ISSN : 0974 - 7435 Volume 10 Issue 24

2014

BioTechnology

An Indian Journal

FULL PAPER

BTAIJ, 10(24), 2014 [15443-15450]

Research on performance optimal control and experiment for gasoline engine under oxygen-enriched air intake condition

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ABSTRACT

The study object in this work is air cooling single cylinder gasoline engine with four strokes. The gasoline engine performance test bed was established based on oxygen-enriched air intake and the mixed air intake with objective oxygen-enriched proportion was prepared. The optimal control of gasoline engine performance under oxygen-enriched air intake conditions was realized, whose control error was not larger than ±1.5% and the response time was not longer than 10 s. The gasoline engine performance verification test was performed by two air intake ways: normal air intake and MAP controllable oxygen-enriched air intake. After comparison between the test data of oxygen-enriched and normal air intake ways, it can be analyzed that the average torque growth rate of oxygen-enriched air intake way under full load condition is 17.76%. The average fuel consumption reduction rate of oxygen-enriched air intake way under the rotate speed of 3000 r/min is 12.68%. The HC average reduction rate of oxygen-enriched air intake way under the rotate speed of 2000 r/min is 14.88%, CO average reduction rate is 17.85%, and NO_x average increase rate is 7.42%. The comprehensive performance of gasoline engine under oxygen-enriched condition is improved and the goal of energy conservation and emission reduction is achieved.

KEYWORDS

Oxygen-enriched air intake; MAP; Gasoline engine; Performance optimization; Test verification.

INTRODUCTION

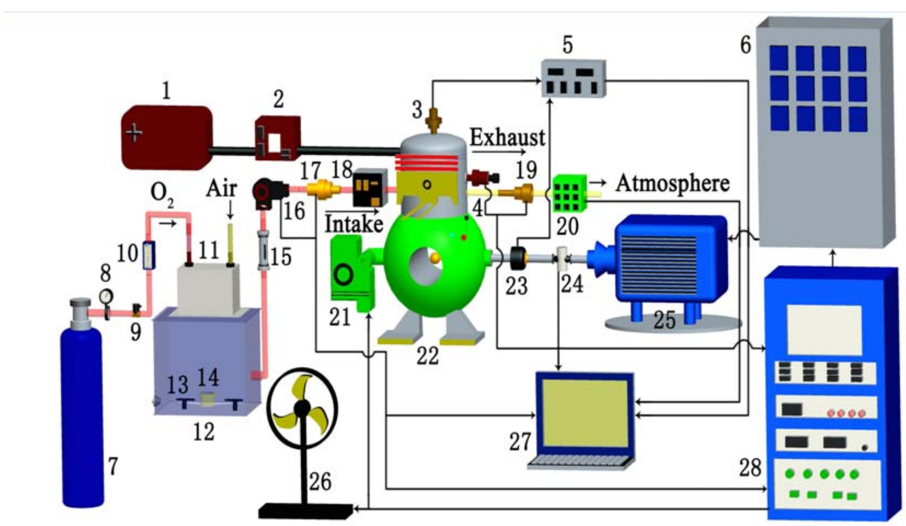
With the gradually strict vehicle emission limit and continuous update of various engine control methods, the combustion control process is required to be improved. Lower emission, superior economy, and higher dynamic property should be gradually realized. Optimal control of engine working process by the air intake methods of oxygen-enriched, nitrogen-enriched, and EGR reforming is the one of the dominate research directions at present[1]. The oxygen-enriched air intake method can effectively increase the combustion temperature, shorten the fire delay time, facilitate the complete combustion of fuel[2], enhance the effective output power of engine, reduce its fuel consumption rate, improve its dynamic property and economic property[3], and reduce the amount of CO and HC originated from incomplete combustion, which is a new approach to realize energy conservation and emission reduction[4-6].

Engine is a dynamic, multivariable, highly non-linear time-varying system with response delay from the view of control technology. Currently, the researches of engine working parameter control methods are mainly focused on the oil injection control, ignition control, and EGR control. But seldom research is carried out on the respect of air intake control[7-9]. The basic MAP corresponding to different operation conditions are parameter set of advance angle of ignition and injection pulse-width when the engine reaches its optimum working performance. It is crucial to obtain the initial MAP. Kinds of MAP control data are usually obtained by filtrating and statistical analysis of plenty of experimental data, which are obtained by engine bed test and road driving test[10, 11].

The research object in this work is air cooling single cylinder gasoline engine with four strokes. The gasoline engine performance is optimal controlled based on air intake MAP under oxygen-enriched air take condition. The oxygen volume fraction in the intake air is accurately controlled by real time recording the MAP image of intake oxygen volume fraction and releasing the control instruction based on the actual working conditions of gasoline engine, making sure that the engine can realize controllable combustion under the objective oxygen-enriched intake air condition. Thus the dynamic and economic performances are optimized on the basis of ensuring non-obvious deterioration of the emission performance. The effect of energy conservation and emission reduction is verified by universal characteristic test.

SET UP OF TEST BED

Industrial oxygen of purity higher than 99.2% and pressure of 13±0.5MPa is provided by oxygen bottle. After the pressure is reduced to standard atmospheric pressure by oxygen bottle pressure reducer, the oxygen is introduced to premix chamber. The other entrance of premix chamber is connected with atmosphere. The industrial oxygen and air are premixed in the premix chamber using several mixing fans. The mixed gas is introduced to the gas chamber and further fully mixed. The air flow and intake oxygen volume fraction are accurately controlled by oxygen flow meter and oxygen flow control valve, forming a mixed intake air with objective oxygen-enriched proportion. Then the mixed gas is provided to engine in the naturally aspirated way. Fig.1 shows the test bed structure of oxygen-enriched optimal control system of gasoline engine. TABLE 1 displays the key technical parameters of test engine.



1-the fuel tank, 2-smart fuel consumption, 3-cylinder pressure sensor, 4-cylinder temperature sensor, 5-Combustion Analyzer, 6-control cabinet, 7-oxygen bottles, 8-oxygen bottle pressure reducer, 9-oxygen flow control valve, 10-oxygen flow meter, 11-pre-mixing chamber, 12-with the gas chamber, 13- gas mixing fan, 14-temperature hygrometer, 15-gas flow meter, 16-throttle position sensor, 17-intake temperature sensor, 18-oxygen analyzer, 19-exhaust gas temperature sensor, 20-exhaust gas analyzer, 21-throttle actuator, 22-engine, 23-incremental encoder, 24-speed torque sensor, 25-DC Electric Dynamometer, 26-cooling fan, 27-monitor and collection system, 28-engine automatic monitoring and control system.

Figure 1 : Test bed structure of oxygen-enriched optimal control system of gasoline engine

TABLE 1 : Key technical parameters of test engine

Parameters	index	parameters	index
cylinder diameter route/mm	56.5×49.5	max power/kW	7.5/(7500 r/min)
displacement/mL	124	rated power/kW	6.5/(6500 r/min)
compression ratio	9:1	max torque/(N·m)	8.5(5500 r/min)
Fuel	$93^{\#}$Gasoline	Max Speed/ r/min	8500

PERFORMANCE OPTIMAL CONTROL OF GASOLINE ENGINE

Control objective

Oxygen-enriched air intake control is aimed at controlling the optimum intake oxygen volume fraction under different working conditions and optimizing the dynamic, economic, and emission performances of gasoline engine. When the intake oxygen volume fraction is changed, the dynamic, economic, and emission performances of gasoline engine are also changed with it. Sensitive degrees of influence of intake oxygen volume fraction on these performances are different with each other. Change situations of emission targets of HC, CO, and NO_x are also not totally the same. It must not only split the difference between economic, dynamic, and emission performances, but also balance the emission targets of HC, CO, and NO_x. Therefore, comprehensive consideration of torque, oil consumption, and emission performances should be chosen as the optimal control objective of gasoline engine performance under oxygen-enriched air intake condition.

Control process

MAP control parameters such as MAP image of oxygen-enriched air intake interpolation, corresponding time period, and single period conducting time are saved beforehand into the read-only memory of MC9S12DP256 type microprocessor by the PC upper computer of measurement and control system. When the engine actual runs, its working condition can be judged according to various working condition parameter signals such as sensor collect rotate speed, throttle percentage, etc. The basic control value of oxygen-enriched volume fraction is acquired by searching MAP image of corresponding oxygen-enriched air intake interpolation based on the optimal control objective. Control instruction is carried out by MC9S12DP256 type microprocessor, as well as adjusting the PWM control parameters such as period and single period conducting time. Thereby the industrial pure oxygen flow in mixed chamber can be accurately controlled, the objective control flow can be stably outputted, and the oxygen-enriched air intake with objective oxygen volume fraction can be stably provided for the test gasoline engine. So the optimal control of gasoline engine under oxygen-enriched air intake condition can be realized. Figure 2 displays the MAP image of oxygen-enriched air intake interpolation.

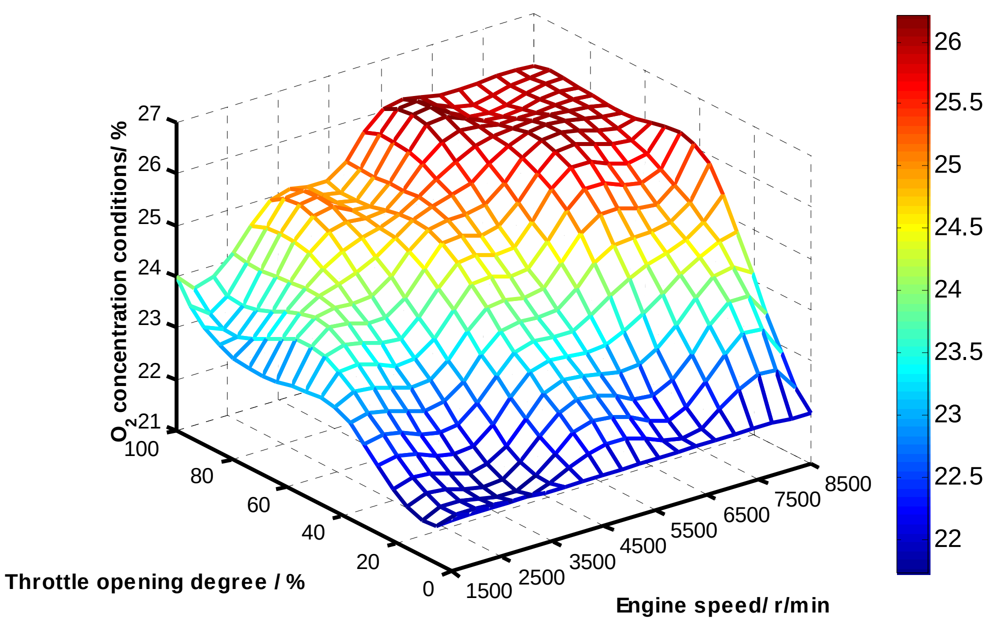


Figure 2 : MAP image of oxygen-enriched air intake interpolation

Control realization

The industrial oxygen flow and engine intake oxygen volume fraction in mixed gas proportion rage can be accurately controlled by matching the duty ratio and controlling the on-off of oxygen flow control valve in the form of output PWM square wave under different working conditions using MC9S12DP256 type microprocessor based on pulse width modulation (PWM) principle. The intake air component is accurately conFigure d for engines with different oxygen-enriched proportion demands. Figure 3 shows the drive circuit of oxygen flow controlled valve. Take the non-load work condition as an example, PWM matching result and control parameters are displayed in TABLE 2.

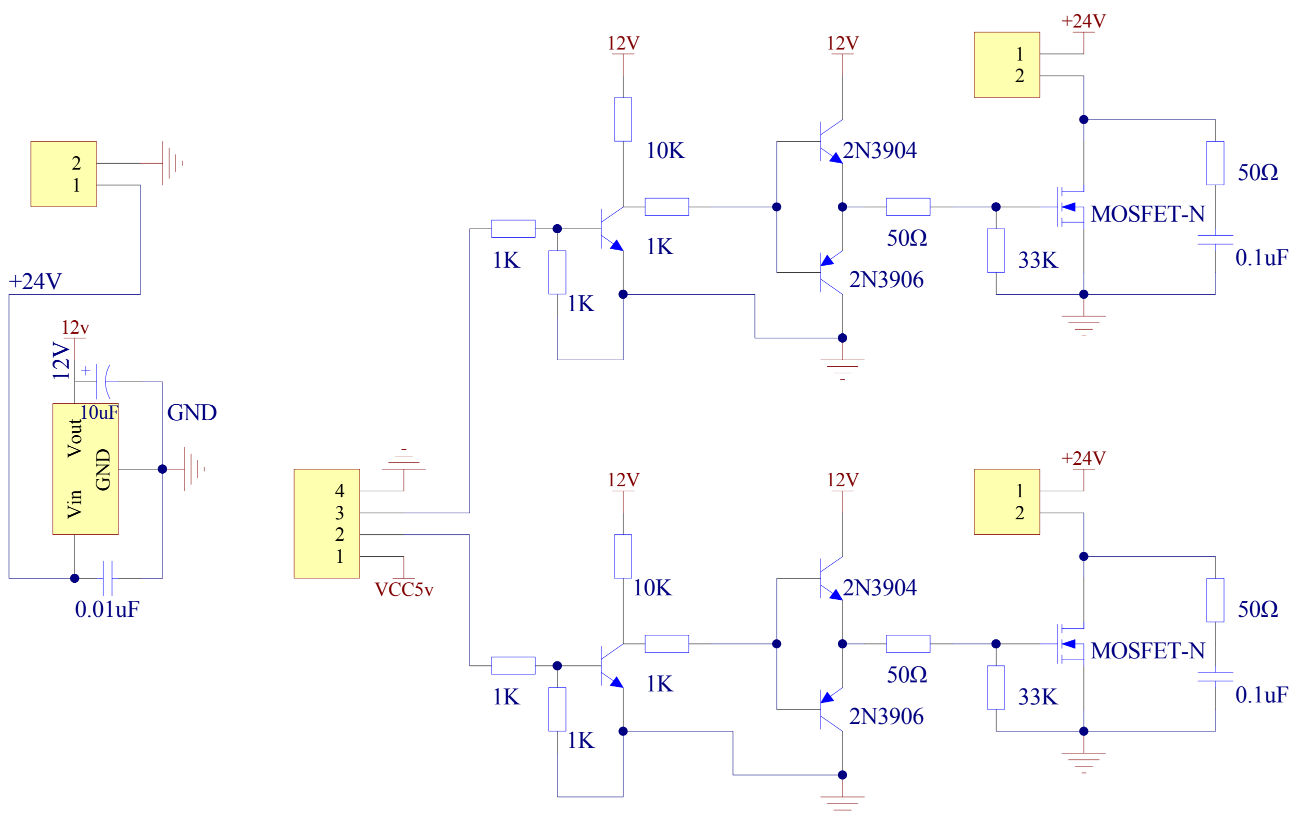


Figure 3 : Drive circuit of oxygen flow controlled valve

OPTIMAL EFFECT TEST AND ANALYSIS

The verification test of gasoline engine performance optimal control effect was performed under oxygen-enriched condition according to the test methods of engine speed characteristic, load characteristic test method, and universal characteristic test method in National Standard “The car engine performance test methods (GB/T 18297-2001)”.

Dynamic performance analysis

The throttle percentage is chosen as 50%, 75%, and 100%, which represent three working conditions of part load, large load, and full load. When the throttle percentage is maintained constant as 50%, 75%, and 100%, respectively, six rotate speed points are chosen as 2000 r/min, 3000 r/min, 4000 r/min, 5000 r/min, 6000 r/min and 7000 r/min. Two air intake ways are adopted such as normal state intake and MAP control oxygen-enriched intake. Oxygen volume fraction of normal state intake is 21%, while that of MAP control oxygen-enriched intake is calculated by MAP image of oxygen-enriched air intake. The speed characteristic test is carried out and its torque indicator data are tested, compared, and analyzed after the gasoline engine works stably. The optimal result is shown in Figure 5. Three red curves marked with symbols of ●, ■, and ▲ represent the gasoline engine speed characteristic curves when the throttle percentage is 50%, 75%, and 100% using normal air intake way. While three blue curves marked with symbols of ○, □, and △ represent the gasoline engine speed characteristic curves when the throttle percentage is 50%, 75%, and 100% using MAP control oxygen-enriched air intake way.

TABLE 2 : L PWM matching result and control parameters

Rotate speed n (L/min)	Objective value λ_O (%)	Conducting time t (ms)	Period T (ms)	Duty ratio β (%)	Calculated pure oxygen flow $Q_{pureoxygen}$ (L/min)	Control pure oxygen flow $Q_{pureoxygen}$ (L/min)	Control value λ_O' (%)	Response time Δt (s)	Control error δ (%)
	22	20	1100	1.82	1.20	0.94	21.79	5	-0.95
	23	29	1150	2.52	2.44	2.58	23.12	3	0.52
1500	24	42	900	4.67	3.70	3.96	24.20	7	0.83
	25	53	950	5.58	5.00	4.87	24.90	6	-0.40
	26	61	1000	6.10	6.33	6.59	26.19	8	0.73
	22	35	1800	1.94	2.00	2.41	22.19	5	0.86
	23	49	1500	3.25	4.06	3.85	22.89	7	-0.48
2500	24	62	1200	5.20	6.17	6.43	24.11	4	0.46
	25	70	1100	6.36	8.33	8.02	24.85	3	-0.60
	26	75	950	7.89	10.56	10.20	25.83	6	-0.65
	22	35	1600	2.19	2.80	2.96	22.04	6	0.18
	23	49	1400	3.50	5.68	5.05	22.77	8	-1.00
3500	24	60	1100	5.40	8.63	8.12	23.81	5	-0.79
	25	65	1000	6.50	11.67	11.98	25.09	3	0.36
	26	73	850	8.60	14.78	15.41	26.18	6	0.69
	22	32	1400	2.29	3.61	3.27	21.91	4	-0.41
	23	45	1200	3.75	7.31	7.04	22.93	7	-0.30
4500	24	54	950	5.65	11.10	11.43	24.08	4	0.33
	25	63	900	7.00	15.00	15.46	25.11	5	0.44
	26	70	750	9.33	19.00	19.61	26.14	7	0.54
	22	30	1300	2.31	4.41	5.02	22.14	4	0.64
	23	45	1100	4.09	8.93	8.16	22.83	6	-0.74
5500	24	53	900	5.90	13.57	12.89	23.86	8	-0.58
	25	62	850	7.30	18.33	19.81	25.30	7	1.20
	26	66	650	10.10	23.23	24.64	26.28	5	1.08
	22	30	1250	2.40	5.21	4.43	21.85	8	-0.68
	23	45	1000	4.50	10.55	9.31	22.77	6	-1.17
6500	24	51	850	6.00	16.04	16.67	24.11	5	0.46
	25	61	800	7.60	21.67	23.04	25.24	3	0.96
	26	65	600	10.80	27.45	29.15	26.29	4	1.11
	22	30	1200	2.50	6.01	5.32	21.89	8	-0.50
	23	45	950	4.74	12.18	11.06	22.82	5	-0.78
7500	24	50	800	6.25	18.50	19.83	24.21	4	0.88
	25	60	750	8.00	25.00	26.51	25.23	7	0.92
	26	63	550	11.50	31.67	33.89	26.33	4	1.27
	22	52	1500	3.47	6.81	8.47	22.24	5	1.09
8500	23	56	1050	5.33	13.80	15.24	23.20	8	0.87
	24	67	950	7.05	20.97	19.28	23.77	6	-0.96

25	74	800	9.25	28.33	26.05	24.69	3	-1.24
26	85	650	13.08	35.90	37.58	26.22	7	0.85

The blue curves of MAP control oxygen-enriched air intake way are always located above the red curves of normal air intake way, indicating the dynamic characteristic of MAP control oxygen-enriched air intake is generally improved in the whole rotate speed range than that of normal air intake way. When the throttle percentage is maintained constant at 100% under full load condition, the curves marked with ▲ and △ represent the gasoline outer characteristic of normal and MAP control oxygen-enriched air intake ways, respectively. The torque increases first and then decrease with the gradually increase of rotate speed, showing an obvious increase trend in all. The torque reaches its largest value 8.2 N·m when torque is 5000r/min under normal air intake condition, while the largest value 9.6 N·m is achieved when torque is 5000r/min under oxygen-enriched air intake condition. Compared with normal air intake with oxygen volume fraction of 21%, under the MAP oxygen-enriched air intake control condition, the torque increase rates of rotate speed of 2000r/min, 3000r/min, 4000r/min, 5000r/min, 6000r/min, and 7000r/min are 11.48%, 15.07%, 16.46%, 17.07%, 22.86%, and 23.64%, respectively, whose average torque increase rate is 17.76%.

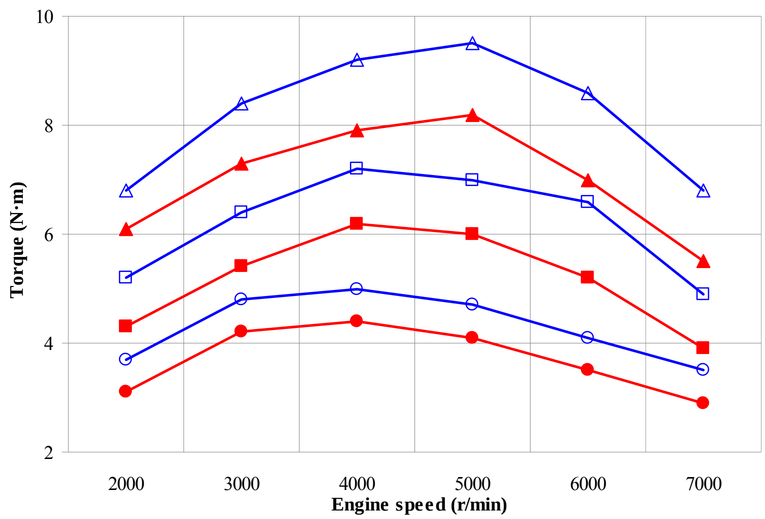


Figure 5 : Dynamic characteristic optimal result using MAP control oxygen-enriched air intake way

Economic characteristic analysis

The rotate speed is constant at 2000r/min and 3000r/min, respectively. The load value is chosen as 0%, 25%, 50%, 75%, and 100%. Two air intake ways such as normal and MAP control oxygen-enriched air intake ways are adopted. The oxygen volume fraction of normal air intake way is 21%. Oxygen volumes fraction of MAP control oxygen-enriched air intake is calculated from the economic type intake air MAP image. The load characteristic is carried out. When the gasoline engine works stably, its oil consumption indicator data are measured, compared and analyzed. The optimal result is shown in Figure 6. Two red curves marked with ● and ■ represent load characteristics curves of gasoline engines using normal air intake way with rotate speed of 2000r/min and 3000 r/min, respectively. While the two blue curves marked with ○ and □ represent load characteristics curves of gasoline engines using MAP control oxygen-enriched air intake way with rotate speed of 2000r/min and 3000 r/min, respectively.

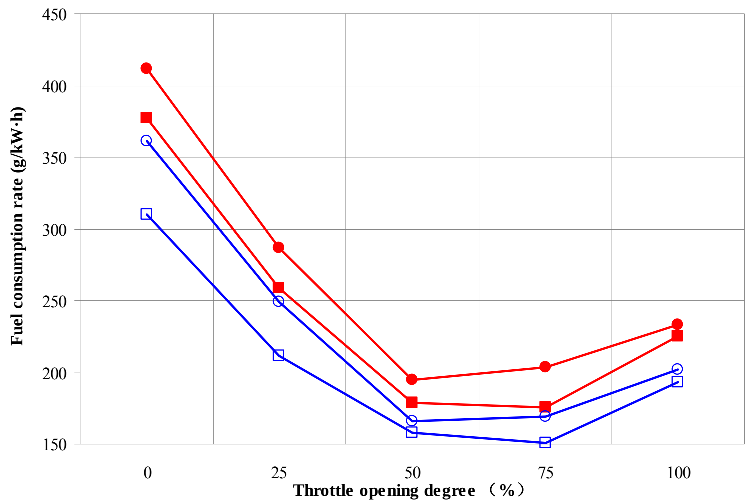


Figure 6 : Economic optimal result of MAP control oxygen-enriched air intake

The blue curves of MAP control oxygen-enriched air intake way are always located below the red lines of normal air intake way, revealing the oil consumption of test gasoline engine using MAP control oxygen-enriched air intake way is generally reduced in the whole load range. When the rotate speed is maintained at 3000r/min, the oil consumption rate firstly reduced rapidly and then slightly increased with the gradually increase of throttle percentage, displaying an obviously reduced trend in all. The oil consumption rate reduced to its lowest point of 176 g/(kW·h) at 75% under normal air intake condition, while oil consumption rate reduced to its lowest value of 151 g/(kW·h) at 75% under oxygen-enriched air intake condition. Compared with the normal air intake with oxygen volume fraction of 21%, the oil consumption reducing rate under MAP control oxygen-enriched air intake condition is 17.77%, 18.15%, 11.73%, 14.20%, and 14.22% when throttle percentage is 0%, 25%, 50%, 75%, and 100% respectively, whose average oil consumption reducing rate is 12.68%.

Emission characteristic analysis

Rotate speed is maintained unchanged at 2000r/min and 3000r/min, and five load points of 0%, 25%, 50%, 75%, and 100% are chosen. Two air intake ways of normal and MAP control oxygen-enriched air intake are adopted, in which the oxygen volume fraction of normal air intake way is 21%. The oxygen volume fraction of MAP control oxygen-enriched air intake is calculated from oxygen-enriched air intake MAP image. Load characteristic tests of emissions of HC, CO, NO_x are carried out. When the gasoline work stably, emissions of HC, CO, NO_x are measured, compared, and analyzed. The optimal result is shown in TABLE 3.

TABLE 3 : Compare result of emissions of MAP control oxygen-enriched air intake way

Performance indicator Emissions	Rotate speed (r/min)	Normal air intake	MAP control oxygen-enriched air intake		
		Lowest value	Lowest value	Reduce/increase rate of lowest value (%)	Average reduce/increase rate (%)
HC ($\times10^{-6}$)	2000	115	94	-18.26	-14.88
	3000	107	92	-14.02	-12.21
CO (%)	2000	0.83	0.69	-16.87	-17.85
	3000	0.90	0.74	-17.78	-14.92
NO_x ($\times10^{-6}$)	2000	66	73	10.61	7.42
	3000	69	75	8.70	7.87

Notes: The NO_x is increased in the table, so its value is positive, while NC and CO are reduced so the values are negative.

Emission of HC is obviously reduced using oxygen-enriched air intake way. The reducing rate of lowest value at 2000r/min condition is 18.26%, and the average reducing rate is 14.88%. Emission of CO is also reduced by a large extent. The reducing rate of lowest value at 2000r/min condition is 16.87%, and the average reducing rate is 17.85%. At the same time, the emission of NO_x is degraded and increased, whose increasing rate of lowest value at 2000r/min condition is 10.61%, and the average increasing rate reaches 7.42%. Emission increase of NO_x is obviously less than the emissions reduction of

HC and CO. Therefore, comprehensive compared the variations between HC, CO, and NO_x, MAP control oxygen-enriched air intake way can split the difference between these emission indicators, reduce the comprehensive emission of test gasoline engine effectively, and improve the emission performance of gasoline engine.

CONCLUSIONS

(1) The test bed of gasoline engine performance is established based on oxygen-enriched air intake way. Mixed intake air is fabricated with an objective oxygen-enriched proportion. The optimal control of gasoline engine is realized under oxygen-enriched air intake condition with a control error of less than ±1.5% and response time of shorter than 10 s.

(2) Verifying test of gasoline engine performance is carried out using normal air intake and MAP control oxygen-enriched air intake ways, respectively. The test result shows that compared with those under the normal air intake way with oxygen volume fraction of 21%, the torque under oxygen-enriched air intake condition increases, the oil consumption reduces, emissions of HC and CO reduces obviously, and emissions of NO_x degrades non-obviously.

(3) After comparison and analysis of test data of oxygen-enriched air intake and normal air intake, the average torque increase rate of oxygen-enriched air intake under full load condition is 17.76%, the average oil consumption reducing rate of oxygen-enriched air intake way under 3000r/min condition is 12.68%, the average reducing rate of HC emission of oxygen-enriched air intake way is 14.88%, average reducing rate of CO is 17.85, and average increasing rate of NO_x is 7.42%. Therefore, the dynamic and economic performances of gasoline engine are obviously optimized under oxygen-enriched condition. The emission performance is enhanced relatively. The comprehensive characteristic of gasoline engine is improved and the goal of energy conservation and emission reduction is achieved.

ACKNOWLEDGEMENT

The work was supported by The Natural Science Foundation for Colleges and Universities of Jiangsu Province of China under Grant(14KJD470002),Supported by Changzhou Key Laboratory of High Technology Project(CM20113001).

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