Combustion characteristics of mixtures of certain hydrocarbon fuels in air

S A Nazarychev, V M Larionov
Kazan Federal University, 18 Kremlyovskaya str., Kazan 420008, Russian Federation
E-mail: nazarichev.sa@gmail.com

Abstract. A theoretical study of the combustion of hydrocarbon fuel mixtures in water heating unit was carried out. The effect of hydrogen impurities and propane-butane fuel on the optimal ($\alpha = 1$) combustion of natural gas in air is established.

1. Introduction
The possibility of burning some industrial waste together with traditional fuel (natural gas) is currently being considered. As you know, the composition of industrial waste can change as time passes [1,2]. Variability in the composition of the fuel affects the gas-dynamic, thermodynamic and environmental characteristics of existing industrial power plants. A laboratory water heating unit [3] was developed and created, which will be used to study the process of heating water as a result of burning methane mixed with lighter or heavier hydrocarbon fuels. To evaluate the capabilities of the setup, to develop an techniques experimental and explain the measurement results, it is necessary to know the specific fuel calorific value and excess air factor. Determining the dependence of these characteristics on the concentration of hydrogen or propane-butane fuel mixed with natural gas is the purpose of this work.

2. Initial data
Liquefied natural gas, propane-butane mixture, hydrogen were used. The composition of these gases was determined by chromatographic method. The results are presented in tables 1-3.

Table 1. The chemical composition of natural gas.

| Gas composition | CH$_4$ | C$_2$H$_6$ | H$_2$S | O$_2$ |
|----------------|--------|-----------|-------|------|
| %              | 94,85  | 0,32      | 3,63  | 1,2  |

Table 2. The chemical composition of propane-butane fuel.

| Gas composition     | C$_3$H$_8$ | C$_4$H$_{10}$ (butane gas) | C$_4$H$_{10}$ (isobutane) | H$_2$S | O$_2$ |
|---------------------|------------|-----------------------------|---------------------------|-------|------|
| %                   | 74,978     | 6,9                         | 8,77                      | 4,13  | 5,2  |

Table 3. The chemical composition of hydrogen.

| Gas composition | H$_2$ |
|----------------|-------|
| %              | 100   |
3. Calculation results

The air volume $V_0$ required for complete combustion of 1 m$^3$ of gas is determined by the expression [4]:

$$V_0 = 0.0476(0.5(b_1+b_2) + 1.5b_3-b_4 \sum c_i a_i),$$  \hspace{1cm} (1)

where $b_1,b_2,b_3,b_4$ - are the volumetric concentrations of CO, H$_2$, H$_2$S, O$_2$, respectively, $c_i$ - is the volumetric concentration of the $i$-th hydrocarbon $C_mH_n$, $a_i=m+n/4$.

The calculation results for natural gas, hydrogen, and propane-butane fuel, respectively, are as follows: $V_1 = 9.29$, $V_2 = 2.38$, $V_3 = 22.75$.

The excess air factor is determined by the formula:

$$\alpha = \frac{V_a}{V_0+V_f}$$  \hspace{1cm} (2)

where $V_a$, $V_f$ - are the volumes of air and fuel, respectively, which enter the combustion chamber, per unit time.

It was shown [5] that the combustion of natural gas in the experimental setup corresponds to $\alpha = 1$, when the flow rate of natural gas is 1.8 l/min, the air flow rate is 17.5 l/min. The following calculation method was used. Consider a mixture of natural gas and hydrogen. We change the hydrogen concentration from 0 to 26%, however, the total flow rate of the mixture is kept constant and equal to the initial flow rate of natural gas. The air flow rate is also constant and equal to the initial value. Similar calculations were carried out for a mixture of natural gas with propane-butane fuel.

The calculation results are presented in the figure.

![Figure 1. Dependence of the excess air factor on the concentration of hydrogen (■) and propane-butane fuel (▲) in a mixture with natural gas.](image)

An increase in the concentration of hydrogen in a mixture with natural gas causes a linear increase in the excess air factor to $\alpha = 1.24$. At the same time, an increase in the concentration of propane-butane fuel mixed with natural gas leads to a linear decrease in $\alpha$ to 0.83, i.e., to incomplete combustion of the fuel. This is explained by the fact that for the complete combustion of hydrogen less air is required than for the complete combustion of the same volume of natural gas. On the other hand, the volume of air required for complete combustion of 1 m$^3$ of propane-butane fuel is greater than the similar volume of air for natural gas.
Knowing the composition of fuels, it is possible to calculate its specific heat of combustion (kJ/m³) using the well-known [4] expression:

\[ Q = 0.01 \sum Q_i b_i, \] (3)

where \( Q_i \) - is the specific heat of combustion of the i-th gas, \( b_i \) - are the volumetric concentrations of CO, H₂, H₂S in the fuel, respectively.

For natural gas, hydrogen and propane-butane fuel, respectively, the following results were obtained:

\( Q_1 = 35068.46 \text{ kJ/m}^3 \), \( Q_2 = 10790 \text{ kJ/m}^3 \), \( Q_3 = 90222.33 \text{ kJ/m}^3 \).

The calculation results of the specific heat of combustion of mixtures of natural gas with hydrogen or propane-butane fuel are presented in Table 4.

| η % | 5   | 8   | 11  | 14  | 17  | 20  | 23  | 26  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Q_mixture MJ/m³ | hydrogen | 33,872 | 33,143 | 32,414 | 31,685 | 30,956 | 30,227 | 29,498 | 28,769 |
| propane-butane | 37,843 | 39,497 | 41,151 | 42,805 | 44,46 | 46,114 | 47,768 | 49,422 |

Specific heat of combustion of hydrogen is less than that of natural gas; therefore, an increase in hydrogen concentration up to 26% in a mixture with natural gas causes a decrease in the specific heat of combustion of fuel by 18% relative to the initial value, which corresponds to natural gas. On the other hand, an increase in the concentration of propane-butane fuel to 26% in a mixture with natural gas causes an increase in the specific heat of combustion of the fuel by 41%, relative to the initial value. This is due to the fact that propane-butane fuel has a higher specific heat of combustion than natural gas.

4. Conclusion
Combustion of mixtures of the natural gas with other fuels in air is studied. It is shown that an increase in the concentration of hydrogen in a mixture with natural gas can cause a significant increase in the excess air factor and a decrease in the specific heat of combustion of the mixture [6]. An increase in the concentration of propane-butane fuel mixed with natural gas gives opposite results. The calculation results will be used in further experimental studies.

Acknowledgements
The work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University. The reported research was funded by Russian Foundation for Basic Research and the government of the region of the Russian Federation, grant № 18-48-160051\18.

References
[1] Lisienko V G, SHHelokov Ya M, Ladygichev M G 2004 Russia B. Toplivo. Ratsional'noe szhiganie, upravlenie i tehnologicheske ispol'zovanie 608.
[2] Saifullin E R, Nazarychev S A, Malahov A O, Misoedova E Y, Larionova I V 2018 Journal of Physics: Conference Series 1058 012059
[3] Saifullin E R, Nazarychev S A, Larionov V M, Vankov Yu V, Sadikov K G, Ananiev Ya V 2019 IOP Conf. Series: Earth and Environmental Science 288 012115
[4] Izdatel'Novo NPO TSKTI 1998 Russia B. Teplovoy raschet kotlov(Normativnyj metod) 256
[5] Larionov V M, Nazarychev S A, Malahov A O, Lovleva O B, Larionova I V Goreniye smesey uglevodorodnykh topliv v vodonagrevatel'nykh ustanovkakh. Inzhenernyy vestnik Dona 1 2020
[6] Larionov V M, Saifullin E R, Konstantinov N V, Nazarychev S A, Malakhov A O, Yunusova E A 2019 Journal of Physics: Conference Series 1328 012048