Design and Operating Characteristics of a Variable Load Rate Engine

Liming Di[1*], Yongsheng Zhao[2], Yaqiang Wang[1], Haoqi Sun[1]

[1] *School of Automobile and Energy Engineering*, Yanshan University, Qinhuangdao, Hebei, 066004, China
[2] *School of Mechanical Engineering*, Yanshan University, Qinhuangdao, Hebei, 066004, China

Abstract **—This paper proposes a variable load rate engine (VLRE) with variable valve timing, a variable compression ratio and variable cycle technology simultaneity. It explains the VLRE's operating principle of three working cycle modes and a variable compression ratio. The concept of engine cycle power frequency is also proposed, with the VLRE possessing continuous interval cycle power frequencies of 1/2, 1/3 and 1/4. The VLRE's port timing and cylinder exhaust port parameters are designed and optimised. A variable cam profile mechanism is presented and the optimal mode switch timing is finally determined near the compression top dead centre. The bench test results indicate that VLRE could feasibly be implemented in variable load rate technology.**

Keywords - Piston engine; Operating mode; Load rate; Variable compression ratio; Variable cycle engine

I. INTRODUCTION

The engine load rate is the speed at which actual loading to the maximum load ratio occurs. Statistically, the urban area load rate of a running vehicle is typically 20~50% with poor fuel economy. The highway load rate is usually 60~90% with good fuel economy. If the engine reserve power can be dynamically changed according to different working conditions to optimise the load rate interval, then the engine performance at all speeds and in all working conditions can be improved efficiently.

The integration of various advanced technologies has gradually become an inevitable trend in the development of vehicle reciprocating piston engines ('engines' hereafter).[1-3] In recent years, the technologies involved in improving engine performance have mainly included variable distribution,[4-11] variable displacement[12,13] or cylinder deactivation, variable compression ratios[14-19] and variable cycles.[20-22] Although these techniques have managed to dynamically change engine load rates to a degree, variable load rate technologies have proven valuable in rating engine performance merit.

Once an engine's effective displacement has been fixed, the maximum power of a two-stroke engine is 1.5~1.7 times that of a four-stroke engine, especially with regard to low speeds and high loads. A two-stroke engine can achieve a higher pulling torque and a slightly more cyclic swing that a four-stroke engine, and the former's output per litre is 50~70% higher than that of the latter. At present, the fuel economy and emission performance problems of two-stroke engines have been solved using stratified charge[23,24] and gasoline direct injection[25,26] strategies.

This paper proposes a variable load rate engine (VLRE) that merges the features of two- and four-stroke engines. A VLRE can achieve three working cycle modes: two-stroke (VLRE-T), four-stroke (VLRE-F) and six-stroke (VLRE-S) modes. This allows its load rate to change dynamically, and its feasibility is proven using engine bench testing.

II. STRUCTURE AND OPERATING PRINCIPLE OF VLRE

A. Structure of VLRE

The VLRE prototype was created by revamping a Honda WH125-6 engine. A schematic diagram of the construction principle is shown in Fig. 1, based on the WH125-6's existing air supply system, carburettor fuel system, cooling system, lubrication system, intake and exhaust device, etc. A cylinder exhaust port with opening and closing that was controlled by a valve was set up near the bottom dead centre of the piston. When the opening and closing times of all of the VLRE valves were controlled by variable distribution devices, the VLRE achieved the switching function of its different working cycle modes.

1 *Address correspondence to this author at the School of Automobile and Energy Engineering, Yanshan University, Qinhuangdao, Hebei, 066004, China; Tel: 0335-8074682;
Fax: 0335-8074682; E-mail: diliming@ysu.edu.cn

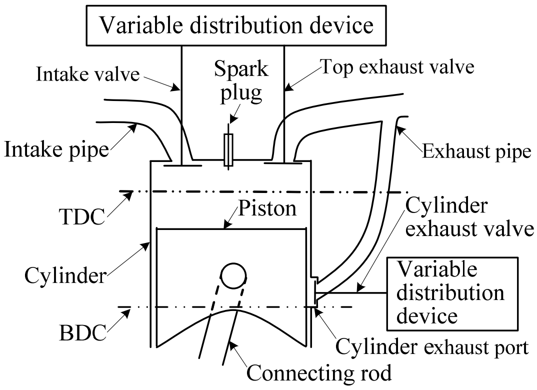

Fig.1 Schematic Diagram of The VLRE Structure

B Operating Principle of the VLRE

The VLRE can achieve VLRE-T, VLRE-F and VLRE-S modes under different working conditions, and the corresponding thermodynamic cycle phase diagrams are shown in Figs 2~4, respectively. TDC denotes the top dead centre of the piston; BDC is the bottom dead centre of the piston; CA is the abbreviation for crank angle; θ is the angle of crankshaft turns; θ with subscript IVO (IVO is the time of the intake valve opening) or EVO (EVO is the time of the exhaust valve opening) denotes the opening time crank angle position of the intake or exhaust valves, respectively; **Error! Reference source not found.** with subscript IVC (IVC is the time of the intake valve closing) or EVC (EVC is the time of the exhaust valve closing) denotes the closing time crank angle position of the intake or exhaust valves, respectively; θ with subscript EPO (EPO is the time of the cylinder exhaust port opening) or EPC (EPC is the time of the cylinder exhaust port closing) denotes the opening or closing time crank angle position of the cylinder exhaust port, respectively; θ with subscript s or p denotes the ignition timing or combustion end time crank angle position, respectively; and θ with superscript T or F denotes the parameter of VLRE-T or VLRE-F, respectively.

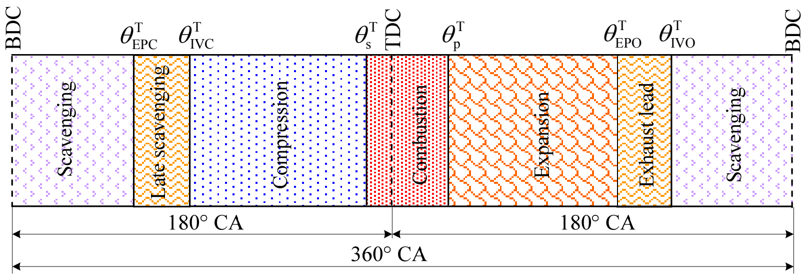

Fig.2 Cycle Phase Diagram of VLRE-T

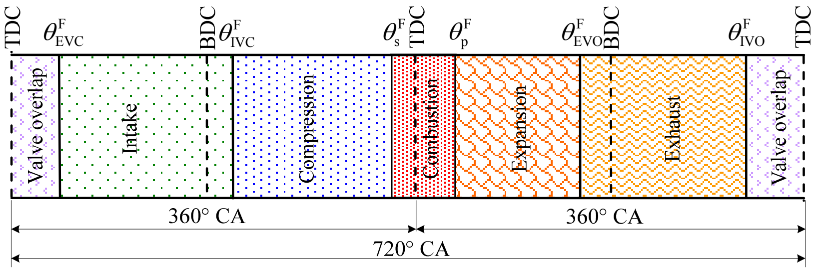

Fig.3 Cycle Phase Diagram of VLRE-F

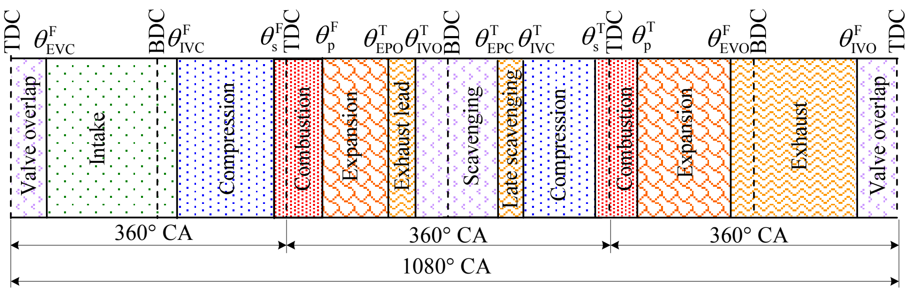

Fig.4 Cycle Phase Diagram of VLRE-S

1) Operating Principle of VLRE-T

One VLRE-T cycle needed 360° CA, and went through six work processes (scavenging, late scavenging, compression, combustion, expansion and exhaust lead) in two piston strokes. The characteristics of VLRE-T were as follows. The gas passing through the cylinder head's intake valve flowed into the cylinder during the gas exchange process, and the exhaust gas flowed out, passing through the cylinder exhaust port. The cylinder head's exhaust valve continued to close all the time in this mode. Given that the port timing was controlled by the valve, VLRE-T could achieve the late scavenging process to improve the gas exchange quality.

2) Operating Principle of VLRE-F

VLRE-F had the same cycle process as a traditional four-stroke engine. One VLRE-F cycle needed 720° CA, and it went through five work processes (intake, compression, combustion, expansion and exhaust) in four piston strokes. VLRE-F achieved the gas exchange process using the cylinder head's intake and exhaust valves, and the cylinder exhaust port continuously closed all of the time in this mode.

3) Operating Principle of VLRE-S

VLRE-S was achieved by embedding the VLRE-T cycle in the VLRE-F cycle. One VLRE-S cycle needed 1080° CA and included two expansion processes in six piston strokes. The first two strokes of VLRE-S were the same processes as the first two strokes of VLRE-F, the third stroke of VLRE-S was the same process as the second stroke of VLRE-T, the fourth stroke of VLRE-S was the same process as the first stroke of VLRE-T and the last two strokes of VLRE-S were the same processes as the third and fourth strokes of VLRE-F. Given the higher requirements for the response characteristic of the valve drive mechanism in VLRE-S, a cam-less valve train was needed, but the technology is not yet mature. Thus, this paper does not contain an in-depth discussion of VLRE-S.

4) Operating Principle of Variable Compression Ratio

At present, most of the known engine variable compression ratio technologies are achieved by changing the combustion chamber volume, but engine combustion chamber volume is affected by multi-valve technology, variable valve timing technology (to avoid valve and piston motion interference), combustion chamber shape design, and so on. As such, the rangeability of the combustion chamber volume is restricted, there are notable changes to the engine body parts, the controlling mechanism is complex and the research and applied cost can be expensive. However, VLRE achieved the interval continuous variable values of engine effective compression ratio ε by changing the effective stroke volume (effective displacement) V_s, and VLRE changed its V_s by controlling the cylinder exhaust valve's opening and closing times with a variable distribution device. This method did not change the components around the combustion chamber volume, which made it simple and reliable. The ε and V_s of VLRE were influenced by the cylinder exhaust port's closing times, due to a close coupling relationship between them. Compared with Atkinson's cycle system, which is realised by controlling valve timing, the method of the variable compression ratio presented in this paper significantly reduced the weakening effect on cylinder turbulent motion in the early stage of a piston's upward movement.

During VLRE, a piston moved from BDC to TDC as the cylinder exhaust valve was opening, such that the gas in the cylinder flowed out by passing through the cylinder exhaust port. This part of the cylinder volume was called loss volume V_e, as it could not hold fresh gas. The effective compression process of VLRE began when the cylinder exhaust valve was closed. The formula for effective stroke volume V_s is shown in Eq. (1). The formula for effective compression ratio ε (actual compression ratio) is shown in Eq. (3). Geometrical compression ratio ε' denotes the ratio of BDC closed volume to TDC closed volume, and its formula is shown in Eq. (4). The relationship between ε and ε' is shown in Eq. (5).

$$V_s = V_s' - V_e = V_s' (1 - \psi) \tag{1}$$

$$\psi = V_e / V_s' = H_e / S \tag{2}$$

$$\varepsilon = (V_e + V_s) / V_c \tag{3}$$

$$\varepsilon' = (V_c+V_s')/V_c = (V_c+V_s)/V_c + V_e/V_c = \varepsilon + \psi V_s'/V_c = \varepsilon + \psi(\varepsilon' - 1) \tag{4}$$

$$\varepsilon = \varepsilon' (1 - \psi) + \psi \tag{5}$$

Where V_s' — Piston displacement,

ψ — Percentage of stroke loss,

H_e — Height of cylinder exhaust port,

S — Piston stroke,

V_c — Combustion chamber volume.

The values for the prototype engine cylinder bore were D = 52.4 mm, S = 57.9 mm and ε = 9.0. When the cylinder exhaust port was a rounded rectangular shape and the port bottom was aligned with BDC, the cylinder exhaust valve was closed after the cylinder exhaust port was closed by moving the piston up. The relationship between the VLRE compression ratio associated parameters and the height of the cylinder exhaust port is shown in Fig. 5.

C Cycle Power Frequency of VLRE

Engine cycle power frequency was defined as the ratio of power time to piston strokes in one working cycle, and indicated engine capacity. Then, the cycle power frequency of a traditional two-stroke engine and VLRE-T was 1/2, the cycle power frequency of a traditional four-stroke engine and VLRE-F was 1/4 and the cycle power frequency of VLRE-S was 2/6 = 1/3. VLRE possessed continuous interval cycle power frequencies of 1/2, 1/3 and 1/4, and it largely expanded the single engine quality working range. A VLRE-S cycle requires the valve control mechanism to switch twice, and the timeliness demand could only be met by excluding a camshaft valve driving mechanism. However, this technology is not yet mature or popular at present. Thus, this paper only examines VLRE-T and VLRE-F.

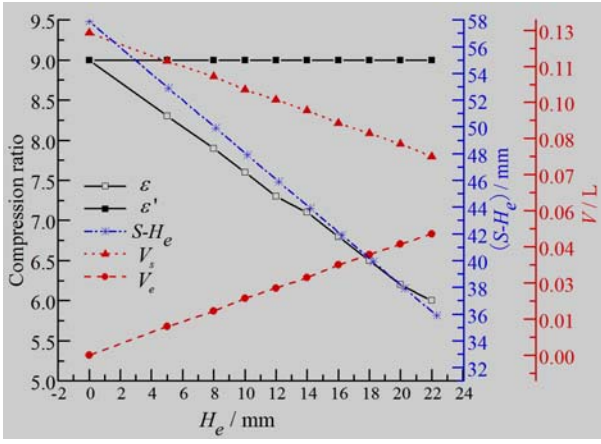

Fig.5 Relationship between the VLRE Compression Ratio Associated Parameters and Cylinder Exhaust Port Height

III.CYLINDER EXHAUST PORT PARAMETER DESIGN AND VALVE TIMING OPTIMISATION

The initial design parameters of a rounded rectangular cylinder exhaust port, based on [27], were a height of H_e = 12 mm, a width of B_e = 33 mm and a fillet radius of r_e = 2.5 mm. The initial design intake valve timing values for VLRE-T were an IVO of BBDC 48° CA and an IVC of ABDC 48° CA. According to [28, 29], the final optimal design parameters were a height of H_e = 14 mm and a width of B_e = 30 mm. The final optimal intake valve timing for VLRE-T was achieved when IVO was BBDC 46° CA and IVC was ABDC 86° CA. Similarly, we achieved the final optimal valve timing of VLRE-F, which is shown in Table I.

IV. MODE SWITCHING OF VLRE

A Mode Switching Time

To ensure that there was enough time for VLRE mode switching, the VLRE mode switching time was selected at around the compression stroke TDC, because the VLRE control system's software and hardware were in a steady state in the meantime, with all of the valves closing and the spark plug carrying out the ignition process.

B Mode Switching Mechanism

The variable distribution device of the VLRE is shown in Fig. 6. The variable phase camshaft driving mechanism operated dynamically, adjusting the valve timing, and the variable cam profile mechanism operated the switching between different mode cams.

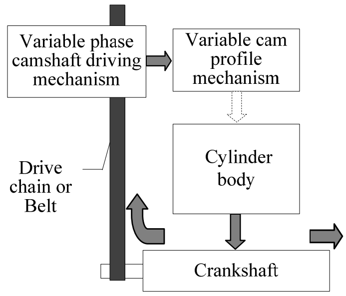

Fig.6 Variable Distribution Device for VLRE

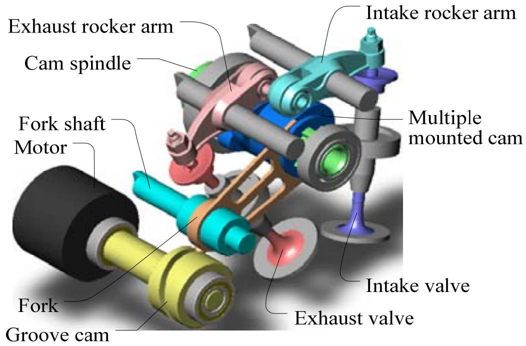

Fig.7 Variable Cam Profile Mechanism for the VLRE

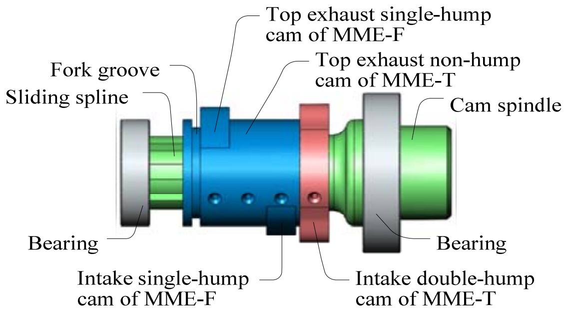

Fig.8 Assembly Camshaft for the VLRE

The variable cam profile mechanism and assembly camshaft for the VLRE are shown in Figs 7 and 8, respectively. There was a fixed connection between the driving motor and the groove cam, and the multiple mounted cam could move along the axial sliding spline using a fork driven by the groove cam. The intake and exhaust rocker arms were driven by the corresponding mode cams when the VLRE was working in a certain mode. The multiple mounted cam included four profile cams. The intake and top exhaust single-hump cams were used for VLRE-F while the intake double-hump and top exhaust non-hump cams were used for VLRE-T. However, the variable distribution device for the VLRE worked for the cylinder exhaust valve, and its multiple mounted cam included two single-hump cams: one that worked in VLRE-T mode and another that worked in VLRE-F mode.

V. VLRE FEASIBILITY BENCH TEST

The distance between the intake and exhaust rocker arms was too short to apply the variable cam profile mechanism in the WH125-6 cylinder head. To prove the feasibility of VLRE, this study designed a multiple mounted cam comprising four profile cams divided into two multiple mounted cams that connected with the cam spindle via sliding spline. The one with intake and top exhaust single-hump cams was used for the VLRE-F bench test, and the one with an intake double-hump cam and a top exhaust non-hump cam was used for the VLRE-T bench test to minimise the difficulty with verification.

To avoid interference between the gap-clearance of the piston rings and the cylinder exhaust port, all of the piston rings had to be circumferentially positioned using pins. The fixed positions of the ring pins are shown in Fig. 9. The ring pins were usually installed in the ring gap, and the top ring pin could not lie in the same direction as the piston marked ‘IN’. All of the ring pins had to avoid the direction of the piston pin boss, and their fixed positons also had to avoid the cylinder exhaust port. Each pin had to maintain the maximum angle interval from the adjacent ring pins. This method can result in an engine achieving better life cycle, fuel economy and noise performance.

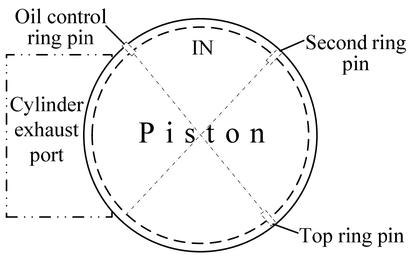

Fig.9 Fixed Ring Pin Position

The VLRE experiment prototype used the carburettor fuel and capacitor discharge ignition systems of WH125-6, such that the original ignition system could make the spark plug spark once each stroke. The cylinder exhaust port was closing all of the time during VLRE-F testing, and opening all of the time during VLRE-T testing. The effective compression ratio and effective displacement of VLRE-T were 7.1 and 0.0948 L, respectively, during bench testing; that is, much smaller than the parameters of VLRE-F. Table I. compares the VLRE prototype and WH125-6.

A comparison of the performance contour curves for the VLRE-T and VLRE-F modes is shown in Fig. 11. Just as the effective compression ratio and effective displacement were much greater, so the performance of VLRE-F was better than that of VLRE-T.

However, this did not conflict with the purpose of getting the best engine load rate by mode switching. The main working speed range of VLRE-T was less than 4000 r/min, typical for high torque working conditions, so the lower engine speed and higher hour fuel consumption restricted its power and specific fuel consumption performance.

TABLE I.COMPARISON OF VLRE PROTOTYPE AND WH125-6 PARAMETERS

Parameters		WH125-6	VLRE-F	VLRE-T
V_s (L)		0.1248	0.1248	0.0948
D (mm)		52.4	52.4	52.4
S (mm)		57.9	57.9	57.9
S-H_e (mm)		57.9	57.9	43.9
ε		9.0	7.1 ~ 9.0	>7.1
Cylinder compression Pressure(MPa)		1.18	1.01	0.68
Piston ring pin		□	√	√
Camshaft		One-piece	Assembled	Assembled
Intake cam		Single-hump	Single-hump	Double-hump
Exhaust cam		Single-hump	Single-hump	Non-hump
Valve timing or Port timing	IVO	BTDC 35° CA	BTDC 43° CA	BBDC 46° CA
	IVC	ABDC 59° CA	ABDC 51° CA	ABDC 86° CA
	EVO	BBDC 70° CA	BBDC 70° CA	Closing
	EVC	TDC 34° CA	TDC 34° CA	Closing
	EPO	Closing	Closing	BBDC 67° CA
	EPC	Closing	Closing	ABDC 67° CA
Roots type super-charger		□	□	√

VLRE-T realised the scavenging process by using the engine to drive the roots supercharger. The test data subtracted the power loss of the driving roots supercharger. Fig. 10 shows the engine bench test platform.

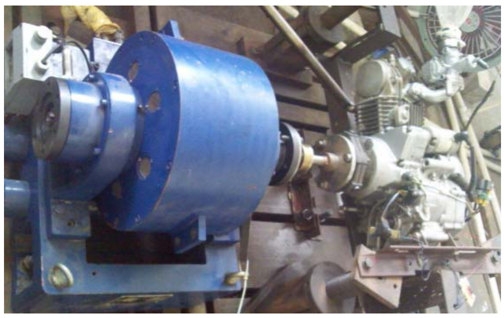

Fig.10 Engine Bench Test Platform

However, the two-cycle operating modes of the VLRE were all smooth running, with stable performance in respective testing speed ranges. The mapping characteristics of VLRE-T are shown in Fig. 12, which reveals better performance during the medium- and high-load rate speed intervals.

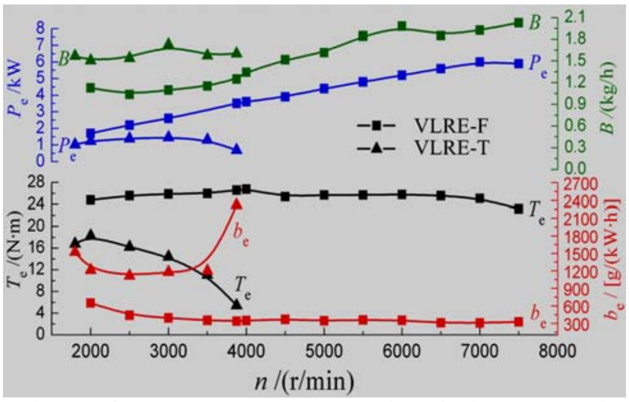

Fig.11 Performance Contour Curve Comparisons for the VLRE-T and VLRE-F Modes

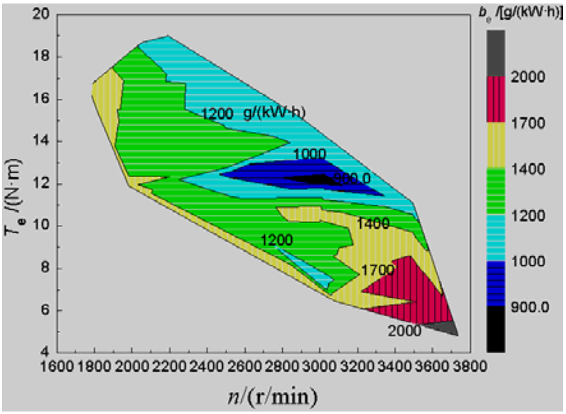

Fig.12-a VLRE-T Mode Mapping Characteristics of Specific Fuel Consumption

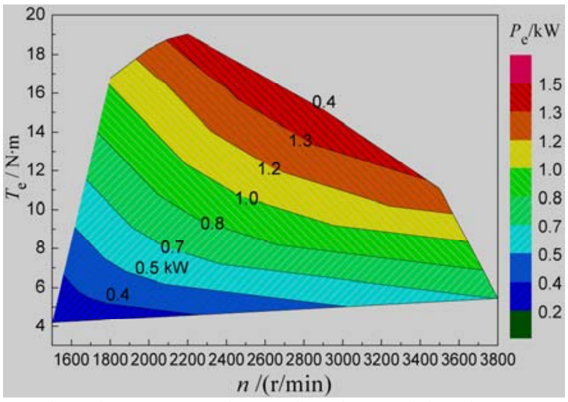

Fig.12-b VLRE-T Mode Mapping Characteristics of Power

The mapping characteristics of VLRE-F are shown in Fig. 13. The characteristic distribution was basically the same as that for WH125-6, but the maximum power and torque were lower due to the reduced compression ratio and changed cylinder flow field, which were caused by the cylinder exhaust port. There was better performance at the medium- and high-load rate speed intervals.

To achieve VLRE mode switching control for continuously working in the optimal load rate interval, a comparative analysis of the various working conditions and load rates for the two VLRE modes at the same working speed range was needed. This ensured that the VLRE could work in the high-load rate mode most of the time.

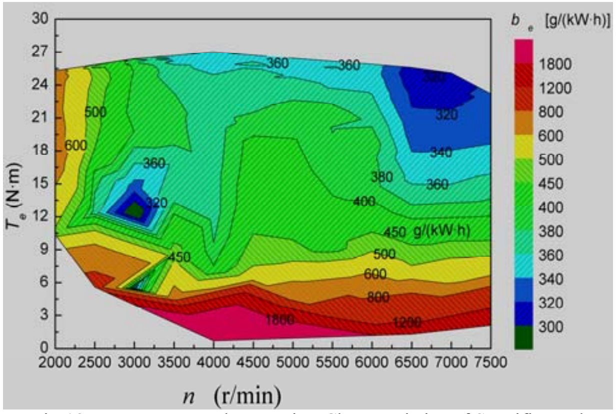

Fig.13-a VLRE-F Mode Mapping Characteristics of Specific Fuel Consumption

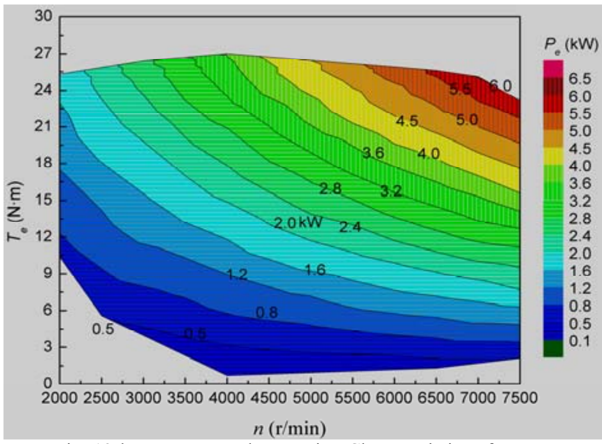

Fig. 13-b VLRE-F Mode Mapping Characteristics of Power

Table II. shows the bench test data for WH125-6 and the two VLRE operating modes at a maximum torque speed of 2000 r/min and a maximum power speed of 3000 r/min for VLRE-T. The VLRE-F performance was very close to that of H125-6 at the two speeds, which met the design objective. At 2000 r/min, the power and torque of VLRE-T were about 75% of that exhibited by VLRE-F, but the power per litre (P_e / V_s) and torque per litre (T_e / V_s) were basically the same. Likewise, the specific fuel consumption of VLRE-F was 75% of that of VLRE-T. At 3000 r/min, the power and torque for VLRE-T were about 56% of that for VLRE-F, but the power and torque per litre of VLRE-T were about 74% of those of VLRE-F, and the specific fuel consumption of VLRE-F was 34% of that of VLRE-T. The test results indicate that while VLRE-T fuel economy requires further improvement, the feasibility of VLRE is proven in that it achieved cycle mode switching control with the optimal load rate target at medium and low speeds all of the time.

TABLE II.COMPARISON OF VLRE AND WH125-6 PARAMETERS

Engine mode	Engine speed (r/min)	Power (kW)	Power per litre (kW/L)	Torque (N·m)	Torque per litre (N·m/L)	Specific fuel consumption [g/(kW·h)]
WH125-6	2000	1.74	13.9	25.6	205.13	650.1
VLRE-F	2000	1.72	13.6	24.8	198.72	652
VLRE-T	2000	1.31	13.71	18.3	193.04	1216
WH125-6	3000	2.71	21.71	27.4	219.55	394
VLRE-F	3000	2.63	21.03	25.9	207.53	398
VLRE-T	3000	1.5	15.82	14.5	152.95	1182

In the primary stage of VLRE fundamental research regarding the feasibility of experimental verification, the performance of VLRE-T reached the same displacement level as a two-stroke engine. The successful completion of the VLRE bench testing proves the validity and feasibility of the VLRE design. The VLRE mode can be dynamically changed according to different working conditions to ensure that it always achieves better load rate intervals.

VI. CONCLUSIONS

(1) A new engine, the VLRE, with a variable load rate function is designed based on the structure of a four-stroke engine. The VLRE possesses three thermodynamic cycle operating modes: a two-stroke mode called VLRE-T, a four-stroke mode called VLRE-F and a six-stroke mode called VLRE-S.

(2) The VLRE possesses continuous interval cycle power frequencies of 1/2, 1/3 and 1/4.

(3) The VLRE achieves a variable effective compression ratio by changing its effective stroke volume and not changing the combustion chamber volume to improve engine reliability.

(4) The VLRE's variable cam profile mechanism is established, and the optimal mode switching time is determined when near the compression TDC.

(5) Engine bench test results prove the feasibility of the VLRE design, which can achieve cycle mode switching control with the optimal load rate target at medium and low speeds.

CONFLICT OF INTEREST

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

ACKNOWLEDGMENT

This work is supported by National Natural Science Foundation of China (Grant No. 51406174), Natural Science Foundation of Hebei Province (Grant No. E2014203066), and Doctoral Foundation of Yanshan University (Grant No. B786).

REFERENCES

[1] SUGIYAMA T, HIYOSHI R, TAKEMURA S, et al. "Technology for improving engine performance using variable mechanisms". SAE Technical Paper, pp;01-1290.2007

[2] JACOBS T J. Developments in internal combustion engines. Fossil Energy: Springer New York, pp;149-219.2013

[3] AKIHISA D, DAISAKU S. "Research on improving thermal efficiency through variable super-high expansion ratio cycle". SAE Technical Paper, 2010.

[4] YEOM K, JANG J, BAE C. "Homogeneous charge compression ignition of LPG and gasoline using variable valve timing in an Engine". Fuel, 86(4): 494-503.2007

[5] FOUTANA G, GALLONI E. "Variable valve timing for fuel economy improvement in a spark-ignition engine". Applied Energy, 86(6): 96-105.2009

[6] XIA Huaicheng. Design theory and critical technical research on variable load rate reciprocating internal combustion engine[Ph.D. thesis]. Yanshan University, 2014. (in Chinese)

[7] FLIERL R, Klüting M. "The third generation of valve trains-new fully variable valve trains for throttle-free load control". SAE Technical Paper, pp;01-1227.2000

[8] BEGG S M, HINDLE M P, COWELL T, et al. Low intake valve lift in a port fuel-injected engine. Energy, 8(26): 1-9.2008

[9] HANNIBAL W, FLIERL R, STIEGLER L, et al. "Overview of current continuously variable valve lift systems for four-stroke spark-ignition engines and the criteria for their design ratings". SAE Technical Paper, pp: 01-1263.2004

[10] CONSTANZO V S, HEYWOOD J B. "Mixture preparation mechanisms in a port fuel injected engine". SAE Technical Paper,pp: 02-2080.2005

[11] BAN Zhibo, XIE Hui, HE Yu. "Energy consumption on a variable valve actuating system of gasoline engine". Journal of Tianjin University(Science and Technology), 47(8): 665-671. 2014(in Chinese)

[12] HAN Zongqi. Study on the technology and application about variable power displacement of car engine[Ph.D. thesis]. Yanshan University, 2010. (in Chinese)

[13] WANG Jianxin. "Technology progress in high efficiency gasoline engine for vehicle". Transactions of CSICE, , 26(suppl): 83-89. 2008(in Chinese)

[14] JEHAD A A Y, MOHAMMAD H D. "Performance simulation of a four-stroke engine with variable stroke-length and compression ratio". Applied Energy, 77(4): 447-463.2004,

[15] CUI Biao, CHANG Siqin, LI Zifei. "Discussion on spark-ignited variable compression ratio engine". Internal Combustion Engines, 8: 39-42. 2011,(in Chinese)

[16] KUTLAR O A, ARSLAN H, CALIK A T. "Methods to improve efficiency of four stroke spark ignition engines at part load". Energy Conversion and Management, 46: 3202-3220.2005,

[17] SUN Changlin, ZHU Yan, XIE Zongfa. "Analyze and study on

present situation of variable compression ratio engine". I.C.E&Powerplant, 129: 52-54. (in Chinese)2012

[18] FLIERL R, SCHMITT S, HANNIBAL W. "First test results of a 1-cylinder engine with variable compression ratio, fully mechanically variable inlet and exhaust valve actuation". SAE Technical Paper, pp: 01-1836.2009

[19] HIYOSHI R, AOYAMA S, TAKEMURA S, et al. "A study of a multiple-link variable compression ratio system for improving engine performance". SAE Technical Paper, 2006: 01-0616.

[20] RICARDO. "Engine uses two and four stroke". Professional Engineering, pp:9- 55. 2008

[21] RICARDO. "Different strokes for different folks-the 2/4 sight concept". Vehicle Technology, 2006, 7: 13-15.

[22] BACCILE A, CECCARINI D, CHENG L, et al. "An innovative control system for a 2/4 stroke switchable engine". SAE Technical Paper, pp: 01-1199. 2007

[23] FANSLER, TODD D, et al. "Invited Review: Combustion instability in spray-guided stratified-charge engines: A review". International Journal of Engine Research,16(3): 260-305. 2015,

[24] ZHENG Zhaolei, TIAN Xuefeng, ZHANG Xiayu. "Effects of split injection proportion and the second injection time on the mixture formation in a GDI engine under catalyst heating mode using stratified charge strategy". Applied Thermal Engineering, 84: 237-245.2015 (in Chinese)

[25] MOMENIMOVAHED A. "Particle number emission factors and volatile fraction of particles emitted from on-road gasoline direct injection passenger vehicles". Atmospheric Environment, pp:105-111.2015

[26] RA Y, REITZ R D. "The application of a multicomponent droplet vaporization model to gasoline direct injection engines". International Journal of Engine Research, 2003, 4(3): 193-218.

[27] DI Liming, YANG Chunjing, ZHAO Yongsheng. "Mathematical model for closed-form solution of parameters of cylinder exhaust port in variable-stroke engine". Advanced Materials Research, pp: 97-101: 2724-2727.2010

[28] DI Liming, XIA Huaicheng, LI Wenyue, et al. "Study on simulation and optimization of engine valve timing". The International Conference on Mechanic Automation and Control Engineering, Wuhan, China, June, pp: 23-26.2010

[29] DI Liming, LI Wenyue, XIA Huaicheng, and ZHAO Yongsheng. "Distribution device optimization of variable-cycle engine based on comprehensive performance evaluation in all speed". Journal of Mechanical Engineering, 48(18): 117-123. 2012, (in Chinese)