right) + 1,61 \cdot \lambda \cdot x \cdot V_a^o}_{V_{\text{H}_2\text{O}}} + \underbrace{0,21(\lambda - 1)V_a^o}_{V_{\text{O}_2\text{exces}}} \quad [m_N^3 \text{flue gas}/\text{kg fuel}] \quad (36)$$

Flue gas flow rate:

$$\dot{V}_{\text{ga}} = B \cdot V_{\text{ga}} \quad [m_N^3 \text{flue gas}/\text{h}] \quad (37)$$

7. Web application

The application that enables the analysis of fuels combustion represent a useful tool for thermo-energetic engineers and not only. We have implemented the methodology described in the previous sections as a web application that users can access it at: http://energy.ugal.ro/Fuel_Combustion.php

The web application allows users to analyze the solid fuel combustion and calculate volumes of oxygen, combustion air and flue gas, for stoichiometric or excess air combustion. The application provides fast and free results to compare emissions and volumes of flue gases, resulted from fuels combustion with different elemental compositions.

Fig. 2, presents the web user interface. The web application is implemented in the most user-friendly way, allowing users to test the methodology without being concerned about the details behind the system.

The user should enter manually the following values into the main window of the application (Fig. 2): elemental composition of the analyzed fuel, (the sum of components must be 100%), the excess air coefficient and the burned fuel flow. After entering the data, the SUBMIT button is pressed in order to initiate the calculations, according to the mathematical model presented previously and the results related to the analysis of fuel combustion are displayed in a new window (Fig. 3).

1. Solid Fuel Combustion

Ultimate analysis of solid fuel

C ⁱ =	75.2	%
H ⁱ =	4.6	%
N ⁱ =	0.5	%
O ⁱ =	8.8	%
S ⁱ =	0.9	%
W ⁱ =	8.0	%
M ⁱ =	2.0	%
x _a =	10.0	%
lambda=	1.0	
(excess air coefficient)		
B _{SF} =	1.0	kg/h
(fuel flow rate)		
<input type="button" value="SUBMIT"/>		

Fig. 2. Main page of web application.

$$V_{ga}^o = V_{CO_2} + V_{SO_2} + V_{N_2} + V_{H_2O}$$

$$V_{ga}^o = 9.23127815625 \quad [m^3_{N_2}/kg \text{ fuel}]$$

Real flue gas volume:

$$V_{ga} = V_{CO_2} + V_{SO_2} + [(22.41/28)N^i + 0.79 \text{ lambda} V_{ga}^o] + [(22.41/2)H^i + (22.41/18)W^i + 1.61 \times \text{lambda} V_{ga}^o] + 0.21(\text{lambda}-1) V_{ga}^o$$

$$V_{ga} = 9.23127815625 \quad [m^3_{N_2}/kg \text{ fuel}]$$

Flue gas flow rate:

$$V_{ga} = B \cdot V_{ga}$$

$$V_{ga} = 9.23127815625 \quad [m^3_{N_2}/h]$$

Fig. 3. Results window.

The web application determines and displays the values for oxygen and air volumes required for fuel combustion and respectively the flow rates of flue gases resulting from the stoichiometric or excess combustion, respectively, taking into account the elemental composition entered by the user, the excess air coefficient and the fuel flow rate.

This application can also be used to determine the oxygen and air flows needed for co-firing of coal and biomass, taking into account the mass participation of the two fuels. The advantages of biomass co-firing with coal, are low

CO₂ and SO₂ emissions and the use of infrastructure for fossil fuel combustion, Wang et al. [18] and Yousaf et al. [19].

The web application can evolve into a more powerful tool, which will respond to the needs and expectations of the users, by developing and implementing in the web application of the following modules: Lower and Higher Heating Values of fuels; Adiabatic flame temperature; Heat content of the flue gas; Dew point and acid dew-point temperatures of the flue gas; Direct or indirect thermal efficiency of power plants; Air pollution control systems.

8. Conclusions

Since fossil fuel burning processes are and will be in the near future, the most common way to generate energy in our civilization, they should be well-managed for environmental and sustainable development reasons. Maximizing combustion process efficiency (complete fuel combustion with minimal heat loss), will lead to economic profit maximization.

This paper presents the design, development and implementation of a web application which can be used to analyze the solid fuel combustion. It has an accessible interface and it is intuitive for users who are interested in combustion processes. The web application can be particularly used to analyze the combustion of fuels with different elemental compositions, for variable fuel flows and different excess air coefficients, presenting the advantage of short-time calculation and avoiding laborious calculations that can induce errors. The web application is still being improved and new features will be added in the future.

Acknowledgment

This work was supported by the scientific research contract no. 664 of 12.11.2015, a research with economic agents from Romania.

References

- [1] Kitto JB, Stultz SC. Steam / its generation and use. Babcock & Wilcox Company; 2010.
- [2] Spiru Paraschiv, Daniel-Eduard Constantin, Simona-Lizica Paraschiv, Mirela Voiculescu. OMI and ground-based in-situ tropospheric nitrogen dioxide observations over several important european cities during 2005–2014. *Int J Environ Res Publ Health* 2017;14:1415.
- [3] Spiru Paraschiv, Lizica-Simona Paraschiv. Analysis of traffic and industrial source contributions to ambient air pollution with nitrogen dioxide in two urban areas in Romania. *Energy Procedia* 2019;157:1553–60.
- [4] Lai Alexandra, Shan Ming, Deng Mengsi, Carter Ellison, Yang Xudong, Baumgartner Jill, Schauer James. Differences in chemical composition of PM_{2.5} emissions from traditional versus advanced combustion (semi-gasifier) solid fuel stoves. *Chemosphere* 2019;233:852–61.
- [5] Sun Jian, Shen Zhenxing, Zeng Yaling, Niu Xinyi, Wang Jinhui, Cao Junji, Gong Xuesong, Xu Hongmei, Wang Taobo, Liu Hongxia, Yang Liu. Characterization and cytotoxicity of PAHs in PM_{2.5} emitted from residential solid fuel burning in the Guanzhong Plain. *China Environ Pollut* 2018;241:359–68.
- [6] Sun Jian, Shena Zhenxing, Zhang Leiming, Zhang Qian, Lei Yali, Cao Junji, Huang Yu, Liu Suixin, Zheng Chunli, Xu Hongmei, Liu Hongxia, Pan Hua, Liu Pingping, Zhang Renjian. Impact of primary and secondary air supply intensity in stove on emissions of size-segregated particulate matter and carbonaceous aerosols from apple tree wood burning. *Atmos Res* 2018;202:33–9.
- [7] Wei Du, Xi Zhu, Chen Yuanchen, Liu Weijian, Wang Wei, Shen Guofeng, Tao Shu, Jetter James J. Field-based emission measurements of biomass burning in typical Chinese built-in-place stoves. *Environ Pollut* 2018;242:1587–97.
- [8] Russell Lynn D, George A. Classical thermodynamics. Saunders College Publishing, Harcourt Brace Jovanovich College Publishers; 1995.
- [9] Sang Heon Han, Lee Yeon Seung, Cho JR, Lee Kyun Ho. Efficiency analysis of air-fuel and oxy-fuel combustion in a reheating furnace. *Int J Heat Mass Transfer* 2018;121:1364–70.
- [10] Baskar P, Senthilkumar A. Effects of oxygen enriched combustion on pollution and performance characteristics of a diesel engine. *Eng Sci Technol Int J* 2016;19(1):438–43.
- [11] Zhang Yuanyuan, Zhao Jiangting, Ma Zhibin, Yang Fengling, Cheng Fangqin. Effect of oxygen concentration on oxy-fuel combustion characteristic and interactions of coal gangue and pine sawdust. *Waste Manag* 2019;87:288–94.
- [12] Jang Ha-Na, Hun Kim Jeong, Back Seung-Ki, Sung Jin-Ho, Yoo Heung-Min, Choi Hang Seok, Seo Yong-Chil. Combustion characteristics of waste sludge at air and oxy-fuel combustion conditions in a circulating fluidized bed reactor. *Fuel* 2016;170(2016):92–9.
- [13] Myrrha E Andersen, Modak Nabanita, Winterrowd Christopher K, Lee Chun Wai, Roberts William L, Wendt Jost OL, Linak William P. Soot, organics, and ultrafine ash from air- and oxy-fired coal combustion. *Proc Combust Inst* 2017;36(3):4029–37.
- [14] Berrin Engin, Hüsnü Atakül. Air and oxy-fuel combustion kinetics of low rank lignites. *J Energy Inst* 2018;91(2):311–22.
- [15] Çengel Yunus, Michael A. Thermodynamics: An engineering approach. McGraw Hill Higher Education; 2011.
- [16] Maurice Reto Strobel, Waldner Helen Gablinger H. Highly efficient combustion with low excess air in a modern energy-from-waste (EfW) plant. *Waste Manag* 2018;73:301–6.

- [17] Ionita Ion. Steam generators. Bucharest: Technical Publishing House; 1990.
- [18] Wang Xuebin, Hu Zhongfa, Wang Guogang, Luo Xiaotao, Ruan Renhui, Jin Qiming, Tan Houzhan. Influence of coal co-firing on the particulate matter formation during pulverized biomass combustion. *J Energy Inst* 2019;92:450–8.
- [19] Yousaf Balal, Liua Guijian, Abbas Qumber, Wang Ruwei, Ali Muhammad Ubaid, Ullah Habib, Liu Ruijia, Zhou Chuncai. Systematic investigation on combustion characteristics and emission reduction mechanism of potentially toxic elements in biomass- and biocharcoal co-combustion systems. *Appl Energy* 2017;208:142–57.