Effect of Cylinder Air Charge bypass on Combustion Characteristics of Gasoline Engine at Low Load

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Abstract. Enhancing TKE (Turbulent kinetic energy) in cylinder is beneficial to accelerate flame propagation, short combustion duration and improve the thermal efficiency. In order to improve the TKE of the engine under low load, the design of air charge bypass was introduced. Based on Converge, the flow in cylinder of different design schemes was analyzed, and the best scheme was selected for combustion analysis experiment. The results show that there is little effect of bypass inclination angle on the flow, and only swirl is changed by the position of bypass channel, however the increase of the diameter of the bypass channel can significantly improve the tumble, swirl and TKE in the cylinder. Compared to the engine without bypass channel, the thermal efficiency of the engine with bypass channel is increased by 16% under low load (BMEP=2bar and engine speed= 3000rpm).

1. Introduction
The latest fuel consumption laws and regulations began to limit the emission of $CO_2$ from fuel vehicles [1], which put forward higher requirements for the thermal efficiency of engines. When the gasoline engine works at a small load, on the one hand, the small opening of the throttle body will lead to an increase in pumping loss [2], on the other hand, the weak flow in the cylinder will lead to a longer combustion duration and an increase in cycle variation [3], so that the thermal efficiency of the engine will decrease when the load is relatively large. Therefore, it is of great significance to study how to improve the thermal efficiency of gasoline engine under small load for reducing $CO_2$ emission.

Therefore, scholars at home and abroad have put forward many methods to improve the thermal efficiency of gasoline engines under small load. VVT can control the intake air to close early or late, so that the gasoline engine can work at a larger throttle opening under the same load, thus reducing the pumping loss [4]. On the one hand, VVL can directly replace the throttle body to control the load, so as to reduce the pumping loss, on the other hand, it can improve the flow in the cylinder under small load [5], but the cancellation of the throttle body will lead to evaporation and mixing of engine fuel injected in the port [6]. Cylinder deactivation technology can make gasoline engine work at a larger throttle opening under small load, thus reducing pumping loss, but it is difficult to control when the engine works under transient conditions [7].

All of the above methods can improve the thermal efficiency of gasoline engine under partial load, and have been studied and applied in different degrees. However, the application of these technologies
will lead to more complex engine structure and control, which will lead to an increase in production costs. In this work, an intake bypass design is introduced, that is, an intake passage with a smaller diameter is designed at the position near the valve. When the engine works at a small load, the in-cylinder charge mainly enters through the bypass passage, and the airflow speed is significantly improved compared with the intake through the intake passage. Under the sheer force of high-speed airflow, low-speed gas will be driven to form tumble and vortex in the cylinder, which will improve the turbulent kinetic energy in the cylinder during ignition, speed up flame propagation, and improve the isochoric degree of engine combustion process, thus improving thermal efficiency. The application of this method will not have a great impact on the original structure of the engine, but how to design to maximize the turbulent kinetic energy in the cylinder is the focus of this study.

In this work, the in-cylinder flow characteristics and combustion characteristics of a two-cylinder four-valve gasoline engine under different bypass design schemes were studied by numerical simulation and combustion analysis test. The changes of in-cylinder flow and combustion under different bypass design parameters are compared, in order to provide some guiding significance for the design and application of bypass intake.

2. Numerical simulation model and experimental system

2.1. Numerical model
The research object is a two-cylinder four-valve four-stroke gasoline engine, the fuel supply is port injection, the combustion chamber is hemispherical, and the first cylinder of the engine is selected as the research object. See table 1 for main structural parameters of engine.

| Table 1. Engine Specification. |
|--------------------------------|
| Number and arrangement of cylinders | In-line double cylinder |
| Cylinder bore/mm | 67 |
| Stroke /mm | 66.8 |
| Connecting rod length/mm | 113.5 |
| Compression ratio/ | 10.7 |
| Eccentricity of crankshaft/mm | 0.7 mm |
| Intake closing IVC/°CA (ABDC) | 80 |
| Intake air on IVO/°CA (BTDC) | 23 |
| Exhaust shutdown EVC/°CA (ATDC) | 50 |
| Exhaust to open EVO/°CA (BTDC) | 80 |

The flow direction of the bypass pipeline is out of plane with the valve movement direction, and other parameters are controlled by the bypass pipe diameter d, the distance δ from the Y axis and the included angle θ from the X axis. The grid size of the corresponding scheme is controlled between 0.125 mm and 4 mm, and the total grid number is 1,600,000. The design parameters and grid results are shown in Figure 1. In-cylinder flow control equation is composed of gas state equation, mass conservation equation, momentum conservation equation, energy conservation equation and turbulence model equation, among which RNG $k - \varepsilon$ model with compression correction is selected, which has been proved to be better in simulating engine in-cylinder flow in many studies [8]. The wall condition of the model uses the standard wall function.
The parameter values of the design scheme are shown in Table 2. In the GT-Power model, by adjusting the throttle opening, the mixture mass at IVC time in cylinder under different bypass diameters is controlled to be 10mg, so that the intake and exhaust manifold pressures and initial conditions in cylinder under different calculation conditions can be obtained.

### Table 2. Parameters of All Cases.

| Working condition number | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|--------------------------|----|----|----|----|----|----|----|----|
| d/mm                     | 3  | 3  | 3  | 4  | 5  | 3  | 3  | 3  |
| θ/°                      | 11 | 15 | 17.5 | 19 | 17.5 | 11 | 11 | 11 |
| δ/mm                     | 22 | 22 | 22 | 22 | 22 | 22 | 7  | -7.5 |

**2.2. Evaluation of in-cylinder flow of engine**

The whole flow characteristics in engine cylinder are measured by tumble ratio, swirl ratio and turbulent kinetic energy.

Swirl ratio,

\[
S_z = \frac{M_z}{I_z} = \frac{\sum_{\text{cells}} \rho_i V_i (x_i y_i - y_i x_i)}{2\pi \frac{N}{60} \sum_{\text{cells}} \rho_i V_i (x_i^2 + y_i^2)}
\]  

(1)

Tumble ratio (Y-axis),

\[
S_y = \frac{M_y}{I_y} = \frac{\sum_{\text{cells}} \rho_i V_i (z_i x_i - x_i z_i)}{2\pi \frac{N}{60} \sum_{\text{cells}} \rho_i V_i (x_i^2 + z_i^2)}
\]  

(2)
Tumble ratio (X-axis),

\[
S_x = \frac{M_x}{I_x} = \frac{\sum_{i} \rho_i V_i (y_i w_i - z_i v_i)}{2\pi N 60 \sum_{i} \rho_i V_i (z_i^2 + y_i^2)}
\]  

(3)

Turbulent kinetic energy,

\[
k = \frac{\sum_{i} \rho_i V_i (u_i^2 + v_i^2 + w_i^2)}{2 \sum_{i} \rho_i V_i}
\]  

(4)

In this formula, \(N\) is the engine speed, \(u_i, v_i, w_i\) is the velocity component of grid element in x axis, y axis and z axis respectively, and \(\rho_i, V_i\) is the density and volume of grid element respectively.

2.3. Combustion analysis experimental system

After the numerical simulation of in-cylinder flow is completed, the best design scheme is verified by combustion analysis experiment. Combustion analysis experiment system is mainly composed of Schneider electric dynamometer, AVL fuel consumption meter, Kistler piezoelectric pressure sensor, DeweSoft data acquisition, Horiba emission meter, oxygen sensor and temperature sensor. See fig. 2 for the test system.

![Fig 2. Schematic diagram of engine bench test.](image)

During the test, the bypass flow is controlled by the motor. Under different bypass openings, the throttle body is controlled so that the engine BMEP is 2Bar, and then the in-cylinder pressure of 200 engine cycles is taken by the in-cylinder pressure sensor. Finally, the in-cylinder combustion speed is obtained by analyzing the cylinder pressure curve [9].
3. Discussion on numerical simulation and combustion analysis results

3.1. Flow results in cylinder under different designs

Comparing the in-cylinder tumble ratio, swirl ratio and turbulent kinetic energy under different bypass designs, on the one hand, we can determine the influence of various design parameters on the in-cylinder flow and provide guidance for the subsequent engine development and design; on the other hand, we can obtain the best scheme for experimental verification through comparison.

Fig. 3 shows the influence of different bypass inclination angles on in-cylinder flow. The bypass pipe diameter \( d = 3\text{mm} \) remains unchanged, and the bypass Y-axis position \( \delta = 22\text{mm} \) remains unchanged. There is no bypass in the original engine, and the tumble ratio in the engine cylinder is attenuated to zero at 450°CA (near the maximum lift of the intake valve), and the swirl ratio is close to zero in the intake and compression strokes. However, in the case of bypass, the tumble ratio (around Y axis) of in-cylinder flow gradually increases during the intake stroke, and reaches the maximum value of 0.58 at 650°CA. The tumble ratio (around X axis) is very weak with or without bypass. Under the condition of bypass, the swirl ratio gradually increases from intake air to reach the maximum value of 0.65 at 580°CA and maintains to 690°CA (near ignition). Turbulent kinetic energy has the same initial change trend with or without bypass, that is, it continuously rises from the initial intake stage to the maximum valve lift, but then it continuously decreases without bypass. The turbulent kinetic energy with bypass can last for a period of time and then decrease. Finally, the turbulent kinetic energy with bypass is 20% higher than that without bypass at 690°CA (near ignition). On the whole, the bypass inclination has little influence on the in-cylinder flow.

![Fig 3. Cylinder Flow in Different Bypass Pipe Angle.](image-url)
Fig. 4 shows the influence of bypass position on in-cylinder flow. The bypass pipe diameter is kept at \( d = 3 \text{mm} \), and the bypass inclination angle is kept at \( \theta = 11^\circ \). The bypass position has little influence on turbulent kinetic energy and tumble ratio, but has significant influence on swirl ratio. The closer the bypass channel is to the cylinder centerline, the more obvious the attenuation of swirl ratio is. This is because when the bypass channel is far away from the cylinder centerline, the shearing action of high-speed jet drives the nearby low-speed gas to move around the cylinder liner, thus improving the swirl ratio.

![Fig 4. Cylinder Flow in Different Bypass Pipe Location.](image)

Fig. 5 shows the influence of different bypass diameters on in-cylinder flow. The bypass position is kept at \( \delta = 22 \text{mm} \) and the bypass inclination angle is kept at \( \theta = 17.5^\circ \). The increase of bypass pipe diameter can obviously improve the tumble ratio, swirl ratio and turbulent kinetic energy, which is because under the same air intake, the increase of bypass pipe diameter will increase the proportion of high-speed jet gas, strengthen the shearing action of high-speed jet, and thus strengthen the flow in the cylinder.

![Fig 5. Influence of Different Bypass Diameters on In-cylinder Flow.](image)
3.2. Flow field change of the best scheme

According to the comparison of the overall flow index under each scheme, scheme 7 (d=5mm, δ=22mm, θ=17.5°) is the best one. Fig. 6 shows the variation law of turbulent kinetic energy between the scheme (lower part) and the original engine (upper part), from which it can be seen that turbulent kinetic energy is higher on the exhaust side at the initial stage of intake. However, after the intake is completed, the turbulent kinetic energy of the scheme with bypass is higher than that without bypass, and the distribution in the cylinder is more uniform. Near ignition time, the scheme with bypass has higher turbulent kinetic energy near spark plug.
Fig. 7 shows the transformation rule of rolling flow between this scheme and the original scheme. At the initial stage of air intake, the airflow direction of the original engine scheme is the same as that of the piston, but under the bypass scheme, some airflow rotates around the Y axis under the shear action of the high-speed airflow in the bypass channel. After the air intake is completed, the airflow of the original engine scheme is still the same as that of the piston, and the bypass scheme forms an obvious rotation center. Near ignition time, the original engine scheme mainly relies on piston and combustion chamber to form squeeze flow, while the bypass scheme still has obvious rotation.

![Fig 7. Comparison of Tumble.](image)

Fig. 8 shows the variation law of eddy current between this scheme and the original scheme. From intake to ignition, the bypass scheme keeps obvious vortex center, and the original scheme has weak flow.

![Fig 8. Comparison of Swirl.](image)

3.3. Comparison of experimental results of combustion analysis

The numerical simulation results show that the turbulent kinetic energy, tumble ratio and swirl ratio in the cylinder will be significantly improved under the condition of bypass intake at small load of gasoline engine, and will be strengthened with the increase of the proportion of bypass ventilation. The increase of turbulent kinetic energy can accelerate the flame propagation speed and shorten the combustion
duration. Fig. 9 shows the combustion data of the engine under different bypass openings and different ignition angles. It can be seen that with the increase of the bypass opening, the flow velocity in the bypass channel will be obviously increased, and the shearing action of high-speed airflow in the cylinder will be increased, which will promote the formation of tumble flow in the engine cylinder and the improvement of turbulent kinetic energy in the later stage, thus obviously reducing the combustion duration. Although the pumping loss of the engine will increase slightly, the indicated thermal efficiency of the engine has been improved obviously. When the ignition advance angle is 27, the indicated thermal efficiency of the engine with the maximum bypass opening will increase from 25% without bypass to 29%, with a relative increase of 16%. After delaying ignition angle, intake bypass improves engine thermal efficiency more significantly.

Fig 9. Comparison of Combustion Test.

4. Summary
1) Gasoline engine can significantly improve the tumble ratio, swirl ratio and turbulent kinetic energy in cylinder by bypassing intake air at small load.

2) The inclination angle of the bypass channel has no obvious effect on the in-cylinder flow, while the bypass channel is far away from the center line of the cylinder, which can obviously improve the swirl ratio in the cylinder. Increasing the diameter of the bypass channel is beneficial to strengthen the shearing action of high-speed airflow under the same inflation rate, thus better improving the tumble ratio, swirl ratio and turbulent kinetic energy in the cylinder.

3) The increase of turbulent kinetic energy in cylinder can significantly shorten the combustion duration of gasoline engine under small load, thus improving the equivalence of gasoline engine combustion process.
4) The pumping loss will increase slightly under bypass intake, but the combustion duration will be shortened more obviously, and the cycle thermal efficiency of the engine under small load will be improved obviously.

Acknowledgments
Supported by Chongqing Technology Innovation and Application Development Project (CSTC2019JS CX-MSXMX0016).

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