Calculation Completeness of Combustion Fuel Using Distribution Characteristics of Flame

I R Galiev and V E Epishkin
Tolyatti State University, st. Belorusskaya, 14, Togliatti, 445020, Russia
E-mail: sbs777@yandex.ru

Abstract. The article is dedicated to experimental and theoretical studies characteristics flame propagation in combustion chamber internal combustion engine with spark ignition and their influence on completeness combustion. It is theoretically and experimentally proved that relationship of flame propagation characteristics with completeness of combustion composite fuel is complex, non-linear, and depends on chemical composition combustible mixture and temperature in combustion chamber. It was revealed that an increase thickness near-wall unburned fuel layer, size of slots in combustion chamber and surface area of combustion chamber contribute to a reduction combustion efficiency of the fuel. It is shown that an increase rate flame propagation and a decrease thickness flame front leads to an increase completeness combustion fuel. It was revealed that proposed formula, using fundamental characteristics of flame propagation, allows to us calculating completeness combustion composite fuel. This indicates feasibility using this formula at the design stage and fine-tuning low-emission and energy-efficient combustion chambers of engines and power plants.

1. Introduction
Due to the constant increase in fuel prices and the legislative tightening of the concentration of toxic components in exhaust gases (exhaust gases) of internal combustion engines (ICE), the issues of improving the environmental and energy characteristics of ICE are becoming urgent. Currently, the trend in the transport energy industry has been shaped by the use of alternative fuels and chemical combustion regulators. The scientific side of this development is formed, among other things, by studies of the activation of combustion by the addition of hydrogen to traditional hydrocarbon fuels [1].

Since the 2000s, new fuel hythane (a mixture of natural gas with hydrogen [2, 3]) has become very popular. Hythane successfully combines the advantages of natural gas (cheap fuel) and hydrogen (environmentally friendly and high heat of combustion) [4]. To create new engines and power plants using hythane, it is necessary to thoroughly study the process of combustion of composite fuel and its impact on energy, economic and environmental characteristics. Since the energy and economic characteristics of the engine are determined by the complete combustion of the fuel, therefore, the study of this issue is an urgent task. Despite the progress achieved in increasing the combustion efficiency, there is still no understanding of the mechanism explaining the complex influence of the characteristics of the turbulent flame (pulsation velocity, turbulence scale, chemical reaction zone width, turbulent velocity), shape and size of the combustion chamber (CC), the composition of the air-fuel mixture (AFM), the size of the cracks in the CC and the extinction temperature of the flame.
As a result, existing solutions for increasing the combustion efficiency are intuitive in nature, and models that predict its values have a high level of empiricism, low accuracy and work in a narrow range of engine operating modes, which makes it difficult to use them when designing energy-efficient combustion chambers. Thus, the chosen theme relevant for research in theoretical and practical terms. Objective work is to develop a method for calculating the completeness of combustion of composite fuel (hythane) using the characteristics of flame propagation.

2. Research methodology
Studies were conducted on a single-cylinder engine with spark ignition. ICE work was carried on angle of ignition timing is equal to $13^\circ$ and the engine speed $n = 900 \text{ min}^{-1}$. The fuel was hythane, with a volume content of hydrogen ($r_h$): 29, 47, and 58%. The fundamental characteristics of flame propagation (flame propagation velocity and the width of the chemical reaction zone) and the maximum flame temperature were determined experimentally using the method of ionization probes [5]. The experimental procedure was in parallel with the signal recording ionization probes, spark ignition, crankshaft position sensor, air flow sensor and the recording waveform using a multi-channel analog-to-digital converter in the memory of a personal computer.

3. Research results
As a result of the research, the values of the maximum flame temperature, the width of the chemical reaction zone and the propagation velocity of the turbulent flame were obtained during the operation of the experimental setup with various hydrogen additions in hythane and air excess factors.

To calculate the completeness of fuel combustion ($\chi$), using the characteristics of flame propagation, the ideal gas equation was used taking into account the equality of pressures in the burned and unburned zone of the combustion chamber. As a result, the formula was obtained:

$$\chi = \left( \frac{R_b \cdot T_b}{R_f \cdot T_{b_{min}}} \cdot \frac{V_{ub}}{V_b - V_{ub}} + 1 \right)^{-1}$$

(1)

where $R_b$ – the gas constant of the combustion products, J/(mol∙K); $R_f$ – the gas constant of the fuel assembly, J/(mol∙K); $T_{b_{min}}$ – flame extinction temperature, K; $T_b$ – maximum flame temperature, K; $V_b$ is the volume of combustion products, m$^3$; $V_{ub}$ – the volume of unburned fuel, m$^3$.

Since the fuel is burned in the entire volume of the combustion chamber, the volume of unburned fuel $V_{ub}$ depends on the volume of slots in the combustion chamber (where the fuel does not burn), the thickness of the unburned fuel layer at the walls of the combustion chamber and the area of the combustion chamber at the time of the end of combustion:

$$V_{ub} = \delta_{ub} \cdot S_{cc} + V_{cr}$$

(2)

where $\delta_{ub}$ is the thickness of the unburned fuel layer at the wall of the combustion chamber, m; $S_{cc}$ – the area of the combustion chamber at the end of the combustion of fuel, m$^2$; $V_{cr}$ – the volume of cracks in the combustion chamber, m$^3$.

The area and volume of the combustion chamber at the time of completion of combustion depends on the size and shape of the combustion chamber, the location of the spark plug and the duration of the combustion process, which was found on the expansion polytrope. The thickness of the unburned wall layer was calculated using the flame distribution characteristics, using the formula (3) proposed by us, which was obtained using the law of V.A. Michelson and the theory of the limits of flame spread Ya.B. Zeldovich [6]:

$$\delta_{ub} = \frac{U_f \cdot \delta}{S_{cc} \cdot \left( S_{ab} / S_{ff} \right)_{max}} \cdot U$$

(3)
where $U_n$ – normal flame velocity, m/s; $U$ – turbulent velocity of the flame, m/s; $\delta$ – width of the zone of chemical reactions of the flame, m; $(S_{cc}/S_{ff})_{max}$ – the maximum possible ratio of the contact area of the flame front with the combustion chamber ($S_{cc}$) to the surface area of the flame front (SFP).

The normal flame velocity was calculated using the well-known formula [7], taking into account the experimental data obtained at the Eindhoven Technical University [8] and the amendments [9], which take into account the peculiarities of burning a mixture of methane with hydrogen in ICE:

$$U_n = U_{n0} \cdot \left( \frac{T_n}{T_0} \right)^{\gamma} \cdot \left( \frac{P_n}{P_0} \right)^{\beta}$$

where $U_{n0}$ – normal flame velocity at temperature $T_0$ and pressure $P_0$, m/s. $T_n$, $P_n$, respectively, temperature and pressure during combustion; $\gamma=2.2$, $\beta=-0.15$ are empirical constants.

The dependence of the normal flame velocity on the coefficient of excess air and the proportion of hydrogen added to the fuel is shown in Figure 1.

![Figure 1. Dependence of the normal flame speed on the coefficient of excess air and hydrogen concentration: ♦, x [10], + [11] – $r_h=0\%$; ■ – $r_h=29\%$; ▲ – $r_h=47\%$; ● – $r_h=58\%$.](image)

Analysis of the curves shows that an increase in the concentration of hydrogen leads to an increase in $U_n$. So, for $\alpha = 1.3$, the addition of hydrogen, $r_h = 58\%$, led to an increase in speed by 23%. It should be noted that at the same hydrogen concentration, but on a rich mixture $\alpha = 0.8$, the increase in speed was only 17%. That is, as the excess air ratio increases, the effect of the hydrogen activating additive on the normal flame velocity becomes more intense. The results obtained are in good agreement with the results of other scientists [10, 11], which indicates the reliability of the results obtained. The reason for this is that in lean air-fuel mixtures the amount of hydrocarbon fuel is less than in rich air-fuel mixtures. Therefore, when $\alpha>1$, the effect of hydrogen additives on the combustion process becomes more noticeable. The increase in the proportion of hydrogen in the air-fuel mixture leads to an increase in the content of atomic hydrogen, which plays a major role in the combustion reactions. Therefore, the addition of hydrogen contributes to the formation of highly active centers of chemical reactions, reducing the ignition energy, extending the limits of combustion of the original fuel and increasing the speed of flame propagation. The maximum possible ratio of the contact area of the flame front with the combustion chamber ($S_{cc}$) to the surface area of the flame front ($S_{ff}$) was determined using the theory of limits of flame propagation by Ya.B. Zeldovich [6]:

$$\left( \frac{S_{cc}}{S_{ff}} \right)_{max} = 0.5 \cdot \left( \frac{T_b - T_0}{R \cdot T_b^2} \right) \cdot \left( \frac{E_a}{E_a - 1} \right)^{-1}$$

where $E_a$ - activation energy, kJ/mol; $T_0$ – temperature of air-fuel mixture, K.
As a result, it was found that combustion of stoichiometric mixtures with addition of hydrogen leads to an increase ($S_{\text{c}}/S_{\text{ff}}$)$_{\text{max}}$, i.e. burning stability increases. The result obtained corresponds to previous studies [10] that recorded an increase stability combustion and an expansion concentration limits of flame propagation with hydrogen addition. Figure 2 shows dependence thickness of unburned wall layer, calculated by formula (3) on coefficient excess air and proportion hydrogen in the fuel.

![Figure 2](image2.png)

**Figure 2.** Dependence width of the unburned wall layer on coefficient excess air and hydrogen concentration: ♦ $r_h=0\%$; ■ $r_h=29\%$; ▲ $r_h=47\%$; ● $r_h=58\%$.

The Figure 2 shows that use of stoichiometric mixtures and additions of hydrogen leads to a decrease in thickness of wall unburned layer. For example, at $\alpha=1$, the addition of hydrogen in amount of 58% leads to a reduction width of the unburned wall surface layer by 52%. This effect is explained promoting effect of hydrogen on combustion process, as a result, the width flame is reduced and intensity of fuel combustion near wall combustion chamber increases. The results obtained are in good agreement with experiments conducted at the Lawrence Berkeley National Laboratory (USA) on a spark-ignition gasoline engine [12], as well as by French specialists from the Peugeot-Citroen concern [13]. In particular, it was experimentally obtained [12, 13]: 1) when burning stoichiometric mixtures, width near-wall unburned layer has smaller values than when burning lean and rich air-fuel mixtures; 2) distance at which flame is extinguished is of the same order as data obtained by us. Thus, the convergence with results of other scientists, speaks about reliability of our results.

Figure 3 shows dependence completeness combustion fuel, calculated by formula (1), on coefficient excess air and proportion of hydrogen in fuel.

![Figure 3](image3.png)

**Figure 3.** Dependence of the completeness of combustion of fuel on the coefficient of excess air and hydrogen additives: —— calculation of $\chi$ using formula (1); ♦, ■, ▲, ● — calculation of $\chi$ according to the indicator diagram; ♦ $r_h=0\%$; ■ $r_h=29\%$; ▲ $r_h=47\%$; ● $r_h=58\%$. 


The Figure 3 shows that, in spite change speed internal combustion engine and hydrogen concentration in fuel, maximum values for fuel combustion are observed at an air excess factor of $\alpha = 1$. Similar results were obtained when processing and analyzing experimental data of Italian and Brazilian scientists devoted to study effect fuel composition on the combustion rate of gasoline in ICE with direct fuel injection [14]. Also, the analysis of Figure 3 showed that with increase proportion hydrogen in fuel, completeness combustion fuel increases, which is explained by an increase rate of fuel combustion in wall layer and a decrease in width of the flame. Similar results were obtained when processing experimental data of British scientists from University of Birmingham [15] and scientists from Yonsei University [16], who studied effect of hydrogen additives on full combustion of fuel in a gas piston engine with spark ignition. This indicates reliability obtained laws and their applicability for engines of different designs. Comparison combustion completeness calculated by proposed formula (1), with $\chi$, obtained on basis analysis experimental indicator diagram using first law of thermodynamics, equation state and two-zone combustion model, showed convergence between data of more than 85%.

4. Conclusion

Thus, the results of experimental and theoretical studies characteristics flame propagation in combustion chamber internal combustion engine with spark ignition and their influence on completeness combustion hythane lead to following conclusions:

1) It is theoretically and experimentally proved that relationship of flame propagation characteristics with completeness of combustion composite fuel is complex, non-linear, and depends on chemical composition combustible mixture and temperature in combustion chamber.

2) It was revealed that an increase thickness near-wall unburned fuel layer, size of slots in combustion chamber and surface area of combustion chamber contribute to a reduction combustion efficiency of the fuel.

3) It is shown that an increase rate flame propagation and a decrease thickness flame front leads to an increase completeness combustion fuel.

4) It was revealed that proposed formula, using fundamental characteristics of flame propagation, allows calculating completeness combustion composite fuel.

This indicates feasibility using this formula at the design stage and fine-tuning low-emission and energy-efficient combustion chambers of engines and power plants.

Acknowledgments

This work was supported by Ministry of Science and Higher Education of the Russian Federation as part program for the appointment of a scholarship President of the Russian Federation for young scientists number SP-3204.2018.1.

References

[1] Sandalcı T, Galata S and Karagoz Y 2019 International Journal of Hydrogen Energy 5 3208-20
[2] Tangoz S, Kahraman N and Akansu S 2017 International Journal of Hydrogen Energy 5 25766-80
[3] Verma G, Prasad R and Agarwal R 2016 Fuel 178 209-17
[4] Shaikin A and Galiev I 2016 Russian Aeronautics 2 249-53
[5] Shaikin A, Ivashin P, Galiev I, Bobrovskij I, Deryachev A and Tverdokhlebov A 2018 IEEE 978-1-5386-7386-7
[6] Zeldovich Ya, Barenblatt G, Librovich I and Makhviladze G 1985 The Mathematical Theory of Combustion and Explosions (New York: Springer USA) p 597
[7] Heywood J B 1988 Internal combustion engine fundamentals (New York : McGraw-Hill) p 931
[8] Hermanns R 2007 Laminar Burning Velocities of Methane-Hydrogen-Air Mixtures (Veenendaal: Universal Press) p 144
[9] Verhelst S, Woolley R, Lawes M and Sierens R 2005 Proceedings of the Combustion Institute 30 209-16
[10] Doosje E 2010 Limits of mixture dilution in gas engines (Eindhoven University of Technology: Doctoral thesis) p 370
[11] Mariani A, Morrone B and Unich A 2012 Review of Hydrogen-Natural Gas Blend Fuels in Internal Combustion Engines (InTech Europe) p 352
[12] Nobuhiko I 1978 Studies of wall flame quenching and hydrocarbon emissions in a model spark ignition engine (Lawrence Berkeley National Laboratory) p 109
[13] Chauvy M, Delhom B, Reveillon J and Demoulin F 2010 Flow, Turbulence and Combustion 369-77
[14] Martinez S, Irimescu A and Merola S 2017 Energies 10 1314-37
[15] Chang A 2002 Improved method of investigation of combustion parameters in a natural gas fuelled SI engine with EGR and H2 as additives (Birmingham: Doctoral thesis) p 196
[16] Park J, Cha H and Song S 2011 International Journal of Hydrogen Energy 8 5153-62