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Experimental investigation on the influences of exhaust gas recirculation coupling with intake tumble on gasoline engine economy and emission performance

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ABSTRACT

To improve the economy and emission performance of gasoline engine under part load, the approach of exhaust gas recirculation coupling with intake tumble was investigated by bench testing. Based on a naturally aspirated gasoline engine, the sweeping test of exhaust gas recirculation rate was conducted in two intake modes (with/without intake tumble), and the parameters related to engine heat-work conversion process and emission performance were measured. Through comparing and analyzing the measured data, the effects of exhaust gas recirculation coupling with intake tumble on gasoline engine economy and emission performance were revealed. The results show that pumping loss decreases gradually while in-cylinder residual gas fraction increases linearly with the exhaust gas recirculation rate increasing; the high-pressure cycle efficiency ascends with exhaust gas recirculation rate increasing due to the decrease of heat transfer loss and exhaust gas energy loss. Thus, the improvement of indicated thermal efficiency is the superposition of double benefits of low-pressure cycle and high-pressure cycle. At 1600 r/min and 2.94 bar, the indicated thermal efficiency can be increased by 4.29%. With the increase of exhaust gas recirculation rate, nitrogen oxide emissions almost fall linearly, but hydrocarbon and carbonic oxide emissions have no obvious change in the effective range of exhaust gas recirculation rate. The biggest advantage of intake tumble is that it can extend the effective range of exhaust gas recirculation rate. As a result, the potential of energy conservation and emission reduction of exhaust gas recirculation is largely improved.

1. Introduction

Due to the multiple advantages, such as high specific power, low noise and vibration, gasoline engine has been widely used as the power source of automobile. In China, about 80% of automobiles take the gasoline engine as power. Owing to the increasing energy crisis and environment pollution, energy conservation and emission reduction have become an important development strategy in the world [1]. Therefore, to promote the fuel economy and emission performance of gasoline engine is not only the requirement of energy conservation and emission reduction, but also the demand for the survival of traditional gasoline engine [2]. Only by continuously improving the combustion and emission performance of gasoline engine, can the traditional gasoline engine continue to hold the leading position in the future transportation [3]. To achieve these goals, a lot of experts and scholars have made unremitting efforts in the last few decades [4].

Generally, the effective thermal efficiency of current gasoline engine is relatively low especially under part load. From the analysis of gasoline engine thermal balance [5], one can see that the thermal efficiency is very low in low-load operating conditions. The main reasons come from two aspects. On one hand, gasoline engine has to suffer a higher throttling loss under part load, which brings a negative impact on the engine thermal efficiency since part of effective work is consumed to overcome the throttling loss [6]. On the other hand, the combustion duration of mixture gas becomes longer under low load [7], and it leads to the bad heat-work conversion efficiency of gasoline engine. Furthermore, for the automotive gasoline engine, in most situations it operates under part load rather than wide open throttle (WOT) conditions [8]. Therefore, to improve the thermal efficiency of gasoline engine under part load operating conditions is of great practical significance for automobile energy saving.

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Nomenclature

α_k	flow coefficient [–]
$\dot{m}$	mass flow rate [kg/s]
$\dot{V}$	volume flow rate [m^3/s]
P	pressure [bar]
T	gas temperature [K]
R_g	gas constant [J/(kg·K)]
A_K	piston area [m^2]
ρ_s	gas density [kg/m^3]
D	bore diameter [m]
c_S	gas flow velocity [m/s]
P_1	upstream pressure [bar]
P_2	downstream pressure [bar]
κ	isentropic exponent [–]
T_R	tumble ratio [–]
c_T	linear rotational speed [m/s]
n	paddle wheel speed [m/s]
D_{MFL}	mean paddle wheel diameter [m]
$\dot{Q}$	energy flow [kJ]
c_P	constant-pressure specific heat [kJ/(kg·K)]
σ	standard deviation [–]
N	cycle number [–]
R_{EGR}	EGR rate [%]
m	mass [kg]
V_h	displacement [L]
η	efficiency [%]
H_u	low heating value [kJ/kg]

Subscripts

air	air
HP	high pressure
eff	effective
exh	exhaust
int	intake
fue	fuel
coo	coolant
out	outlet
in	inlet
act	actual
the	theoretical
cyl	cylinder
std	standard state

Abbreviation

EGR	exhaust gas recirculation
NA	naturally aspirated
WOT	wide open throttle
RGF	residual gas fraction
PMEP	pumping mean effective pressure
NMEP	net mean effective pressure
IMEP	indicated mean effective pressure
TDC	top dead center
MFB	mass fraction burned
COV	coefficient of variation
SI	spark ignition
NOx	nitrogen oxide
HC	hydrocarbon
CO	carbonic oxide

Since exhaust gas recirculation (EGR) can effectively reduce the pumping losses of gasoline engine under part load, it became another energy saving technology for gasoline engine and attracted much attention in recent years [9]. As is well known, EGR is a common technique for IC engine combustion control and emission reduction [10]. A large number of studies demonstrate that EGR can effectively reduce the combustion temperature, thus it can restrain the generation of nitrogen oxide (NO_X) [11]. For this reason, EGR plays an increasingly important role in engine combustion and emission control technology. Ivanič et al. [12] investigated the effects of hydrogen enhancement on efficiency and NOx emissions of lean and EGR-diluted mixtures in a spark ignition (SI) engine, and concluded that the effect of EGR at equal dilution on NOx is substantially greater than the effect of excess air. Grandin and Angström [13] stated that both lean homogeneous operation and cooled EGR are possible replacements of fuel enrichment, and the cooled EGR allows the use of a three-way catalytic converter at all operating conditions, resulting in substantially lower tailpipe emissions of carbonic oxide (CO) and hydrocarbon (HC) compared to rich operation. Cairns and Blaxill [14] investigated the effects of combined internal and external exhaust gas recirculation on gasoline controlled auto-ignition. They found that introducing additional external exhaust gas can retard ignition, reduce the rate of heat release and limit the peak knocking pressure. Mardi et al. [15] conducted a numerical investigation on the influence of EGR in a supercharged SI engine fueled with gasoline and alternative fuels, and stated that 10% of EGR is the most desirable amount from the viewpoint of emissions and power. Papagiannakis [16] studied the effects of EGR and air inlet preheating on engine emission and performance, and demonstrated that combination of EGR and air inlet preheating could reduce BSFC and CO without NO increase. Abd-Alla [17] made a review on the potential of EGR to reduce the exhaust emissions, particularly NOx emissions, and to delimit the application range of this technique. In recent years, EGR was commonly used also in gasoline engines together with other advanced techniques [18]. Tang et al. [19] studied the influences on combustion characteristics and performance of EGR vs. lean burn in a gasoline engine, and revealed the theoretic potential and practical limitations on pumping loss reduction via in-cylinder dilution in a SI engine. Zhang et al. [20] investigated the influence of EGR and oxygen-enriched air on diesel engine NO-Smoke emission and combustion characteristic, and achieved the optimal NO-Smoke emission at various conditions. Liu et al. [21] studied the effect of EGR coupling lean-burn gasoline engine on NOx purification of lean NOx trap based on experimental research and CHEMKIN software, and analyzed the effect of exhaust gases on NOx deterioration. Bozza et al. [22] studied the potentials of cooled EGR and water injection for knock resistance and fuel consumption improvements of gasoline engines. The presented results highlight that both the solutions involve significant BSFC improvements, especially in the operating conditions at medium engine speeds.

Although lots of studies were carried out on EGR as well as EGR together with other technologies, the existing research mainly focused on the effects of EGR on engine combustion characteristics and emission performance. To the authors' knowledge, the research on the combined effects of EGR coupling with intake tumble on gasoline engine working processes especially the heat balance and in-cylinder RGF is relatively less, and the experimental data about gasoline engine EGR related to tumble flow are still scarce. As a result, the relationships among EGR rate, intake tumble, gas exchange performance, in-cylinder RGF, energy