Modelling of flame propagation in the gasoline fuelled Wankel rotary engine with hydrogen additives

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Abstract. Recently, hydrogen has been considered as an alternative fuel for a vehicles power unit. The Wankel engine is the most suitable to be adapted to hydrogen feeding. A hydrogen additive helps to decrease incompleteness of combustion in the volumes near the apex of the rotor. Results of theoretical researches of the hydrogen additives influence on the flame propagation in the combustion chamber of the Wankel rotary engine are presented. The theoretical research shows that the blend of 70% gasoline with 30% hydrogen could accomplish combustion near the T-apex in the stoichiometric mixture and in lean one. Maps of the flame front location versus the angle of rotor rotation and hydrogen fraction are obtained. Relations of a minimum required amount of hydrogen addition versus the engine speed are shown on the engine modes close to the average city driving cycle. The amount of hydrogen addition that could be injected by the nozzle with different flow sections is calculated in order to analyze the capacity of the feed system.

1. Introduction

The main advantages of the rotor-piston engine, also known as the Wankel engine, include higher power-to-weight and power-to-size ratios than those of traditional engines. It is simpler, more compact and has less components, almost balanced and has lower vibration [1, 2].

Thereby Wankel engines may be considered as an alternative to the petroleum-fueled internal combustion engines (ICE) such as two-stroke ones for boats or four-stroke ones for general aviation [3] and hybrid vehicles [4-6].

However, the Wankel engine has a higher level of unburned hydrocarbons and fuel consumption. One of the reasons is a combustion incompleteness of the fuel-air mixture near the rotor's T-apex due to one direction flow. The twin spark plug ignition system allows improving combustion, but it cannot ensure that all of the mixture is burnt [3, 7, 8].

It can be assumed that increasing the flame speed in the combustion chamber could improve burning of the air-fuel mixture. One of the ways to increase the flame speed of the conventional fuel is addition of hydrogen [9, 10].

Hydrogen has the highest combustion heat and flame speed than any other hydrocarbon fuels. Main properties of hydrogen in comparison with other fuels are listed in table 1 [9-13]. In addition, it has a small quenching distance so it would be burned near the apex of the rotor. Moreover, many researchers point that the Wankel engine is more suitable for hydrogen feeding than the piston engine due to less probability of pre-ignition or backfire [6, 14]. However, hydrogen has low density, so the use of pure hydrogen is limited by difficulties of on board storage or production [15-17]. It seems that addition of a hydrogen portion to the main fuel could resolve those problems [14].

Table 1. Properties of fuel

Property	Hydrogen	Gasoline	LPG	Methane
Density [kg/m^3]	0.089	750	2.1	0.72
Autoignition temperature [C]	510	350-450	500	436
Maximum laminar flame speed [cm/s]	275	30	46	37
Lower heating value (LHV) [Mj/kg]	120	44	46	50
Stoichiometry [kg air/kg fuel]	34.3	14.9	15.1	17.2
Diffusion coefficient [cm^2/s]	0.63	0.06	0.08	0.16
Quenching distance [mm]	0.64	2.51	1.95	2.03

2. Model details

Theoretical investigation of combustion incompleteness has been carried out with multizone modeling of flame propagation.

The combustion chamber of the Wankel engine has a compound shape, and, as a rule, it is equipped with two spark plugs, so we have to divide the inner space into five zones (figure 1): three of them are with the unburned mixture (marked as u_1, u_2 and u_3) and the rest ones – with burned gases (marked as b_1 and b_2). The zone of burned gases has expanded by the moving of flame front through the unburned mixture.

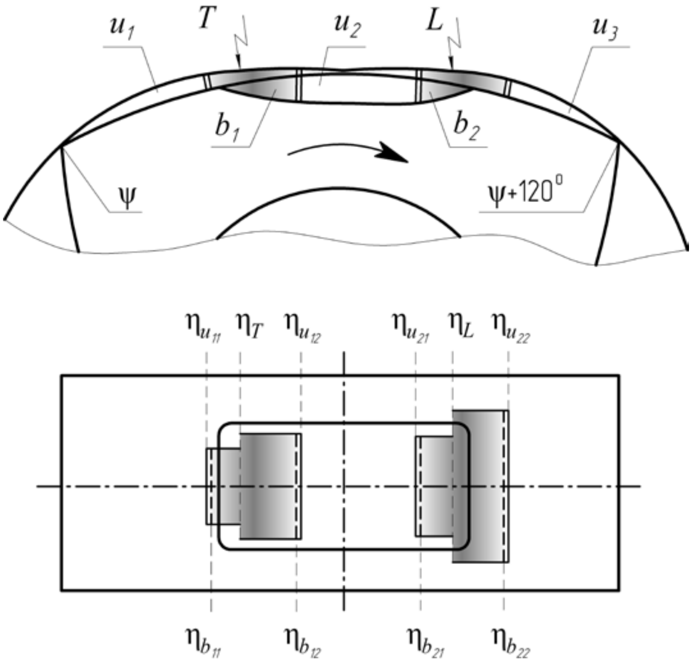

Figure 1. The plane of flame distribution in the Wankel engine: ψ – a T-apex angular coordinate; η_T, η_L – spark kernel angular coordinates; η_{u11}, η_{u12}, η_{u21}, η_{u22} – flame front angular coordinates; η_{b11}, η_{b12}, η_{b21}, η_{b22} – angular coordinates of burned gaseous zones.

It is considered that the flame is expanded from the spark plug in both directions: in the longitudinal one and in the cross one. Moreover, each of zones is subdivided into two subzones that are bordered by the flame front. One of them moves to the T-apex, another one moves to the L-apex.

The model is based on the following system of equations:

The energy-conservation equation for the initial zone with unburned gases:

$$\frac{k_{ui}}{k_{ui}-1}p\frac{dV_{ui}}{d\psi}+\frac{1}{k_{ui}-1}V_{ui}\frac{dp}{d\psi}=c_{pui}\cdot T_{ui}\frac{dm_{ui}}{d\psi}-\frac{dQ_{Wui}}{\omega}. \quad (1)$$

The energy-conservation equation for the zone with combusted gases:

$$\frac{k_{bj}}{k_{bj}-1}p\frac{dV_{bj}}{d\psi}+\frac{1}{k_{bj}-1}V_{bj}\frac{dp}{d\psi}=\left(Q_{LHV}-Q_D\right)\frac{dm_{bj}}{d\psi}-\frac{dQ_{Wui}}{\omega}+ \\ +c_{puj}\cdot T_{uj}\frac{dm_{bj1}}{d\psi}+c_{pu(j+1)}\cdot T_{u(j+1)}\frac{dm_{bj2}}{d\psi} \quad (2)$$

The equations of the state for the initial zone with unburned gases:

$$p\cdot V_u=m_u\cdot R_u\cdot T_u, \quad (3)$$

and the zone with combusted gases:

$$p\cdot V_b=m_b\cdot R_b\cdot T_b. \quad (4)$$

The volumes conservation equation is

$$\sum_1^3\frac{dV_{ui}}{d\psi}+\sum_1^2\frac{dV_{bj}}{d\psi}=\frac{dV_{\Sigma(\psi)}}{d\psi}, \quad (5)$$

and the mass conservation equation is

$$\sum_1^3 m_{ui}+\sum_1^2\sum_1^2 m_{bji}=m_a, \quad (6)$$

where i and j – is the zone index; p – is the pressure; T_{ui}, V_{ui}, m_{ui}, R_u and T_{bi}, V_{bj}, m_{bj}, R_b – is the temperature, volume, mass and specific gas constant for the initial zone with unburned gases and the area with combusted gases, respectively; Q_{LHV} and Q_D – combustion heat and the heat of dissociation, respectively; Q_W – heat losses in the walls of the combustion chamber; k and c_p – the adiabatic exponent and specific heat at constant pressure, respectively; ψ – the angle of rotation of the rotor; ω – the angular speed of the rotor; $V_{\Sigma(\psi)}$ – the instant volume of the combustion chamber; m_a – the mass of the fresh mixture in the combustion chamber.

To take into account the influence of hydrogen additives, thermal properties of equations of unburned and burned gas were adapted. The lower heating value of fuel was calculated as

$$Q_{LHV}=Q_{CH}\cdot(1-g_{H_2})+Q_{H_2}\cdot g_{H_2}, \quad (7)$$

where Q_{CH}, Q_{H_2} - lower heating values of gasoline and pure hydrogen, respectively; g_{H_2} - the mass fraction of hydrogen.

The stoichiometric air-fuel ratio was calculated as

$$AF=AF_{CH}\cdot(1-g_{H_2})+AF_{H_2}\cdot g_{H_2}, \quad (8)$$

where AF_{CH}, AF_{H_2} - the stoichiometric ratios of gasoline and pure hydrogen, respectively.

The system of equations (1) - (6) could be solved with the Runge-Kutta method. Moreover, the system of the equations is complemented by equations for calculation of the shape of the combustion chamber, turbulent characteristics and the combustion duration of turbulent moles dipped in the flame front. The growth of the combusted gases volume and hence unburned gases volume decrease is determined by simulating the turbulent flame moving. The model called "dipping" has been used to describe flame front propagation [8, 18]. This model suggests that the movement of the flame front depends on turbulent characteristics of the incoming unburned mixture flow. Combustion of the mixture occurs in a great number of laminar fronts with the surfaces.

Experimental data [11, 12] of the laminar flame speed of gasoline-air and hydrogen-air mixtures are also used. To determine laminar flame speed w_{nm} of the gasoline-air mixture with hydrogen addition, the following equation is used:

$$w_{nm}=w_{nCH}\cdot(1-g_{H_2})+w_{nH_2}\cdot g_{H_2}, \quad (9)$$

where w_{nCH}, w_{nH_2} – the flame speed of gasoline and pure hydrogen, respectively.

3. Results and discussion

3.1. Flame propagation

The combustion chamber of the Wankel engine VAZ-311 was used in calculation. The engine technical specifications are listed in table 2.

Table 2. The technical specifications of Wankel rotary engine VAZ-311

Engine manufacturer	Volga Automobile Plant, Russia
Number of rotors	Single rotor
Cooling	Water cooled
Ignition source	Two spark plugs per rotor
Working volume of each chamber	654 cm^3
Compression ratio	9.3
Width of rotors	80 mm
Eccentricity	15 mm
Maximum power output	52 kW at 6000 rpm
Maximum torque	95 Nm at 4000 rpm

The mode of the engine is a full throttle at a speed of the eccentric shaft equal to 2000 rpm and the equivalence ratio is 1. The spark advance is 26 deg for the L-spark plug and 30 deg — for the T-spark plug.

Theoretical research shows that the hydrogen additive allows fixing combustion completeness near the T-apex both in the stoichiometric and poor mixtures. Figure 2 shows the flame front propagation ignited by two spark plugs versus the amount of hydrogen. The hydrogen mass fraction in the total fuel mass varies from 0% to 40%. The additive of 20% of hydrogen causes the reduction of the combustion duration. Additives of 30% and more of hydrogen have allowed the flame front to achieve the T-apex before the power stroke is finished. Let us note that the additive of hydrogen has a negligible influence on the flame velocity in the direction to the L-apex. From our point of view, it depends on the mixture flow speed in the combustion chamber.

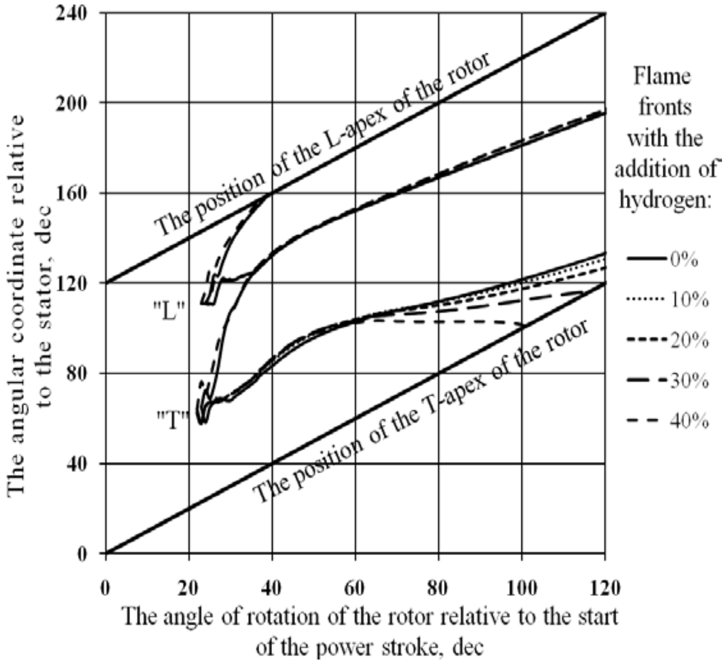

Figure 2. Propagation of the flame front versus hydrogen additives (λ=1; n=2000 rpm).

Hydrogen feeding in the Wankel engine can be realized by means of distributed injection into the inlet manifold [14, 15, 19, 20]. It is obvious that the amount of hydrogen addition needed for perfect combustion is caused by the mode of operation of the engine. It is illustrated in figure 3 where the relations of the minimum required amount of hydrogen addition versus the engine speed are shown on the engine modes close to the average urban driving cycle ($n \leq 3000$ rpm; $\varphi_{th} \leq 30\%$). It is noticed that the engine speed has a stronger influence than the load mode does.

We assume that it is due to the fact that the average speed of the mixture relative to the stator is increased with the engine speed so the flame front propagation on the rear apex of the rotor is hampered.

Hydrogen has the least density than other gases, so the implementation of the engine operation with the hydrogen additives is connected with special requirements for the feeding system [15]. The feed system must provide supply of the required quantity of hydrogen in the whole range of engine modes up to a full throttle. The last one is distinguished as a mode with the minimum duration of the intake, while hydrogen addition must be close to maximum. So, the amount of hydrogen addition that could be injected by the nozzle with different flow sections is calculated in order to analyze the capacity of the feed system.

3.2. Injection time

In figure 4, both the theoretical injection duration of hydrogen through the nozzle with a 1.2 mm^2 flow section and the duration of the intake are plotted versus the speed of the eccentric shaft. An excessive pressure is taken to be equal to 300 kPa that corresponds to the vehicle commercial onboard generator of hydrogen [15, 17].

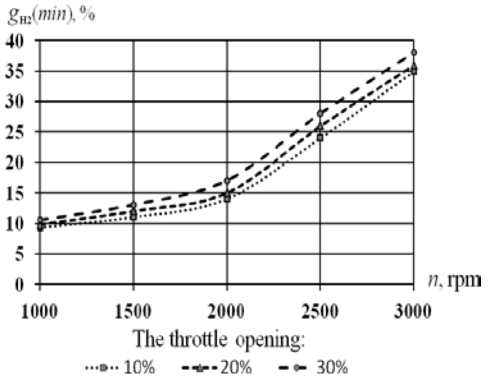

Figure 3. The minimum required amount of hydrogen addition in different driving modes.

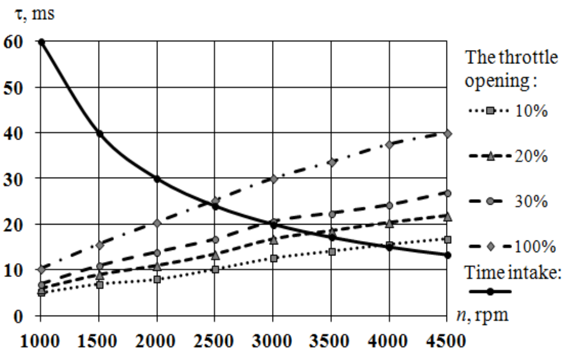

Figure 4. The intake duration and duration of hydrogen injection versus operation modes.

As we can see, the duration of the intake decreases significantly as the engine speed increases so it leads to complication of injection of a great amount of hydrogen. The nozzle that we use allows injecting the required quantity of hydrogen in a wide range of operation modes from almost idle load to the average urban driving mode. The intersections of the intake duration line with each of the lines of the hydrogen injection duration point on the limiting engine speed provide the required quantity of hydrogen and perfect combustion of mixtures. For example, in a 30% throttle opening mode, the implemented nozzle provides minimum hydrogen addition at an engine speed of up to 3000 rpm.

In some operation modes, the required hydrogen injection duration is shorter than that of the intake duration. In this case, the hydrogen injection must be started closer to the end of the intake stroke. It would increase the concentration of hydrogen near the T-apex where the incompleteness of combustion is observed.

It was calculated that the nozzle with the flow section of 4 mm^2 could provide necessary hydrogen feeding in all the operation modes of the investigated engine. However, the use of this nozzle is linked with the problem of the dispensing accuracy of the injection in the idle mode and with low loads. So, the solution is the implementation of the twin nozzles feeding system. One of them would operate in all modes, and the other one would be joined only in a high speed mode and a full throttle.

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4. Conclusion

The obtained results show that hydrogen additives to gasoline-air mixtures can improve completeness of combustion in the quenching area near the T-apex.

Hydrogen addition can be realized by means of injection into the intake manifold through the twin-nozzle feeding system. During the study, it turned out that a number of factors, such as the operation mode, the nozzle capacity, the rate of the minimum hydrogen addition and the duration of the intake process should be taken into consideration.

After the stock-list of nozzles had been looked through, it was found out that the nozzle for LPG or methane – could be used to fuel the Wankel engine with the same parameters by hydrogen.

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