Use of phased supply of hydrogen additives for improvement of the ecological characteristics of the Wankel rotary engine

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Abstract. The Wankel rotary engine, designed according to Wankel's scheme, is more adaptable for running on hydrogen fuels than traditional reciprocating engines, possessing lower pre-ignition and backfire probability. Hydrogen additive to main air-fuel mixture helps to decrease incompleteness of combustion in the vicinity of rear rotor apex. Experimental data for Wankel rotary engine VAZ-311 performance on hydrogen blends with hydrocarbon fuel is presented. Researches are performed on partial loads, where hydrogen mass fraction additions to the fuel mixture didn’t exceed 5%. It is shown that for partial loads (20% of full load) and engine speed \( n = 2000 \text{ min}^{-1} \) 5% hydrogen addition by mass yields to 4.2% decrease of brake specific fuel consumption (hydrogen consumption was converted to gasoline consumption computed proportionally to their combustion heats ratio). Amount of unburned hydrocarbons for the conditions mentioned reduces in a factor of 2 and emission of carbon monoxide reduces to 40%.

1. Introduction

The majority of internal combustion engines for transportation vehicles are reciprocating piston engines. Engines of such kinematic scheme are constructible and have the optimum ratio of combustion chamber surface area to its volume. At the same time the presence of rather massive parts executing reciprocating motion is one of disadvantages of such engines due to considerable inertial forces [1]. To resist the loads from inertial forces the parts mentioned demand strengthening and that correspondingly requires higher weight and leads in turn to decrease of engine speed.

The intention to overcome reciprocating engines disadvantages caused many attempts to create various types of internal combustion rotary engines. The majority of schemes developed appeared to be unworkable [2]. Recently functional design of rotary engines with acceptable parameters is based on the Felix Wankel scheme [1–4].

Due to the absence of crank and gas distribution mechanisms balancing of such engines is easy and dynamic characteristic and specific quantity of metal are also good. Wankel rotary engines (WRE) posses high specific capacity and dense of components arrangement. To obtain the capacity series a certain number of same-type sections must be used while the unification level reaches 85-90%. The WRE advantages presented make it possible to consider this engine type to be the serious alternative to two-stroke gasoline engines of small boats and four-stroke engines of light aerial vehicles [5–7]. However the application of WRE in transportation industry is limited by relatively high fuel consumption and unburned hydrocarbons level in exhaust gases. The latter is the result of incomplete fuel burning in the vicinity of rotor rear (counter rotation) apex. It is the bulk air-fuel mixture flow that
follows rotor rotation and prevents flame front propagation to the area mentioned. Relatively high square/volume ratio of WRE combustion chamber comparing to reciprocating engine and its oblong shape cause flame hindering in the boundary layer. As the result the considerable air-fuel mixture amount remains unburned to the start of exhaust stroke.

So it’s obvious that the reduction of unburnt fuel amount can be obtained by complete flame coverage of the rear apex vicinity volume. In principal there are two ways of this problem solution. In principal there are two ways of this problem solution. First – to decrease the distance of flame front propagation from the ignition source to the rotor rear apex. The second way is to increase flame propagation speed.

Currently the installation of additional spark plug in WRE is considered to be the main method for incomplete burning reduction [8, 9]. It’s also determined by engine construction – oblong shape of combustion chamber in the rotor side direction allows installation of two ignition spark plugs, one closer to front rotor apex and the other closer to the rear for the ignition event start.

Unfortunately the installation of additional spark plug displaced to the rear rotor apex doesn’t solve the problem completely [9]. For the majority of WRE performance modes the flame front propagating from the additional spark plug does not reach the rear rotor apex till the exhaust stroke starts.

Flame propagation speed depends on air-fuel mixture ratio. But generally it’s necessary to take into account the type of fuel. If WRE runs on gasoline the ratio for all speed and loading modes is close to stoichiometric and the normal flame propagation speed reaches its maximum. It’s known that the increase of flame propagation speed in air-gasoline mixture can be achieved by gaseous hydrogen addition [10–12]. The increased concentration of hydrogen that posses high reactivity level and combustion heat enables to raise flame propagation speed in the air-fuel mixture towards the rotor rear apex direction[13–15].

Thermophysical properties of hydrogen differ significantly from those of hydrocarbon fuels. It should be noted that hydrogen has the highest diffusion coefficient comparing to all gaseous fuels. They also observed the highest laminar flame propagation speed in air-hydrogen mixtures, and the lowest ignition energy.

However computational study of WRE combustion process showed that elimination of incomplete burning in the rear rotor apex vicinity requires more than 10% hydrogen addition to the basic fuel. [16, 17].

The necessity of such considerable hydrogen amount adds complexity to practical realization of the method presented because devices that can generate the latter onboard the vehicle and providing technical and economical efficiency are unknown [18,19]. To reduce the quantity of gaseous hydrogen that provides the complete air-fuel burning it’s preferable to consider the opportunity of stratification of the air-fuel mixture properties varying the value of hydrogen concentration in WRE combustion chamber volume, i.e. charge stratification.

2. Time-phased fuel injection
The directed motion of air-fuel bulk flow in WRE combustion chamber enables to organize the stratification of incoming charge. Thus to reduce the incomplete combustion it’s desirable to avoid fuel penetration into the rotor rear apex vicinity volume. Considerable success was reached by firm Curtiss-Wright [20, 21]. The direct injection process in WRE combustion chamber that was organized by application of two nozzles one injecting parallel to the big stator axis in the main flow direction and the other placed near spark plug made it possible to reach efficiency comparable with those of spark ignition piston engines. Representatives of Curtiss-Wright also declared that stratification of air-fuel charge and when near spark plug there’s ignition mixture enhance control of WRE performance. However the organization of such direct-injection process demands the application of high pressure fuel system.

The stratification of hydrogen addition in WRE combustion chamber volume can be achieved by phased hydrogen supply during intake stroke. To concentrate the hydrogen addition in the working chamber volume that boarders with rear rotor apex where the incomplete burning takes place, the start
of hydrogen injection process must be shifted from the moment of inlet port opening and intake stroke starts.

Evaluation of this hydrogen injection shift from the moment when the intake stroke starts can be based on the analysis of inlet process procedure that is specific for WRE design scheme presented in figure 1.

![Figure 1. The moment of the beginning of hydrogen supply during stratification of the air-fuel charge in the Wankel rotary engine: 1 - stator; 2 - epitrochoid surface; 3 - rotor; 4, 5, 6 - rotor tops; 7, 8, 9 - working chambers rotary engine; 10 - side inlet window; 11 - outlet window; 12 - leading spark plug "L"; 13 - top spark plug "T".](image)

The start of intake process is determined by the moment when rotor moving from top dead center (TDC) opens side inlet ports and that enables the mixture of air and basic carbon fuel to enter the working chamber. To place the main body of hydrogen addition in the rear rotor apex zone, the hydrogen nozzle must shift the start of hydrogen injection from TDC to the angle \(\phi_T\) accordingly its rear apex that corresponds the ignition moment in the previous combustion process for spark plug «T».

3. Experimental conditions
To determine the optimum moment of hydrogen injection during the intake stroke experiments were carried out on one-sectional WRE VAZ-311. The engine with 649 cm³ volume of each chamber and compression ratio 9.3 was placed on the test stand equipped with the measuring tools necessary. As
the main fuel gasoline was used, feeding by injector. The additional injector for hydrogen supply was installed near the WRE intake manifold. It was connected with hydrogen jet built in the intake manifold by short flexible pipe. The axis of the jet formed the acute angle with axis of gasoline injector. The control system provided the opportunity to vary in a broad range the injection start and duration for both nozzles.

Tests were carried for averaged mode of the urban driving cycle: \( n=2000 \text{ min}^{-1}, \rho_e=0.2 \text{ MPa} \). Spark advance angles for both spark plugs were fixed to provide optimum performance for running on gasoline and were not varied when hydrogen was added. The advance angle for leading spark plug «L» was 26° degrees of eccentric angle(DEA) before TDC, for spark plug «T» 30° DEA BTDC.

The registration of pressure in WRE working chamber was carried out by «Kistler» piezoelectric sensor (type 6118B) installed in spark plug «L». Besides pressure impulses from hydrogen injector and TDC position sensor were transmitted to other analog-to-digital converter channels. The example of record is presented in figure 2.

Figure 2. Example of recording signals from sensors of the engine VAZ-311:1 – pressure in the chamber of the rotary engine; 2 – TDC; 3 – hydrogen injector open signal.

The experimental study was carried in two steps. At the first step hydrogen feeding started simultaneously with gasoline feeding. The quantity of injected hydrogen was varied. At the second step quantity of hydrogen remained constant, but hydrogen injection start was varied thus changing relative position of gasoline and hydrogen injection phases. For all tests the air-fuel mixture was kept stoichiometric. Injection timing and injection duration for gasoline remained constant.

4. Results and discussion

In figure 3 the results of first experimental stage are plotted as the unburned hydrocarbons (CH) and carbon monoxide (CO) quantities versus hydrogen addition fraction for averaged urban driving cycle mode. It can be seen that 5% hydrogen addition leads to twice reducing CO emission and to 42% reducing CH emission.

Values of eccentric shaft angles hydrogen corresponding the start of hydrogen injection at the second stage of experiment from specific fuel consumption and standard deviation for peak cycle pressure are presented in table 1. The angle \( \Psi_1 \) is the moment of hydrogen injection start relative to the beginning of inlet port opening by front top of the moving rotor, while \( \Psi_2 \) is the same relative to TDC of adjacent in the clockwise direction working chamber. The first line of data presented corresponds to the case when hydrogen and gasoline injection start simultaneously. For such conditions volume averaged hydrogen mass fraction is 2%.
Figure 3. Relationship between the incomplete burning products quantities and the hydrogen addition for the urban driving cycle.

Figure 4. Relationship between the incomplete burning products quantities and the moment of supply of 2% hydrogen for the urban driving cycle.

To obtain quantitative information about the cycle-to-cycle variability (CCV), pressure traces were processed in at least 30 consecutive cycles. As a quantitative measure of the CCV, the value of the standard deviation of the maximum pressure was chosen:

$$\sigma_{p_z} = \left( \frac{\sum (p_i^{max} - \bar{p}^{max})^2}{n} \right)^{1/2}$$  \hspace{1cm} (1)

In equation (1) $p_i^{max}$ is the maximum pressure of the cycle, MPa; $\bar{p}^{max}$ is the mean value of maximum pressure of the $n$ consecutive cycles, MPa; $n$ is number of the consecutive cycles.

The analysis of data presented in table 1 enables to get the optimum hydrogen injection shift that corresponds maximum effect of hydrogen addition. It is seen that the lowest specific fuel consumption and standard deviation for peak cycle pressure are reached for $\Psi_1$ in the interval 90 to 100°DEA. It corresponds 45 – 55° delay of hydrogen injection relative to gasoline injection start.

Table 1. Charge stratification test results.

| $\Psi_1$° DEA | $\Psi_2$° DEA BTDC | $\sigma_{p_z}$, MPa | $g_c$, g/(kW·h) |
|---------------|--------------------|--------------------|----------------|
| 45            | 105                | 0.060              | 526.9          |
| 63            | 87                 | 0.057              | 524.4          |
| 80            | 70                 | 0.056              | 514.7          |
| 97            | 53                 | 0.051              | 504.8          |
| 113           | 37                 | 0.057              | 517.1          |
| 129           | 21                 | 0.068              | 529.1          |

In figure 4 variation of unburned hydrocarbons and carbon monoxide emissions are plotted as functions of angle $\Psi_1$.

For optimum phasing adjustment of hydrogen and gasoline injection fraction of the unburned hydrocarbons in exhaust reduced in 16.2% and for carbon monoxide in 30% comparing to the simultaneous injection start. Optimum phasing adjustment also produces the considerable effect on specific fuel consumption, reducing it in 4.2%.

So for averaged urban driving cycle mode the optimum moment for hydrogen injection start is 97° after intake begins that is 53° DEA BTDC for combustion process in the previous chamber. However it should be mentioned that for better accuracy hydrogen transporting system delay must be taken into consideration that shifts the injection start closer to TDC.
5. Conclusions

Using of small hydrogen additions to the main fuel enables to enhance the ecological characteristics of WRE. Thus addition of 2% hydrogen mass fraction to the main gasoline fuel for simultaneous injection decreases unburnt hydrocarbons emission in factor 1.2 and carbon oxides in 1.3.

The hydrogen injection being phased enables to stratify the air-fuel charge during the intake stroke. The purpose of the method proposed is the transportation of charge volumes enriched by hydrogen directly to the zone where flame front and bulk flow propagates in opposite directions. As the result there is more complete combustion that leads in turn to decrease of required hydrogen additions, specific fuel consumption and incomplete burning products emission.

The phased injection of 2% hydrogen addition to the main fuel mass fraction further reduces the amount of unburnt hydrocarbons in exhaust gases by 16.2% and carbon monoxide by 30% comparing to simultaneous injection.

Moreover hydrogen economy is important result because generation and storage of hydrogen onboard the vehicle in considerable quantities is a complex problem.

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