Springer

KSME

Journal of Mechanical Science and Technology 26 (9) (2012) 2929~2939
www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-012-0704-0

Correlation analysis of factors influencing the electronic unit pump cycle fuel injection quantity under overall operating conditions for diesel engines †

Yao Chong[1,*], Fan Li-yun[1], Dong Quan[2], Song En-zhe[1] and Tian Bing-qi[1]

[1]*College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China*
[2]*Internal Combustion Engine Institute, Dalian University of Technology, Dalian 116024, China*

(Manuscript Received March 26, 2011; Revised February 10, 2012; Accepted April 29, 2012)

Abstract

Electronic unit pump (EUP) can satisfy both diesel engine emission legislation and fuel economy by improving injection pressure and numerical control. Fluctuations in cycle fuel injection quantity (CFIQ) of EUP determine the coherence and stability of the EUP fuel injection system. The EUP simulation model is developed in the AMESim environment. The method for the simulation experiment is designed in the MODDE environment using the design of experiments method. The results of the simulation reveal the variation laws of correlation between parameters with interaction or no interaction under overall operating conditions of diesel engines. In addition, the results also show the EUP system is a complex nonlinear system. Under overall operating conditions, all the characteristic parameters, such as fuel supply pressure, cam profile velocity, control valve lift, injector opening pressure, injector needle lift, and injector flow coefficient, have significant correlation with CFIQ. The interacting first-order factors exhibit the most significant correlation with CFIQ. The self-interacting second-order factors have significant secondary correlation with CFIQ.

Keywords: Electronic unit pump; Overall operating conditions; Cycle fuel injection quantity; Correlation analysis; Design of experiments

1. Introduction

The use of electronic unit pump (EUP) offers digital control to fuel injection, relatively higher injection pressure, and improvement of fuel economy and exhaust emission characteristics [1-3]. It has been proved that CFIQ affects the stability and conformity of the mounted engine operation [4]. Many researchers have done a lot of works on the effects of one or a part of EUP characteristic parameters on CFIQ until now [5-7]. However, due to the influence of EUP pulse injection characteristics and the complicated interaction among EUP parameters, it is difficult to globally describe the effects of EUP parameters on the characteristics of CFIQ. Meanwhile, qualitative analysis on the changing law of CFIQ in typical operating conditions can not satisfy the requirement of modern diesel engines on the accuracy control of fuel injection. From this standpoint of view, the comprehensive comparison of the influences of different EUP parameters on CFIQ is carried out in this paper by using design of experiments (DoE) method which is a much effective methodology to design experiment plan. The correlation coefficients of EUP parameters and CFIQ in all operating states are solved by means of numerical simulation method. The crucial parameters that have significant correlation to CFIQ and the key factors of the interaction of parameters should also be illustrated by quantitative comparison, which are very important for optimizing the characteristic parameters of EUP, decoupling the interaction of parameters, and promoting the conformity of performance of the EUP fuel injection system in overall operating states.

As shown in Fig. 1, EUP consists of a solenoid valve control unit and pressure building unit (plunger unit). The solenoid valve control unit consists of an electromagnet, anchor, control valve-stem, anchor offsetting spring, and so on. The pressure building unit consists of a plunger, plunger bushing, and plunger spring. EUP uses a solenoid valve to control the fuel injection operation. When the power of electromagnet is supplied, the control valve-stem is drawn to block the fuel path as the sealing cone closes. At the same time, the desired fuel injection pressure is built in the pump chamber. The control of CFIQ and fuel injection timing are implemented by regulating the closing duration and timing of the control valve-stem.

2. Research method and parameter setting

Fig. 2 shows the whole research process and method. A more efficiency research method without reducing the result reliability is adopted in this paper.

*Corresponding author. Tel.: +86 451 82518036, Fax.: +86 451 82568316
E-mail address: yaochong@hrbeu.edu.cn
† Recommended by Associate Editor Kyoung Dong Min

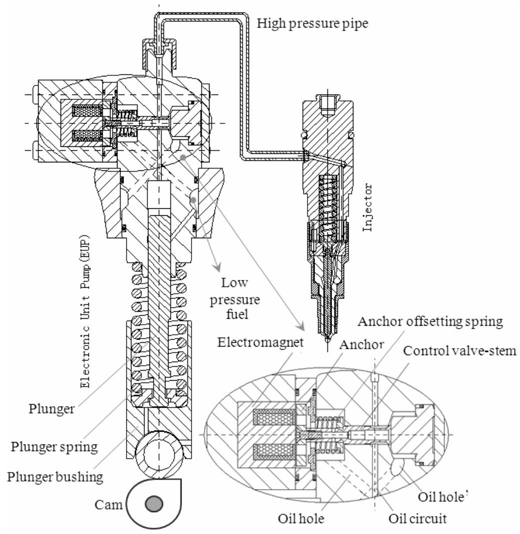


Fig. 1. Technical drawing of EUP system.

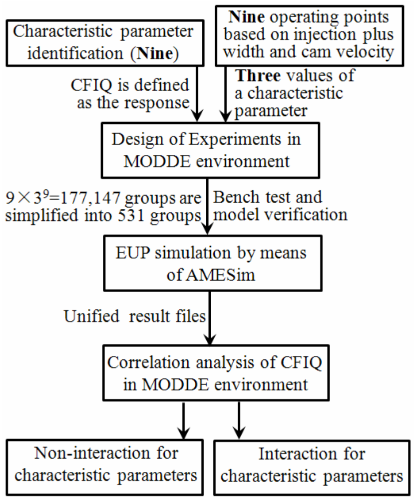


Fig. 2. Flow process of research on EUP.

2.1 Workload account

EUP is a complex system assembling electric field, magnetic field, mechanical movement, and flow field. It consists of many characteristic parameters. In the first stage, nine characteristic parameters are identified. The characteristic parameters affecting CFIQ are supply fuel pressure, cam velocity, plunger matching clearance, control valve lift, anchor residual clearance, control valve matching clearance, injector opening pressure, injector needle lift and nozzle discharge coefficient.

Engine speed, namely cam velocity, and pulse width of fuel injection are the important parameters affecting the characteristics of fuel injection. CFIQ with reference values corresponding to the different cam rotate speed and pulse width conditions of fuel injection are shown in Fig. 3. Considering the operating performance of diesel engines assembled with EUP, the overall operating conditions of EUP are summarized into six characteristic lines based on speed and pulse width as

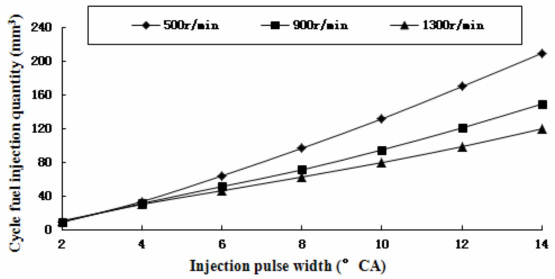
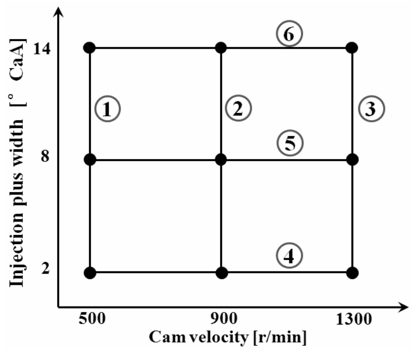


Fig. 3. Variation of CFIQ as the increase of pulse width and cam velocity.



Legend: (1) low-speed load line; (2) medium-speed load line; (3) high-speed load line; (4) short pulse width speed line; (5) medium pulse width speed line; (6) long pulse width speed line.

Fig. 4. Schematic plan of the nine operating condition points.

expressed in Fig. 4. According to the data of the CFIQ characteristics in the nine operating condition points, the variation laws of correlation coefficient in overall operating states are obtained, which provides an insight for achieving global calibration map of CFIQ in overall operating conditions.

In addition, CFIQ is affected by the characteristic parameters of fields, and it fluctuates as these characteristic parameters change. The reasons for the variation of the different characteristic parameters are as follows:

(a) Difference of part parameters of fuel injection system induced by manufacturing accuracy in the production process.

(b) Variation of part parameters of fuel injection system generated in the operation process, e.g., differential friction and parts clearance.

Based on the actual product parameters, the reference value and variation range of different characteristic parameters are identified as shown in Table 1.

Studies on EUP must consider the influence of the nine characteristic parameters on diesel performance and the interaction among these characteristic parameters, which must be examined through a mass of experiments in nine operating conditions with three values corresponding to a characteristic parameter. A total of 9×3^9 = 177147 groups of experiments must be conducted to investigate in conventional research method. Meanwhile, the complex effects of multiple physical fields of the EUP system also increase the workload and complexity of experiments; therefore, a reasonable experimental

Table 1. Reference values and variations of characteristic parameters.

Characteristic parameters	Min. value	Ref. value	Max. value
Supply fuel pressure (MPa)	0.2	0.3	0.4
Cam velocity (mm/ºCaA)	0.31	0.34	0.37
Plunger matching clearance (μm)	5	10	15
Control valve lift (mm)	0.14	0.15	0.16
Anchor residual clearance (mm)	0.09	0.1	0.11
Control valve matching clearance (μm)	2	7	12
Injector opening pressure (MPa)	22	27	32
Injector needle lift (mm)	0.25	0.35	0.45
Nozzle discharge coefficient	0.7	0.8	0.9

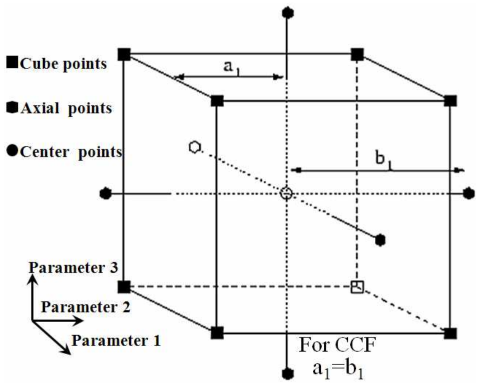


Fig. 5. Example points of a central composite face design with three input parameters.

plan is necessary.

2.2 Design of experiments

Based on the above situation, the design of experiments (DoE) is adopted in this paper. DoE techniques have the capability to determine simultaneously the individual and interactive effects of the characteristic parameters affecting the CFIQ, while provides a full insight of interaction between these characteristic parameters.

Specifically, the design method of central composite face (CCF) is used in MODDE Ver. 7.0 environment [9], which is often classified as a response surface methodology. In the CCF design, the axial points are centered on the faces of the cube, as expressed in Fig. 5. This implies that all factors have three levels, rather than five, and that the experimental region is a cube, and not a sphere. For the detailed question, the factors influence of the EUP characteristic parameters are regarded as the research objects, while the experiment plan is designed with the CFIQ set as the response. Thus, the analysis of three horizontal interactions among the nine operating points as well as the nine influencing factors requires only 9 × 59 = 531 groups experiments by the simplification of DoE.

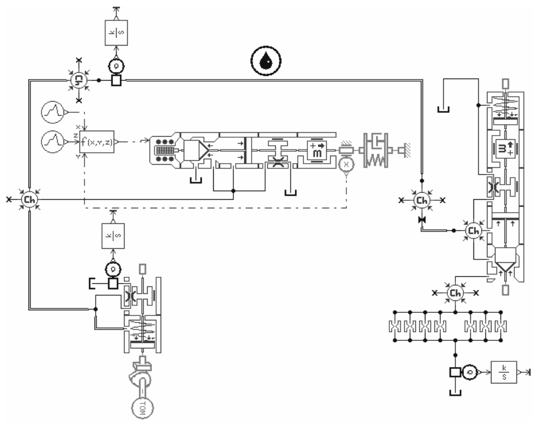


Fig. 6. AMESim simulation model of EUP.

2.3 Mathematical equations for EUP simulation

The calculation modeling of the EUP fuel supply system is constructed by the simulation software AMESim Ver. 9.0 as shown in Fig. 6 [9].

The electromagnetic field coupled equation is

$$U = iR + \frac{d\lambda}{dt} \tag{1}$$

where U is coil ports voltage and i the electromagnet drive current to perform closed-loop control for pulse width modulation by software, R and λ are the coil resistance and value of flux linkage, respectively, which are related to the structural parameters of electromagnetic valve.

The equation of mechanical motion for valve rod is

$$m\frac{d^2x_l}{dt^2} = F_{mag} - F_f - k(x_l + x_0) \tag{2}$$

where m is the mass of moving body including valve rod, armature and spring etc., x_l is the displacement of valve rod, F_{mag} is the electromagnetic force on armature, F_f is the force considering flow effect, k is the stiffness of spring, and x_0 the amount of spring predeformation and the time.

It is recommended that F_f is defined by computational fluid dynamics (CFD) because of the poorer accuracy for F_f calculated via flow characteristics approximate equation resulting from the complex shape of armature.

The wave equation in fuel pipe is

$$\frac{\partial u}{\partial x} + \frac{1}{a^2\rho}\frac{\partial p}{\partial t} + \frac{u}{a^2\rho}\frac{\partial p}{\partial x} = 0 \tag{3}$$

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x}\right) + \frac{\partial p}{\partial x} + 2k\rho u = 0 \tag{4}$$

where ρ is density of the fuel, u is velocity and p is the pressure, k is the flow resistance coefficient, and a is the velocity of pressure wave propagating in fuel passage, namely sonic velocity for short.

2.4 Correlation analysis of CFIQ

The variation laws of CFIQ corresponding to different influencing factors are analyzed further by guiding the simulation results of AMESim into the software in MODDE environment. With multiple linear regression (MLR), the coefficients of the model are computed to minimize the sum of squares of the residuals, i.e. the sum of squared deviations between the observed and fitted values of the response. MODDE uses the singular value decomposition (SVD) to solve the system of equations:

$$Y = X*B+E \quad (5)$$

where Y is an n*m matrix of responses. X (the extended design matrix) is an n*p matrix, with p the number of terms in the model including the constant. B is the matrix of regression coefficients, and E is the matrix of residuals. In this paper, Y is defined as CFIQ. X is defined as the characteristic parameter, while B is the correlation coefficient that we need to obtain. E is used to control and ensure the reliability and accuracy. Based on this method, the correlation coefficient between the characteristic parameters and CFIQ are obtained. Subsequently, the correlation analysis is divided into two parts. First, only the first-order variable of the characteristic parameters is considered. That is, the correlation between the first-order factors of the characteristic parameters and the CFIQ is analyzed without considering the interaction of characteristic parameters. Then, the correlation between the first-order factors (characteristic parameters themselves) and CFIQ, as well as the correlation between the second-order and multi-order factors (the product of the characteristic parameters) and CFIQ is analyzed with considering the interaction for characteristic parameters. Ultimately, the variation laws of the correlation of these factors (including the first-order, second-order, and multi-order characteristic parameters) and CFIQ in all operating states are obtained regardless of parameter interaction.

3. Bench test and model verification

Fig. 7 shows the experiment bench of EUP system, and Table 2 shows the main system parameters. The experimental works and simulation research are carried out respectively.

As shown in Figs. 8-10 and 11, the predicted results are in excellent agreement with the experimental data on pump pressure, injector pressure, and fuel injection rate. Moreover, the numerical model exhibits a fair predictability over a wide cam velocity range with a maximum deviation of 7% in Fig. 11.

4. Results and discussion

4.1 Correlation analysis of CFIQ under non-interaction for characteristic parameters

The correlation analysis of CFIQ regardless of the interac-

Table 2. Main parameters for simulation and experiment.

Component	Parameter/Unit	Value
Plunger	Plunger diameter/mm	11
	Cam profile speed/mm/ºCaA	0.34
High pressure fuel pipe	Inner diameter/mm	1.8
	Length/mm	470
Injector	Flow rate mL/ (30 sec.100 bar)	575
	Open pressure/MPa	27
	Needle lift/mm	0.35
Fuel pump	Flow rate/L/min	8
Fuel returning valve	Working pressure/MPa	0.4

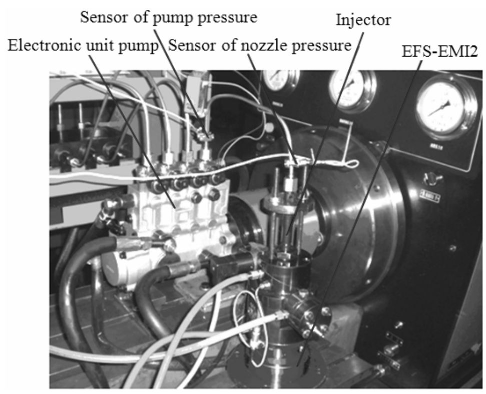


Fig. 7. Experiment bench of EUP fuel injection system.

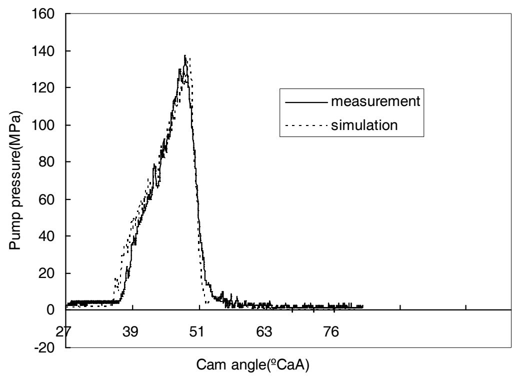


Fig. 8. Comparison curve of pump pressure.

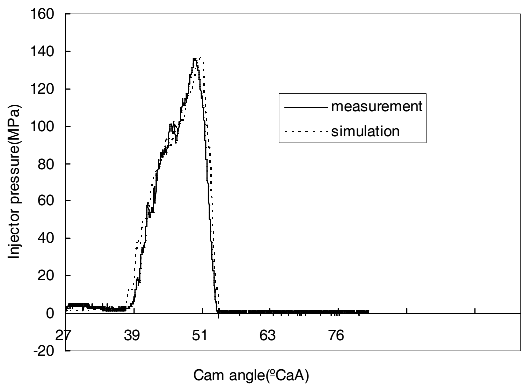


Fig. 9. Comparison curve of injector pressure.

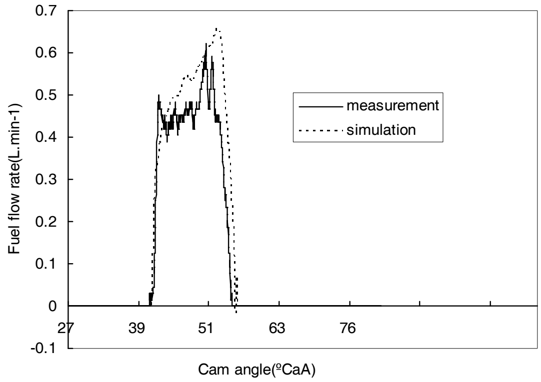


Fig. 10. Comparison curve of fuel injection rate.

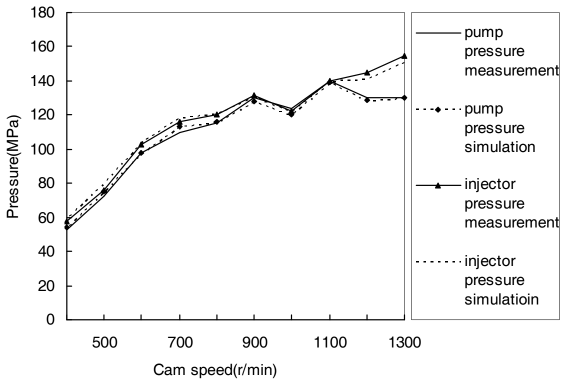
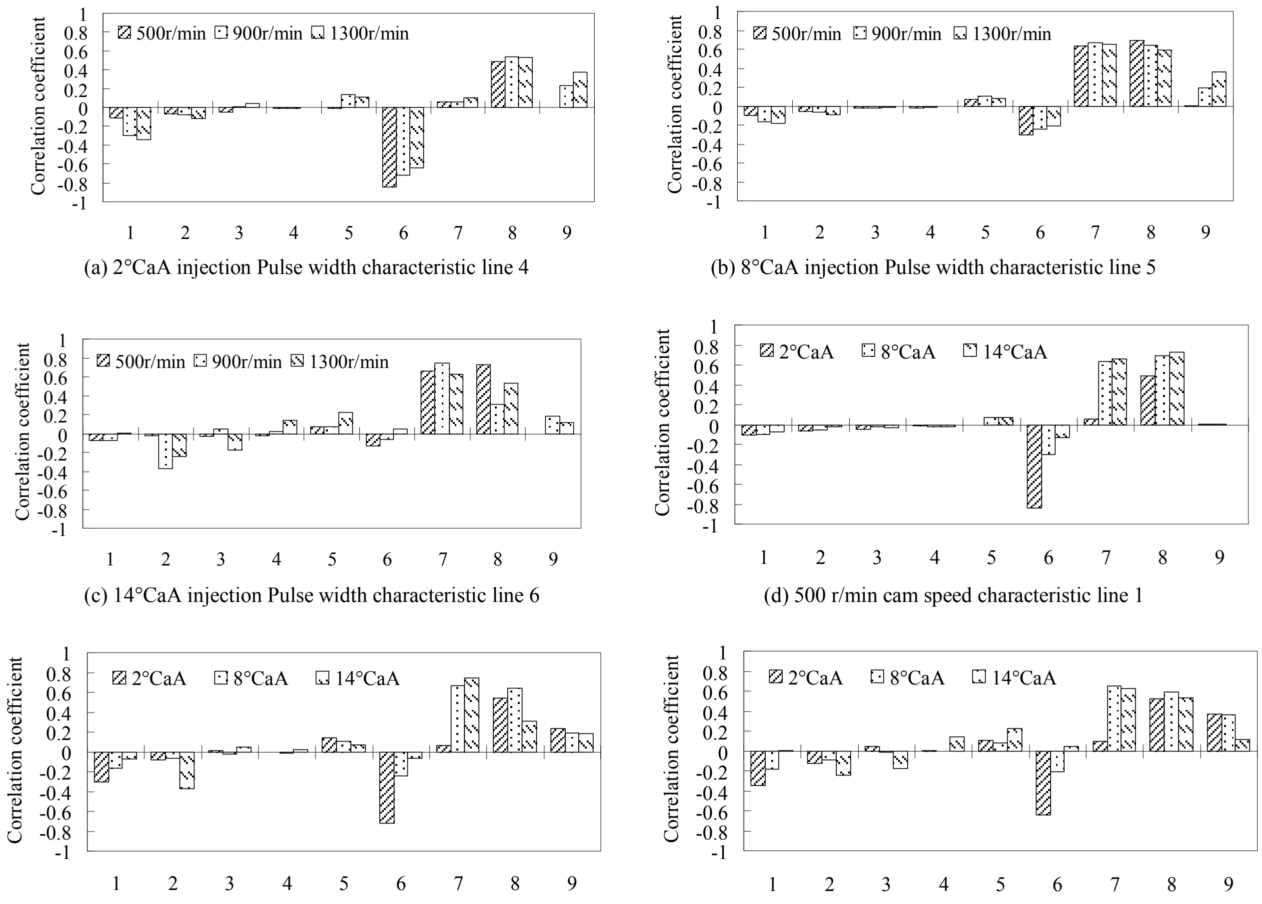


Fig. 11. Comparison of measured and simulation pressure at different cam speed.



(a) 2°CaA injection Pulse width characteristic line 4

(b) 8°CaA injection Pulse width characteristic line 5

(c) 14°CaA injection Pulse width characteristic line 6

(d) 500 r/min cam speed characteristic line 1

(e) 900 r/min cam speed characteristic line 2

(f) 1300r/min cam speed characteristic line 3

Legend: (1) Valve lift; (2) Anchor residual clearance; (3) Plunger matching clearance; (4) Valve matching clearance; (5) Injector needle lift; (6) Injector opening pressure; (7) Nozzle flow coefficient; (8) Cam velocity; (9) Supply fuel pressure.

Fig. 12. Correlation of different factors with cycle fuel injection quantity under non-interaction.

tion of characteristic parameters is performed. Fig. 12 and Table 3 show the results of the correlation analysis. Each characteristic line in Fig. 12 is corresponding to each line in Fig. 4.

4.1.1 Control valve lift

Under operating points with short and medium pulse width conditions, correlation coefficient of the control valve lift and CFIQ is negative, which proves that the absolute value of correlation coefficient is directly proportional to cam velocity.

Table 3. Correlation analysis value of different factors with cycle fuel injection quantity under non-interaction.

Operating condition points / Characteristic parameters	Injection pulse width	2°CaA			8°CaA			14°CaA		
	Cam speed	500 r/min	900 r/min	1300 r/min	500 r/min	900 r/min	1300 r/min	500 r/min	900 r/min	1300 r/min
Valve lift		-0.1100	-0.2987	-0.3410	-0.1016	-0.1652	-0.1834	-0.0682	-0.0705	0.0054
Anchor residual clearance		-0.0671	-0.0783	-0.1215	-0.0512	-0.0651	-0.0866	-0.0251	-0.3742	-0.2422
Plunger matching clearance		-0.0509	0.0123	0.0461	-0.0235	-0.0249	-0.0092	-0.0285	0.0482	-0.1720
Valve matching clearance		-0.0118	-0.0058	0.0017	-0.0196	-0.0111	-0.0042	-0.0245	0.0227	0.1441
Injector needle lift		-0.0053	0.1379	0.1089	0.0740	0.1106	0.0845	0.0718	0.0711	0.2273
Injector opening pressure		-0.8426	-0.7184	-0.6453	-0.3059	-0.2388	-0.2107	-0.1313	-0.0656	0.0499
Nozzle flow coefficient		0.0576	0.0612	0.0987	0.6338	0.6657	0.6511	0.6600	0.7467	0.6263
Cam velocity		0.4904	0.5404	0.5276	0.6927	0.6396	0.5899	0.7267	0.3136	0.5292
Supply fuel pressure		0.0017	0.2347	0.3743	0.0030	0.1946	0.3591	-0.0013	0.1849	0.1134

Moreover, the absolute value of short pulse width is not only larger than that of long pulse width but also unstable. On the other hand, under operating points with long pulse width and low/medium speed conditions, correlation coefficient of the control valve lift and CFIQ is also negative. As speed increases, the trend of the absolute value of correlation coefficient slightly increases. With high speed, correlation coefficient is positive but the magnitude is relatively small.

The absolute value of correlation coefficient corresponding to different speed conditions is inversely proportional to fuel injection pulse width; the variance ratio of correlation coefficient achieves the maximum value under high speed conditions. Specifically, under short/medium pulse width and high-speed conditions, correlation coefficient is negative and the absolute value decreases as injection pulse width is increased. However, under long pulse width and high speed conditions, correlation coefficient and its magnitude becomes positive and relatively small. The maximum value of correlation coefficient (-0.34) appears under operating points of high speed and short pulse width conditions. With low/medium speed, correlation coefficient is negative.

The control valve lift dominates the movement time of the control valve during opening and closing processes, and affects the rate of release and velocity of pressure in the plunger cavity. Under overall speed range of short/medium pulse width and low/medium speed range of long pulse width conditions, the increase in control valve lift prolongs the movement time of the control valve during the closing process. Due to the prolonged operating time, a relatively high pressure in the plunger cavity is achieved, which leads to an increase in leakage time and fuel leakage quantity from sealing cone. The rate of increase in pressure tends to decrease as fuel leakage quantity increases. From this point of view, the variation of pressure in the plunger cavity directly affects the characteristic of CFIQ. Meanwhile, as cam rotation speed is increased, the reduced fuel supply time makes the variation of control valve lift exert significant influence on CFIQ, and causes the absolute value of negative correlation coefficient to increase.

Within the whole range of medium/low-speed injection pulse width and high-speed short/medium pulse width, pressure building time in the plunger cavity increases as the extension of pulse width. Due to the weakened influence of the increase in control valve lift on pressure building in the plunger cavity, the absolute value of correlation coefficient diminishes.

For the operating points of long injection pulse width, the prolonged fuel pressure building time in plunger cavity caused by the increase in control valve lift decreases CFIQ to a certain degree. On the other hand, the compression time of the plunger is relatively long, and the increase in amplitude of fuel pressure in the plunger cavity is also high as a result of high speed and long injection duration. Therefore, the fuel pressure by the time fuel injection is finished is significantly higher than the fuel pressure at the early stage of fuel injection. The open time of the control valve is shorter than the closing time. However, high-pressure injection can be continued due to the higher fuel pressure. This not only compensates for the decrease in CFIQ as the control valve increases, but also promotes a slight increase in CFIQ. Based on the analysis above, correlation coefficient on this operating point becomes positive, the absolute value of which is small.

4.1.2 Anchor residual clearance

Anchor residual clearance is also a critical parameter dominated by the force of the solenoid control valve. Anchor residual clearance with the control valve lift determines the movement time of the opening and closing processes of the control valve, and affects the velocity of pressure building and further release of fuel pressure in the plunger cavity. Correlation coefficient between anchor residual clearance and CFIQ is negative, and its variation law is same as that of the control valve lift and CFIQ.

Compared with the effect of anchor residual clearance, the influence of control valve lift on the closing time of the control valve is more obvious. Thus, the correlation coefficient of the anchor residual clearance and CFIQ is smaller than that of the control valve lift and CFIQ under the main operating conditions. Under high speed and long pulse width conditions, the absolute value of correlation coefficient is relatively large. The peak value (-0.37) appears in the operating point of medium speed and long pulse width; this nonlinear characteristic of the fuel injection system has a close relationship with the unstable critical flow as a result of high fuel pressure.

4.1.3 Plunger matching clearance

Plunger matching clearance is regarded as the scale of fuel leakage rate of plunger matching in fuel supply operations. Thereby, plunger matching clearance and CFIQ has a negative correlation. Except when correlation coefficient is -1.7 under high speed and long pulse width conditions, the absolute value of correlation coefficient is less than 0.05 in the other operating conditions. The reason for this negative correlation is that plunger and plunger bushing is a couple of precision matching parts, which has extremely small clearance variation. Under overall operating conditions, the influence of plunger matching clearance on CFIQ is quite insignificant, and correlation coefficient is small. However, under high-speed and long pulse width conditions, plunger matching clearance significantly affects CFIQ as the cavity pressure of plunger matching and fuel leakage time increases.

4.1.4 Control valve matching clearance

Control valve matching clearance determines the leakage rate of high-pressure fuel in the control valve. The control valve and pump body are also a couple of matching parts; hence, the negative correlation between control valve matching clearance and CFIQ under overall operating conditions is identified, except in the operating point of long pulse width with medium/high speed. The absolute value of correlation coefficient is smaller than 0.025. For the operating point of long pulse width with medium/high speed, correlation coefficient becomes positive. The positive-negative change in correlation coefficient is affected by the unstable critical flow, the fluctuation in fuel pressure in the pump cavity, and the flow damped variation of control valve matching parts. Such nonlinear characteristic of correlation coefficient can be reduced by increasing the machining accuracy of the control valve matching parts.

4.1.5 Injector needle lift

Under overall operating conditions, the injector needle lift and CFIQ generally have positive correlation, except under short pulse width conditions in which they have slightly negative correlation. Except under operating conditions of short pulse width with low speed (or long pulse width with high speed), correlation coefficient decreases as the injection pulse width increases within the whole speed range. In contrast, correlation coefficient is inversely proportional to the increase in cam speed under different pulse width conditions. The injector needle lift dominates the needle movement time during the opening and closing operations. The increase in pulse width shortens the percentage of needle movement time, resulting in effective injection time. The increase in cam speed and fuel injection pressure promotes needle movement velocity and reduces needle movement time. Hence, the influence of needle lift on CFIQ is decreased. However, the increase in the rate of fuel pressure is slow under short pulse width with low speed conditions, which in turn slows down the speed of needle opening. Thus, the choking effect on fuel flow is relatively large on needle movement, which causes CFIQ to decrease slightly as the needle lift increases. Correlation coefficient under this operating point condition is -0.005. In contrast, under long pulse width with high speed conditions, relatively high fuel pressure and needle lift increase the duration of needle movement during the opening and closing processes as well as the quantity of fuel injection during needle movement. Hence, CFIQ significantly increases due to the combined effects of fuel pressure and needle movement duration. Correlation coefficient under this operating point condition is 0.23.

4.1.6 Injector opening pressure

Injector opening pressure and CFIQ have a negative correlation, except in the operating point of long pulse width with high speed (under which the injector opening pressure and CFIQ have a positive correlation). Under different rotation speed conditions, correlation coefficient of injector opening pressure is inversely proportional to the increase in pulse width. Likewise, under different pulse width conditions, correlation coefficient decreases as cam speed increases. The maximum absolute value of correlation coefficient (-0.84) is achieved under low speed and short pulse width conditions.

Injector opening pressure determines the delay duration of fuel injection. As fuel injection pulse width increases, the percentage of fuel injection delay relative to effective fuel injection time decreases. As cam speed increases, the rate of increase in fuel pressure in the nozzle cavity becomes faster. The increased fuel pressure promotes the opening velocity of the needle and shortens the injection delay. The negative correlation coefficient decreases with the increase in pulse width and cam speed. However, while cam speed and pulse width continually increases, increasing the injector opening pressure will not only prolong the fuel injection delay and decrease CFIQ, but also increase the initial injection pressure and compensate for the decrease in CFIQ caused by the increase in injection delay. Therefore, given that CFIQ slightly increases, the injector opening pressure and CFIQ have positive correlation in this operating point.

4.1.7 Nozzle discharge coefficient

Under overall operating conditions, nozzle discharge coefficient and CFIQ in general have positive correlation coefficient. Nozzle CFIQ is a function of time and pressure; thus, the increase in injection pulse width and injection duration will promote the increase in CFIQ as cam speed and fuel injection pressure increase. Under operating point with long pulse width and medium/high speed conditions, correlation coefficient of nozzle discharge coefficient increases as pulse width and cam speed increase, which correspond to different speed and pulse width conditions. The maximum positive correlation coefficient is 0.75. Nozzle discharge coefficient represents the characteristic of nozzle flow. Under the same condition, a relatively large nozzle discharge coefficient corresponds to a relatively high fuel injection quantity as a result of the difference in high pressure in upstream and downstream nozzle orifice. Therefore, a relatively high pressure difference would slightly reduce nozzle discharge coefficient according to the internal flow characteristics of the nozzle holes. This is the reason the correlation coefficient decreases to a certain extent.

4.1.8 Cam velocity

Cam velocity directly dominates fuel supply efficiency, and the influence of cam velocity on CFIQ is determined by effective action time during fuel injection. Therefore, cam velocity has positive correlation with CFIQ under overall operating conditions. As shown in Fig. 12, correlation coefficient decreases as cam velocity increases. On the other hand, correlation coefficient increases as the fuel injection pulse width increases. Under low velocity and long pulse width conditions, correlation coefficient reaches the peak value of 0.73.

4.1.9 Supply fuel pressure

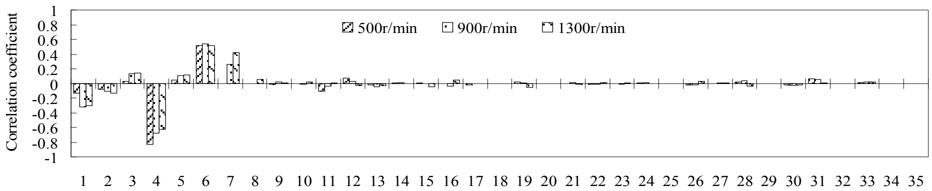
In overall operating states, supply fuel pressure and CFIQ are related. Under low-speed conditions, the correlation of supply fuel pressure and CFIQ can be ignored. Under medium/high-speed conditions, the correlation between supply fuel pressure and CFIQ becomes obvious. As the fuel injection pulse width decreases, correlation coefficient increases. Correlation coefficient is inversely proportional to fuel injection pulse width. In low/medium injection pulse width, speed is directly proportional to correlation coefficient; correlation coefficient reaches the maximum value of 0.37 under high-speed and short pulse width conditions. Under long pulse width conditions, correlation coefficient shows an arched characteristic as speed increases; this correlation is due to the supply fuel pressure dominating the fuel suction capability of the EUP system. Relatively low speeds can effectively prolong the fuel suction time and significantly limit the influence on CFIQ. As speed increases, the effective fuel suction time significantly decreases, which in turn also increases the variation of CFIQ and correlation coefficient. The most obvious influence on CFIQ and largest correlation coefficient would appear under high speed and short pulse width conditions as a result of the shortest fuel suction time and the worst fuel suction effect. However, under high speed and large pulse width conditions, relatively high fuel injection pressure and long fuel injection duration can compensate and relieve the influence of insufficient fuel suction on CFIQ, which promotes the generation of an arched trend.

Based on the analysis above, under overall operating conditions, the characteristic parameters that have significant correlation with CFIQ are supply fuel pressure, cam velocity, plunger matching clearance, control valve lift, anchor residual clearance, control valve matching clearance, injector opening pressure, injector needle lift, and nozzle discharge coefficient. Compared with the other characteristic parameters, the influence of injector opening pressure, nozzle discharge coefficient, and cam velocity on CFIQ are the most powerful, the correlation of which are also the most significant. Specifically, cam velocity becomes one of the main influential factors for CFIQ due to the internal pulsatile characteristics of the EUP fuel supply. By adding a pressure-stabilizing tank and improving the machining accuracy of cam profile and shaft coupling, CFIQ caused by the variation characteristics of cam velocity fluctuates. Under operating points of medium/long pulse width conditions, the effects of nozzle discharge coefficient on CFIQ become prominent. Therefore, the machining accuracy and production technology of nozzle orifices should be strictly controlled to avoid the fluctuation and inconsistency of CFIQ induced by the inconsistent discharge coefficient of each hole. In addition, the influence of injector opening pressure on CFIQ becomes the leading factor under short pulse width conditions, which can also be controlled by optimizing the cam profile, increasing the building velocity of nozzle cavity pressure, shortening injection delay, and increasing the injection pressure. The stability of injector opening pressure is thus the critical factor for achieving CFIQ consistency under operating points of short pulse width conditions.

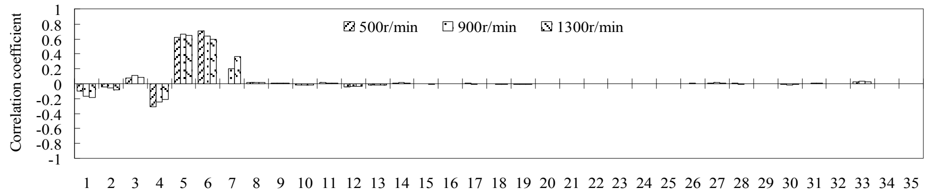
The control valve lift and injector needle lift affect the injection characteristics and effective injection time under medium/high cam velocity conditions. Supply fuel pressure has a significant effect on the fuel suction degree of the EUP system under medium/high speed operating states. Therefore, these three characteristic parameters have obvious correlation with CFIQ under medium/high speed conditions. The influence of these three parameters on CFIQ can be offset by controlling the feedback signal of the control valve, strictly controlling the motion of needle, and increasing supply fuel pressure and spill valve performance stability.

4.2 Correlation analysis of CFIQ under interaction for characteristic parameters

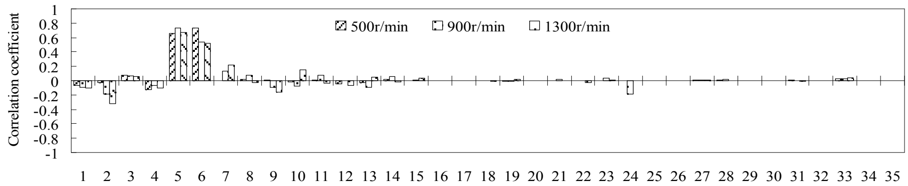
The correlation analysis of CFIQ identifies the critical parameters affecting the characteristics of CFIQ under conditions of non-interaction characteristic parameters. CFIQ correlation analysis is conducted to investigate further the effects of interaction factors on the duration of CFIQ fuel injection without considering the minor effects of plunger matching clearance and Control Valve Matching Clearance. Fig. 13 and Table 4 show the results of correlation analysis of CFIQ and characteristic parameters under the interaction of 35 factors. Each characteristic line in Fig. 13 is corresponding to each line in Fig. 4.



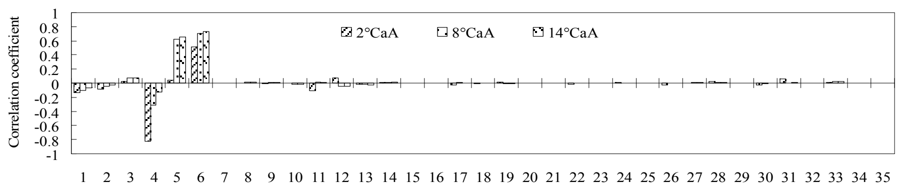
(a) 2°CaA injection pulse width characteristic line 4



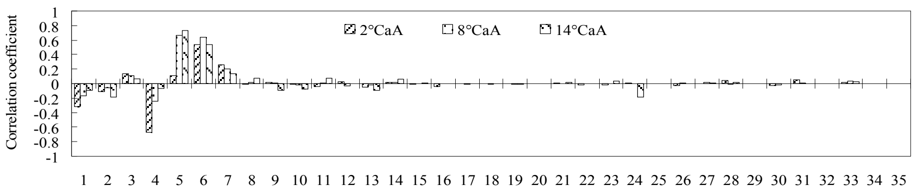
(b) 8°CaA injection pulse width characteristic line 5



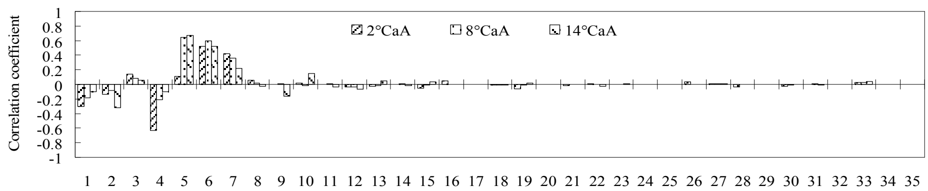
(c) 14°CaA injection pulse width characteristic line 6



(d) 500 r/min cam speed characteristic line 1



(e) 900 r/min cam speed characteristic line 2



(f) 1300 r/min cam speed characteristic line 3

Legend: (1) control valve lift; (2) anchor residual clearance; (3) injector needle lift; (4) injector opening pressure; (5) nozzle flow coefficient; (6) cam velocity; (7) supply fuel pressure; (8) control valve lift & control valve lift; (9) anchor residual clearance & anchor residual clearance; (10) injector needle lift & Injector needle lift; (11) injector opening pressure & injector opening pressure; (12) nozzle flow coefficient & nozzle flow coefficient; (13) cam velocity & cam velocity; (14) supply fuel pressure & supply fuel pressure; (15) control valve lift & anchor residual clearance; (16) control valve lift & injector needle lift; (17) control valve lift & injector opening pressure; (18) control valve lift & nozzle flow coefficient; (19) control valve lift & cam velocity; (20) control valve lift & supply fuel pressure; (21) anchor residual clearance & injector needle lift; (22) anchor residual clearance & injector opening pressure; (23) control valve lift & nozzle flow coefficient; (24) anchor residual clearance & cam velocity; (25) anchor residual clearance & supply fuel pressure; (26) injector needle lift & injector opening pressure; (27) injector needle lift & nozzle flow coefficient; (28) injector needle lift & cam velocity; (29) injector needle lift & supply fuel pressure; (30) injector opening pressure & nozzle flow coefficient; (31) injector opening pressure & cam velocity; (32) injector opening pressure & supply fuel pressure; (33) nozzle flow coefficient & cam velocity; (34) nozzle flow coefficient & supply fuel pressure; (35) cam velocity & supply fuel pressure.

Fig. 13. Correlation of different factors with CFIQ under interaction.

Table 4. Correlation analysis value of different factors with CFIQ under interaction.

Operating condition / points — Injection pulse width	2°CaA			8°CaA			14°CaA		
Cam speed	500	900	1300	500	900	1300	500	900	1300
Control valve lift	-0.1304	-0.3183	-0.3013	-0.1027	-0.1677	-0.1811	-0.0705	-0.0964	-0.1033
Anchor residual clearance	-0.0808	-0.1072	-0.1330	-0.0455	-0.0628	-0.0801	-0.0270	-0.1848	-0.3223
Injector needle lift	0.0290	0.1305	0.1398	0.0734	0.1111	0.0816	0.0739	0.0681	0.0580
Injector opening pressure	-0.8263	-0.6747	-0.6262	-0.3125	-0.2403	-0.2123	-0.1300	-0.0692	-0.1049
Nozzle flow coefficient	0.0458	0.1095	0.1114	0.6185	0.6632	0.6496	0.6588	0.7279	0.6744
Cam velocity	0.5113	0.5393	0.5191	0.7052	0.6415	0.5935	0.7306	0.5364	0.5220
Supply fuel pressure	0.0000	0.2621	0.4227	0.0000	0.2052	0.3626	0.0000	0.1348	0.2210
Control valve lift & control valve lift	-0.0002	-0.0053	0.0549	0.0130	0.0132	0.0130	0.0144	0.0737	-0.0257
Anchor residual clearance & anchor residual clearance	-0.0098	0.0201	0.0012	0.0101	0.0112	0.0081	0.0125	-0.0941	-0.1589
Injector needle lift & Injector needle lift	-0.0004	-0.0101	0.0199	-0.0170	-0.0177	-0.0136	-0.0156	-0.0791	0.1531
Injector opening pressure & injector opening pressure	-0.1051	-0.0381	0.0025	0.0194	0.0069	0.0056	0.0123	0.0766	-0.0294
Nozzle flow coefficient & nozzle flow coefficient	0.0723	0.0276	-0.0296	-0.0394	-0.0357	-0.0350	-0.0408	0.0014	-0.0681
Cam velocity & cam velocity	-0.0189	-0.0486	-0.0266	-0.0196	-0.0191	-0.0138	-0.0255	-0.0900	0.0524
Supply fuel pressure & supply fuel pressure	0.0075	0.0136	-0.0029	0.0113	0.0129	0.0110	0.0133	0.0568	-0.0181
Control valve lift & anchor residual clearance	0.0015	-0.0068	-0.0471	-0.0024	-0.0025	-0.0051	-0.0016	0.0043	0.0350
Control valve lift & injector needle lift	0.0000	-0.0407	0.0471	-0.0019	0.0036	0.0012	-0.0007	0.0001	-0.0005
Control valve lift & injector opening pressure	-0.0215	0.0000	-0.0008	0.0054	-0.0077	0.0003	0.0008	0.0015	0.0001
Control valve lift & nozzle flow coefficient	-0.0048	-0.0040	-0.0072	-0.0022	-0.0084	-0.0076	-0.0020	-0.0035	-0.0062
Control valve lift & cam velocity	0.0191	0.0019	-0.0583	-0.0096	-0.0044	-0.0089	-0.0046	-0.0056	0.0130
Control valve lift & supply fuel pressure	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Anchor residual clearance & injector needle lift	-0.0016	0.0098	-0.0157	-0.0002	-0.0003	0.0004	0.0000	0.0128	0.0025
Anchor residual clearance & injector opening pressure	-0.0155	-0.0132	0.0108	0.0002	0.0006	0.0003	-0.0004	-0.0011	-0.0212
Control valve lift & nozzle flow coefficient	-0.0032	-0.0159	0.0021	-0.0017	-0.0028	-0.0034	-0.0010	0.0321	0.0091
Anchor residual clearance & cam velocity	0.0083	0.0125	-0.0041	-0.0022	-0.0029	-0.0024	-0.0007	-0.1842	-0.0011
Anchor residual clearance & supply fuel pressure	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Injector needle lift & injector opening pressure	-0.0253	-0.0223	0.0299	-0.0036	0.0104	0.0028	0.0001	0.0011	0.0019
Injector needle lift & nozzle flow coefficient	0.0000	0.0025	0.0075	0.0087	0.0127	0.0105	0.0090	0.0099	0.0082
Injector needle lift & cam velocity	0.0250	0.0420	-0.0343	0.0069	-0.0043	-0.0016	0.0045	0.0146	0.0007
Injector needle lift & supply fuel pressure	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Injector opening pressure & nozzle flow coefficient	-0.0242	-0.0284	-0.0214	-0.0086	-0.0133	-0.0095	-0.0028	-0.0031	-0.0006
Injector opening pressure & cam velocity	0.0612	0.0545	0.0037	-0.0008	0.0122	0.0103	0.0047	-0.0006	-0.0096
Injector opening pressure & supply fuel pressure	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Nozzle flow coefficient & cam velocity	0.0107	0.0170	0.0214	0.0263	0.0296	0.0264	0.0272	0.0278	0.0399
Nozzle flow coefficient & supply fuel pressure	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Cam velocity & supply fuel pressure	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

5. Conclusions

(1) Without considering the parameter interactions, the characteristics of parameters having significant correlation with CFIQ under overall operating conditions are identified: supply fuel pressure, cam velocity, control valve lift, injector opening pressure, injector needle lift, and nozzle flow coefficient.

(2) Considering the parameter interactions, the first-order factors have the most obvious correlation with CFIQ under overall operating conditions. Moreover, the self-interacting second-order factors also have relatively higher correlation with CFIQ than the other second-order factors.

(3) The present study proves that CFIQ of the EUP fuel injection system is affected by different characteristic parameters, as well as by their interaction. The EUP system is a complex nonlinear system.

Acknowledgment

This work is supported by the Program for New Century Excellent Talents in University (NCET), National Natural Science Foundation of China (NSFC 50909024), China; the Fundamental Research Funds for the Central Universities, China; the Science Fund of State Key Laboratory of Automotive Safety and Energy, China.

References

[1] G. Cantore, E. Mattarelli and A. A. Boretti, Experimental and theoretical analysis of a diesel fuel injection system, *SAE Paper*, 1999-01-0199 (1999).

[2] C. Arcoumanis, M. Gavaises and E. Abdui-Wahab, Modeling of advanced high-pressure fuel injection systems for passenger car diesel engines, *SAE Paper*, 1999-01-0910 (1999).

[3] G. Greeves, S. Tullis and B. Barker, Advanced two-actuator EUI and emission reduction for heavy-duty diesel engines, *SAE Paper*, 2003-01-0698 (2003).

[4] A. E. Catania, C. Dongiovanni and E. Spessa, Delivery-valve effects on the performance of an automotive diesel fuel-injection system, *SAE Paper*, 1999-01-0914 (1999).

[5] M. G. Yang and S. C. Sorenson, Modeling of the dynamic processes in an electronic diesel fuel injection system, *SAE Paper*, 9202400 (1992).

[6] A. Mulemane, J. S. Han and P. H. Lu, Modeling dynamic behavior of diesel fuel injection systems, *SAE Paper*, 2004-01-0536 (2004).

[7] L. Y. Fan, W. Q Long and Y. X. Zhu, A characteristic study of electronic in-line pump system for diesel engines, *SAE Paper*, 2008-01-0943 (2008).

[8] Umetrics AB, MODDE Users Guide, Version 7.0 (2003).

[9] IMAGINE SA, AMESim User Manual, Version 9.0 (2009).

Yao Chong received his B.S. degree in Communication and Transportation Engineering and M.S. degree in Power Machinery and Engineering from Harbin Engineering University, China, in 2003 and 2006, respectively. Mr. Yao is currently a lecturer at College of Power and Energy Engineering at Harbin Engineering University, China. His research interests include diesel control and fuel injection system design and simulation.