

SHORT COMMUNICATION

OBTAINING FRESH WATER FROM NATURAL AND SYNTHETIC FUELS IN THE ENERGY SECTOR

SERGEY E. SHCHEKLEIN^{1*}, ALEXEY M. DUBININ¹ & NASEER T. ALWAN²

¹ Ural Federal University, Russia.

² Kirkuk Technical College, Northern Technical University, Iraq.

ABSTRACT

In this work, a comparative study of the specific air consumption and water vapor emissions in combustion products was performed based on the analysis of stoichiometric equations for air oxidation reactions both of energy fuels (petrol, diesel fuel, gaseous fuel, wood) and synthetic fuels converted from biomass and coal fuels (ethanol, methanol, etc.), as well as hydrogen fuel. For the limit process temperature, the excess air ratio for various types of fuels and the real volumes of air and fuel consumption and water vapor emissions were determined. Theoretically, abnormally high consumption of atmospheric air when using hydrogen and gas fuel was shown. The feasibility of the beneficial use of the products of oxidation of organic fuels and hydrogen to produce fresh water was substantiated. The analysis procedure presented in the study was revealed to be universal and can be applied to investigate any existing and newly created fuel compositions.

Keywords: diesel, fresh water, fuels, gasoline, hydrogen, methanol.

1 INTRODUCTION

In recent decades, the problems of freshwater scarcity have become increasingly apparent all over the world. Rapid population growth, the coverage of the benefits of civilization for an ever-increasing number of people, the growth of agricultural and industrial water consumption requires fresh water of more than 7,000 km³ per year [1, 2]. The problem is aggravated by domestic and industrial pollution of water bodies. There is a particularly urgent need for water in the countries of the Middle East [3], and in the coming decades, this is forecasted to happen in several European countries [4]. Traditional methods to obtain fresh water by desalinating sea water or by extracting water vapor from the air are very energy-intensive or have extremely low productivity [5].

At the same time, it is known that the main process of production of electric and thermal energy from organic fuels, based on the use of the heat of combustion of fossil fuels (wood, coal, oil) and new types of fuel (methanol, ethanol, hydrogen, etc.) [6–11] occurs as a result of an oxidation reaction. Moreover, oxygen contained in atmospheric air is typically used as an oxidizing agent in the process, and water is one of the products of the fuel oxidation reaction. At the current level of consumption of fossil fuels in the world, approaching 20 billion tons of equivalent fuel per year [12], the volume of water generated in the energy sector counts hundreds of millions of tons.

* ORCID: <https://orcid.org/0000-0003-2140-0321>

The aim of this study is to analyze the possibility of using chemically-related hydrogen in organic fuels to produce water as an additional product in modern energy technologies.

2 METHOD AND RESULTS

In this work, the quantitative analysis of the water formation in the products of combustion of a number of synthetic and natural fuels was performed both under stoichiometric conditions, i. e. at the ratio of excess air ($\alpha = 1$), providing complete oxidation of the fuel and in the real combustion mode at a temperature of 1400 °C ($\alpha > 1$), determined by the limiting capabilities of materials of modern energy. The studies were carried out by the method of thermodynamic analysis of the physical and chemical processes of oxidation of fuels of different chemical compositions in stoichiometry and real combustion conditions. In the latter case, the combustion temperature was set at 1400 °C, which allowed the determination of the corresponding ratios of excess air - α .

2.1 Fuel oxidation at stoichiometry conditions ($\alpha = 1$)

It is known that the complete oxidation of fuel in air is described by stoichiometric equations that depend on the chemical composition of the fuel. The composition of the products of the combustion reaction at $\alpha = 1$ is the theoretical fuel-to-air ratio at which oxygen and fuel are both completely consumed during oxidation [13].

In a generalized form [13, 14], stoichiometric equations of the reaction for hydrocarbon fuels and alcohols can be expressed as follows:

$$C_m H_n + (m + n/4) (O_2 + 3.76 N_2) = mCO_2 + n/2H_2O + 3.76(m + n/4)N_2 \quad (1)$$

$$C_m H_{2m+1} OH + 1.5m(O_2 + 3.76 N_2) = mCO_2 + (m+1)H_2O + 3.76(1.5m)N_2. \quad (2)$$

For wood fuel, a more complex combustion scheme takes place. The wood contains volatiles (CH_4 , CO , H_2 , CO_2 , O_2) which occur during the thermal decomposition of the resin (hydroquinone $C_6H_4(OH)_2$) with following oxidation by atmospheric oxygen and formation of associated water. Since the hydrogen-to-carbon ratio in the wood is $\beta^* = H^w/C^w = 3.9/30 = 0.13$, then the yield of combustible volatiles on dry ash free basis will be equal to $V_v^c = 0.4$ kg/kg of wood [15]. In addition, in wood, the total associated and natural humidity reaches 40%. Therefore, the formation of water vapor for dry and wet wood will be significantly different. Table 1 shows the equations of water formation for several synthetic and natural fuels.

Table 1: Stoichiometric equations of water formation reactions for a range of fuels ($\alpha = 1$).

Fuel	Formula	Stoichiometric equation
Hydrogen	H_2	$H_2 + 0.5(O_2 + 3.76 N_2) = H_2O + 1.88N_2$
Ethanol	$C_2 H_5 OH$	$C_2 H_5 OH + 3(O_2 + 3.76 N_2) = 2CO_2 + 3H_2O + 11.28N_2$
Methanol	$C H_3 OH$	$C H_3 OH + 1.5(O_2 + 3.76 N_2) = CO_2 + 2H_2O + 5.64N_2$
Petrol	$C_7 H_{16}$	$C_7 H_{16} + 11(O_2 + 3.76 N_2) = 7CO_2 + 8H_2O + 41.36N_2$
Diesel	$C_8 H_{18}$	$C_8 H_{18} + 12.5(O_2 + 3.76 N_2) = 8CO_2 + 9H_2O + 47N_2$
Methane	CH_4	$CH_4 + 2(O_2 + 3.76N_2) = CO_2 + 2H_2O + 7.52N_2$
Dry wood	$C_6 H_4(OH)_2$	$C_6 H_4(OH)_2 + 6.5(O_2 + 3.76 N_2) = 6CO_2 + 3H_2O + 24.44N_2$

Oxidation of fuel according to the stoichiometric reaction equation is characterized by a certain temperature of the combustion process described by the equation [16]:

$$Q_{low}^w = C_{op}^s(t_{op}^{st}) \cdot t_{op}^{st} \quad (3)$$

where $C_{op}^s(t_{op}^{st})$ is the specific true isobaric heat capacity of oxidation products at a theoretical oxidation temperature, kJ/K·kg of fuel; (t_{op}^{st}) is the theoretical oxidation temperature, °C.

The method for determining the theoretical temperature of oxidation [17] consists in determining, under adiabatic conditions, the temperature at which the enthalpy of oxidation products $C_{op}^s(t_{op}^{st}) \cdot t_{op}^{st}$ is equal to the lower heating value of fuel combustion Q_{low}^w . The results of calculations of the temperature of oxidation, air and fuel consumption and water vapor output in the composition of the oxidation products at $\alpha = 1$ are shown in Table 2.

It can be concluded from the data presented in Table 2 that, at $\alpha = 1$, complete oxidation of the fuel occurs at high temperatures with absorption of a large amount of atmospheric air. Particularly large consumers of air are fuels that do not contain oxygen — hydrogen, gasoline, diesel fuel and methane.

2.2 Real fuel oxidation by air at $\alpha > 1$.

Modern energy equipment is designed to operate at a lower level of combustion temperatures compared to the theoretical one. These temperatures, determined by the limiting capabilities of modern energy materials [18], are achieved by supplying air enriched fuel mixtures to the engine's working volume. The ratio of the real consumption of the oxidizing agent (air) to that necessary for complete oxidation is characterized by the excess air ratio α . In this case, formulas (1) and (2) can be written as follows:

$$C_m H_n + \alpha(m + n/4)(O_2 + 3.76N_2) = mCO_2 + (n/2)H_2O + 47N_2 + (\alpha - 1)(m + n/4)(O_2 + 3.76N_2), \quad (4)$$

$$C_m H_{2m+1} OH + \alpha(1.5m)(O_2 + 3.76N_2) = mCO_2 + (m + 1)H_2O + 3.76(1.5m)N_2 + (\alpha - 1)(1.5m)(O_2 + 3.76N_2). \quad (5)$$

Table 2: Specific consumption of air and fuel and water output, $\alpha = 1$.

Fuel	Combustion heat MJ/kg	Theoretical oxidation temperature °C	Amount of air kg/kg of fuel	Specific fuel consumption kg/MJ	Specific air consumption kg/MJ	Specific water vapor output, kg/MJ
Hydrogen	121	2020	34.32	0.0083	0.284	0.074
Ethanol	27.785	1880	8.95	0.0360	0.322	0.042
Methanol	21.131	1900	6.44	0.0473	0.305	0.053
Petrol	44	1850	15.1	0.0227	0.343	0.033
Diesel	41.8	1780	15	0.0239	0.359	0.034
Methane	49.09	1860	17.16	0.0204	0.350	0.046
Dry wood	28.4	2200	8.1	0.0352	0.285	0.0173

Table 3: Fuel combustion at a temperature of 1400 °C.

Fuel	Excess air ratio α	Formula
Hydrogen	1.7	$H_2 + 0.85(O_2 + 3.76N_2) = H_2O + 3.196N_2 + 0.35O_2$
Ethanol	1.55	$C_2H_5OH + 4.66(O_2 + 3.76N_2) = 2CO_2 + 3H_2O + 17.52N_2 + 1.66O_2$
Methanol	1.5	$CH_3OH + 2.25(O_2 + 3.76N_2) = CO_2 + 2H_2O + 8.46N_2 + 0.75O_2$
Petrol	1.6	$C_7H_{16} + 17.6(O_2 + 3.76N_2) = 7CO_2 + 8H_2O + 66.176N_2 + 6.6O_2$
Diesel	1.4	$C_8H_{18} + 17.5(O_2 + 3.76N_2) = 8CO_2 + 9H_2O + 65.8N_2 + 5O_2$
Methane	1.43	$CH_4 + 2.86(O_2 + 3.76N_2) = CO_2 + 2H_2O + 10.7536N_2 + 0.86O_2$
Dry wood	1.79	$C_6H_4(OH)_2 + 11.635(O_2 + 3.76N_2) = 6CO_2 + 3H_2O + 5.135O_2 + 43.7476N_2$

Table 4: The excess air ratio, air consumption and fuel, water vapor output at the oxidation temperature of 1400 °C.

Fuel	Excess air ratio α	Amount of air kg/ kg of fuel	Amount of water vapor kg/kg of fuel	Specific fuel consump- tion kg/MJ	Specific air consump- tion kg/MJ	Specific water vapor output kg/MJ
Hydrogen	1.7	58.3	9	0.0083	0.482	0.074
Ethanol	1.55	13.9	1.17	0.0360	0.500	0.042
Methanol	1.5	9.65	1.125	0.0473	0.457	0.053
Petrol	1.6	24.16	1.44	0.0227	0.549	0.033
Diesel	1.4	21	1.42	0.0239	0.502	0.034
Methane	1.43	24.53	2.25	0.0204	0.500	0.046
Dry wood	1.79	14.52	0.49	0.0352	0.51	0.0173

In the process of oxidation of a fuel mixture with excess air, the heat of combustion of the fuel is spent on heating the combustion products (at $\alpha = 1$) and excess air to a temperature of t_{op} . The fuel oxidation reactions at a temperature of $t_{op} = 1400$ °C acquire a slightly different form (Table 3).

If the expenditure of heat on radiation in the external environment, the dissociation of CO_2 and H_2O and the initial temperature of the fuel and air are taken to be insignificant; in this case equation (3) takes the following form:

$$Q_{low}^w = [C_{op}^s(t_{op}) + (\alpha - 1)C_{air}^s(t_{op})]t_{op} \quad (6)$$

Table 5: Process characteristics for the drying stage of wood and the water vapor output at 100 °C.

Fuel	Excess air ratio α	Amount of air kg/kg of fuel	Amount of water vapor kg/kg of fuel	Specific fuel consumption kg/MJ	Specific air consump- tion kg/MJ	Specific water vapor output kg/MJ
Wet wood	1.2	4.43	0.204	0.0978	0.433	0.0218

where $C_{op}(t_{op})$ is the specific true isobaric heat capacity of oxidation products at a temperature of t_{op} and $\alpha = 1$, kJ/K·kg of fuel; $C_{air}(t_{op})$ is the specific true isobaric heat capacity of oxidation products at a temperature of t_{op} , kJ/K·kg of fuel; Q_{low}^w is the lower heating value of fuel oxidation, kJ/kg of fuel; α is the excess air ratio and t_{op} is the temperature of oxidation products, °C.

From equation (6), the coefficient α , at the initial temperature of the air and fuel $t_{air} = 0$, $t_{fuel} = 0$ and the given temperature of the combustion products t_{op} , can be found as follows:

$$\alpha = 1 + [Q_{low}^w - C_{op}^s(t_{op})] / [C_{air}^s(t_{op})]. \quad (7)$$

The results of calculating the excess air ratio, consumption of air and fuel, and water vapor output are given in Table 4.

For wet wood kept at low temperatures (< 0 °C), it is required to expend energy for melting ice, heating the water to a vaporization temperature (100 °C) and evaporating the water. After evaporation of the water, the temperature of the wood rises, and decomposition of the resin begins with the formation and burning of volatiles. Under continuous wood supply to the furnace, water vapor will first form from evaporation of moisture (drying), and then from the oxidation of volatiles. The process characteristics for the drying stage of wood are shown in Table 5.

Thus, when using wood with natural moisture as a fuel, the total output of water vapor generated will be equal to $0.0173 + 0.0218 = 0.0391$ kg/MJ.

3 FURTHER RESULTS AND DISCUSSION

Analysis of the calculation results shows a significant difference in the environmental load caused by using different types of fuels. Figures 1 and 2 show absolute and specific air consumption for several organic fuels at $\alpha = 1$ and $\alpha > 1$, respectively. It is seen that under stoichiometric conditions, the absolute consumption of atmospheric air is highest for hydrogen and hydrocarbon fuels. Combustion at $\alpha > 1$ leads to an increase in air consumption for all the fuels considered.

However, the difference in combustion heat value (Table 2) leads to equalization of air consumption, necessary to obtain equal energy amount. The lowest air consumption was found for methanol, hydrogen and ethanol. The highest air consumption was required when using gasoline, diesel and methane as a fuel.

In accordance with the chemical reactions of the oxidation processes presented in Tables 1 and 3, water is contained in the composition of the oxidation products of all the fuels considered. Figure 3 shows the calculated data on the formation of water from the combustion of fuels with an equal energy effect.

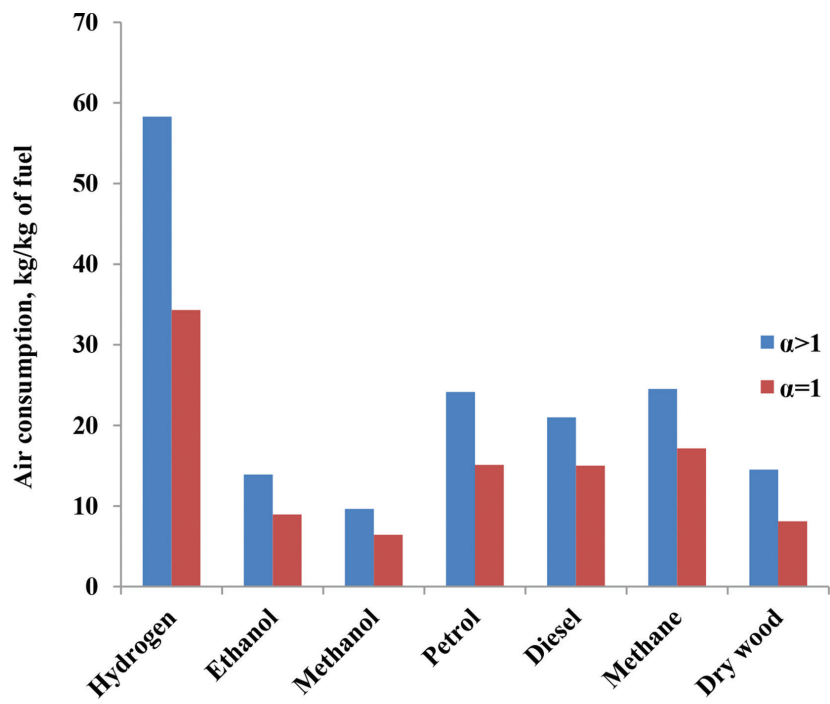


Figure 1: Atmospheric air consumption for the stoichiometric $\alpha = 1$ and real-life $\alpha > 1$ combustion modes.

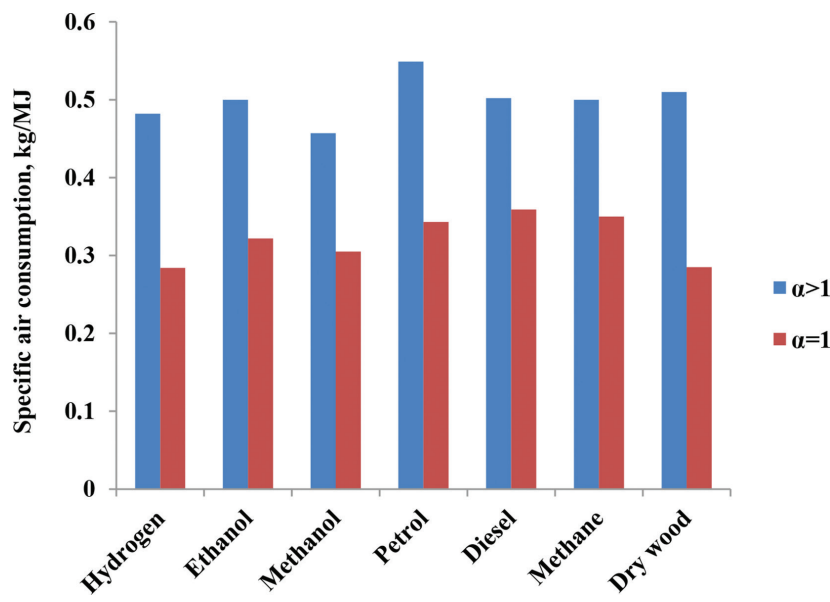


Figure 2: Specific air consumption for the stoichiometric $\alpha = 1$ and real-life $\alpha > 1$ combustion modes.

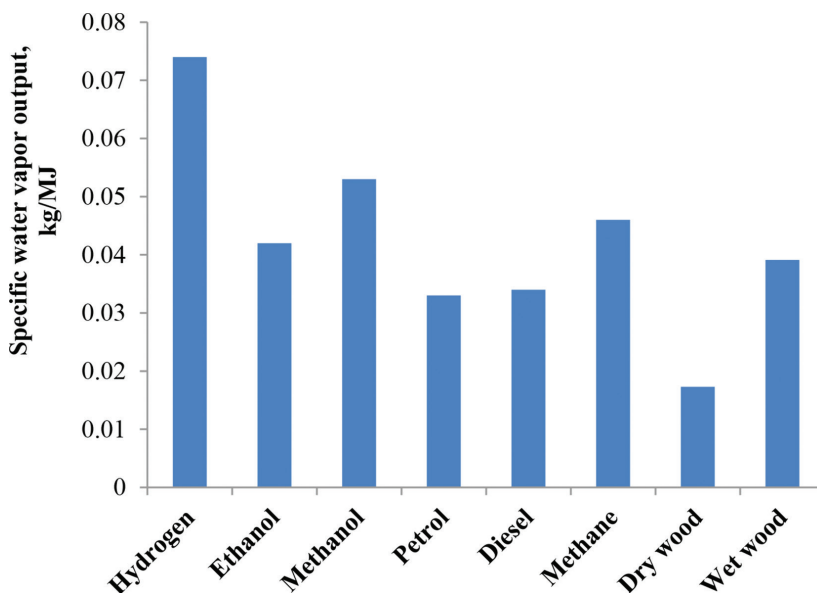


Figure 3: Specific water vapor output for the stoichiometric and real-life combustion modes.

Water vapor generation in fuel combustion products is the same for both stoichiometric ($\alpha = 1$) and real ($\alpha > 1$) combustion modes. For stoichiometric conditions, the maximum output can be obtained for the gases - hydrogen and methane and alcohols - ethanol and methanol. Dry wood gives the minimum water vapor output. At the same time, wet wood releases water vapor at the level equal to that of the liquid fuels. For natural gas (methane), a widely distributed source of energy, the level of water vapor output is quite high. So, for a modern thermal power plant using natural gas with a capacity of 1,000 MW, operating for 8,000 hours during a year, the volume of water production will be more than 3 million tons per year.

4 CONCLUSIONS

The real possibilities of modern power engineering, limited by the durability of constructional materials, require increased air consumption during fuel combustion in energy systems.

In these conditions, the greatest water emission is delivered from hydrogen and natural gas combustion; the lowest water vapor output is obtained when using dry wood and conventional motor fuels such as petrol and diesel.

The transition of the energy sector from methane ($\alpha = 1.43$) to hydrogen fuel ($\alpha = 1.7$) will increase the formation of fresh water during oxidation by 1.6 times.

The development of technologies for the efficient extraction of water vapor from gaseous products of combustion (oxidation) of energy fuels can contribute to the creation of an additional large source of fresh water, commensurate with natural sources of water and will contribute to increasing energy and environmental efficiency of traditional energy facilities.

NOTATION

Greek symbols

α – ratio of excess air; μ – molecular weight, kg/kmol; β – fuel ratio of Bunte

Latin symbols

B - water output, kg/kg of fuel; b - specific water output, kg/MJ; C - specific heat capacity kJ/K kg; Q - energy density, kJ/kg, kJ/m³; T - temperature, K; t - temperature, °C

Upper indices

* - modified; w - on the working mass; o - under standard conditions; c - on the flammable mass

Lower indices

air – air; *op*- oxidation products; *st*- theoretical (stoichiometric) oxidation; *v*- volatile; *low*-lowest; *fuel*- fuel.

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