ANALYSIS OF FUEL EVAPORATION FOR PFI GASOLINE ENGINE AT HIGH ENGINE BODY TEMPERATURE

Ma Zongzheng[1], Xu Ping[2], Wang Xinli[1], Yang Anjie[1],Pan Bobo[1], Dong Shaohua[1]

In order to analyze the principles of fuel evaporation for intake-port fuel injection engine (PFI) at high body temperature. The effects of impingement points, injection timing, back flow and injection distance on wall-film evaporation were studied using numerical methods based on the validation of the simulation model. The results show that higher engine body temperature is helpful to fuel evaporation and the influence of those facts on fuel evaporation is changed with the engine body temperature. Compared with other different impingement points, when the impingement point was located at the intake valve can improve the fuel evaporation. It also shows that the injection timing has little effect on fuel evaporation but the back flow can also improve the wall-film evaporation because of high temperature. The effect of distance between the nozzle and impingement point changes with distance and the long distance can also improve the fuel evaporation because of large wall-film distribution area.

Keywords: Gasoline engine; PFI; Engine body temperature; Simulation; Fuel evaporation; Wall-film

1. Introduction

The continuous restrictions on engine emissions have determined the installation of Port Fuel Injection (PFI) on spark ignition (SI) engines to comply with regulations [1-3]. Due to the space limitation the intake port wall-film is inevitable which might be enter the combustion chamber in liquid form from the valve gaps and result in high HC emission and engine performance deterioration.

Brenn et al. [4] measured the temporal and spatial distributions of a pulsed spray in a steady flow rig with a simplified intake port system and the results show that the dynamic behavior of the spray depend on the velocity of the air flow, therefore the evaporation of fuel and subsequent combustion of the air-fuel mixture are also affected with the air flow.

[1] School of Mechanical Engineering, Henan University of Engineering, Zhengzhou, 451191 China

[2] · Collage of Civil Engineering, Henan University of Engineering, Zhengzhou, 451191 China

The effects of injection timing on in-cylinder mixture composition and engine performance were researched by Oliveira [5], which found that injection occurred at the valves closed state resulted in better drivability of the engine and lower concentrations of unburned hydrocarbons compared to injection at the valves open state. Bianchi GM [6] also found that either advance or retard injection timing could be drastically reduced the amount of liquid fuel entering the cylinder during the intake stoke, and advance injection timing can maintain a very good distribution of the air-fuel mixture because of longer time available to mixture in the intake port. Wang X Y [7] simulated the air fuel mixture process in a single engine working cycle of PFI gasoline engine under 3500r/min full load condition and 800 r/min idle conditions with closed valve injection (CVI) mode Using KIVA code, and the results present that both of the two working conditions have similar fuel distribution, but at idle condition there is wall films in the port and parts of the film cannot evaporate totally. However, with the PDA technology Nemecek [8,9] observed the that with open valve injection (OVI) mode, the air flow in the intake port can accelerate fuel droplet's velocity of all sizes, which can reduce the transit time and has the potential improvement of engine transient response. The conclusion of injection timing from Luan Y F shows [10] that CVI mode usually gives a more homogeneous intake charge mixture, and improves combustion quality and reduces emissions, while OVI mode results in portion of the fuel entering into the cylinder by intake charge flow in the same cycle.

There are also some researches focuses on effect of the temperature on fuel evaporation[11]. Almkvist measured the wall-film thickness located at intake port using laser induced fluorescence technique and concluded that the wall-film thickness fall more than 50% when the cooling water temperature rose from 30ºC 90ºC [12].The study from Yukihiro Takahashi et al also shows that the wall-film thickness reduces with increase of coolant temperature[13]. And it also proved by Ji S B that the wall temperature has a very important influence on wall film evaporation rate [14]. Dementhon and Vannobel [15] researched the spray behavior in a transparent intake manifold, and the results indicated that under unsteady flow conditions the injection time has a major effect on spray characteristics. The effects of injection timing on in-cylinder mixture composition and engine performance were also researched by Posylkin [16], which found that injection at the CVI mode resulted in better drivability of the engine and lower concentrations of unburned hydrocarbons compared to injection with the OVI mode.

Meanwhile, it is known from the Stanglmaier experiment that there was wall-film located in the cylinder wall at OVI mode when the fuel particles diameter was measured in a driven engine [17].It also can be concluded from the results of Zughyer that most of the fuel injected into the cylinder in liquid form and might not be evaporated until the ignition which could cause high HC emissions at the OVI mode [18].Therefore, how to reduce the liquid fuel in the cylinder is very important for the PFI gasoline engine no matter which mode is selected. And more studies from Erik showed that relative velocity between the intake air and fuel particles is determined by the engine speed, and only fuel particles with small diameter are significantly accelerated by the intake air when the engine speed is higher than 3000r/min, because the velocity of the intake air is greater than the value fuel particles [19]. And the same conclusion was got from Shi and Cheng who observed the wall-film development process in a mole intake port [20].

For the air cooling motorcycle gasoline engine, its body temperature is generally high. And the effect facts, such as impingement points, injection timing, back flow and injection distance, will have different effect on fuel evaporation at high body temperature. So the changes of influence factors for the fuel evaporation are studied using numerical simulation method in this paper.

2. Simulation mesh and conditions

The model setup and validation can be found from reference [21] and [22] which is not mentioned in this paper.

2.1 Simulation mesh

Simulation is based on the K157 FMI motorcycle engine which is air cooling and the parameters of the engine are listed in table 1.

Table.1

Parameters of the K157 FMI engine

Bore×sroke/mm	Swept volume/mL	Compression ratio	Rated speed /r．min-1
56.5×49.5	124	9:1	7500

In order to simulate the intake and compression process the simulation mesh consists of intake port and cylinder, which is shown in figure 1 and the area of the intake valve is refined. It also should be noted that during the intake stroke the volume of combustion cylinder is changed, then the mesh-moving method is used which simulates the piston moving process.

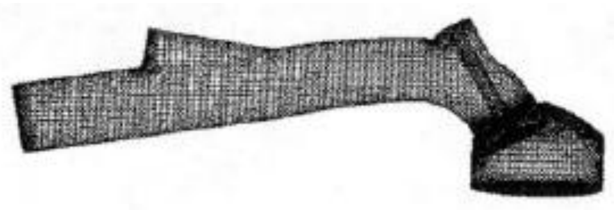


Fig.1 Mesh model

2.2 Simulation conditions

In order to analyze the effects on fuel evaporation, the engine speed, fuel injection pressure remains constant. And the initial and boundary condition are listed in Table 2 and the combustion chamber temperature is set as 130ºC based on the real engine temperature.

It should be noted that the top dead center of intake stoke is defined as 360ºCA and the residual gas temperature is set as the same for simplicity and fuel injection pulse width remains 2.5ms whose mass is 2.63mg for different throttle opening, despite there are different at real operating condition.

Tab.2 Initial and boundary conditions

Contents	Parameters	Value
Boundary conditions	Intake-port temperature	80º C
	Intake valve temperature	120º C
	Chamber temperature	130º C
	Intake air flow	Mass flow
Initial conditions	Intake port	Temperature10º C,Pressure100kPa
	Chamber	Temperature 800º C, Pressure 100kPa
	Engine speed	1000r/min

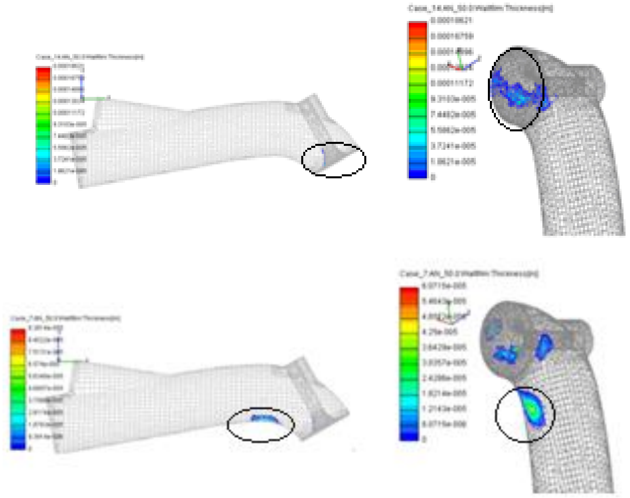
3. Analysis of influence factors for the fuel evaporation at high body temperature

For the PFI engine, there are two types of injection mode, CVI mode and OVI mode. The CVI mode is used to describe the fuel injection completed at closed valve condition while the OVI mode is used to describe fuel injection partly completed at open valve condition.

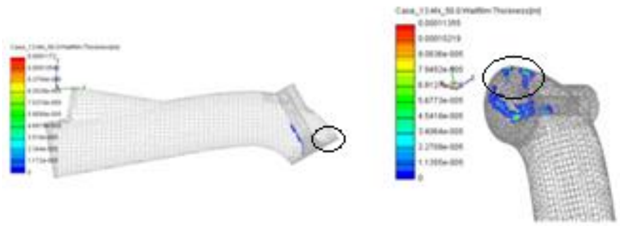
It is known that the fuel evaporation include the fuel evaporation during the injection process (can be called space evaporation) and the wall-film evaporation. From the reference [15] it can be found that the space evaporation can be negligible at the CVI mode. So the space evaporation is not considered during the analysis and only the wall-film evaporation is considered because of the CVI mode is used in the analysis.

3.1 Effect of impingement points on fuel evaporation

The impingement points for analysis are shown in figure 2 which is (a) the back of the intake valve, (b) the bottom of the intake port and (c) the upper junction of the back of the intake valve and the bottom of the intake port. It is should be noted that the nozzle position is fixed and the start of injection timing(SOI) is 40 ºCA.



(a) Back of the intake valve (b) Bottom of intake port



(c) Upper junction

Fig.2 Comparison of impingement points

The comparison of wall-film evaporation for different impingement points can be seen in figure 3. It can be concluded that the there is a rapid increase of fuel evaporation at about 60°CA and the minimum value appears when the impingement point is at the bottom of intake port which the value can be reached 1.76mg at 700°CA . While the evaporation value of the upper junction of the back of the intake valve and the bottom of intake port is 2.45 and 2.35mg respectively at 700°CA.

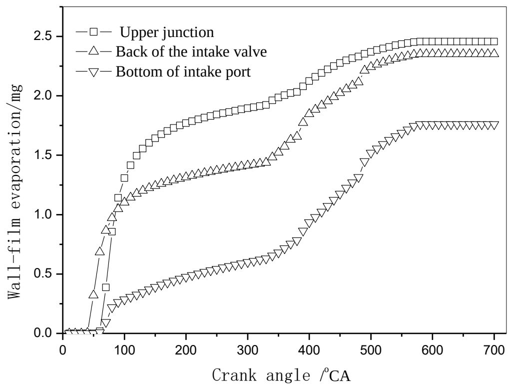


Fig.3 Comparison of wall-film evaporation at different impingement points

The reason can be got in figure 4 which is the comparison of the wall-film thickness of different impingement points. It can be seen from the figure that there is relative small wall-film thickness when the impingement point is the upper junction of the back of the intake valve and the bottom of the intake port respectively. Then a larger amount of wall-film evaporation can be got because of small wall-film thickness can improve the wall film evaporation because of significant interaction between the intake airflow and wall film. However, when the impingement point is the bottom of the intake port, the wall-film distribution area is small and the temperature of the intake port wall is also lower than the intake valve. So the wall film evaporation became difficult and the amount of wall film evaporation is small.

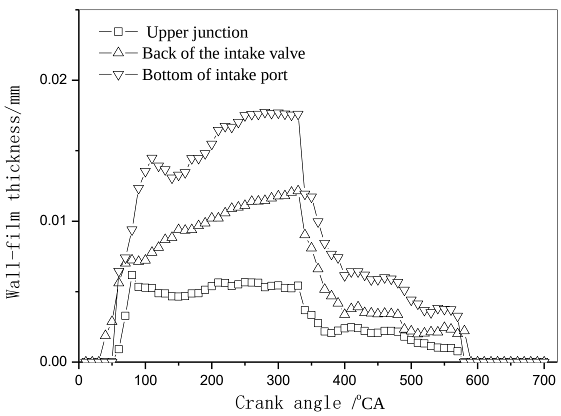


Fig.4 Comparison of wall-film thickness at different impingement points

3.2 Effect of injection timing on fuel evaporation

In order to analyze the effect of injection timing on fuel evaporation, the SOIs were set as 20ºCA, 40ºCA and 60ºCA respectively.

Figure 5 is the wall film evaporation mass comparison chart of different SOI. It can be found from the figure that the wall film evaporation mass is nearly 2.35mg for different SOI. From the before analysis [16], it can be found that the wall film evaporation depends on the heat absorbing and interaction between the wall-film and intake air. For the CVI mode the influence of the interaction between the wall films is the same and the difference comes from the heat absorbing. When the injection time retards the fuel evaporation time becomes shorter and the heat absorbed from the intake port wall will decrease. However, when the engine body temperature is high the influence will be decreased for the heat absorbing. So it can be concluded that the high body temperature can reduce the influence of the SOI on the wall film evaporation can be even ignored.

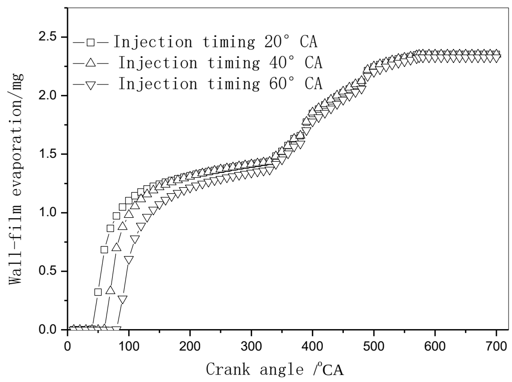


Fig.5 Comparison of wall-film evaporation at different injection timing

3.3 Effect of back flow on fuel evaporation

Backflow is the process of the air fuel mixture with high temperature and pressure return to the intake port at the beginning of the intake stroke which has important effects on fuel evaporation especially on the wall film evaporation. Figure 6 shows the comparison of wall film evaporation with and without back flow.

It can be observed that there is a rapid increase of wall film evaporation at the beginning of fuel impingement and there is another rapid increase when the intake valve is opening .And the value can be reached to 2.3mg at the ignition time considering the back flow. But the value is only 2.2mg without backflow at the ignition time despite the rapid increase is also appearing.

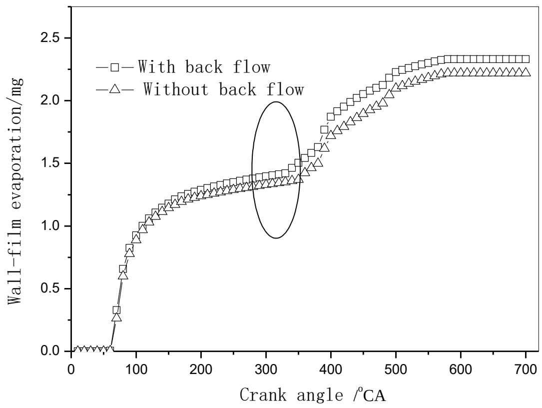


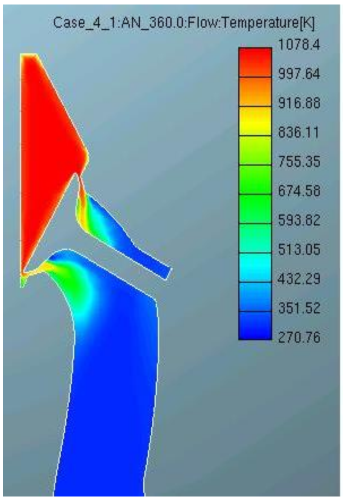
Fig.6 Comparison of wall-film evaporation with and without back flow

As we know that the wall film evaporation is affected by surrounding temperature. From the figure 7 which shows the temperature field with and without back flow at 360º CA it can be revealed that the temperature is relative high with back flow. And the wall-film evaporation mass $\dot{m}$ can be calculated using the following equation.

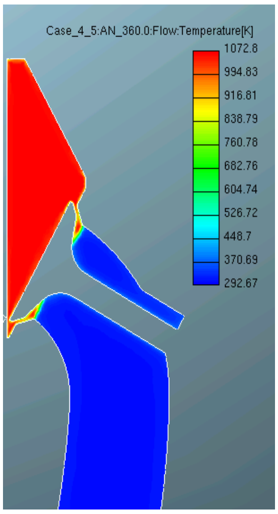
$$\dot{m} = \left[\frac{\rho_v (D_{12} + D_t)}{1 - c_I} \right] \frac{\partial c}{\partial y} (kg / sm^2)$$

Where, the $\frac{\partial c}{\partial y}$ is concentration gradient which is decreased with the fuel saturation increase; the D_{12} is interface diffusion coefficient which is decreased with the temperature decrease; the D_t is the turbulent diffusion coefficient; the c_I is the concentration; the ρ_v is the fuel gas density.

As soon as the fuel reaches the port wall, the fuel saturation is almost the same because of lack of fuel evaporation and the wall film evaporation rate is also the same. But when there is back flow, the hot gas will back to the intake port and it will increase the heat conduction through the heat absorbing. So the back flow can improve the wall-film evaporation.



（a）With back flow



（b）Without back flow

Fig.7 Wall-film distribution and temperature field at 360°CA

3.4 Effect of injection distance on fuel evaporation

Fig. 8 is the comparison of wall film evaporation with the increase of crank angle when the impingement point is the back of the intake valve and the injection distance is 100mm and 60mm respectively. In order to ensure the fuel reaches the wall at the same time the injection timing postponed 10°CA when the injection distance is 60mm. It can be seen that wall-film evaporation is 2.50mg and 2.35mg respectively for different injection distance at the ignition time.

Then reason can be got from the figure 9 which shows the comparison of the wall film distribution area at different injection distance. When the injection distance becomes long the wall film distribution area is increased and it is easy to evaporate for the wall film because of thin thickness. So the difference of wall-film evaporation appeared.

Therefore, in the design of the nozzle position the impact of the injection distance should be considered in order to avoid fuel located at lower temperature area. At the same time, the intake flow is also should be considered in the nozzle position design.

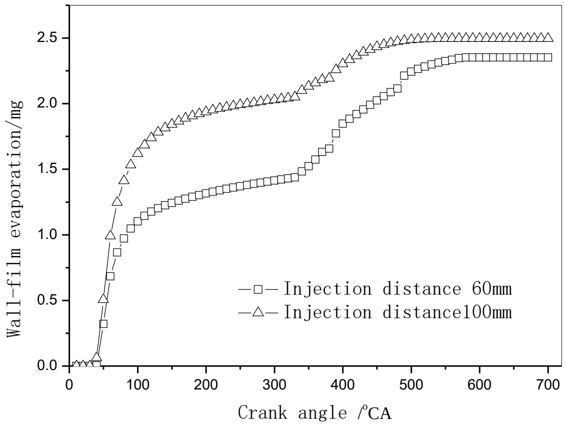


Fig.8 Comparison of wall-film evaporation at different injection distance

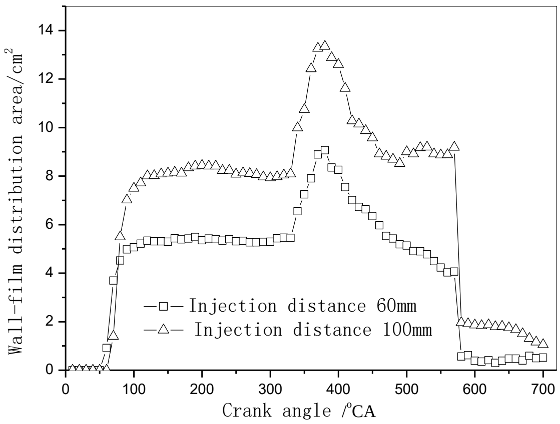


Fig.9 Comparison of wall-film distribution area at different injection distance

4. Conclusion

The effects of impingement points, injection timing, back flow and injection distance on wall-film evaporation are studied using numerical methods at high engine body temperature. And some conclusions got as follows.

(1)For the PFI gasoline engine, the wall-film evaporation becomes more difficult when the impingement point is at the bottom of intake port at CVI mode which is not helpful to the fuel evaporation.

(2)The influence of the injection timing on the wall-film evaporation for different injection timing can be negligible because the wall film evaporation mass difference is less than 0.1mg when the engine body temperature is high.

(3)Back flow can improve the wall-film evaporation at CVI mode since the back flow back into the intake port has high temperature which can improve the wall-film evaporation.

(4)Longer injection distance can improve the wall-film evaporation at CVI mode when the engine body temperature is high due to its lager distribution wall-film area which can increase the interface between the wall-film and intake port and decrease the thickness of wall-film.

Acknowledgement

The paper is supported by Young key teachers Supporting Project of Henan Province (2014GGJS-120), the Reliability Test Center and Modern Design Method Research Center of Henan Institute of Engineering. The authors would like to express appreciation of financial support by the Reliability Engineering Center of Henan Institute of Engineering and the Power-driven Machinery and Vehicle Engineering Research Center of Henan Institute of Engineering.

REFERENCES

[1] *Jia N,Gao D W, Guo X Y, et al*. Experimental study into the effect of EGR on a turbocharged port fuel injection gasoline engine. Chinese Internal Combustion Engine Engineering, 2016,37(2):43-47.

[2] *Hushim M F, Alimin A J, Rashid L A, et al.* Influence of fuel injector position of port-fuel injection retrofit-kit to the performances of small gasoline engine. AIP Conference Proceedings, 2012,1440(1):418-424

[3] *Chen Z, Liu J P, Wu, Z K, et al.* Effects of port fuel injection (PFI) of n-butanol and EGR on combustion and emissions of a direct injection diesel engine. Energy Conversion & Management, 2013, 76: 725-731

[4] *Brenn, G, Domnick, J, Dorfner, V, et al*. Unsteady gasoline injection experiments:comparison of measurements in quiescent air and in a model intake port// SAE Paper. Detroit, MI, USA, 1995-950512

[5] *Oliveira P M R, Moreira A L N, Durão D F G.* Effect of a cross-flow on spray impingement with port fuel injection systems for HCCI engines.Fuel, 2013,106:249-257.

[6] *Bianchi G M, Brusiani F, Postrioti L, et al.* CFD Analysis of Injection Timing Influence on Mixture Preparation in a PFI Motorcycle Engine// SAE Paper. Detroit, MI, USA, 2006-32-0022

[7] *Wang X Y, Chen G H.* Three dimensional transient simulation of air-fuel mixture process in PFI gasoline engine. Journal of Huazhong University of Science and Technology (Natural Science edition), 2007, 35(6):92-95.

[8] *Nemecek, L M, Wagner, R M, and Drallmeier, J A.* Fuel Droplet Entrainment Studies for Minimization of Cold-Start Wall-Wetting// SAE Paper. Detroit, MI, USA, 1995-950508.

[9] *Nemecek, L M, Wagner, R M, and Drallmeier, J A.* Fuel And Air Studies for Spark Ignition Engine Cold Start Applications//Proceedings of ILASS American, Washington, America, 1994,1:132-139.

[10] *Luan Y F, Naeim A H, and Mauro K T.* Port-Fuel-Injection Gasoline Engine Cold Start Fuel Calibration// SAE Paper. Detroit, MI, USA, 2006-01-1052

[11] *Li T, Deng KY, Peng H Y, et al.* Effect of partial-heating of the intake port on the mixture

preparation and combustion of the first cranking cycle during the cold-start stage of port fuel injection engine. Experimental Thermal & Fluid Science,2013, 49:14-21.

[12] *Almkvist G, Denbratt I, Josefsson G, et al*. Measurements of Fuel Film Thickness in the Inlet Port of an SI Engine by Laser Induced Fluorescence//SAE Paper. Detroit, MI, USA, 1995: 952483.

[13] *Yukihiro T, Yoshihiro N.* Analysis of the Fuel Liquid Film Thickness of a Port Fuel Injection Engine//SAE Paper. Detroit, MI, USA, 2006:2006-01-1051.

[14] *Ji S B, Cheng Y, Ma Z Z, et al*. Influence Factor Analysis of Fuel Evaporation in Intake Stroke. Transactions of the Chinese Society for Agricultural Machinery,2013,44(5):25-30.

[15] *Dementhon J. B. and Vannobel F.* Phase Doppler anemometry in gasoline sprays: in atmosphere and in a steady flow rig. Spray and Aerosol 91-ILASS， 48.

[16] *Posylkin M., Taylor A. M. K. P., and hitelaw J. H.* Fuel Droplets inside a Firing park-Ignition Engine[C]. SAE Paper: 941989.

[17] *Stanglmaier R.S, Matthew J. and Ronald D. Matthews.* In-Cylinder Fuel Transport during the First Cranking Cycles in a Port Injected 4-Valve Engine//SAE Paper. Detroit, MI, USA, 1997:970043.

[18] *Zughyer J., Zhao, F. Q., Lai, M.-C., et al.* A Visualization Study of Fuel Distribution and Combustion inside a Port-Injection Gasoline Engine under Different Start Conditions //SAE Paper. Detroit, MI, USA, 2000: 2000-01-0242.

[19] *Erik S., Munch K. W., and Alfred L.*. Interaction of airflow and injected fuel spray inside the intake port if a six cylinder four valve si engine// SAE Paper. Detroit, MI, USA, 1997:972984.

[20] *Shin Y., Kyoung D.M. and Cheng W. K.*.Visualization of Mixture Preparation in a Port Fuel Injection Engine During Engine Warm-up//SAE Paper. Detroit, MI, USA, 1995:952481.

[21] *Ma Z Z, Chen Y, Ji S B, et al.* Influences of Intake Flow on Spray and Wall-film for Port Fuel Injection Gasoline Engine. Transactions of the Chinese Society for Agricultural Machinery,2012,43(3):10-15.

[22] *Ma Z Z, Chen Y, Ji S B, et al.* Effects of Intake Back-Flow on Fuel Evaporation for Mass PFI Gasoline Engine. Journal of Combustion Science and Technology, 2012, 18(1): 67-72.