The Effect on Gasoline Engine Emission Characteristics of Variable Composition Oxygen-Enriched Intake Air Systems and Analysis of Heat-Resistant and Anti-Corrosion Coatings with Remanufacturing

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Abstract: In this paper, taking air-cooled, four-stroke, single cylinder gasoline engine as the research object, oxygen-enriched intake air systems and gasoline engine performance test bed were built. In the range of 21% to 26% enrichment ratio, based on MAP chart of variable component enriched intake, control parameters were adjusted according to the PWM principle, and a gas mixture of different oxygen and nitrogen components was prepared for the test engine. Under the conditions of different components intake air, an HC, CO and NO_x emission characteristics of gasoline were comparatively analyzed through universal characteristic test. The results show that the lowest HC emissions and CO emissions under conditions of variable components of the oxygen-enriched intake air were reduced by 17.59% and 17.14% compared with the normal intake. The lowest NO_x emission was 53×10^{-6}, which increased by 7.55%. Under conditions of variable component oxygen-enriched intake air, HC and CO emissions of gasoline engine significantly reduced, and NO_x emissions deteriorated slightly, which improved the relatively integrated emission performance of gasoline engine. Aiming at the engine corrosion problems raised under high temperature, oxygen-enriched, heat-resistant and anti-corrosion coatings on key parts of the engine corroded easily by advanced manufacturing technology were proposed. Based on the above method, the reliable operation of the engine can be ensured and the technical life and economic life can also be prolonged.

Keywords: Gasoline engine, oxygen-enriched intake air, remanufacturing, universal characteristic, variable composition

1. INTRODUCTION

Nitrogen-based flame-retardant component and oxygen-based combustion component constitute flame-retardant and combustion-supporting characteristics constrained engine combustion [1]. Combustion control of variable component intake is an active control method proposed to save fuel for the engine, strengthen power and improve the emissions, and it is a new way to achieve energy saving [2]. Variable component oxygen-enriched intake air can directly affect the combustion characteristics and the working process of the engine, effectively improve engine combustion temperatures, decrease ignition delay and promote fuel combustion [3]. Meanwhile, it can effectively improve output power of the engine, reduce its fuel consumption and improve its dynamic performance and economic performance [4]. It can not only reduce CO and HC emission produced from incomplete combustion, but also it will lead to the deterioration of NO_x emissions [5].

Commonly, membrane oxygen-enriched cylinders were used to achieve oxygen-enriched intake air of the engine. However, since the oxygen-enriched intake air components provided are not stable, it is difficult to fully grasp the actual working conditions and performance parameters of the engine [6].

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As electric-hydraulic machine's integration of highly integrated products changes an automobile's technical condition or characteristics leading to the electric-hybrid machine deterioration. The changes include not only machinery damage modes including surface wear, fatigue fracture, plastic deformation, corrosion and aging, but also electronic damage modes including short circuit, ablation, breakdown, drift, overheat and burn injury [7]. Remanufacturing engineering is a generic term of a series of technical measures or engineering activities for repairing or modifying used products, which is guided by product life cycle design and management, is aimed at quality, efficiency, energy, and materials and environmental safety [8]. With the development of engine remanufacturing industry and the extension of automobile scrapped cycle in China, the engine overhaul will certainly be replaced by remanufacturing. Compared with new products, the remanufacturing could save upto 50% cost, energy, 60% and materials, 70% [9]. Under oxygen-enriched conditions, some key components such as exhaust valves, cylinder head and cylinder walls can be corroded easily, which results in the reduction of engine life cycle [10-12].

In this paper, taking air-cooled, four-stroke, single cylinder gasoline engine as the research object, oxygen-enriched intake air systems and gasoline engine performance test bed were built, which prepared different oxygen- and nitrogen-enriched components for the test engine. Precise

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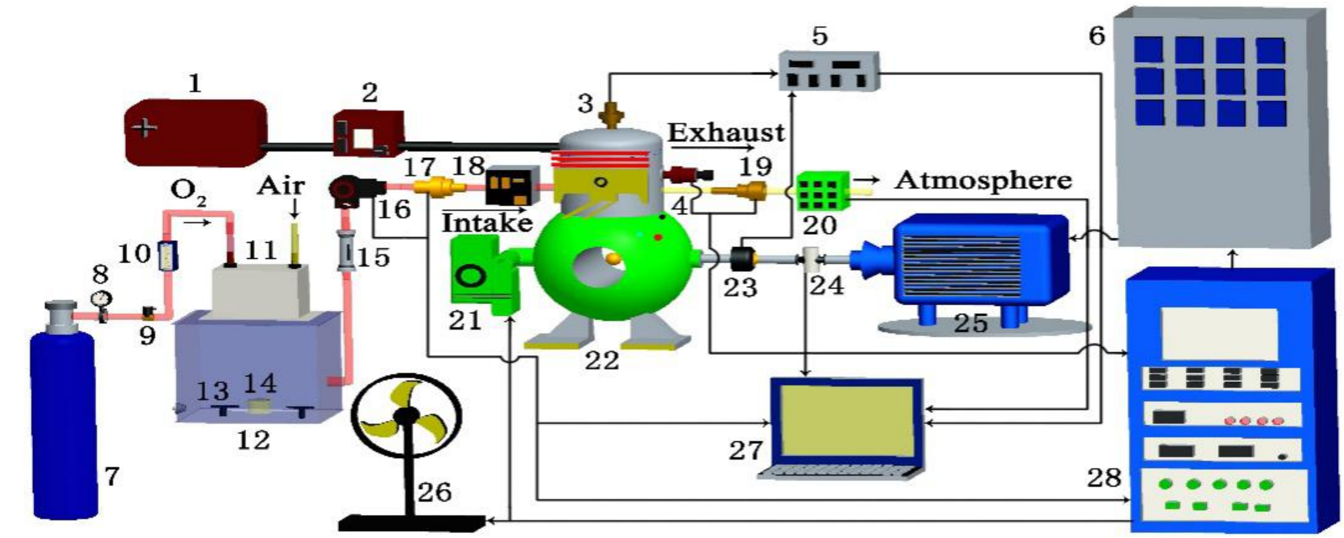


1-fuel tank, 2-smart fuel consumption, 3-cylinder pressure sensor, 4-cylinder temperature sensor, 5-combustion analyzer, 6-control cabinet, 7-oxygen bottles, 8-oxygen bottle pressure reducer, 9-oxygen flow control valve, 10-oxygen flow meter, 11-pre-mixing chamber, 12-gas chamber, 13-gas mixing fan, 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.

Fig. (1). Diagram of oxygen-enriched intake air test bed.

control of oxygen concentration ensures that the engine can perform stable operation under conditions of the target component, which is confirmed by analyzing HC, CO and NO_x emission characteristics of gasoline engine. Aiming at reducing the engine corrosion and prolonging engine life cycle to solve the corrosion problems under high temperature oxygen-enriched condition, the heat-resistant and the anti-corrosion coatings that are applied on key parts of the engine by advanced manufacturing technology has been discussed.

2. BUILDING TEST BED OF OXYGEN-ENRICHED INTAKE AIR

Oxygen-enriched intake air test bed of gasoline engine was composed of: air-cooled, four-stroke, single cylinder gasoline engine, gas distribution systems, fuel tank, smart fuel consumption, cylinder pressure sensor, cylinder temperature sensor, combustion analyzer, control cabinet, oxygen bottles, oxygen bottle pressure reducer, oxygen flow control valve, oxygen flow meter, pre-mixing chamber, gas chamber, gas mixing fan, temperature hygrometer, gas flow meter, *etc*. The structure of test bed is shown in Fig. (**1**), and key technical parameters of test engine are listed in Table **1**.

3. PREPARATION OF VARIABLE COMPOSITION OXYGEN-ENRICHED INTAKE AIR

3.1. Valve-Train

Valve-train is an important part of oxygen-enriched intake air test bed of gasoline engine. It is composed of pre-mixing chamber, gas chamber, oxygen bottle, oxygen bottle regulator, oxygen flow control valve, oxygen flow meter, mixing fan, temperature hygrometer, gas flow meter, oxygen analyzer and oxygen intake monitoring system. The main instruments and types are shown in Table **2**. Among them, the monitoring system of oxygen-enriched intake air consists of a microprocessor, PC host computer, programmable DC power supply, crystal oscillator circuit, PC control unit, data acquisition unit and the communication unit. Mainly electronic components and types are shown in Table **3**.

3.2. The Oxygen-Enriched Proportion of Intake Air

Using valve-train to prepare oxygen-enriched intake air of different components of oxygen and nitrogen for the test engine, industrial oxygen whose purity was higher than 99.2% and filling pressure was 13 ± 0.5 MPa, had been provided through oxygen bottles. After its pressure dropped to standard atmospheric pressure by oxygen cylinder

Table 1. The key technical parameters of engine test.

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

Table 2. Main instrument and type of oxygen-enriched intake and valve system.

Name	Type	Name	Type
Oxygen bottle	QR1114X-40	Oxygen analyzer	KY-2F
Oxygen bottle regulator	QD-3A	Gas flow meter	EF80
Oxygen flow control valve	PVD1-08D	Mixing fan	8025
Oxygen flow meter	GR-LUGB	Temperature hygrometer	TH603A

regulator, it had been passed into the pre-mixing chamber; another inlet of the pre-mixing chamber was connected to the atmosphere. Using a plurality of mixing fans, industrial oxygen and air were premixed in a pre-mixing chamber, and then the mixture was passed into the gas chamber to mix sufficiently. By oxygen flow meter and oxygen flow meter control valve, the flow of industrial oxygen and proportion of intake oxygen concentration were controlled precisely to form the target variable component mixing gas of oxygen-enriched intake air. Then it was provided to the naturally aspirated test engine. Based on the pulse-width modulation (PWM) principle, using MC9S12DP256 microprocessors, duty ratio was matched to control on or off of oxygen flow control valve. Precise control of industrial oxygen flow and proportion of intake oxygen concentration of the engine prepared intake air for the test gasoline engine under different conditions.

Table 3. Main electronic component and type.

No.	Name	Type
1	Programmable DC power	IPD-3303SLU
2	Microprocessor	MC9S12DP256
3	PC host computer	IBM-R400
4	Data acquisition unit	PCI1710L

Oxygen-enriched intake air can promote rapid ignition, shortened delay period, increase burning speed, accelerate low-temperature burning, rise combustion temperature and promote full combustion, which have significant effects on power, economy and emission performance of gasoline engine. When the proportion of oxygen-enriched intake air increased to a certain extent, the amplitude of flame temperature in cylinder gradually slowed, but the corresponding costs of continuing to increase the oxygen-enriched intake air proportion increased significantly. If the proportion of oxygen-enriched intake air is too high, it can cause knocking of the engine, unstable output torque, deterioration of NO_x emissions, *etc*. The selected proportion of oxygen-enriched intake air was 22% ~ 26% in this paper.

3.3. Principle of Variable Composition Oxygen-Enriched Intake Air

According to the PWM principle, adjusting the period and single-period conducting time of oxygen flow control valve matched oxygen concentration control amount of target compound for each node, and the matching results are shown in Table **4**. Corresponding period and the control amount of single-cycle on-time are shown in Table **5**. The MAP chart of variable component oxygen-enriched intake air is shown in Fig. (**2**). On the PC host computer, the MAP chart of oxygen-enriched intake air, the corresponding period of oxygen flow control valve and the single-period conducting time were stored in MC9S12DP256 microprocessor. During actual engine operation, the operating condition of the engine was determined in accordance with various sensors, acquisition speed, throttle opening degree, *etc*. According to MAP chart of oxygen-enriched intake air, the basic control volume of oxygen concentration can be determined. Adjusting the control parameters of PWM and controlling flow of industrial oxygen provided a stable oxygen-enriched intake air of target component for the test gasoline engine.

4. EMISSION CHARACTERISTIC TEST ANALYSIS OF GASOLINE ENGINE

According to test methods of engine's universal characteristic reported in national standards, "car engine performance test method (GB / T 18297-2001)", under the condition of oxygen-enriched ratio of 22% to 26%, universal characteristic test of HC, CO, NO_x emissions was conducted. 1500 r/min, 2500 r/min, 3500 r/min, 4500 r/min, 5500 r/min, 6500 r/min, 7500 r/min and 8500 r/min speeds were selected, and 0%, 20%, 40%, 60%, 80% and 100% load points were selected. Normal intake air and variable component oxygen-enriched intake air were used, respectively. Oxygen volume fraction was 21% under the condition of normal intake air, and oxygen volume fraction can be calculated by the MAP chart shown in Fig. (**2**) under the condition of variable component oxygen-enriched intake air. After the gasoline engine was stable, HC, CO, NO_x emissions had been measured and comparatively analyzed. Controlled amount of MAP and the corresponding experimental data are shown in Tables **6** and **7**.

4.1. HC Emission Analysis

Taking rotational speed (r/min) as the x-axis and throttle opening degree (%) as y-axis, the universal characteristic curve of HC emissions is shown in Fig. (**3**).

As can be seen from Table **6** and Fig. (**3**), the high HC emissions are mainly concentrated in the middle and high speed zone of low load conditions and large load zone. As part of load operating conditions, HC emission was lower, which reflected better HC emissions of engine. Minimum

Table 4. Duty ratio match of MAP control amount under the condition of variable components oxygen- enriched intake air.

Throttle Opening Degree (%) / n (r/min)	0		20		40		60		80		100	
	Oxygen (%)	Duty Ratio (%)	Oxygen (%)	Duty Ratio (%)	Oxygen (%)	Duty Ratio (%)	Oxygen (%)	Duty Ratio (%)	Oxygen (%)	Duty Ratio (%)	Oxygen (%)	Duty Ratio (%)
1500	22	1.82	22	2.00	23	2.32	23	2.55	24	2.78	24	2.94
2500	22	1.94	22	2.19	23	2.44	24	2.67	24	2.89	25	3.18
3500	22	2.19	22	2.38	24	2.71	24	2.76	25	3.06	25	3.29
4500	22	2.29	23	2.53	24	2.75	25	2.95	25	3.18	26	3.56
5500	22	2.31	23	2.74	24	2.82	25	3.22	26	3.50	26	3.76
6500	22	2.40	23	2.94	25	3.25	26	3.44	26	3.87	26	4.13
7500	22	2.50	24	3.22	25	3.50	26	4.12	26	4.29	26	5.43
8500	22	3.47	24	4.47	25	4.83	25	5.14	26	6.83	26	7.64

Table 5. Period and single-period time conducting of MAP control amount under the condition of variable component oxygen-enriched intake air.

Throttle Opening Degree (%) / n (r/min)	0		20		40		60		80		100	
	T (ms)	*t* (ms)	*T* (ms)	*t* (ms)	*T* (ms)	*t* (ms)	*T* (ms)	*t* (ms)	*T* (ms)	*t* (ms)	*T* (ms)	*t* (ms)
1500	1100	20	1050	21	950	22	1100	28	900	24	850	25
2500	1800	35	1050	23	900	22	1050	28	900	26	850	27
3500	1600	35	1050	25	850	23	1050	29	850	26	850	28
4500	1400	32	950	24	800	22	950	28	850	27	900	32
5500	1300	30	950	26	850	24	900	29	800	28	850	32
6500	1250	30	850	25	800	26	900	31	750	29	800	33
7500	1200	30	900	29	800	28	850	35	700	30	700	38
8500	1500	52	850	38	600	29	700	36	600	41	550	42

**T* stands for period, *t* stands for single-period on-time.

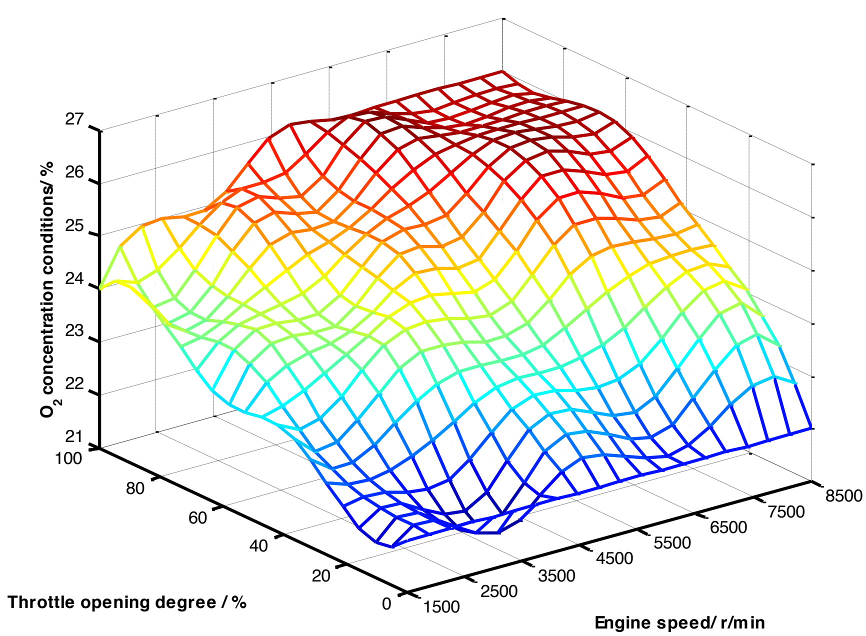


Fig. (2). MAP figure of variable composition oxygen-enriched intake air.

Table 6. Controlled quantity and HC emission of variable composition oxygen-enriched intake air.

Throttle Opening Degree (%) / N (r/min)	0		20		40		60		80		100	
	HC Emission ($\times10^{-6}$)	Oxygen (%)	HC Emission ($\times10^{-6}$)	Oxygen (%)	HC Emission ($\times10^{-6}$)	Oxygen (%)	HC Emission ($\times10^{-6}$)	Oxygen (%)	HC Emission ($\times10^{-6}$)	Oxygen (%)	HC Emission ($\times10^{-6}$)	Oxygen (%)
1500	129	22	109	22	96	23	94	23	110	24	135	24
2500	126	22	105	22	93	23	91	24	106	24	132	25
3500	123	22	102	22	92	24	89	24	103	25	130	25
4500	125	22	103	23	94	24	92	25	107	25	133	26
5500	130	22	104	23	97	24	95	25	110	26	135	26
6500	133	22	107	23	99	25	97	26	112	26	137	26
7500	136	22	110	24	102	25	100	26	115	26	139	26
8500	139	22	113	24	104	25	102	25	117	26	142	26

Table 7. CO and NO_x emission.

Throttle Opening Degree (%) / n (r/min)	0		20		40		60		80		100	
	CO Emission (%)	NO_x Emission ($\times10^{-6}$)	CO Emission (%)	NO_x Emission ($\times10^{-6}$)	CO Emission (%)	NO_x Emission ($\times10^{-6}$)	CO Emission (%)	NO_x Emission ($\times10^{-6}$)	CO Emission (%)	NO_x Emission ($\times10^{-6}$)	CO Emission (%)	NO_x Emission ($\times10^{-6}$)
1500	1.03	57	0.88	126	0.73	182	0.65	230	0.76	264	1.17	275
2500	1.12	66	0.96	131	0.83	188	0.71	239	0.87	275	1.21	283
3500	0.94	80	0.79	145	0.70	198	0.61	246	0.73	282	1.09	291
4500	0.87	89	0.72	160	0.63	217	0.55	261	0.66	290	1.01	296
5500	0.78	83	0.65	152	0.54	203	0.48	250	0.58	285	0.94	294
6500	0.67	76	0.60	145	0.49	193	0.40	244	0.52	278	0.83	286
7500	0.59	68	0.46	128	0.40	187	0.34	237	0.44	270	0.79	279
8500	0.53	63	0.42	122	0.34	181	0.29	230	0.35	269	0.72	274

HC emission was 89×10^{-6}, when the throttle opening was 60%, and rotation speed was 3500 r/min at part load conditions. Compared with the minimum emission of normal intake air (108×10^{-6}), HC emission decreased to 17.59%, and the decline extent was very significant.

4.2. CO Emission Analysis

Taking rotational speed (r/min) as the x-axis and throttle opening degree (%) as y-axis, the universal characteristic curve of CO emission is shown in Fig. (**4**).

As can be seen from Table **7** and Fig. (**4**), the high CO emissions are mainly concentrated in the low speed zone of both low load conditions and large load conditions. As part of load operating conditions, CO emission was lower, which reflected better CO emission of engine. Minimum CO emission was 0.29%, when the throttle opening was 60%, and rotation speed was 8500 r/min at part load conditions. Compared with the minimum emission of normal intake air (0.35%), CO emission decreased by 17.14%, and the decline extent was very significant.

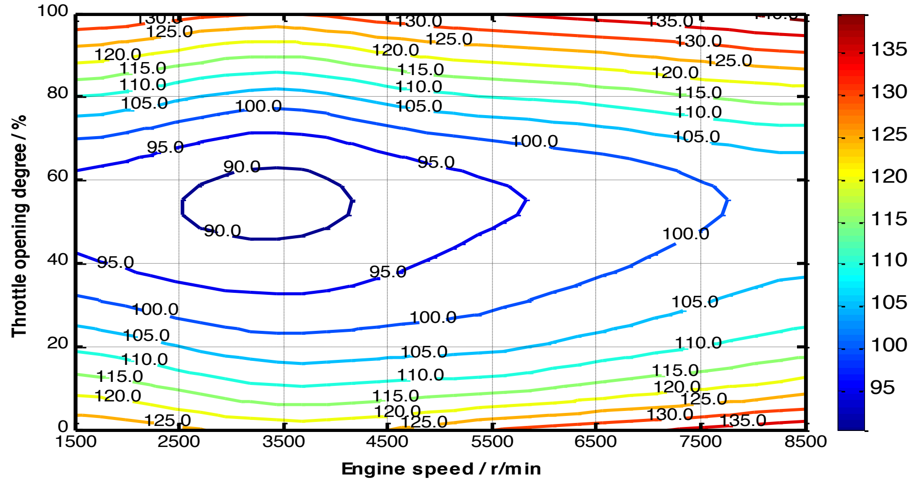
4.3. NO_x Emission Analysis

Taking rotational speed (r/min) as the x-axis and throttle opening degree (%) as y-axis, the universal characteristic curve of NO_x emission is shown in Fig. (**5**).

As can be seen from Table **7** and Fig. (**5**), the high NO_x emissions are mainly concentrated in the middle speed zone of large load conditions. However, emission values increased modestly compared with the normal condition. Under the condition of small load conditions, NO_x emission was lower. Minimum NO_x emission was 56×10^{-6}, when the throttle opening was 0%, and rotation speed was 1500 r/min. Compared with the minimum emission of normal intake air (53×10^{-6}), NO_x emission increased by 17.59%, and the decline extent was not very significant.

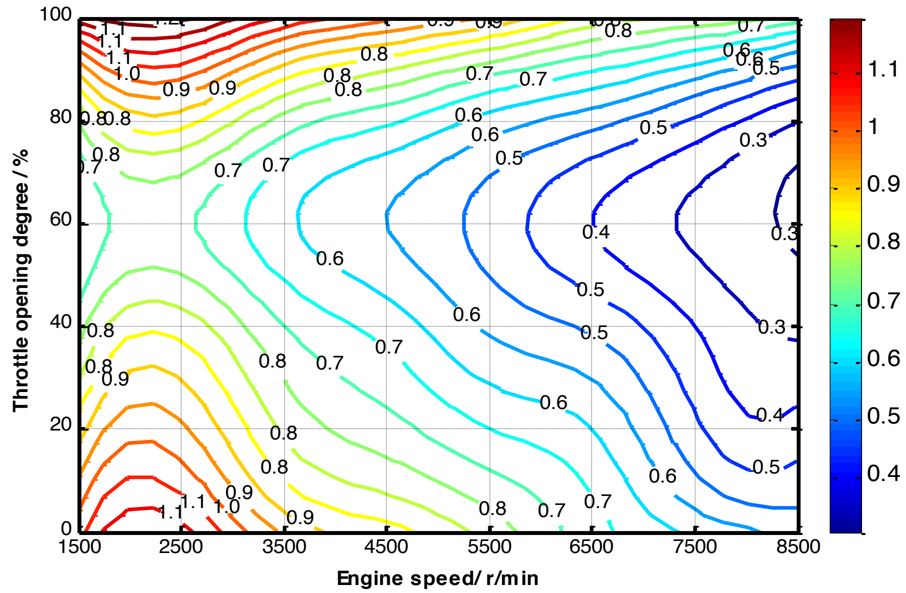
5. HIGH TEMPERATURE AND ANTI-CORROSION COATING ANALYSIS WITH REMANUFACTURING

Corrosion is the phenomenon of metal destruction caused by the surrounding medium, and it is widespread during the



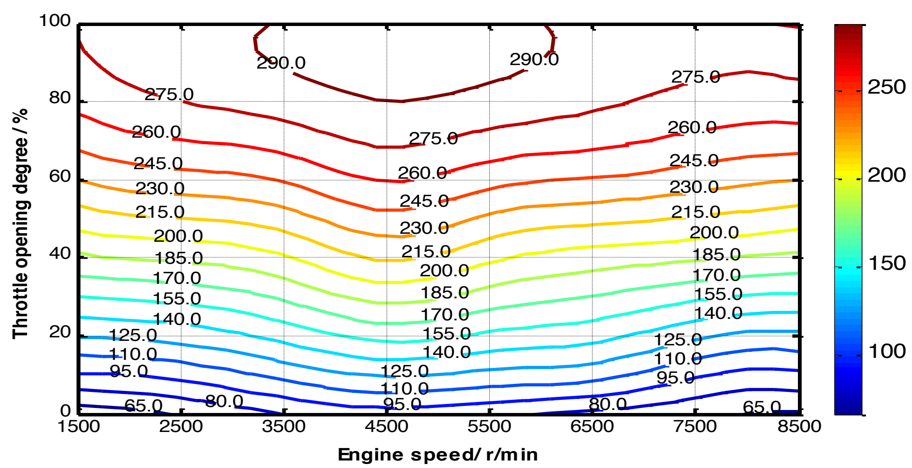
Note: The values marked in the figure represent HC emission (10^{-6}).

Fig. (3). Universal characteristic curve of HC emission.



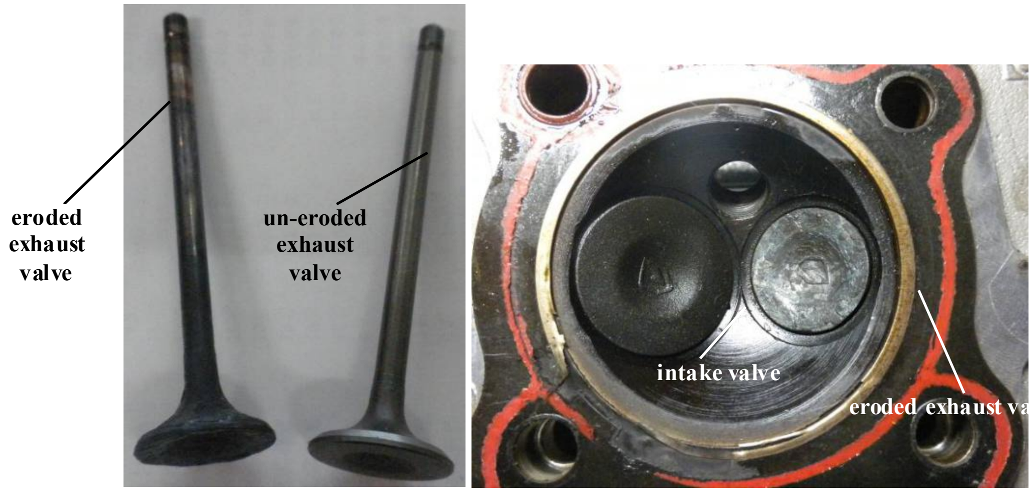
Note: The values marked in the figure represent CO emission (%).

Fig. (4). Universal characteristic curve of CO emission.



Note: The values marked in the figure represent NO_x emission (10^{-6}).

Fig. (5). Universal characteristic curve of NO_x emission.



(**a**) comparison between eroded and (**b**) comparison between intake valve and exhaust un-eroded exhaust valve after erosion.

Fig. (6). Comparison diagram of exhaust valve combustion.

engine parts operation. Ablation phenomenon of engine parts is associated with high-temperature oxidation corrosion, namely the process of corrosion of metal engine parts involves a chemical reaction with the surrounding high temperatures and strong oxidizing gaseous medium.

In an oxygen-enriched intake air MAP test process, when the oxygen volume fraction is more than 29% and is continuously under heavy load and high-speed condition, gasoline engine exhaust valves undergo serious erosion phenomenon; the ablated row valve and engine block is shown in Fig. (**6**). Fig. (**6a**) shows a comparison of ablated exhaust valve and new one. Fig. (**6b**) shows a comparison of the engine block before and after ablation.

Fig. (**6**) shows that the exhaust valve is ablated seriously after a long time at high temperature and strong oxidizing environment, and the size of exhaust valve significantly reduced with the uneven surface. As a result, engine operating condition deteriorates seriously causing substantial decline in the engine cylinder air-tightness.

The combustion speed can be accelerated through the oxygen-enriched intake air control of test engine. In addition, the fire can be caught more quickly, the ignition delay period can be shorted, the full combustion can be promoted, the combustion temperature can be improved, and the combustion efficiency also can be enhanced. Therefore, the engine economy and power are enhanced significantly, and overall emissions efficiency of the engine is also improved. However, the ablation phenomenon is a series of key components including: engine exhaust valve, cylinder head, cylinder liner, cylinder walls, pistons, piston rings set and valve mechanism, which result in the life cycle reduction of engine under high-temperature oxygen-enriched environment.

Therefore, on the basis of failure analysis and life cycle assessment, the corrosion reaction can be prevented or even reduced under high temperature and oxygen-enriched environment through further coating of high temperature anti-corrosion coatings with some advanced remanufacturing technologies such as nano-brushing electroplating technology, the high-performance supersonic plasma spraying technology, the automatic high velocity arc spraying technology, the micro-plasma cladding rapid prototyping technology, and the robot welding rapid prototyping technology. Thereby, the stable and reliable operation of engine in a high temperature oxygen-enriched condition can be ensured, so that the life of the engine technology and economic life can be prolonged.

CONCLUSION

(1) Variable component oxygen-enriched intake air can significantly reduce HC and CO emissions of gasoline engine, while deterioration of NO_x emission was not significant, which can improve the overall emission performance of gasoline engine.

(2) Under the condition of Part load conditions, the HC and CO emissions were lower. The lowest HC emission was 89×10^{-6}, when the throttle opening was 60%, and rotation speed was 3500 r/min. The lowest CO emission was 0.29%, when the throttle opening was 60%, and rotation speed was 8500 r/min. Compared with the minimum emission of normal intake air, HC and CO emissions decreased by 17.59% and 17.14%, respectively.

(3) Under the condition of small load conditions, NO_x emission was lower. Minimum NO_x emission was 56×10^{-6}, when the throttle opening was 0%, and rotation speed was 1500 r/min. Compared with the minimum emission of normal intake air (53×10^{-6}), NO_x emission increased by 17.59%, and the decline extent was not very significant.

(4) Oxygen-enriched intake air can accelerate combustion speed and promote the full combustion. Therefore, the engine economy and power are enhanced significantly, and overall emissions efficiency of the engine is also improved. However, the ablation phenomenon is a series of key components of engine. The corrosion reaction can be prevented and reduced under high temperature and oxygen-enriched condition through further coating of high temperature

anti-corrosion coatings with some advanced remanufacturing technologies. The stable and reliable operation of engine at a high temperature oxygen-enriched condition can be ensured, so that the life of the engine technology and economic life can be prolonged.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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