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Research Paper

Comparative study on the pumping losses between continuous variable valve lift (CVVL) engine and variable valve timing (VVT) engine

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HIGHLIGHTS

- The gross IMEP is approximately proportional to engine cylinder pressure at BDC.
- The mechanism and influence factors of intake loss in CVVL and VVT engines were compared.
- The theoretic limitations of engine intake loss were deduced.
- The suggestions were proposed for CVVL engine to approach the theoretical minimum pumping loss.
- The BSFC of CVVL engine can be further reduced by more than 20%.

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ABSTRACT

VVL and VVT are two common approaches to reduce engine pumping loss at part loads, however, the comparative study on their potentials and influence factors of pumping loss reduction is scarce. In this paper, the gas exchange processes of CVVL and VVT engines were investigated by bench testing. The mechanism and influence factors of pumping loss in the two types of engines were comparatively analyzed, the theoretic limitations of pumping loss in intake process were deduced and the suggestions to approach the theoretic minimum were proposed. The results show that the gross indicated mean effective pressure (IMEP) of engine is approximately proportional to cylinder pressure at bottom dead center (BDC) for both traditional throttle control strategy and early intake valve closing (EIVC) strategy. The difference of pumping losses between CVVL and VVT engines results from intake process. Due to the differences of intake modes, the CVVL engine has lower intake loss than VVT engine by nature. The pumping loss in intake process of CVVL engine is much closer to the theoretical minimum, and the BSFC of CVVL engine can be reduced by more than 20% at 2000 r/min and 2.3 bar IMEP by increasing the maximum lift of intake valve. All these have provided guidance for pumping loss reduction of gasoline engine.

1. Introduction

With the situation of global energy crisis and environment pollution becoming increasingly severe, it is imperative to improve the energy efficiency by various advanced technology such as high-efficient combustion and waste heat recovery [1–4]. As one of the most commonly used energy equipment, gasoline engines have attracted increasing attentions on its fuel efficiency. It is well known that gasoline engines for passenger cars often work at low to medium speeds and part loads [5,6]. Therefore, the thermal efficiency of gasoline engine at part loads is the decisive factor for the fuel economy of vehicle. However, it is usually very poor at part loads, one of the main reasons is the high pumping loss under these conditions [7,8]. For a stoichiometric operation gasoline engine, its working load is regulated by throttle valve. At part load, the pumping loss of gasoline engines is more obvious due to the pressure loss at throttle valve [9]. According to the previous studies on energy balance for gasoline engine [6,10], pumping loss accounts for about 8% of total fuel energy under FTP-75 cycle, and this proportion is larger than 10% under idling and deceleration conditions. Due to the above reasons, the pumping loss of gasoline engine at part loads has attracted increasing attentions from both scientists and engineers.

It is well known that VVT has a stronger influence on the gas exchange process of engine, which is considered to be of capacity to

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Nomenclature

Const	constant [–]
H_u	low heating value [kJ/kg]
V	cylinder volume [L]
V_h	cylinder displacement [L]
P	cylinder pressure [bar]
P_{in}	intake pressure [bar]
P_{BDC}	cylinder pressure at BDC [bar]
k	adiabatic exponent [–]
η_e	effective thermal efficiency [–]
η_N	net indicated thermal efficiency [–]
η_M	mechanical efficiency [–]

Abbreviations

CVVL	continuous variable valve lift
VVT	variable valve timing
IMEP	indicated mean effective pressure
FMEP	friction mean effective pressure
NMEP	net mean effective pressure
BMEP	brake mean effective pressure
PMEP	pumping mean effective pressure
IVC	intake valve closure
BDC	bottom dead center
TDC	top dead center
EGR	exhaust gas recirculation
MVL	maximum valve lifts
SI	spark ignition
GDI	gasoline direct injection
BSFC	brake specific fuel consumption
ISFC	indicated specific fuel consumption
EIVC	early intake valve closing
RGF	residual gas fraction
PD	proportional-derivative
NOx	nitric oxides
IVO	intake valve open

reduce the pumping loss and improve engine performance [11–13]. Lots of previous studies were carried out on the influences of valve timing and lift on gas exchange process and in-cylinder air motion of engine [14–16]. Deng et al. [17] investigated the sensitivities of valve timing on a high-speed spark-ignition (SI) engine fueled with butanol blend fuel, and claimed that the effects brought by VVT were more obvious at partial loads and low speeds (or moderate speeds, depending on the operating speed range of a specific engine) than those at full load and high speeds. As for the influences of valve timing on engine performance, Leroy et al. [18] proposed a model of in-cylinder air mass and residual gas fraction of a turbocharged spark-ignition (SI) engine with VVT actuators. VVT devices were used to produce internal EGR at part load, providing beneficial effects in terms of fuel consumption and exhaust emission [19,20]. Fontana et al. [21] discussed the potential of fuel economy improvement in a small SI engine through a simple VVT system, and claimed that VVT system is a useful system in optimizing both torque delivery and fuel consumption at part loads. Atashkari et al. [22] conducted the multi-objective optimization on a VVT SI engine using polynomial neural networks and evolutionary algorithms. Through their research, some interesting and informative optimum design aspects have been revealed for the VVT engine with respect to the control variables of engine speed and valve timing.

However, there still exist some disadvantages in current VVT technologies. On one hand, VVT can only change the valve opening (or closing) time without the ability to change the valve opening duration. On the other hand, it is unable to adjust the valve lift. Thus, the effect of VVT on the gas exchange performance of engine especially the pumping loss reduction is also very limited. In recent years, the emergence of VVL mechanism provides another effective way to reduce the pumping loss of engine [23]. By using VVL technology, both the timing and lift of valve can be adjusted neatly according to engine operating conditions, and thus the gas exchange process as well as engine performance can be improved. The application of VVL technology also leads to the variation of regulation mode of engine load. With the VVL technology employed, the engine load (actually, it is the intake gas mass) can be adjusted by changing the intake valve lift and thus the throttle can be removed, which is beneficial to reduce the pumping loss caused by throttle valve.

Due to the above disadvantages in VVL, lots of scholars have done tons of researches on influences of VVL on engine performance from various aspects [24–26]. Hu et al. [27] proposed a CVVL mechanism for a diesel engine, and demonstrated that the VVL mechanism is effective and reliable for realizing continuous VVL in engines by experimental results. Flierl et al. [28] designed a fully variable valve lift and timing system for a four-cylinder gasoline engine. By using this system, it was possible to improve fuel consumption of engine by up to 13% compared with the identical basic engine. Kreuter et al. [29] studied the strategies to improve SI engine performance by means of variable intake lift, timing and duration. The investigations showed that additional efforts are necessary to convert the potential of minimized pumping losses due to unthrottled SI-engine load control into reduced fuel consumption and good drive ability. Wang et al. [30] investigated the in-cylinder tumble flow characteristics with reduced maximum valve lifts (MVL). This experimental work was conducted in a modified four-valve SI test engine with optical methods for measuring in-cylinder air motion in the vertical direction, and the results showed lower MVLs result in higher values including higher total kinetic energy and higher fluctuating energy [31]. Furthermore, the vortex centres results demonstrated lower MVLs could enhance cycle-to-cycle variation due to the weakened tumble vortex [32]. As a result, it is necessary to manage strong tumble or other bulk flow (such as swirl flow) in order to improve the stability of ignition and combustion for GDI engines with VVL, especially at the lower MVL conditions [33].

Moreover, the relations between combustion and pumping loss in VVT/VVL engines were also concerned by lots of scholars [34,35]. In Ref. [17], the effects of valve timing on both the pumping loss and combustion were well summarized. VVT strategies have a stronger influence on gas exchange process of engine, including RGF, volumetric efficiency, pumping loss, density of charge, and the unburned gas temperature, which in turn influences the combustion process. For a specific operating condition, the lower pumping loss usually corresponds to the lower RGF, which is conducive to accelerate the combustion velocity. Cinar et al. [36] demonstrated that combustion is retarded with low lift cams due to more trapped residual gas, while the trapped residual gas has an obvious influence on pumping loss. As summarized in Ref. [37], late IVC strategy leads to a noticeable delay in ignition timing by decreasing the effective compression ratio over all the operating range, and it is also a very effective approach for NOx emission reduction in the whole operating range.

Although there are lots of previous studies on the effects of VVT on gasoline engine performance, the research on the quantitative relations between pumping loss and its influence factors in VVT engine is still less. Moreover, even though VVL technology is relatively mature and has been applied in many advanced gasoline engines, the previous work on the theoretical limitation of pumping loss reduction and fuel economy improvement through VVL is still less, let alone quantitative analysis on the influence mechanism of VVL on engine gas exchange process. Meanwhile, the authors failed to find a similar study about the comparison between VVL and VVT on pumping loss reduction and fuel