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A STUDY OF FUEL TEMPERATURE DYNAMIC CHARACTERISTICS FOR DIESEL ENGINE COMBINATION ELECTRONIC UNIT PUMP SYSTEM

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Key words: combination electronic unit pump (CEUP), unit pump, fuel temperature, dynamic characteristic, numerical simulation.

ABSTRACT

The combination electronic unit pump (CEUP) is a type of electronic unit pump fuel injection system specially designed for meeting the requirements on emission and fuel efficiency of diesel engines. It is a fairly complex product which is assembled together by mechanical, hydraulic and electrical magnetic systems. The fuel temperature dynamic characteristics of CEUP which reflects heat load characteristics of the whole system are investigated both by bench test in the laboratory and numerical simulations. The research on dynamic characteristics of high-pressure fuel injection temperature (FIT) reveals the effects of fuel tank temperature and injection pulse width on FIT. The results show that FIT goes up with the increase of fuel injection pulse width when the cam rotational speed is kept constant. A maximum FIT of 118°C is recorded at 10°CaA pulse width, 1400 rpm cam rotational speed and 50°C fuel tank temperature. It is concluded from research that increasing the pulse width by 4-6°CaA and 6-10°CaA results in FIT variation rate of 0-4°C/°CaA and 4-5°C/°CaA respectively. The research on the low-pressure fuel supply temperature (FST) dynamic characteristic illustrates that the increase of FST in low-pressure system is the result of thermal transmittance of the fuel flowing back from the high-pressure system to the low-pressure system after the end of fuel injection. Moreover, FST in the low-pressure system tends to climb up with the increase of cam rotational speed and injection pulse width. In addition, the deviation between entrance fuel temperature and exit fuel temperature in low-pressure system ranges between -0.7°C and 3.4°C, and the same tendency has been observed when the numbers of unit pumps in CEUP are increased. It is also concluded that the variation of FST in high/low pressure system is due to the transient coupling process of the fuel.

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I. INTRODUCTION

In order to adapt to the increasingly strict diesel engine emission regulations, more and more diesel engines have been loaded the more flexible fuel injection control system, such as common rail system, electric control allocation pump, combination electronic unit pump (CEUP), etc. Among them, CEUP won the favor of the diesel factory for its strong adaptability, high injection pressure, flexible injection control and reliable performance (Zhu et al., 2008; Zhao et al., 2014). CEUP is a time-controlling impulse electronic diesel injection system, and both of its injection timing and fuel injection quantity are precisely controlled by the solenoid valve providing an advantageous feature of soft and accurate readjustment to the injection timing (Yang et al., 1992; Aditya et al., 2004; Qiu et al., 2008; Wang et al., 2011). CEUP is assembled together with a low pressure supply pump and a high-pressure injection system by coupling mechanical, hydraulic and electrical magnetic system. CEUP can, therefore, operate under higher injection pressure conditions reaching up to 1800 bar. High-pressure fuel injection temperature (FIT) and low-pressure fuel supply temperature (FST) represent the heat load characteristics of CEUP system. The influence of fuel temperature on direct-injection diesel engines is quite significant and it affects the fuel injection, combustion, performance and emissions of diesel engines (Chen, 2009). Variation of FIT in high pressure section of CEUP can affect the consistency in both the cycle fuel injection quantity of each cylinder and the cylinder-by-cylinder cycle fuel injection quantities (Fan et al., 2008, 2012; Wu et al., 2013). Meanwhile, variation of FST in low pressure section of CEUP can affect the fuel supply quantity transferred to high-pressure section of CEUP and consequently can cause variations in high-pressure fuel injection characteristics. Moreover, FIT also has some impact on FST during fuel injection process when fuel returns back to low-pressure section from high-pressure section.

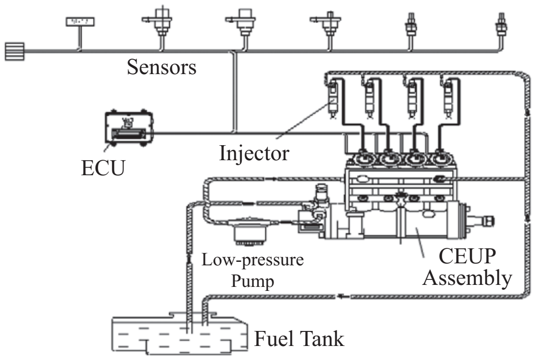


Fig. 1. Schematic plan of combination electronic unit pump (CEUP) system.

From aforementioned point of view, a detailed research on dynamic characteristics of fuel temperature of CEUP system is of great significance for its development and improvement. Therefore a study on the fuel temperature dynamic characteristic of CEUP system based on numerical simulation and experimental research has been carried out in order to achieve the elemental rules governing the dynamic characteristics of high-pressure FIT and low-pressure FST.

II. COMPOSITIONS AND PRINCIPLE OF CEUP SYSTEM

Fig. 1 shows the schematic plan of CEUP system. It is mainly composed of electric control system and mechanical hydraulic system. In this paper, the mechanical hydraulic system has been further classified into two subsystems, namely high-pressure system and low-pressure system based on building-up process of fuel pressure during injection. High-pressure system includes combination pump body, plunger, control valve spool, high pressure pipe and injector. Low-pressure system consists of fuel tank, low-pressure pipe, fuel filter, low-pressure pump, combination pump box and oil spill valve. Fuel inside the cavity of combination pump box is sucked into the high-pressure system through the sealing taper face of solenoid valve spool by downward motion of plunger inside plunger chamber. Fuel is then compressed by the upward motion of plunger actuated by the cam shaft and subsequently the fuel is injected through injector when the pressure exceeds closing pressure of injector needle. During the whole injection process fuel injection quantity and injection timing are adjusted by the detailed cut-off duration and cut-off timing of control spool.

III. RESEARCH METHODS

The CEUP system is a fairly complex system combining electromagnetic theory, mechanical kinetics and dynamic flow in a complicated high/low pressure coupled dynamic injection system (Fan et al., 2008). Numerical modeling and simulation of CEUP system have been done together with experiments on pump test bench in laboratory. These two methods when combined complement and verify each other for the research on fuel temperature dynamic characteristic of CEUP system. The experiments have been conducted to investigate the dynamic characteristics of high pressure FIT and low pressure FST when reaching thermal equilibrium, as shown in Section 4 and the first half of Section 5. The simulation model of CEUP system has been utilized to predict the transient temperature variation of fuel caused by transient coupling characteristics of fuel temperature in high/low pressure system, which is difficult to be measured through experiments, as presented in the lower half of Section 5.

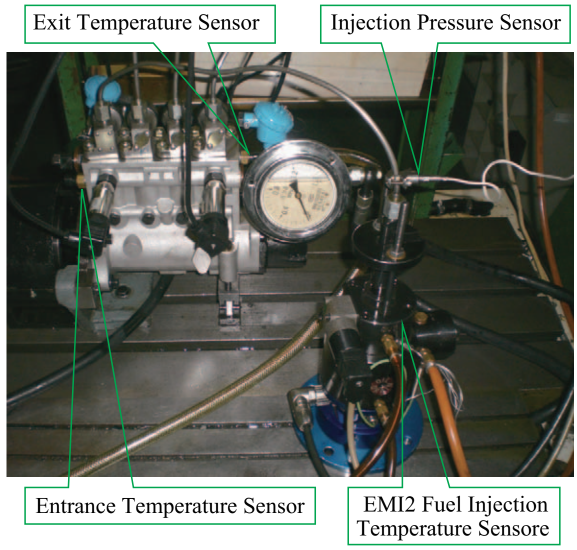


Fig. 2. Test bench of combination electronic unit pump (CEUP) system.

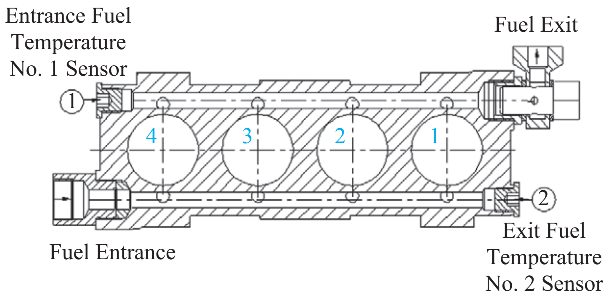


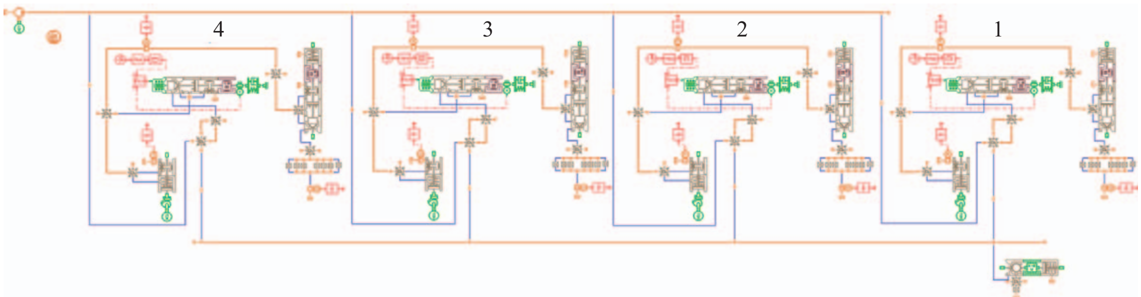
Fig. 3. Measuring positions of low-pressure system and the numeral order of unit pumps.

1. Experimental Stup

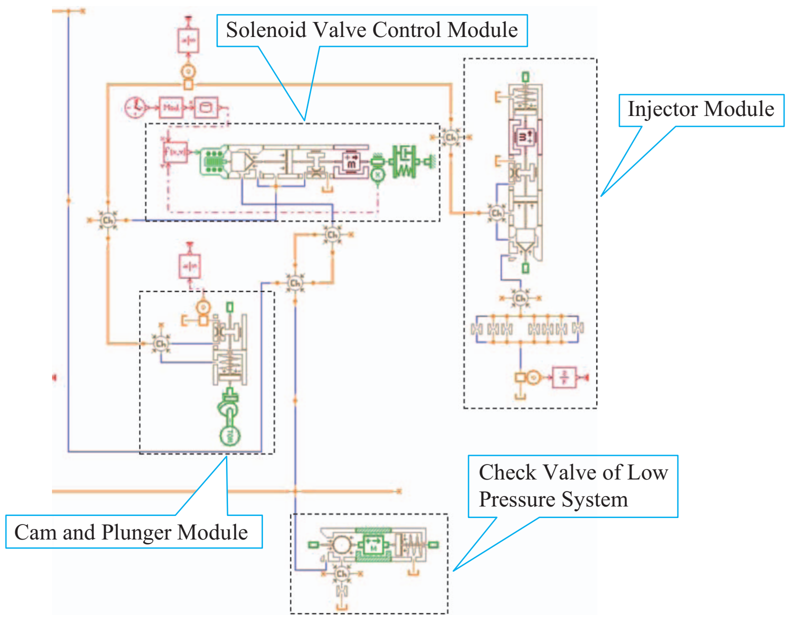
Fig. 2 shows the experimental bench setup of CEUP system. Two temperature sensors are used to measure the transient temperature variation of fuel at the entrance and exit of low-pressure combination pump box. Fig. 3 of combination pump box shows the position of four unit pumps designated as No. 1 to No. 4 and two temperature sensors. Placement of temperature sensors has been selected in order to get the optimal temperatures at both ends of low-pressure system. Moreover, placing temperature sensors in the path of fuel entrance and exit can provide the temperatures of fuel tank and high-pressure system respec-

Table 1. Experimental equipment and apparatus.

Equipment Apparatus	Object, Function	Applied Range	Maker
Test bench PSD370	Cam rotate output	0-37 kW	TTJM Co., Ltd
Oscilloscope 54624A	Pressure, temperature signal	0-100 MHz	Agilent Technology
High-pressure sensor KISTLER 4067	Fuel injection pressure	0-200 MPa	Kistler
Temperature sensor EMI2	Fuel injection temperature	All Operating Cases	EFS
Temperature sensor WG1S	Low-pressure fuel temperature	-40-120°C	Siemens



(a) CEUP model



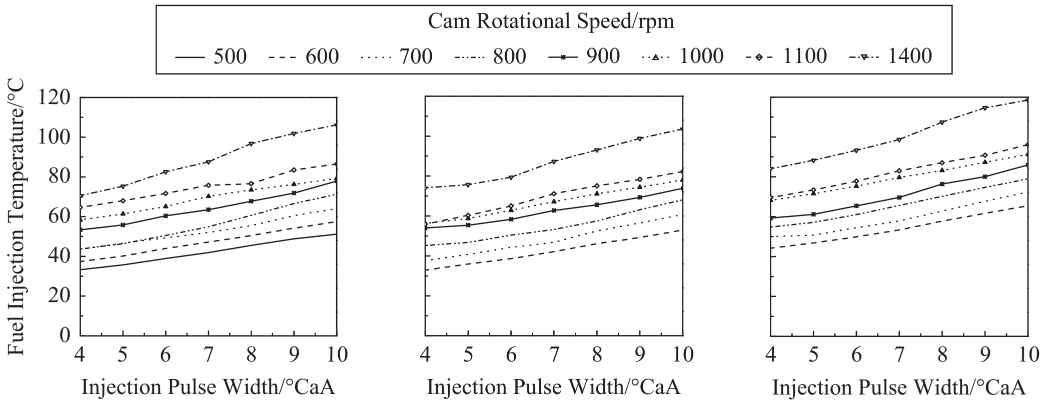
(b) The 1st EUP model

Fig. 4. AMESim simulation model.

tively. High-pressure FIT is measured by the sensor (EMI2, EFS) mounted on the exit downstream of high-pressure pipe as shown in Fig. 2. Table 1 shows the parameters of major equipments we have used in our experimental bench setup.

2. Numerical Modeling of CEUP System

The entrance/exit fuel temperature sensors placed at both ends of low-pressure system are widely applied in parameter measurement of diesel engines with response time of several seconds in diesel fuel, while the EMI2 in instantaneous mode refreshes the calculated average temperature values at a rate of less than 3 displays per second (EFS, 2012), which means the transient response of temperature sensors is not fast enough to capture the dynamic characteristic of fuel temperature caused by the transient coupling characteristics of fuel temperature in high/low pressure system. Thus, a numerical model of CEUP system including low-pressure system and high-pressure system has been modeled in advanced modeling environment for performing simulation of engineering systems (AMESim). By using this numerical model, the dynamic characteristics of high-



(a) Fuel tank temperature of 30°C (b) Fuel tank temperature of 40°C (c) Fuel tank temperature of 50°C

Fig. 5. Characteristic of fuel injection temperature with three fuel tank temperature conditions.

pressure FIT, low-pressure FST and temperature variation due to high/low pressure coupling have been predicted and investigated. The numerical model has been developed by choosing components from AMESim library modules. The compressibility, viscosity, density, sound velocity, and absolute saturation vapor pressure of diesel fuel; the friction loss, inertial effect and volume effect of the fuel when moving in the hydraulic circuit; the frictional drag of moving parts; the leakage of matching parts have been considered. The moving parts influencing the fuel injection process like valve body and mechanical spring have been regarded as mass modules, and the plunger cavity, needle valve cavity, control cavity and the hydraulic junction of most of components have been connected with volumetric modules. The volume effect, inertial effect, pressure wave transmission and loss in the high-pressure pipe have been taken into account. Important factors like heat eliminating from the pump body and high-pressure pipe, thermal transmittance of fuel circuit and plunger matching parts have also been considered. Whereas, heat energy generated by solenoid control spool and potential energy changes of fuel along the fuel flow path have been neglected. For more information about this modeling approach, see the papers by Fan LY (Fan et al., 2012). Figs. 4(a) and (b) illustrate the CEUP AMESim simulation model and the enlarged drawing of the 1st EUP model.

IV. DYNAMIC CHARACTERISTIC OF HIGH-PRESSURE FIT

Dynamic characteristics of high-pressure FIT have been investigated with the variation of low-pressure FST under all operating conditions on pump test bench. Figs. 5(a)-(c) illustrate the dynamic characteristic maps of high-pressure FIT with the fuel tank temperature of 30°C, 40°C and 50°C, respectively. Since the environment temperature was only 16°C approximately, the fuel tank was heated with an electric heater to keep the temperature constant. It is noticed that FIT ascends with the increase of both cam rotational speed and injection pulse width except at few conditions. With the constant cam rotational speed, FIT rises with the increase of injection pulse width. Highest FIT of 118°C is recorded when fuel tank temperature is 50°C, cam rotational speed is 1400 rpm and injection pulse width is 10°CaA. The reason is that the degree of diesel fuel compression goes up with the increase of injection pulse width and injection pressure which directly affects the fuel temperature. The coefficient of compressibility -β which can be represented with $\overline{\beta}$ is demonstrated in Eqs. (1)-(3).

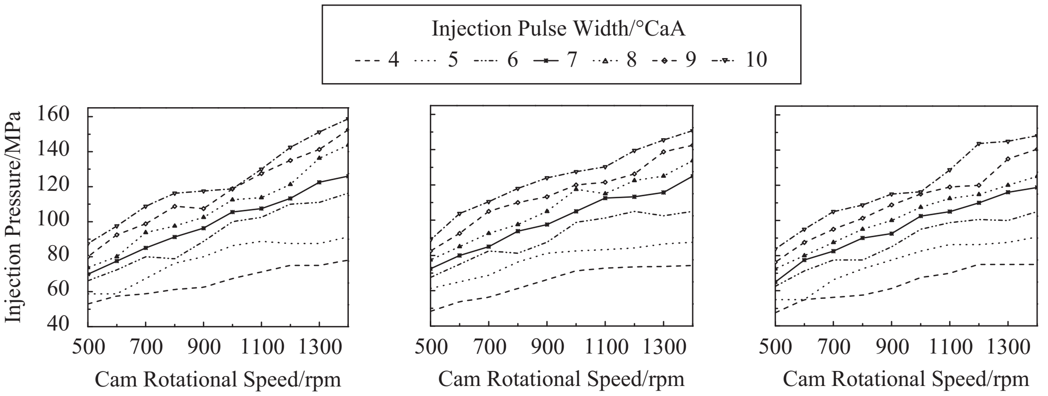
$$\beta = \frac{1}{E_V} = -\frac{1}{V}\frac{dV}{dp} = \frac{1}{\rho}\frac{d\rho}{dp} \tag{1}$$

$$\overline{\beta} = -\frac{1}{V_1}\frac{V_2 - V_1}{p_2 - p_1} \tag{2}$$

$$\beta = \frac{V_1}{V_2}[\overline{\beta} + (p_2 - p_1)\frac{d\overline{\beta}}{dp}] \tag{3}$$

where E_V is the bulk modulus of elasticity; the subscript 1 and 2 represent the state before fuel compression and after fuel compression; V, p, and ρ are the volume, pressure, and density of diesel fuel, respectively.

In the case of keeping injection pulse width constant, fuel temperature shows a tendency to rise with the increase of cam rotational speed which is also attributed to the increase of injection pressure, and the injection pressure variation as injection pulse width and cam rotational speed change with three fuel tank temperatures is demonstrated in Fig. 6. A maximum FIT of 118°C is obtained at 50°C fuel tank temperature, 1400 rpm cam rotational speed and 10°CaA injection pulse width. The graphs in Figs. 5(a)-(c) illustrate that the fuel temperature has nearly no significant change at high cam rotational speed (1200 rpm - 1400 rpm) and a short pulse width level (3°CaA - 5°CaA) when keeping cam rotational speed constant. The main reason is that the increase of cam rotational speed at constant pulse width has nearly no significant effect on injection pressure and consequently injection temperature.



(a) Fuel tank temperature of 30°C (b) Fuel tank temperature of 40°C (c) Fuel tank temperature of 50°C

Fig. 6. Fuel injection pressure variation with cam rotational speed and fuel injection width.

Comparison of high-pressure FIT at different fuel tank temperatures illustrate that under all operating conditions the FIT corresponding to 50°C fuel tank temperature is higher than that of 40°C fuel tank temperature. However, the FIT corresponding to 40°C fuel tank temperature is lower than that of 30°C fuel tank temperature. The reason is that at 30°C the fuel viscosity is higher than that at 40°C, which means lower injection rate with the same initial conditions, and thus, more fuel will be retained in the high-pressure fuel pipe with the same fuel supply condition, which gives rise to higher injection pressure at 30°C. Simultaneously, at 30°C the fuel density in the fuel tank is relatively higher than 40°C. This causes relatively more fuel pumped inside high-pressure cavity of CEUP with the same fuel volume at 30°C, which also results in higher injection pressure, more cycle fuel injection quantity and the increase of FIT at 30°C compared with those at 40°C. Obviously, the fuel density is smaller at 50°C than that at 30°C and 40°C, which leads to relatively smaller injection pressure. However, under the influence of both smaller fuel density and higher initial temperature, the higher fuel tank temperature plays a significant role in the rise of fuel injection temperature after compression, which gives rise to the feature that the FIT corresponding to 50°C fuel tank temperature is higher than that of 40°C fuel tank temperature.

From Figs. 5(b) and (c), it can also be seen that in short injection pulse width (4°CaA - 5°CaA) and at low cam rotational speed (500 rpm - 700 rpm), the fuel injection temperature is even lower than fuel tank temperature. That can be explained as the followings: the fuel temperature increase in high-pressure system fuel temperature in the compression process depends upon two factors, namely fuel compression rate in the plunger cavity and the heat exchange between fuel and body. As shown in Eqs. (4)-(6), rate of change of total energy of the fuel in high-pressure system is the sum of net incoming transport energy produced during compression and heat exchange between fuel and body.

$$\frac{dE_{hps}}{dt} = \frac{dE_{comp}}{dt} + \frac{dQ_{exchange}}{dt} \tag{4}$$

$$E_{hps} = \int \rho (u + \frac{v^2}{2}) dV \tag{5}$$

$$\begin{aligned} E_{comp} &= E_{transpin} - E_{transpex} \\ &= \rho_1 V_1 (u_1 + \frac{p_1}{\rho_1} + \frac{v_1^2}{2}) - \rho_2 V_2 (u_2 + \frac{p_2}{\rho_2} + \frac{v_2^2}{2}) \end{aligned} \tag{6}$$

where E_{hps}, E_{comp} and $Q_{exchange}$ are the total energy of high-pressure system (neglecting potential energy), net incoming transport energy due to compression and heat exchange between fuel and body; v and u are the fuel velocity and internal energy per unit mass fuel; $E_{transpin}$ and $E_{transpex}$ are the incoming transport energy and outgoing transport energy, respectively. In short injection pulse width and at low cam rotational speed, the degree of compression reflecting heat generation by fuel compression is relatively small, and the environmental temperature is much lower than the fuel tank temperature, which means more heat dissipation between the outer wall of high pressure pipe and the environment, giving rise to more heat conduction between the inner and outer wall of high pressure pipe, and then more heat convection between the fuel and the inner wall of high pressure pipe. In addition, the sample time is long enough for the system to reach heat exchange balance. All these above result in that the heat generation by fuel compression cannot compensate the heat dissipation with the surrounding environment under the latter two conditions, thus the feature is shown that the fuel injection temperature is lower than fuel tank temperature in short injection pulse width and at low cam rotational speed.

As analyzed above, it can be concluded that the variation of FIT is regarded as the result of complex combined effect of fuel tank temperature, injection pressure and the environment temperature.

Temperature variation rates of high-pressure FIT which is defined as the FIT variation produced by unit injection pulse width change at constant cam rotational speed are measured. Figs. 7(a)-(c) show the corresponding FIT variation rate characteristics with reference to the data results in Figs. 5(a)-(c). Ac-

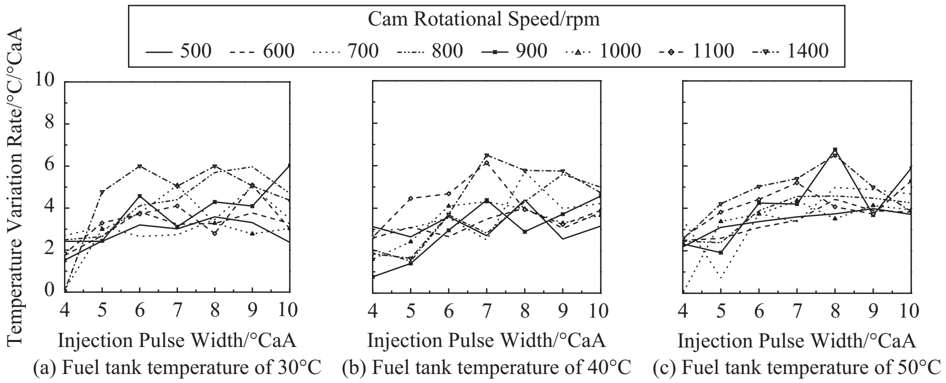


Fig. 7. Characteristic of fuel injection temperature variation rate with three fuel tank temperature conditions.

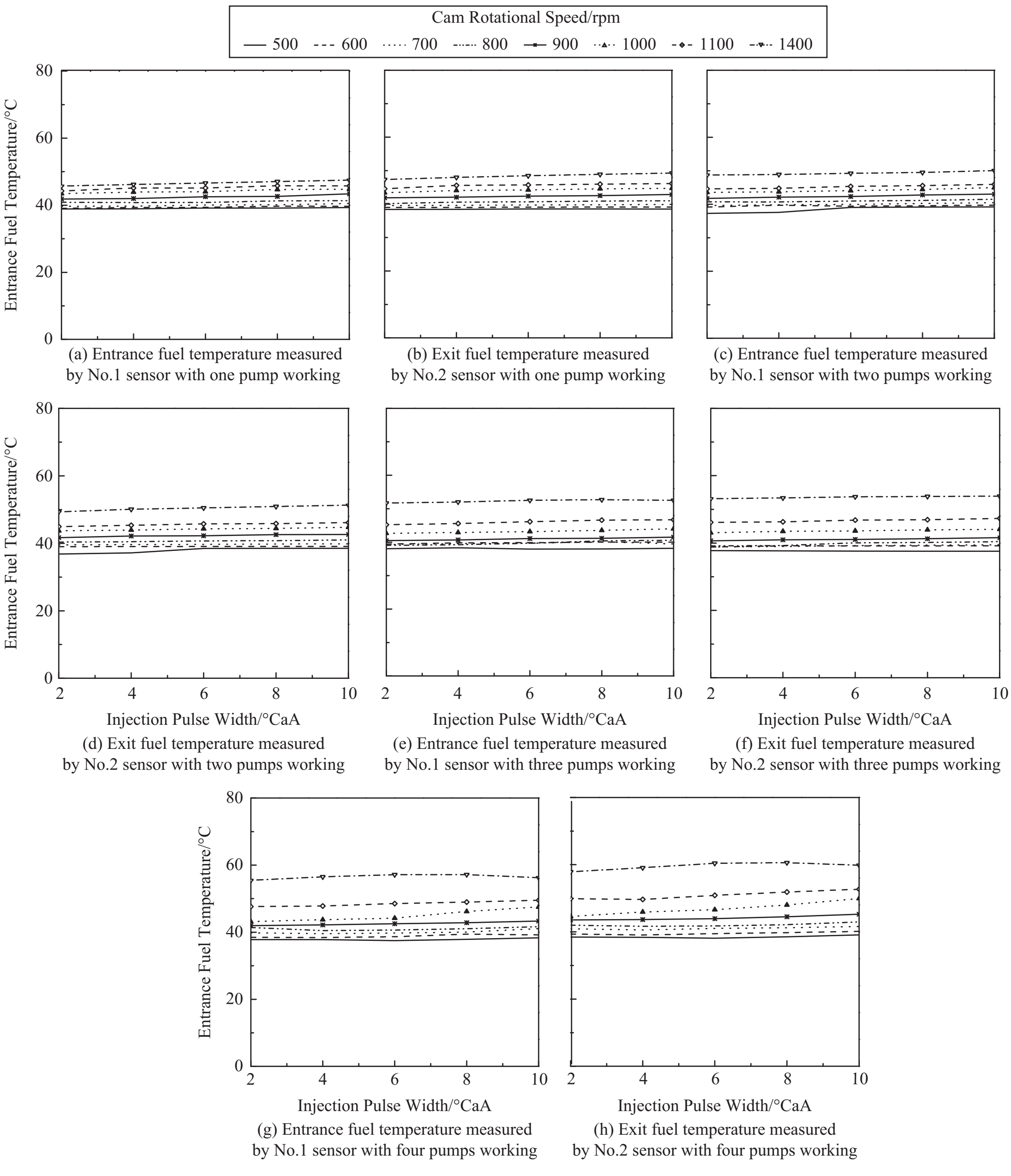


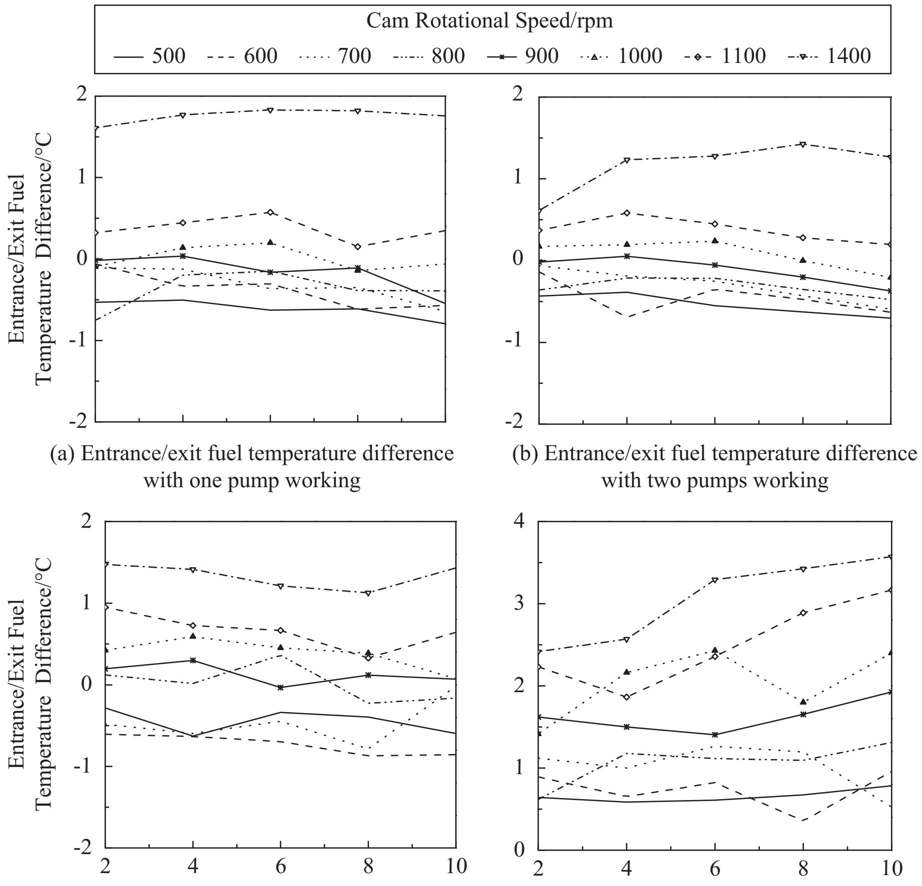
Fig. 8. Fuel temperature characteristic of low-pressure system.

cording to Figs. 7(a)-(c), the FIT variation rates of different fuel tank temperature conditions have a similar variation range and trend. The peak value of temperature variation rate under all operating conditions does not exceed 7°C/°CaA. Because the temperature variation rate of high-pressure FIT is in proportion to the fuel compression rate and the heat exchange balance. Before the start of fuel compression during injection process, high-pressure volume in high-pressure system is the same for all temperatures of fuel tank. Keeping cam profile and nozzle hole diameter unchanged, initial temperature of low-pressure fuel has little effect on compression rate, and it mainly affects the dynamic heat exchange ($Q_{exchange}$) between fuel and the body, which. Figs. 7(a)-(c) illustrate that with the increase of injection pulse width, the fuel temperature variation rate increases more in short pulse width as compared to long pulse width. The reason is that for a short injection pulse width, rate of increase in $Q_{exchange}$ shares the significant portion of total rate of increase in E_{hps}, whereas rate of increase in E_{comp} takes over most portion in longer injection pulse width. Thus, increase in 4-6°CaA injection pulse width results in the fuel temperature variation rate of 0-4°C/°CaA, while increase in 6-10°CaA injection pulse width results in the fuel temperature variation rate of 4-5°C/°CaA, as shown in Fig. 7.

V. DYNAMIC CHARACTERISTIC OF LOW-PRESSURE FST

The dynamic characteristics of low-pressure FST along the fuel flow path at all operating conditions are studied by measuring the transient fuel temperature variation at both entrance and exit sides of low-pressure system. Temperature difference between two adjacent unit pumps is estimated from right to left by interpolation of measured temperatures at entrance and exit. Based on these results the fuel density difference of each pump position can also be estimated and therefore the consistency of cycle fuel injection quantity (CFIQ) of each unit pump can be predicted. This approach is more useful for CEUP with 6 or more pump units. If there exists a large temperature difference between pumps then adjusting the injection pulse width for individual pump through Electronic Control Unit (ECU) may result in better fuel efficiency and correct injection pressure. The heat exchange between the high-temperature fuel back flow from high-pressure system after injection process and the low-temperature fuel pumped from fuel tank to the low-pressure fuel cavity by the low-pressure pump determines the final low-pressure FST. Due to this reason, the fuel temperature of low-pressure system is closely related to high-pressure system operations. In order to grasp the coupling characteristics of fuel temperature of the high/low pressure system, the dynamic characteristic of low-pressure FST on four high-pressure system operations is researched. Four operating conditions are considered, namely one pump working (No. 1 pump), two pumps working (No. 1 and No. 2 pump), three pumps working (No. 1, - No. 3 pump) and four pumps working (No. 1 - No. 4 pump). Fig. 8 shows the fuel temperature measurements at the low-pressure system entrance (No. 1 sensor) and low-pressure system exit (No. 2 sensor) for four operating conditions mentioned above. Temperature differences between sensor No. 1 and sensor No. 2 for the four operating conditions are shown in Fig. 9. The comparison indicates that the fuel temperature at entrance and exit positions increases significantly with the increase of cam rotational speed and increases slightly with the increase of injection pulse width. Moreover, as the number of working pumps is increased, the trend in temperature increase is more noticeable at higher cam rotational speed (1000 rpm - 1400 rpm) than at lower one (500 rpm - 900 rpm). The reasons about this can be attributed to that the increase of fuel temperature of low-pressure system is determined by the heat energy of fuel returning back from high-pressure system. Moreover, the temperature of fuel returning back is determined by the cam rotational speed and injection pulse width. Therefore, the increase of back flow temperature brings about the increase of FST, as well as FIT. It is important to mention here that the experiments are carried out in a sequence of starting from low cam rotational speed and varying the pulse width while keeping the cam rotational speed constant. Temperature measurements are recorded exactly after running the engine for exactly two minutes. After one set of reading of a cam rotational speed, the next set of reading are recorded for higher cam rotational speed. It is observed that because the change of fuel temperature in low-pressure system is the outcome of complicated heat diffusion and mixing process, the variation of pulse width has little impact on the fuel temperature.

The increase of the number of working pumps adds the back flow quantity of the compressed fuel, which causes the increase of fuel temperature as mentioned above. However, this effect of number of working pumps is more defined at high cam rotational speed than that at low rotational speed. This is why the fuel temperature curves bunch together at low rotate rotational speed for four operating conditions. Contrary to low cam rotational speed, at high cam speed the amount of fuel returning from high-pressure system increase, and therefore, the temperature curves spread out and become prominent with the increase of pulse width. A maximum fuel temperature of 60°C is recorded when four pumps are working together which is 11°C higher than the one under the condition of one pump working. Fig. 9 presents the entrance and exit temperature difference of low-pressure system. A maximum temperature difference of 3.4°C is recorded. The fuel temperature difference ranges from -0.7°C to 3.4°C. The entrance/exit temperature difference changes towards the positive values with the increase of number of working pumps. When all four pumps are working, the exit fuel temperature is always higher than the entrance fuel temperature regardless of cam rotational speed. The reason for this behavior is that the temperature of low-pressure fuel coming from fuel tank through filter is kept constant at 40°C, and at low cam rotational speed the returning fuel from high-pressure system is in small quantity as compared to relatively cold fuel already present there, which causes less temperature difference between entrance/exit of low-pressure system. Similarly, at high cam rotational speed larger quantity with high temperature is returned back causing notice-



(a) Entrance/exit fuel temperature difference with one pump working
(b) Entrance/exit fuel temperature difference with two pumps working
(c) Entrance/exit fuel temperature difference with three pumps working
(d) Entrance/exit fuel temperature difference with four pumps working

Fig. 9. Entrance/exit fuel temperature difference of low-pressure system.

able temperature difference between entrance/exit of low-pressure system. After analyzing the temperature variations at the entrance/exit temperature difference of low-pressure fuel circuit, it is considered unnecessary to correct the fuel temperature coefficient of the low-pressure fuel circuit. Aforementioned experimental results and analysis on entrance/exit fuel temperature in low-pressure system illustrate the coupling interaction between low-pressure system and the work state of high-pressure system.

At the same time these temperature measurements are taken utilizing the AMESim numerical model on account of the limits for the experimental research on transient coupling characteristics of fuel temperature of high/low pressure system. Fig. 10 shows the transient temperature characteristic of multi-cycle high-pressure cavity in plunger matching parts and low-pressure cavity under a typical operating condition (cam rotational speed of 1400 r/min, cycle fuel injection quantity of 80 mm^3). Comparing these results with the experimental data shown in Fig. 8, the predicted results of simulation research are in an excellent agreement with the experiment data. A regular change of transient temperature characteristic is seen in Fig. 10 regardless of whether it is high-pressure system or low-pressure system. The fluctuating range of fuel temperature of high-pressure cavity in the whole injection process does not exceed 20°C and the fluctuating range of low-pressure cavity is always below 2°C. The transient increase of fuel temperature in the high-pressure cavity is aroused by the pressure increase during fuel injection, and in the same way high-temperature fuel return back to low-pressure system leads to the transient increase of temperature in low-pressure system. The comparison of temperature fluctuation amplitude of high/low pressure system reveals that each fuel injection corresponds to temperature impact of 0.5°C on the low-pressure system. The reason is that the total heat energy of four-times fuel injections in one working cycle contributes to the maximum 2°C temperature rise. Practical temperature curves of low-pressure system are shown in Fig. 10(b). Fig. 10(b) also illustrates the large wave crest with four small wave crests in one cycle. Large wave crest is regarded as the result of one fuel compression cycle of low-pressure system and four small wave crests show heat interchanges with high-temperature fuel returning back from high-pressure system. Considering the fuel flow shown in Fig. 3, the temperature difference of adjacent unit pumps always remain within 1.5°C. Due to this, the temperature difference of fuel injected from corresponding adjacent injectors is also within 1.5°C. Thus it can be concluded that the rela-

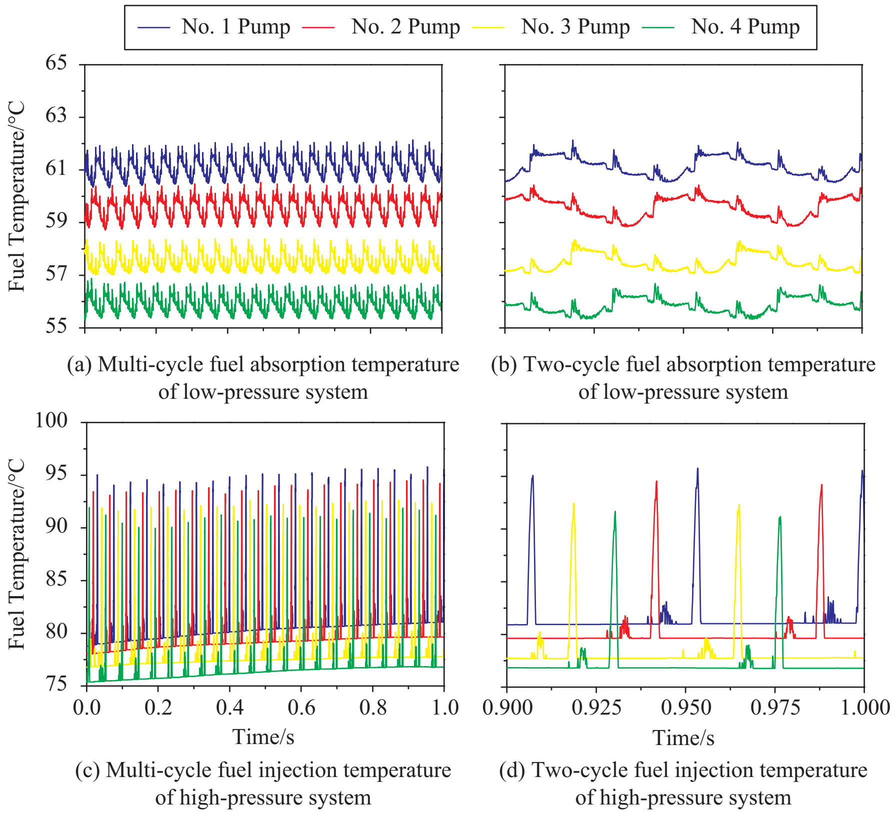


Fig. 10. Transient fuel temperature characteristic of high/low pressure system.

tionship between the low-pressure system and the high-pressure system is not unidirectional. The cooling effect of low-pressure system on high-pressure system has been identified and the range of influence is always below 1.5°C. In summation, the fuel temperature of high/low pressure system is a complex combination of time-sequence mixing of high/low pressure system fuel temperatures, initial temperature of fuel tank, injection pulse width and cam rotational speed, which lasts for the whole operating process of the entire system.

VI. CONCLUSIONS

The temperature characteristics of CEUP system is studied under multi-operating cases. A one-dimension numerical model is built for correcting and complementing the experimental results of pump test bench. An overall consideration based on data of simulation and experiment is used to analyze the temperature characteristics of high/low system of CEUP. The following are the main findings:

(a) Study on dynamic characteristic of high-pressure FIT draws a conclusion that the injected fuel temperature is determined by the comprehensive function of fuel tank temperature and fuel injection pulse width. Keeping cam rotational speed constant, FIT rises with the increase of injection pulse width. A maximum FIT of 118°C is recorded at 10°CaA injection pulse width, 1400 rpm cam rotational speed and 50°C fuel tank temperature.

(b) Based on lab experiments, the characteristic of fuel injection temperature variation rate caused by the increase of unit injection pulse width has been defined. A 4-6°CaA increase in injection pulse width results in the fuel temperature variation rate of 0-4°C/°CaA and 6-10°CaA increase in injection pulse width results in the fuel temperature variation rate of 4-5°C/°CaA. Initial fuel temperature plays a critical role on the FIT except at higher injection pressure, when the net incoming transport energy produced due to compression (E_{comp}) is more dominant than heat exchanges between fuel and body ($Q_{exchange}$).

(c) Research on the dynamic characteristics of the low-pressure FST indicates that the rise in fuel temperature of low-pressure system is due to heat interchange with the fuel returning back from high-pressure system. The entrance/exit temperature difference of low-pressure system varies between -0.7°C - 3.4°C. If there exists a large temperature difference between individual pumps of CEUP, adjusting the injection pulse width for individual pump through Electronic Control Unit (ECU) may bring about better fuel efficiency and correct injection pressure.

(d) The results of numerical simulation prove that the fuel temperature variation of high/low pressure system is to the outcome of the transient coupling process of both the systems. The fluctuating range of fuel temperature in high-pressure and low-pressure system does not exceed 20°C and 2°C, respectively. Each fuel injection causes nearly 0.5°C rise in temperature of low-pressure system.

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