Test bed for farm vehicle onboard hydrogen production system with microwave plasma

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Abstract: Energy conservation and emission reduction are the focus worldwide. Farm vehicle engine would be more efficient if it is injected a little hydrogen during work, meanwhile, the emission of the vehicle would be decreased. Nowadays, there are many kinds of onboard hydrogen production methods, among which the microwave plasma method is regarded as the best. In order to develop an onboard hydrogen production system using microwave plasma, a new corresponding test bed was designed and developed in this research. The ethanol, water and air from the three supply pipelines were mixed and evaporated into gas mixture, and then the mixture was further created into hydrogen through microwave plasma reaction. In the test bed, a hydrogen production environment required for the reaction was provided, and hydrogen would come into being when the air was broken down by the plasma under the conditions of 0.1-0.7 atm. Furthermore, the reaction conditions could be controlled precisely, and real-time environmental data and spectral data could be collected during the hydrogen production. The experimental results showed that onboard hydrogen production could be achieved on this test bed, and the hydrogen amount produced could be adjusted to simulate real vehicle working conditions. In addition, the system is of rapid response, high precision and reliability, which can be applied in new products developments of the onboard hydrogen production system.

Keywords: hydrogen production, test bed, microwave, plasma, farm vehicle, emission, steam reforming, partial oxidation
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1 Introduction

The hydrogen, immediately produced in the travelling farm vehicles, can be applied in not only the fuel cells, but also the mixed hydrogen combustion[1-4]. It is stated that, the compression ratio can be boosted to achieve a lean combustion if the amount of the hydrogen in the range of 3%-5% is mixed into a diesel or gasoline, which would contribute to the enhancements of the EGR and average efficiency of vehicles[5]. To solve the environment pollution problem due to vehicle emissions, researchers worldwide have made various experiments and put forward many constructive techniques, among which the majority have been focused on onboard hydrogen production (combustion controller) to achieve lean combustion for reducing vehicle emissions[6,7].

To produce hydrogen from methane, researchers in Massachusetts Institute of Technology (MIT) began to study hydrogen production by means of the partial oxidizing with steam in 1998[8,9], they developed a plasma generator with the low-current and cold plasma characteristics in 2000. Moreover, they developed an efficient engine fuel management system with flex-fuel and methanol based fuel in 2009[2,4]. Simultaneously, Russia made a microwave discharge converter, and

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research group on the thermodynamics of ionized gases at Orleans University (GREMI) in France did a sliding arc discharge converter[10,11].

In order to produce hydrogen through methane cracking, Kvarner Oil & Gas Company in Norway proposed a CB & H technology (hydrogen production based on natural gas thermal plasma pyrolysis)[12], and Fulcheri research team in France did a plasma torch, through which a three-phase alternating current was connected to its three graphite electrodes[11]. Furthermore, the Dalian Institute of Chemical Physics (DICP) in China presented a method to produce hydrogen through methane cracking, with which the plasma was created by a microwave excitation material.

Focused on producing hydrogen from methanol, MIT took arc discharge as thermal plasma generator, with which methanol was processed using the plasma from the inspired air. At the same time, Tanabe et al.[13] took argon, excited by dielectric barrier discharge, as a plasma gas source to process methanol. In addition, Kabashima et al.[14] decomposed methanol by using the plasma generator, which was filled with ferroelectric substance inner and electrodes outer.

And to produce hydrogen from petrol and diesel, Bromberg et al.[4,5] in MIT, by using means of the arc thermal plasma generator, made a number of experiments to produce hydrogen from isooctane and diesel with partial oxidation. In addition, Sekiguchi et al.[15-18] did that from hexane and its steam by using microwave discharge method. Nevertheless, the research of farm vehicle onboard plasma reactor is still in its infancy. Therefore, there are two aspects of studies need to do, one is to optimize the existing plasma reactor both in the excitation energy and raw materials supplied, the other is to investigate control algorithm about reaction process.

It is known that the plasma reaction method has many advantages, including quick starting, wide available raw materials, small size, light weight, large power, so it has long been a focus for concern in the hydrogen production technology. Consequently, this method is more suitable for onboard hydrogen production. This system can create a certain amount of hydrogen through plasma reaction, which is mixed with the burning gas to achieve a lean combustion, so as to improve working efficiency and to reduce emission. Figure 1 shows the gas flowchart of the combustion engine with a combustion controller.

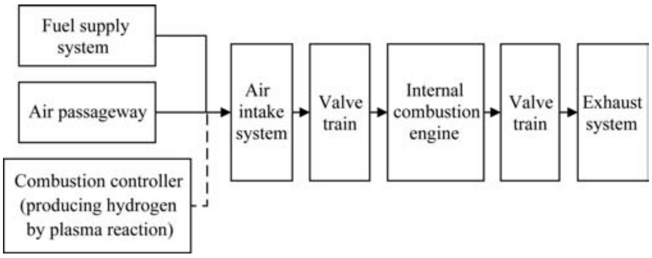

Figure 1 Gas flowchart of an engine with controller

In order to study the onboard hydrogen production system using plasma, its development tool must go ahead of the rest. The test parameters, such as flow rates, temperatures, pressures and other information about each of the pipelines, can be collected by the test bed. Meanwhile, the state of the related equipment, experimental data and curves can be displayed. Moreover, the air, peristaltic, vacuum pumps and other equipment can also be controlled by the monitoring software. Ultimately, an efficient hydrogen production can be achieved through the system. For the new onboard hydrogen production system using microwave plasma, all performance parameters could also be optimized by this test bed.

2 Materials and methods

2.1 System setup

There are three kinds of fuel reforming functions on this onboard hydrogen production test bed, including steam reforming, partial oxidation reforming and auto-thermal reforming. Three feeding pipelines were equipped in the front-end of the test bed to carry out the experimental study for the three reactions. Two of them, water and ethanol, must be evaporated because they are liquids. The purpose of the real-time measuring about temperature, pressure and flow rate is to calculate and determine the proportion of the reactants according to the gas state equation[19,20].

Figure 2 shows the system configuration. It consists of computer, microwave plasma system, I/O front, pipelines, data acquisition and monitor system, spectral collection section etc. Furthermore, the production pipelines used for reaction environment are shown in Figure 3. These plasma reactor pipelines, including the ethanol, water and air supply pipelines used for their reactants, are the key elements of the test system.

The system also covers:

(1) Control part for adjusting reaction conditions, which is mainly used to provide the reaction pipelines with suitable temperature and pressure;

(2) Reaction chamber, which consists of a reaction chamber and a microwave system, the reaction chamber provides the test system with a plasma reactor site, and the microwave system provides the plasma reactor with energy needed;

(3) Resultant collection pipeline;

(4) Condenser inside this reaction pipeline, which is used for separating the remaining ethanol and water that are not fully reacted. In addition, the whole system was mounted into a test cabinet to make it smaller, of higher availability and easier for troubleshooting and servicing.

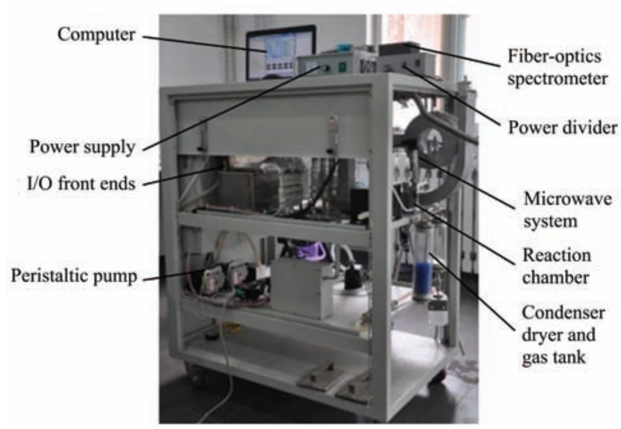

Figure 2 Experimental device

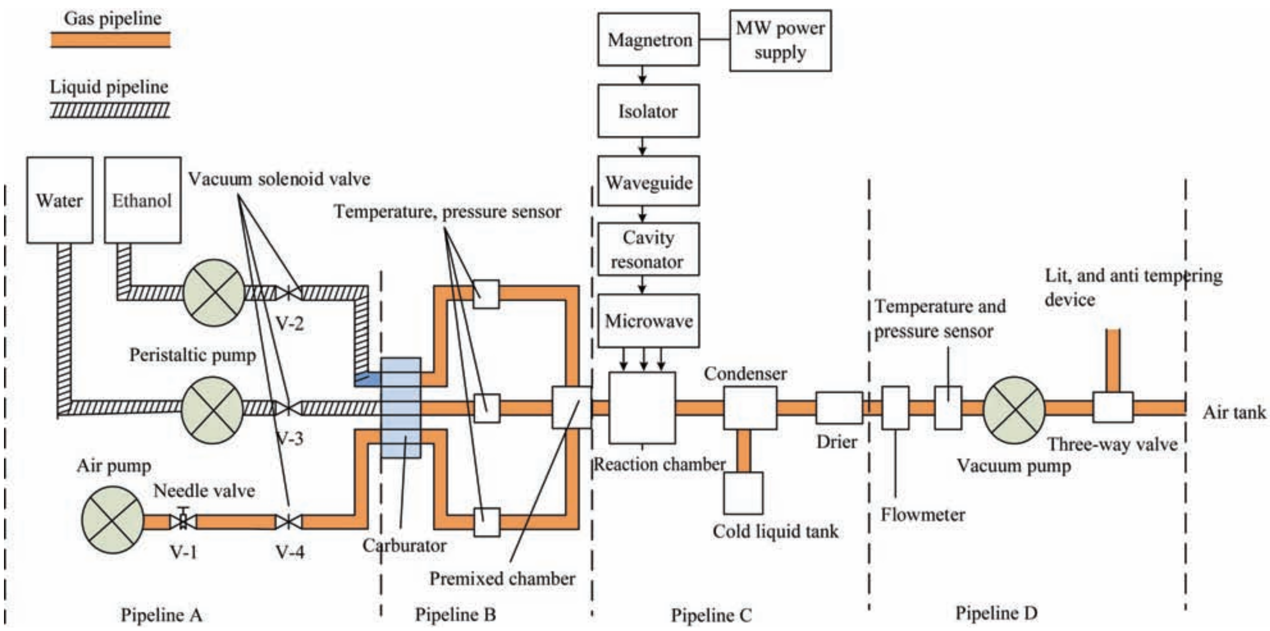

Figure 3 Reaction pipelines for hydrogen production

2.2 Microwave plasma and its testing system

2.2.1 Microwave plasma generation

The plasma consists of some active particles, including ions, electrons etc. Due to the special nature of the plasma, the hydrocarbon fuels would be reformed to produce hydrogen under the certain circumstances[2,4,9,21]. In general, plasma hydrogen production devices are relatively simple and useful, so various studies and experiments on plasma hydrogen production have been carried out. On the other hand, there are a variety of methods used for the plasma excitation. In view of its small size and strong directionality, microwave exciter was chosen to excite gas ionization in this research, simultaneously, the plasma reaction energy was provided by microwave system.

An essential part of the test system used for hydrogen production is the microwave plasma system. Hydrogen is obtained by microwave plasma system through the interaction between hydrogen plasma and magnetic field, where the plasma reaction is controlled by adjusting the power, direction and distribution of the electromagnetic waves. During the hydrogen production process using microwave plasma reaction, the hydrogen gas continuously gained energy from the outside to form the plasma. Meanwhile, a large number of high-energy electrons and free radicals formed inside the plasma as the energy had been continuously absorbed by the plasma. Under certain conditions, these high-energy electrons and free radicals can be combined into a new compound. In the process of the plasma reaction, a relatively large energy in the inlet of the reaction chamber is needed to provide ionizing gas into plasma, and then the less energy is required for maintaining the plasma reaction.

In this study, the microwave plasma system was used to provide the reaction with energy needed, which was customized at Xi'an Hengda Microwave Technology Development Co., Ltd (HCMT). It consists of high voltage power supply, magnetron and power dispatch reflector. The high voltage power supply is used for generating power energy required by microwave, the magnetron for converting power energy into microwave, the power dispatch reflector for dispatching the microwave generated by the magnetron, which is partially used for ionizing gas, partially for maintaining the plasma.

2.2.2 Microwave plasma test method analysis

The fiber spectrometer and fiber probes were used in the system for testing and analyzing. With which the qualitative and quantitative analysis about the particles in the reaction can be carried out by using the spectra of the plasma. While, the main products come from the reaction can be known during the whole process, which is helpful to control a reaction proceeding. To increase hydrogen generation rate, the necessary analysis of the major part should be investigated, such as the water flow, temperature and pressure, ethanol flow and air flow in the pipelines. Generally speaking, two dual-line spectral methods are useful for testing the microwave plasma, i.e. an excitation temperature of a light is measured by testing the intensities of two light emission lines of the same element. Now a more useful multi-line method, comes into being, which is to measure multiple lines instead of just two lines, so as to improve accuracy of the measurement, and its test error is also small compared with the double line method[22-24]. The relation equation of the spectral intensity is shown as follows:

$$I = \frac{h\nu}{4\pi}\frac{gA}{Z}N\exp(-\frac{E}{kT}) \tag{1}$$

where, g is statistical weight, kg; A is transition probability; E is excitation potential; k is Boltzmann constant; T is absolute temperature, K; h is Planck's constant; v is frequency, Hz. The transition probability A gives way to the oscillator strength f, takes the form of logarithm to the formula above, then:

$$\log\frac{I\lambda^3}{gf} = -\frac{5040}{T}E + c \tag{2}$$

where, c is a constant.

If the temperature is measured by multiple lines of one element, the corresponding excitation temperature can be figured out through a plotting, with which E is horizontal axis, $\log\frac{I\lambda^3}{gf}$ is vertical axis, $-\frac{5040}{T}$ is a straight line through every point. Derivative spectrometer is a technique to improve the spectral resolution, which can be used to resolve overlapping peaks and eliminate the interference spectrum.

According to the main groups tested in the plasma reactor, there were three Balmer lines of radicals H (434 nm, 486 nm, 656 nm), as well as CH+(395.3 nm), C2 (469.8 nm, 560.1 nm) and OH (513.5 nm). So the S3000 fiber spectrometer should be selected. Where, the wavelength range was between 200 nm and 800 nm, slit width 50 μm, grating 600 lines with 250 nm, the minimum exposure time 3 ms, the maximum exposure time 60 ms.

2.3 Monitoring software

There are mainly two tasks carried out by the monitoring software on the test bed. One is to collect the real-time temperatures and pressures in the pipelines when the plasma is reacting, where there are four temperature signals and four pressure signals to be collected. The other is to control the conditions of the devices according to the collected data. There are two heaters, two peristaltic pumps and two air pumps need to be controlled. The data flowchart of the monitoring system is shown in Figure 4.

Due to the friendly graphical user interface and powerful data processing capabilities, MATLAB GUI was used to program for the monitoring software of the test device, whose user interface consists of the control tab, test tab and coordinate axis tab. The control tab includes the setting panel, control buttons, mode selection, device switch status, data display bar and message bar. The flowcharts of the monitoring software including the start stage subroutine and control loop stage subroutine are shown in Figures 5-7. In brief, all the process of the work can be carried out by the main system program through calling the two subroutines.

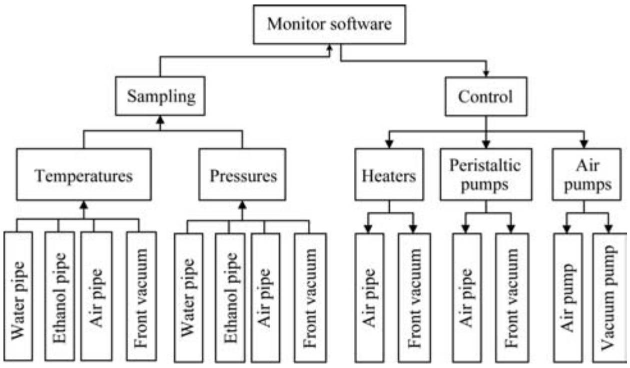

Figure 4 Data flowchart of the monitoring system

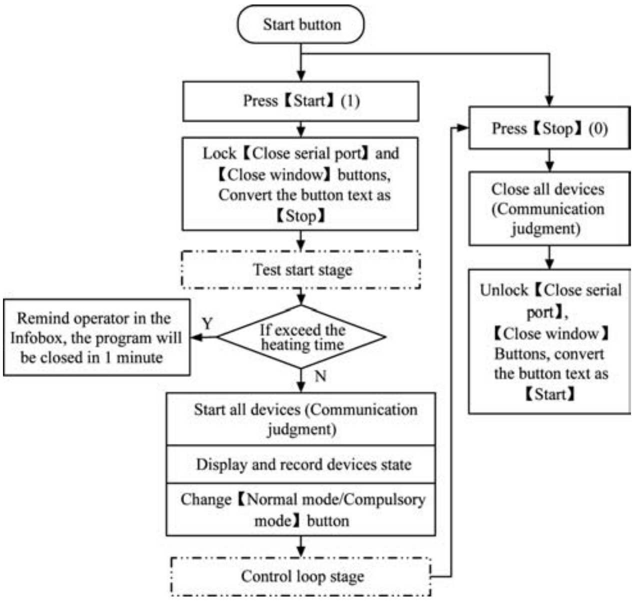

Figure 5 The system flowchart

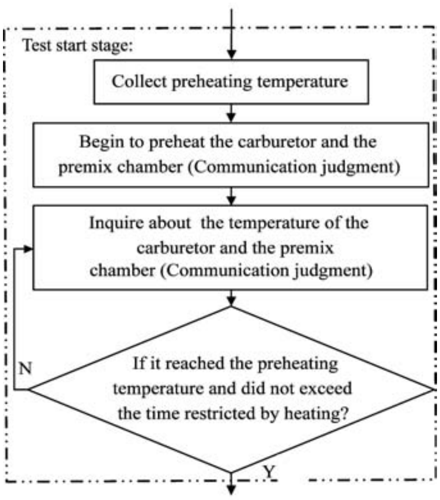

Figure 6 Flowchart of start stage

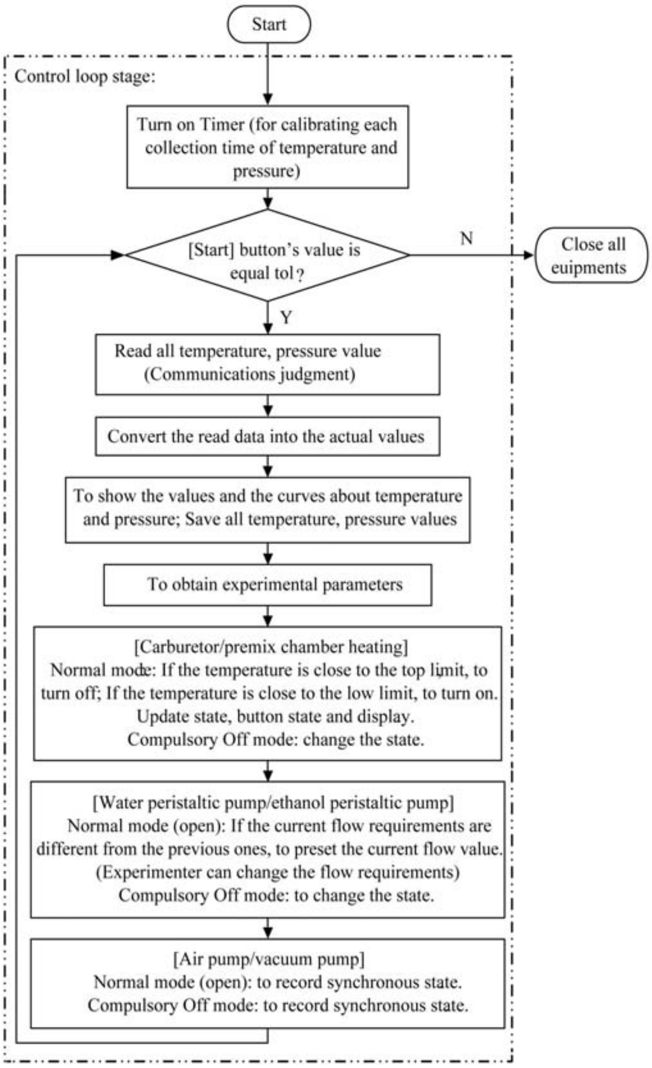

Figure 7 Control loop stage flowchart of the monitoring software

2.4 System control algorithm

In order to reach the objective point quickly and accurately, Kalman filter and data PID controller were employed in this system. Kalman filter is quite useful to restore the original signal without the larger noise[25]. It does not need all the past observations, and is only based on the previous estimate and the most recent observations to estimate the current value of the signal. So that, it is a state equation and method for recursive estimation of the signal, thus the invariance and smooth are not required in Kalman filter. The controlled objects, such as the peristaltic pumps, air pumps, needles, carburetor and power, should be capable of being operated under a range of work conditions, which are needed by the plasma reaction. As mentioned before, the performance of 2.0 L gasoline engine would be improved if the engine was added into 3%-5% of hydrogen[5]. The gas volume flow range of water, air and ethanol were calculated in accordance with the hydrogen consumption of 5%, so as to determine the control range of PID[26]. For a 2.0 L gasoline engine, the water flow in the water pipelines should be stabilized from 0.544 mL/min to 0.98 mL/min, steam flow from 5.27 L/min to 9.48 L/min by controlling the speed of the peristaltic pump. Furthermore, the speed of the peristaltic pump and mass flow controller can be adjusted to regulate the flow of the ethanol vapor, so that the liquid flows of the ethanol could be kept from 0.7 mL/min to 1.254 mL/min, ethanol vapor flow rate from 2.311 L/min to 4.16 L/min. In addition, the air pump and needle valve can be adjusted to regulate the air flow rate from 4.16 L/min to 7.5 L/min. Finally, the pressure signals in the pipeline can be received and displayed by the computer, which should be stabilized from 0.2 atm. to 0.5 atm. by adjusting the speed of the vacuum pump.

3 Experiment and results analysis

After the test preparation, the experiment will be started. Subsequently, the communication between the computer and test bed must be set up. Then, the calibrations should be performed, including the control part and data collection part. After that, the pressures of all the pipelines should be checked and adjusted to the certain operational state. Finally, the test can be carried out according to the flow shown in Figures 5-7.

3.1 Flow control

The control voltage of the peristaltic pumps is set from 0 V to 5 V in the process of the flow control, which is outputted by the I/O front. Furthermore, the I/O front receives commands from the computer, and the communication signals between the computer and I/O front are digital. In this way, the computer controls the pumps by digital. The digitals received by the I/O front have been converted into analogs by itself with 12 bits, i.e. the control voltage, which is 0-5 V, can be described by the integers from 0 to 4095. Consequently, the error of the control voltages were 5/4096×100%, i.e. 0.12%. As the errors of the peristaltic pumps are less than 0.5%, taking into account the A/D convertor errors, the combined errors of the flow controls from the computer to the peristaltic pumps are about 0.5%. Naturally, it is very difficult to control a micro-flow. Moreover, the flow data of the peristaltic pumps in actual practice should be certain to deviate more or less from the control curves given by manufacturer. Therefore, before experiment, the calibrations of the ethanol and water peristaltic pumps should be carried out respectively, the method is to measure the liquid volume squeezed from the peristaltic pump at different voltages (0.5 V interval) in 10 min per voltage. The experimental results showed that the actual operations of the two kinds of peristaltic pumps were able to meet the control requirements. Nevertheless, within the ranges of the control voltages, with regard to the ideal values provided by the manufacturer, each of the peristaltic pumps was subject to a margin of error. The contrast data between the ideal control curve and actual one in the ethanol peristaltic pump are shown in Table 1 and Figure 8, and those in the water peristaltic pump are shown in Table 2 and Figure 9. As can be seen from them, the flows were all deviated from the values given by the vendor, and the higher the flows, the bigger the error. The reason is that the calibration was made without any pipeline in the manufacturer, but in fact, there are some pipelines in our test bed. In fact, the resistance of the pipeline resulted in these errors. So, our calibration parameters other than the manufacturer ones should be chosen. In this way, the two peristaltic pumps were able to accord the control linear and accuracy requirements, and their performances were stable.

Table 1 Ethanol pump calibration data

No.	Control Voltage/V	Ethanol flow (manufacture)/mL·min^{-1}	Ethanol flow (calibration)/mL·min^{-1}	Error /%
1	0	0	0.085	−2.982
2	0.5	0.285	0.320	−1.228
3	1.0	0.570	0.554	0.561
4	1.5	0.855	0.789	2.315
5	2.0	1.140	1.023	4.105
6	2.5	1.425	1.258	5.859
7	3.0	1.710	1.492	7.6493
8	3.5	1.995	1.727	9.403
9	4.0	2.280	1.961	11.192
10	4.5	2.565	2.196	12.947
11	5.0	2.850	2.430	14.736

Table 2 Water pump calibration data

No.	Control Voltage/V	Ethanol flow (manufacture)/mL·min^{-1}	Ethanol flow (calibration)/mL·min^{-1}	Error/%
1	0	0	0.085	−3.04
2	0.5	0.28	0.287	−0.25
3	1.0	0.56	0.488	2.57
4	1.5	0.84	0.690	5.36
5	2.0	1.12	0.891	8.18
6	2.5	1.40	1.093	10.98
7	3.0	1.68	1.294	13.79
8	3.5	1.96	1.496	16.57
9	4.0	2.24	1.697	19.39
10	4.5	2.52	1.899	22.18
11	5.0	2.80	2.104	24.86

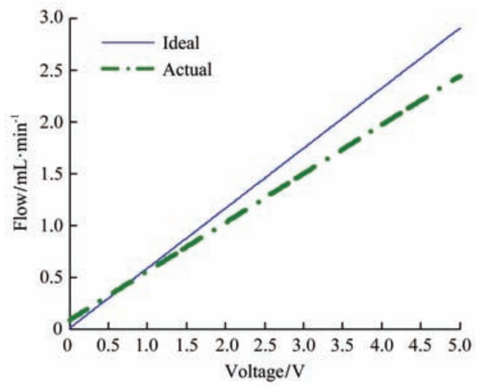

Figure 8 Ethanol pump curves

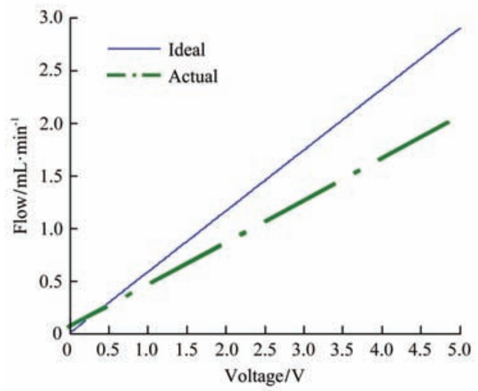

Figure 9 Water pump curves

3.2 Temperature collection

The full scale of the I/O front analog signal is 10 V, and the A/D convertor is 12 bit, so the basic error of the I/O front analog signal is (10/4096)×100%, i.e. about 0.2%. Moreover, the error of the PT100 platinum resistance is 0.12%. According to the calculation method of the serial error, the combined error is about 0.23%. There are two heaters in the test device, they are carburetor heater and premix chamber heater. The real-time temperature map of the carburetor and the premix chamber obtained under the conditions of 55°C-65°C is shown in Figure 10. As can be seen, the carburetor temperature is substantially maintained within the desired temperature range, which is relatively stable. While the temperature fluctuation in the premix chamber is relatively large, and a jump would occur when the temperature reaches the minimum. As we known, the temperature control ought to be of hysteresis, the jump appearance may attribute to that the space between the sensor and the heater is too small.

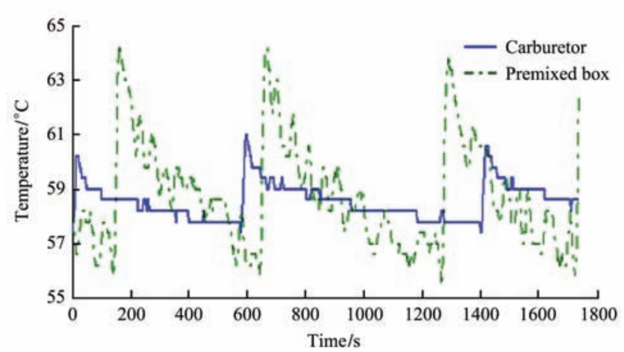

Figure 10 Temperature curves in the carburetor and premix

3.3 Pressure collection

As mentioned above, the basic error of the I/O front analog signal is 0.2%, the error of the pressure transmitter SST-808 is smaller than 0.25%. According to the calculation method of the serial error, its combined error is about 0.32%. The real time pressure curves are shown in Figures 11 and 12.

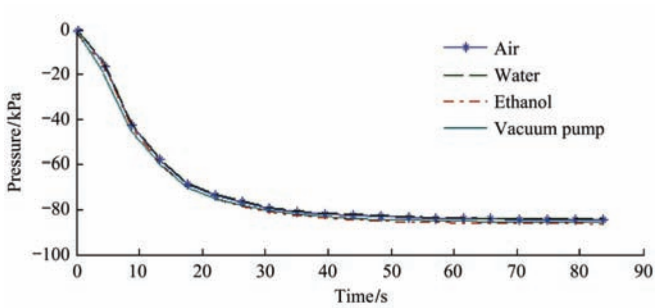

Figure 11 Real-time pressure curves when the air pump was off completely and the vacuum pump was open fully

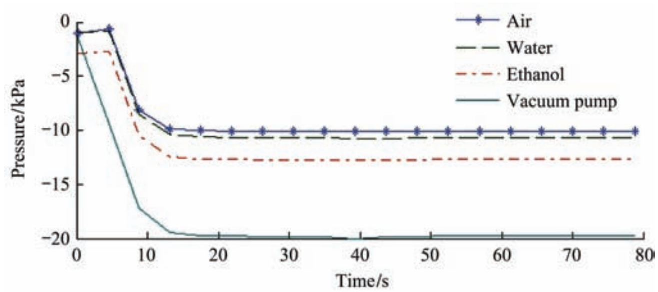

Figure 12 Real-time pressure curves when the air pump was open completely and the vacuum pump was open fully

It can be seen that the pressure inside the pipe is more consistent and can reach 20 kPa. On the other hand, as the air pump is fully open, the vacuum would be fully open, the pressure in front of the pump is lower than 80 kPa, and the pressures of the other three ways are all about 90 kPa. It shows that the pipeline pressure can be adjusted to any value between 20 kPa and 90 kPa by adjusting the valve.

4 Discussion

The system should be capital of carrying out three kinds of onboard hydrogen production experiments, including steam reforming, partial oxidation reforming and self-heating reforming. For this purpose, three feeding pipelines, including ethanol supply, water supply and air supply had been equipped respectively for the three reactions. To be on the safe side, these three feeding pipelines were all fitted with a manual valve, their flows can be controlled, and can also be fully closed. Results were achieved as below:

(1) The effect of the steam reforming method was the best among these three methods of hydrogen production. If the system operated under the condition of 0.1 atm., the hydrogen content of hydrogen production would account for 59%-60%, CO content about half of the hydrogen, the total contents of the two compounds were above 86%-90%, O_2 0.2%, N_2 8%-9%. While the other two methods were less effective, and the nitrogen content were all more than 40%-50%, and the proportion of hydrogen was smaller.

(2) The air was broken down to ignite safely only when an inside pressure in the range of 0.1-0.7 atm. was required.

(3) When the pressure inside was maintained within about 0.2-0.5 atm., the temperature inside were maintained 300°C-1600°C. In this range, the hydrogen production capacity can meet the requirements of a running vehicle under different conditions, and the system would be also safe, as shown in Figure 13.

(4) The system was not safe when the reaction chamber was above 0.7 atm., the reaction chamber temperature would reach 2000°C-3000°C, and seven quartz tubes were damaged under this condition, as shown in Figure 14.

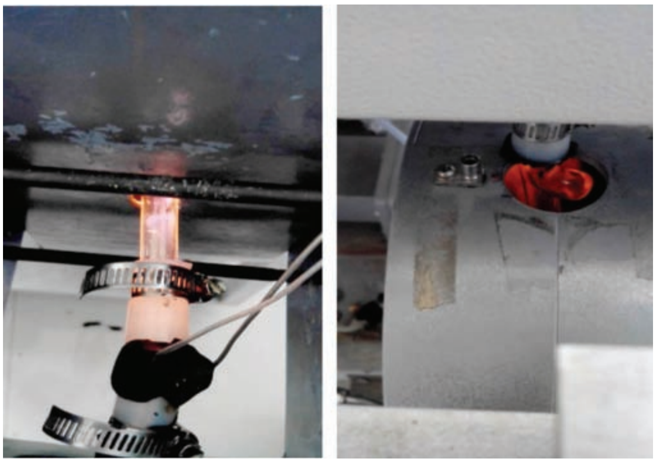

Figure 13 Hydrogen came into being when the inside pressure was in the range of 0.2-0.5 atm.

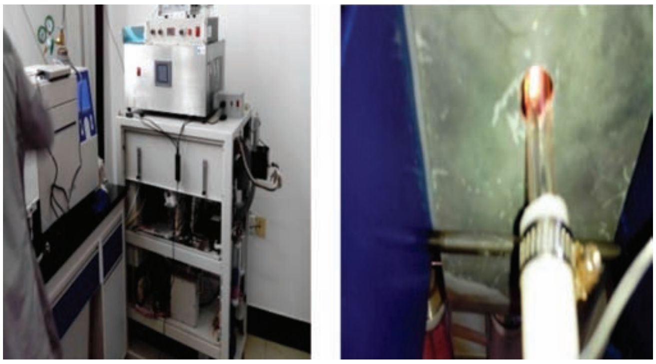

Figure 14 Hydrogen came into being when the inside pressure was over 0.7 atm.

(5) This is only an exploratory experiment. Meanwhile, the results were achieved by means of spectral analysis, chromatography analysis, pressure analysis, and reaction rate analysis. All in all, these analyses used above were basically consistent, and microwave plasma can be used to build a hydrogen production environment for farm vehicle onboard hydrogen production.

5 Conclusions

A complete new set of test system for farm vehicle onboard hydrogen production was proposed in this research. In which a variety of circumstances and conditions required for the hydrogen production reaction could be provided and adjustable. Meanwhile, the real time environmental data could be collected during hydrogen production process, and its combined error is 0.32%. This was a joint development project about the onboard hydrogen production, undertook by Jilin University, Beijing Jiaotong University and the Chinese Academy of Science. Now the experimental device has been put into use in Jilin University, and a docking experiment with 2.0 L gasoline engine has been carried out. Hydrogen would come into being when the air was broken down by the plasma under the conditions of 0.1-0.7 atm. The initial results showed that the power, economic and emission performances of the engine have been significantly improved. It is suggested that this test bed is all-purpose available, which can be used to calibrate and inspect onboard combustion controllers, match an engine combustion system with an onboard combustion controller. In the future, the test bed can be made into a removable and onboard cart.

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[References]

[1] Bromberg L. CFD modeling of plasmatron methane reformer. Plasma Science and Fusion Center, Massachusetts Institute of Technology, PSFC/JA-05-14, 2005.

[2] Bromberg L. Startup characteristics of plasmatron gasoline reformers. Plasma Science and Fusion Center, Massachusetts Institute of Technology, PSFC/JA-05-49, 2005.

[3] Bromberg L, Cohn D R, Rabinovich A, Alexeev N. Plasma catalytic reforming of methane. International Journal of Hydrogen Energy, 1999; 24(12): 1131–1137.

[4] Bromberg L, Hadidi K, Cohn D R. Plasmatron reformation of renewable fuels. Plasma Science and Fusion Center, Massachusetts Institute of Technology, PSFC/JA-05-3, 2005.

[5] Bromberg L, Cohn D R, Rabinovich A. Plasmatron fuel converter-catalyst systems for after-treatment of diesel vehicle emissions. Int. Journal of Vehicle Design, 2001; 25(4): 275–282.

[6] Bromberg L, Cohn D R, Rabinovich A, Surma J E, Virden J. Compact plasmatron boosted hydrogen generation technology for vehicular applications. Int. Journal of Hydrogen Energy, 1999; 24(4): 341–350.

[7] Boretti A. Advances in hydrogen compression ignition internal combustion engines. International Journal of Hydrogen Energy, 2011; 36(19): 12601–12606.

[8] Bromberg L, Cohn D R, Rabinovich A, Alexeev N, Samokhin A, Hadidi K, et al. Onboard plasmatron hydrogen production for improved vehicles. MIT Plasma Science and Fusion Center, PSFC JA-06-3, 2006.

[9] Berger R J, Marin G B. Investigation of gas-phase reactions and ignition delay occurring at conditions typical for partial oxidation of methane to synthesis gas. Industrial and Engineering Chemistry Research, 1999; 38(7): 2582–2592.

[10] Gaudernack B, Lynum S. Hydrogen from natural gas without release of CO_2 to the atmosphere. International Journal of Hydrogen Energy, 1998; 23(12): 1087–1093.

[11] Fulcheri L, Schwob Y. From methane to hydrogen, carbon black and water. International Journal of Hydrogen Energy, 1995; 20(3): 197–202.

[12] Gaudernack B, Lynum S. Hydrogen from nature gas without release of CO_2 to the atmosphere. International Journal of Hydrogen Energy, 1998; 23(12): 1087–1093.

[13] Tanabe S, Matsuguma H, Okitsu K, Matsumoto H. Generation of hydrogen from methanol in a dielectric-barrier discharge-plasma system. Chemistry Letters, 2000; 2000(10): 1116–1117.

[14] Kabashima H, Einaga H, Futamura S. Hydrogen generation from water, methane, and methanol with nonthermal plasma, IEEE Transactions on Industry Applications, 2003; 39(2): 340–345.

[15] Sobacchi M G, Saveliev A V, Fridman A A, Kennedy L A. Experimental assessment of a combined plasma/catalytic system for hydrogen production via partial oxidation of hydrocarbon fuels. Int. J Hydrogen Energy, 2002; 27(6): 635–642.

[16] Bromberg L, Crane S, Rabinovich A, Kong Y, Cohn D R, Heywood J, et al. Hydrogen generation from plasmatron reformers: A promising technology for NOx adsorber regeneration and other automotive applications. Plasma Science and Fusion Center, Massachusetts Institute of Technology, PSFC/JA-03-27, 2003.

[17] Gray B F, Griffiths J F, Goulds G A, Charlton B G, Walker G S. The relevance of thermo kinetic interactions and numerical modelling to the homogeneous partial oxidation of methane. Industrial and Engineering Chemistry Research, 1994; 33(5): 1126–1135.

[18] Kirwan J E, Quader A A, Grieve M J. Advanced engine management using on-board gasoline partial oxidation

reforming for meeting super-ULEV (SULEV) emissions standards. SAE Technical Paper, 1999-01-2927, 1999.

[19] Li H Q, Zou J J, Liu C J. Progress in hydrogen generation using plasmas. Progress in Chemistry, 2005; 17(1): 69–77. (in Chinese with English abstract)

[20] Chen J Y. Stochastic modeling of partially stirred reactors. Combustion Science and Technology, 1997; 122(1-6): 63–94.

[21] Deminsky M, Jivotov V, Potapkin B, Rusanov V. Plasma-assisted production of hydrogen from hydrocarbons. Pure Appl. Chem, 2002; 74(3): 413–418.

[22] Jamal Y, Wyszynski M L. On-board generation of hydrogen-rich gaseous fuels: A review. International Journal of Hydrogen Energy, 1994; 19(7): 557–572.

[23] Herzberg G, Spinks J W T. Molecular spectra and molecular structure. Upper Saddle River: Prentice-Hall, 1966.

[24] Landsman M L, Kwant G, Mook G A, Zijlstra W G. Light-absorbing properties, stability, and spectral stabilization of indocyanine green. Journal of Applied Physiology, 1976; 40(4): 575–583.

[25] Grewal M, Andrews A. Kalman Filtering: Theory and Practice Using MATLAB. Hoboken: Wiley-IEEE Press. 2008.

[26] Yu C C. Auto tuning of PID controllers. Springer, 2006.