

The effect of hydrogen additives on fuel consumption and hydrocarbon emissions in gasoline fuelled Wankel rotary engine

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Abstract. Experimental data for Wankel rotary engine performance on hydrogen blends with hydrocarbon fuel is presented. Researches are performed on partial loads and idle. Hydrogen mass fraction additions to the fuel mixture didn't exceed at partial loads 5% and idle mode 9%. The excess air ratio was stoichiometric. It is shown that for partial loads (20% of full load) and engine speed 2000 rotary per minute 5% hydrogen addition 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 1.8 and emission of carbon monoxide in a factor of 2.3. Hydrogen addition notably increase effective leaning limit, thus for idle mode tests Wankel rotary engine showed steady performance even for excess air ratio 1.16, while in the absence of addition instability displayed itself for excess air ratio exceeding 0.95.

1 Introduction

Probably the first assumptions of the hydrogen using possibility in technical devices belong to Jules Verne in the novel the «Mysterious Island».

In the Soviet Union in 1941 during World War II this novel inspired the Lieutenant Boris Shelisch to use hydrogen from barrage balloons as a motor fuel for military trucks [1]. He offered to supply hydrogen through a hose to the intake manifold of the engine. Bypassing the carburetor, the gas enters the cylinders. The throttle provided the dosage of hydrogen and air. The patent for the method of unit operation with balloons barrier was published January 31, 1945 [2].

Experimental data [3-9] shows that hydrogen addition to the basic air-fuel mixture in the reciprocating spark ignition engines improves their characteristics, especially ecological. This event is recognized [10-12] to be the effect of promoting influence of gaseous hydrogen on the hydrocarbon fuels combustion process especially on the laminar flame propagation speed. For Wankel rotary engines (WRE) high flame propagation speed is exceptionally important because one-dimensional air-fuel flow in the combustion chamber caused by rotor rotation hinders flame propagation towards the “rear” (counter rotational) apex. Therefore, for the majority of WRE operating conditions the combustion speed is insufficient to provide

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the complete burning in the rear apex vicinity. This very thing to a considerable extent explains relatively high fuel consumption and unburned hydrocarbon emissions typical for WRE.

In the recently years there was a number of publications [6, 7, 9-11, 13-15] where results of theoretical and experimental studies have been reported concerning the influence of hydrogen addition to the basic air-fuel mixture on the reciprocating engine performance. Amrouche et al [6, 7] tested air cooled WRE with displacement 530 cm³, compression ratio 8.75 manufactured by Marine (USA). The engine was operated at full load and eccentric shaft speed was 3000 rotary per minute (rpm). Hydrogen mass fraction in the mixture was determined as to provide the certain energy percentage in the global heat release of hydrogen-fuel blend and it reached 10%. Experimental study showed the increase of cycle thermal efficiency and decrease of pollution emissions (C_xH_y, CO) proportionally to the gaseous hydrogen mass fraction. At the same time, the significant growth of NO_x specific emission was observed. Therefore, series of experiments were carried out to find the ways of NO_x emission decrease for engine running on lean air-fuel mixture with gaseous hydrocarbon addition [15].

Our theoretical study carried out using numerical model of WRE combustion process developed in Volgograd State Technical University [16, 17] made it possible to conclude that incomplete combustion of the air-fuel mixture in the rear rotor apex area can be eliminated by gaseous hydrogen addition in quantity of 20% mass fraction approximately. Unfortunately, this addition leads to the engine power output decrease. Furthermore, the practical realization of such performance with relatively large hydrogen addition for the vehicle conditions demands bi-fuel supply system with hydrogen storage device.

Our study concerns the influence of relatively small hydrogen additions to the main fuel not exceeding 5% mass fraction on the emission of unburned hydrocarbons and on fuel efficiency of WRE on partial and idle loads. Parameters of Wankel rotary engine VAZ-311 tested are presented in table 1.

Table 1. Wankel rotary engine VAZ-311 technical specifications.

Engine manufacturer	Volga Automobile Plant (now AVTOVAZ), Russia
Number of rotors	Single rotor
Cooling	Water cooled
Ignition source	Two spark plugs
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	m at 4000 rpm

2 Tests conditions

The basic fuel (gasoline) was injected in the intake manifold by the nozzle mounted so that the fuel jet entered the intake port. Hydrogen injector installed near the intake manifold was connected with latter by short pipe. The axis of the hydrogen jet was directed towards the inlet window of the WRE at an acute angle to the axis of the gasoline injector. The phased fuel injection system made it possible to vary the start time and duration of fuel injection over a wide range. The hydrogen overpressure at the injector inlet was varied from 140 to 160 kPa.

WRE was mounted on the test bench equipped with registering and monitoring apparatus required. Along with the basic characteristics such as torque, engine speed, fuel and air consumption unburned hydrocarbons and carbon monoxide fractions were metered in the exhaust gases.

During experiment hydrogen and gasoline supply was determined by injection duration the latter obtained from nozzle consumption characteristics and the required mass rate of hydrogen (G_{H_2}) and gasoline (G_g). The latter was computed in accordance with assumed hydrogen mass fraction g_{H_2} in the hydrogen-gasoline mixture:

$$G_{H_2} = \frac{g_{H_2} \cdot G_g}{1 - g_{H_2}} \quad (1)$$

Gasoline consumption is determined by mass of hydrogen addition required and excess air ratio λ :

$$G_g = \frac{G_{air}}{\left(\frac{g_{H_2}}{1 - g_{H_2}} \cdot AF_{H_2} + AF_g \right) \cdot \lambda} \quad (2)$$

where G_{air} – air mass flow rate, kg/s; λ – excess air ratio;

AF_{H_2} , AF_g – stoichiometric ratios of gasoline and pure hydrogen respectively.

During experiment spark advance angles were defined to provide optimum performance for running on gasoline fuel and remained constant regardless of hydrogen editions. The spark advance angle for «L» spark plug $\Theta_L = 26$ degree crank angle before top dead center (DCA BTDC), for «T» $\Theta_T = 30$ DCA BTDC.

Tests were performed at mean effective pressure $p_e = 0.2$ MPa and $n=2000$ rpm and on idle mode. Hydrogen mass fraction additions to the fuel mixture didn't exceed at partial loads 5% and idle mode 9%.

Indicating of WRE clearance volume was performed by measuring spark plug Kistler (type 6118B) installed instead «L» spark plug. The sensor monitored pressure in the combustion chamber from 75 DCA BTDC to 90 DCA after top dead center (ATDC). In addition, pressure pulses from the hydrogen injector and the TDC position sensor were transmitted to other channels of the analog-to-digital converter. An example of a record is shown in Fig. 1.

The content of hydrocarbons C_xH_y and carbon monoxide CO in the WRE exhaust gases was monitored using the ASCON-02 gas analyzer. Gas sampling was carried out at a depth of 300 mm from the cut of the outlet pipe of the standard muffler, which was equipped with the WRE engine at the stand.

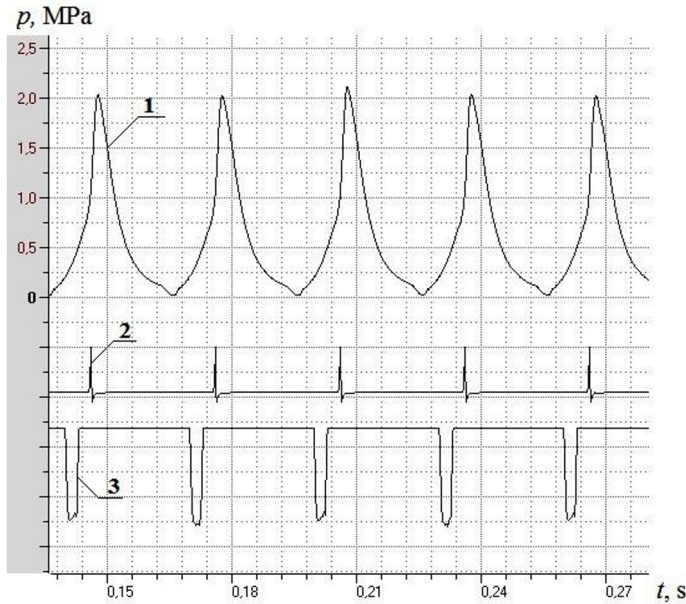


Fig. 1. An example of recording signals from WRE sensors: 1 – pressure in the chamber; 2 – TDC; 3 – hydrogen injector open signal

3 Results and discussion

In urban traffic, the car engine operates most of the time at partial loads and idling. These modes are characterized by an increased concentration of products of incomplete combustion in the exhaust gases, which is due to the low value of the filling factor and the high value of the coefficient of residual gases. In this regard, studies in bench conditions were carried out precisely in these modes.

3.1 Pressure in the combustion chamber

For a quantitative assessment of the degree of influence of hydrogen additives on the cycle-by-cycle variations of the working process the WRE was indexed, which worked with and without hydrogen additives.

Fig. 2 shows the plots of pressure in WRE working chamber averaged for 100 consequent cycles and a number of hydrogen addition levels for the operation conditions $n=2000$ rpm, $p_e=0.2$ MPa. Following the hydrogen fraction increase burning process starts earlier and this can be explained by decreasing of initial burning zone formation timing. The displacement of the maximum pressure point of the cycle towards TDC is the result of not only a reduction in the duration of the formation of the initial combustion site, but also an increase in the flame propagation velocity due to the addition of hydrogen

Quantitatively cycle-by-cycle variation can be defined by coefficient of variation of cycle indicated mean pressure

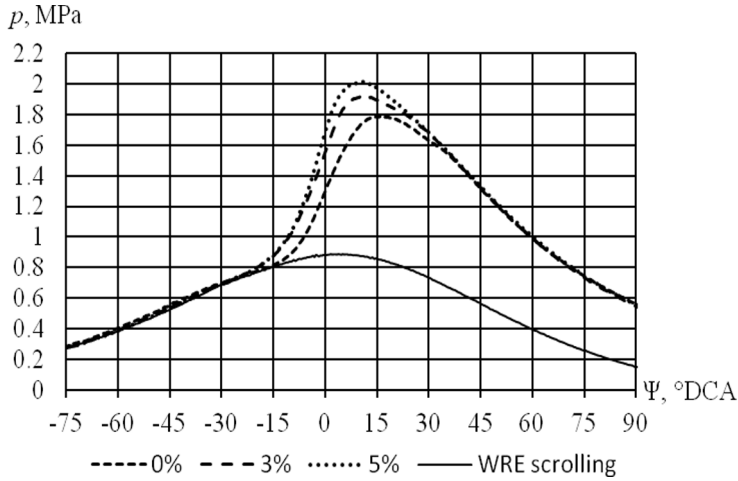


Fig. 2. Pressure indicated for WRE running on hydrogen-blended mixtures.

$$\delta_{pi} = \frac{\sigma_{p_i}}{\langle p_i \rangle}, \quad (3)$$

where $\langle p_i \rangle$ – mean value of cycle indicated mean pressure,

σ_{p_i} – standard deviation of value of cycle indicated mean pressure.

$$\sigma_{p_i} = \sqrt{\frac{\sum (p_i - \langle p_i \rangle)^2}{n}} \quad (4)$$

Value of $\langle p_i \rangle$ was calculated for 100 consequent cycles.

Adding 5% hydrogen reduces the variation coefficient to 2.5% in the specified engine operation mode. Therefore, hydrogen addition not only cuts down duration of initial burning zone formation but also leads to decrease of cycle-by-cycle variations.

3.2 Emissions

The idling mode is characterized by particularly large, in relative terms, emissions of unburned hydrocarbons and carbon monoxide. For WRE, in contrast to conventional piston engines, the situation is exacerbated by the overall increased level of emissions of unburned hydrocarbons.

In the Fig. 3 carbon monoxide (CO) and unburned hydrocarbons (C_xH_y) emissions amount in the exhaust gases are plotted versus hydrogen addition mass fraction for the idle mode ($n=900$ rpm). The excess air ratio of air-gasoline-hydrogen mixture was stoichiometric ($\lambda = 1$). However without hydrogen additions the engine could run steadily with excess air ratio of not more than $\lambda = 0.95$ because the increase of λ led to instability of engine performance.

Experimental study showed (Fig. 3) that 8% hydrogen addition to the air-gasoline mixture leads to 3 time reduction of unburned hydrocarbons and to 2.8 time reduction of carbon

monoxide fractions. Hydrogen additions make it possible to use the leaner mixtures down to $\lambda = 1.16$ and this in turn leads to decrease of CO fraction in exhaust gases to 0.1%.

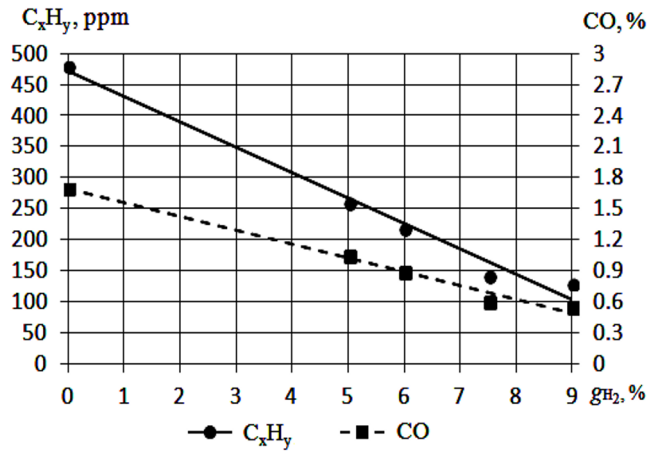


Fig. 3. The influence of hydrogen addition mass fraction on WRE emissions toxicity for idling mode.

Taking into account that idle performance timing for automobile engines can reach 35% for urban cycle, we can state that reduction of toxic emissions for this mode will contribute the significant enhance of corresponding operating and ecological characteristics.

As well as for the idle mode it turned out that for the regime of low load ($n=2000$ rpm, $p_e=0.2$ MPa) the effect of hydrogen additions on toxic emissions is rather notable. In Fig. 4 experimental plots of incomplete combustion products and carbon monoxide emissions as functions of hydrogen addition mass fraction are depicted.

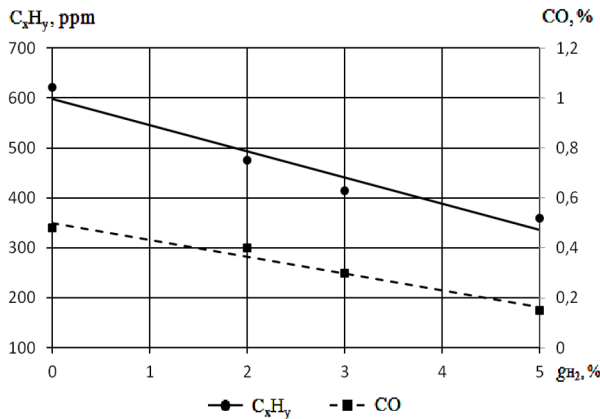


Fig. 4. The dependence of incomplete combustion products and carbon monoxide amount on hydrogen addition mass fraction.

Evidently CO emissions reduced by 2.3 times and those for C_xH_y decreased by 42% due to 5% hydrogen addition. It's worth mentioning that during the low load tests hydrogen and gasoline injection timings were selected as to provide stoichiometric air-fuel mixture in WRE working chamber.

Obtaining a stoichiometric air-fuel mixture at the above engine operating modes when changing the proportion of added hydrogen allows the use of three-component exhaust gas neutralizers to further reduce toxic emissions.

3.3 Fuel consumption

Fuel efficiency of the internal combustion engine depends on the degree of fuel heat utilization. Quantitatively the fuel efficiency with account of hydrogen thermo physical properties can be characterized by specific brake fuel consumption and thermal brake efficiency.

Specific brake fuel consumption was calculated as follows:

$$g_e = \frac{G_g + G_{H_2} \cdot H_{uH_2} / H_{ug}}{N_e}, \quad (5)$$

where H_{ug} and H_{uH_2} - are lower heating values of gasoline and pure hydrogen respectively; N_e – brake power of engine.

Thermal brake efficiency with account of hydrogen supply:

$$\eta_e = \frac{N_e}{G_g \cdot H_{ug} + G_{H_2} \cdot H_{uH_2}}. \quad (6)$$

Plots of specific brake gasoline consumption as function of hydrogen addition mass fraction for the mentioned averaged WRE mode are presented in Fig.5. Thermal brake efficiency is also plotted in the same coordinate frame.

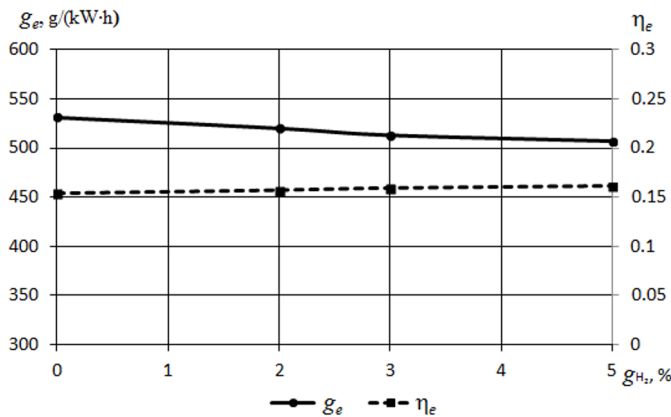


Fig. 5. Effective data versus hydrogen mass fraction.

As seen from experiments hydrogen addition have less influence on specific brake fuel consumption and thermal brake efficiency then on toxic emissions. Thus, 5% hydrogen addition reduces specific brake fuel consumption only to 4.2%. To our opinion, the reason of relatively small influence of gaseous hydrogen additions on fuel efficiency at low loads is the increase of specific fuel consumption that follows the growth of gas exchange losses. Losses caused by incomplete combustion vary insignificantly with load reducing so their contribution to the total losses decreases.

4 Conclusion

The researches carried out on Wankel rotary engine showed that gaseous hydrogen addition to the basic air-gasoline mixture performed during the intake stroke enhances combustion completeness and primarily the consequence of this is the significant decrease of unburned hydrocarbons and carbon monoxide emissions. With the addition of 5% hydrogen for idle and 20% of full WRE load CO emissions decreased to 1.7 and 2.3 times respectively, C_xH_y

emissions decreased to 1.8 times. This confirms that incomplete combustion is the main reason of high content of this toxic component in Wankel rotary engines exhaust gases.

Fuel consumption for the modes mentioned decreases insignificantly for contribution of incomplete combustion losses to the total losses is rather small.

Experimental studies have established that the use of small additions of hydrogen (up to 5% by mass) makes it possible to increase the maximum pressure in the rotary engine working chamber and increase the stability of the combustion process.

References

1. V. N. Fateev, S. A. Grigoriev, E. A. Seregina, *Nanotechnologies in Russia* **15**, 256-272 (2020)
2. B. Shelisch, USSR Patent 64209 (1945)
3. C. M. White, R. R. Steeper, A. E. Lutz, *Int J of Hydrogen E* **31**, 1292-1305 (2006)
4. S. Verhelst, T. Wallner, *J Progress in E and Combustion Science* **35**, 490-527 (2009)
5. J. B. Greenwood, P. A. Erickson, J. Hwang, E. A. Jordan, *Int J of Hydrogen E* **39**, 12980-12990 (2014)
6. F. Amrouche, P. Erickson, J. Park, S. Varnhagen, *Int J Hydrogen E* **39**, 8525-8534 (2014)
7. F. Amrouche, P. Erickson, J. Park, S. Varnhagen, *Int J Hydrogen E* **41**, 14261-14271 (2016)
8. C. G. Bauer, T. W. Forest, *Int J Hydrogen E* **26**, 55-70 (2001)
9. Y. Karagöz, Ö. Balcı, H. Köten, *Int J Hydrogen E* **44**, 14243-14256 (2019)
10. N. Donohoe, A. Heufer, W. K. Metcalfe, H. J. Curran, M. L. Davis, *Combustion and Flame* **161**, 1432-1443 (2014)
11. A. R. Khan, M. R. Ravi, A. Ray, *Int J Hydrogen E* **44**, 1192-1212 (2019)
12. Di V. Sarli, Di A. Benedetto, *Int J Hydrogen E* **32**, 637-646 (2007)
13. A. Boretti, S. Jiang, J. Scalzo, *SAE Technical Papers* 2015-01-0007 (2015)
14. K. V. Shivaprasad, S. Raviteja, P. Chitrakar, G. N. Kumar, *J Procedia Technology* **14**, 141-148 (2014)
15. Y. Karagöz, T. Sandalcı, A. S. Dalkılıç, *Int J Hydrogen Energy* **40**, 8607-8619 (2015)
16. E. A. Fedyanov, E. A. Zakharov, K. V. Prihodkov, Y. V. Levin, *Modelling of flame propagation in the gasoline fuelled Wankel rotary engine with hydrogen additive*, in *IOP Conference Series: Materials Science and Engineering*, 27–29 October 2016, Tomsk, Russian Federation (2017)
17. E. M. Itkis, E. A. Fedyanov, Y. V. Levin, *Experimental and numerical investigation of influence of hydrogen addition to hydrocarbon fuel on Wankel rotary engine performance*, in *Proceedings of the 4th International Conference on Industrial Engineering, ICIE*, 15-18 May 2018, Moscow, Russia (2019)