Gaseous hydrogen addition to the basic fuel as the way for improvement of Wankel rotary engine ecological characteristics

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Abstract. Recently hydrogen is recognized to be an alternative fuel for vehicles. Onboard storage of hydrogen amount that is sufficient for internal combustion engine feeding is a rather complex problem. So the application of relatively small hydrogen addition to the basic hydrocarbon fuel that enhances burning rate and has positive influence on burning completeness is of great interest. Wankel rotary engines are more accommodated to hydrogen feeding then reciprocating ones due to less probability of pre ignition and backfire. Furthermore, for Wankel engines the growth of flame propagation speed due to the gaseous hydrogen addition results in decrease of the unburned fuel amount in the vicinity of rotor rear (counter rotation) apex that is common for engines of this type. In this paper experimental data is presented concerning the influence of gaseous hydrogen addition to the basic hydrocarbon fuel on ecological characteristics of Wankel rotary engine VAZ-311. The data mentioned shows that 5% by mass fraction hydrogen addition make it possible to enhance ecological characteristics of the engine on partial loads and idling mode.

1. Introduction
Wankel rotary engines (WRE) have a number of advantages over reciprocating ones in such characteristics as specific capacity, specific quantity of metal, dynamic balance, manufacturing laboriousness [1–4]. Thus Wankel engines can be considered to be the serious alternative to two-stroke reciprocating gasoline engines of small boats, four-stroke engines of light aerial vehicles and to hybrid engines of transportation vehicles [5–8]. However wide application of WRE in transporting sector is restricted by their relatively high fuel consumption and relatively high percentages of hydrocarbons in exhaust gases [6,7,10].

Tests results presented [11,12] that were carried out on a range of WRE engines show that the level of unburned hydrocarbons in the exhaust gases leaving the working chamber of WRE is from 6 to 8 times higher comparing to reciprocating engines. It should be noticed that nitric oxides level in the exhaust of WRE is less on 20-30% then of reciprocating engine. The reason of such reduced NOx quantity is decreased temperature in WRE combustion chamber that is the consequence of burning process shifting towards expansion stroke.

The studies show [13–15] that the main reason of high fuel consumption and high level of unburned hydrocarbons in exhaust gases is incomplete burning in WRE working chamber. Relatively high square/volume ratio of WRE working chamber comparing to reciprocating engine and one-dimensional flow movement in the chamber that follows rotor rotation hinders flame propagation towards the rear (counter rotation) apex. As the result the considerable quantity of air-fuel mixture remains unburned to the moment when the exhaust stroke starts.
A number of studies observed [16-20], and those carried out by our group in Volgograd state technical university [21,22] revealed that reduction of incomplete burning in the vicinity of the WRE rear apex can be obtained by hydrogen addition to the basic fuel.

The Wankel engine to a greater extent is adapted to work on hydrogen than the reciprocating one [6,22,23]. As intake and compression strokes proceed in the so called «cold» stator wall zone, and spark plugs are located in special pre-chambers the probability of pre ignition of the mixture is eliminated.

2. Experimental setup
For experimental study of the hydrogen addition effect on WRE ecological characteristics one-section engine VAZ-311 (Volga Automobile Plant, Russia) was used. The engine technical specifications are listed in table 1.

| Specifications                        | Value                        |
|---------------------------------------|------------------------------|
| Number of rotors                      | 1                            |
| Number of spark plugs                 | 2                            |
| Working volume of each chamber        | 654 cm$^3$                   |
| Compression ratio                     | 9.3                          |
| Width of rotor                        | 80 mm                        |
| Eccentricity                          | 15 mm                        |
| Maximum power output                  | 52 kW at 6000 rpm            |
| Maximum torque                        | 95 Nm at 4000 rpm            |

The tests were run for idling and partial loads mode with eccentric shaft speed 2000 min$^{-1}$. During experiment spark advance angles for both spark plugs were defined to provide optimum performance for running on gasoline fuel and remained constant regardless of hydrogen additions amounts. Ignition timing for low spark plug was 26 degree shaft angle before top dead center (DSA BTDC), for top spark plug was 30 DSA BTDC.

As the basic fuel gasoline was used feeding by injector. The axis of injector was directed right to the WRE stator side inlet port. Extra injector for hydrogen supply was mounted near the intake manifold (figure1) and was connected with hydrogen jet installed in the manifold mentioned by short flexible pipe. Axis of the jet is directed towards the inlet port and forms an acute angle with axis of gasoline injector. System of timed-port injection enabled to vary within broad range injection start and injection timing.

![Image](image1.png)

**Figure1.** Experimental setup equipped with injectors: 1 – gasoline; 2 – hydrogen.
3. Results and discussion

The percentage of idle mode for the transport vehicle can reach 35% to all engines run. Increased concentration of unburned products in the exhaust gases is typical for this mode is caused by low volumetric efficiency and high residual gases ratio values. Factors mentioned also reduce flame propagation speed that in turn contributes to incomplete burning of air-fuel mixture. In contrast with reciprocating engines for WRE the situation is compounded by generally increased level unburned hydrocarbons.

In figure 2 experimentally obtained values of unburned hydrocarbons \(\text{C}_x\text{H}_y\) and carbon monoxide (CO) in exhaust gases are plotted as functions of hydrogen addition mass fraction \((g_{\text{H}_2})\) for Wankel engine idle mode. The excess air ratio of air-gasoline-hydrogen mixture was stoichiometric \((\alpha=1)\). However it must be noted that in the absence of hydrogen additions the engine ran on slightly enriched air-fuel mixture \((\alpha=0.95)\) because the increase of \(\alpha\) led to instability of engine performance.

![Figure 2](image1.png)

**Figure 2.** Influence of hydrogen mass fraction value on the toxicity of WRE exhaust gases for idle mode.

![Figure 3](image2.png)

**Figure 3.** Toxic substances concentration as function of excess air ratios and various hydrogen additions.

As seen in the figure 2, 9% hydrogen addition to the air-gasoline mixture leads to 3-time reduction of unburned hydrocarbons and to 2.8-time reduction for carbon monoxide. It can be noted that portion of unburned hydrocarbons that are contained in the exhaust gases decreases with increase of hydrogen addition in greater degree than portion of carbon monoxide. This trend corresponds to theoretical conclusion that hydrogen addition primarily decreases the amount of unburned mixture in WRE combustion chamber.

There is the new option to obtain stoichiometric air-fuel mixture on idle mode by varying the fraction of hydrogen addition and it enables to use three component neutralizers of exhaust gases for further reducing toxic emissions. It was experimentally proved that hydrogen addition provides Wankel rotary engine stable running on idle mode even for leaner mixtures (figure 3).

In figure 3 experimental results concerning the variation of unburned hydrocarbons and carbon monoxide level in WRE exhaust gases for idle mode with hydrogen addition are presented. In the plots near the experimental data hydrogen addition amounts are depicted that provided stable running on corresponding leaning of air-fuel mixture. It is notable that leaning in experiments mentioned was achieved only by gasoline supply reducing while the hydrogen addition amount remained constant as well as hydrogen injector opening duration and this occurred for all \(\alpha\) examined.

The plot in figure 3 shows the opportunity to reach stability of engine performance by addition of hydrogen for \(\alpha=1.16\). This value of air-fuel ratio leads to 3-time reduction of unburned hydrocarbons in WRE exhaust gases then comparing with pure gasoline fuel and \(\alpha=0.95\). The same comparison for carbon monoxide fraction gives us 0.04% and 1.7% respectively.

As well as for the idle mode hydrogen addition had a pronounced effect on exhaust toxicity of Wankel engine running loaded modes. Figure 4 and 5 present experimental plots of unburned hydrocarbons and carbon monoxide concentrations versus loading mode for WRE eccentric shaft
rotational speed 2000 min\(^{-1}\). Upper curves correspond to the tests without hydrogen addition. The rest two curves in each figure obtained for 3% and 5% hydrogen addition respectively. For all loads and all hydrogen additions the mixture was maintained stoichiometric.

**Figure 4.** Relationship between unburned hydrocarbons quantity and brake mean effective pressure.

**Figure 5.** Relationship between carbon monoxide fraction and brake mean effective pressure.

Free gaseous hydrogen addition to the basic air-gasoline mixture enables to reduce the level of unburned hydrocarbons and carbon monoxide in exhaust for all loads studied while \(n=2000\) min\(^{-1}\). Thus, for example 5% hydrogen addition leads to 1.5 times reduction of unburned hydrocarbons concentration for \(p_e=0.2\) MPa and to 1.55 reduction for \(p_e=0.4\) MPa. Carbon monoxide content reductions are 2.3 and 2.7 respectively.

It is interesting to evaluate the implementation of air-fuel mixture leaning as the way to obtain extra reduction of the unburned hydrocarbons fraction for loaded engine mode. Such evaluation was carried out for the WRE mode \(p_e=0.2\) MPa, \(n=2000\) min\(^{-1}\) and for various excess air ratios (figure 6).

**Figure 6.** Unburned hydrocarbons quantity as function of the excess air ratio.

As seen in figure 6 the level of unburned hydrocarbons in WRE exhaust decreases following the fuel mixture leaning approximately linearly. It should be noted that the incline of all plots depicted in figure 6 is the same, so hence for all \(\alpha\) values hydrogen addition decrease the level of unburned hydrocarbons by the same factor. According to this it’s evident that the only reason that causes reduction of unburned hydrocarbons in exhaust for the leaner air-fuel mixture and fixed hydrogen addition is the decrease of the basic fuel amount.
4. Conclusions
Finally, we can state that experiments carried out confirm the positive influence of gaseous hydrogen addition to the basic air-gasoline mixture on WRE ecological characteristics. Substantial reduction of unburned hydrocarbons and carbon monoxide concentration in exhaust gases for idling and partial loads shows that hydrogen addition contributes to increase of burning completeness in WRE. The use of hydrogen addition provides the performance stability of the engine on lean mixture on partial loads and idling mode.

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