Modelling and analysis of fuel temperature during fuel injection process of electronically controlled injector

Jun Wang¹, Yanbin Liu¹,³, Yi Jin¹ and Youtong Zhang³

¹ Department of Vehicle Engineering, Academy of Army Armoured Force, 21 Dujiaokan, Fengtai District, Beijing, China
² School of Mechanical and Vehicular Engineering, Beijing Institute of Technology, 81 South Zhongguancun Street, Beijing, China
³ E-mail: marcyoulia@hotmail.com

Abstract. In order to explore fuel temperature variation during the process of fuel injection, mathematical model of the fuel heat-temperature in electronic controlled injector (ECI) is founded, fine thermal simulation modelling of ECI is fulfilled by software AMEsim, fuel temperature change of different place in ECI is analysed. The analysis results show that injection pressure and initial fuel temperature have a great effect on the fuel temperature of the needle chamber and the control room, injection duration has little influence on the fuel temperature of the needle chamber, the fuel density decreases with the increase of fuel temperature under a certain pressure.

1. Introduction
Electronic controlled injector (ECI) is a key component of high pressure common rail system in diesel engine, it can realize multiple-injection flexibly and has become a necessary technical means for diesel engine to meet the strict emission regulations [1]. The fuel flow in the injection process is often regarded as isothermal due to shorter injection duration, in fact, when high pressure fuel flows through the needle valve cavity and injection orifice, fuel pressure change of local area will cause the change of fuel temperature and liquid-gas two-phase flow properties [2], therefore, it is more necessary to consider the influence of local temperature and pressure on fuel physical properties and on cavitations of injection orifice in the research process of internal flow refinement of injectors [3]. Current study on fuel temperature in injector mainly focuses on the steady-state effect of given temperature on fuel flow characteristics, He Xu studied cavitation flow characteristic in the nozzle under different fuel temperature by experiment [4], He Zhixia analysed fuel temperature effect on fuel injection process by means of experimental data [5], Zhao Jiahui explained the relationship between the steady-state temperature of injector, the injection pressure and the injection cycle [6], Su Haifeng researched the influence of different fuel temperature on multiple injection [7], these works only covered a short range of variation of the fuel temperature at the injector inlet. Due to smaller injection orifice, higher fuel pressure and shorter injection duration, it is difficult to measure fuel temperature in the injector in real time by test, R. Payri presented an adiabatic 1D model of common-rail injector and investigated the temperature variations of fuel [8], G. Strotos studied transient heating effects in high pressure injector in CFD modelling of the nozzle flow [9], study on continuous temperature change of fuel is important to explain the characteristics of inflow and spray formation, a fine thermal model of ECI is
established, the change of fuel temperature in different position is analyzed during injection, it provides basic data for the study of liquid-gas two-phase flow and cavitations in injector.

2. Electronic controlled injector
Electronic controlled injector (ECI) is an injector controlled by an electric actuator, which consists of needle valve coupling, control plunger, fuel inlet orifice, fuel return orifice and high-speed solenoid valve [10], as shown in Figure 1. When solenoid is energized, the solenoid of the injector drives the ball valve to open the fuel return orifice, high pressure fuel in the control room flows out of the fuel return orifice, fuel pressure in the control room drops rapidly, control plunger moves upward and drives the needle valve to lift, the fuel flows through the needle valve chamber and enters the injection orifice to start injection. When solenoid is powered off, the electromagnet pushes the ball valve to close the fuel return orifice, and the high-pressure fuel enters the control room through the fuel inlet orifice, fuel pressure in the control room rises and makes the control plunger move downward, and pushes the needle valve to seat, and prevented fuel to enter injection orifice, fuel injection stops.

![Figure 1. ECI structure.](image1)

![Figure 2. Fine thermal model of ECI.](image2)

3. Mathematical model of heat temperature
Because the injection duration is generally within 2ms and the injection speed is more than 500m/s, the thermodynamic process of fuel flow in the injection process is different. Firstly, when the fuel flows through small bore pipes and injection orifices in high speed, the very short flow time makes the fuel too late to exchange heat with the surrounding environment, the injection process is regarded as adiabatic flow. Secondly, there is no increase of external energy when fuel flows through pipes and orifices, its thermodynamic process is an irreversible isenthalpic process.

3.1. Model of friction generates heat
Due to the viscous effect of fuel, internal friction exists in the boundary layer flowing through the inner wall of fuel pipe and fuel passage, and internal friction forms a uniformly distributed internal heat source in the whole fluid. If the stress generated by internal friction is $\tau$, its calculation formula is as follows according to the resistance of the smooth tube turbulence.

$$\tau = \frac{\lambda}{8} \rho_f u^2$$ (1)

$$\lambda = 0.32 \left(\frac{2ru^2}{v}\right)^{-1/4}$$ (2)
Where: $\lambda$ is the thermal conductivity of fuel delivery, $\rho_f$ is the fuel density, $u$ is the fuel instantaneous flow rate, $r$ is the radius of fuel path, $v$ is the viscosity of fuel motion.

The heat generated in the whole fuel passage is expressed as [11]:

$$Q = \tau \pi d l u$$  \hspace{1cm} (3)

Where: $l$ is the length of the passage, $d$ is the diameter of the inner wall of the passage.

3.2. Model of fuel inlet and return orifice

When fuel flows through the small orifice, there will be throttling. There is no heat exchange and no hard work in the throttling process, when the change of kinetic energy and potential energy is ignored, the steady-state thermodynamic flow energy equation is used to describe the throttling process, in this state, the enthalpy of the inlet and outlet throttling devices is equal.

$$h_i = h_{out}$$  \hspace{1cm} (4)

$$T_{out} - T_{in} = \frac{V (p_{in} - p_{out})}{c_p}$$  \hspace{1cm} (5)

The formula for calculating the outlet temperature of the orifice is:

$$T_{out} = \frac{V (p_{in} - p_{out})}{c_p} + T_{in}$$  \hspace{1cm} (6)

Where, $h_i$ and $h_{out}$ are input enthalpy of throttling inlet and outlet respectively, $T_{in}$ and $T_{out}$ are temperature of throttling inlet and outlet respectively, $c_p$ is specific heat under a certain pressure, $V$ is fluid volume, $p_{in}$ and $p_{out}$ are the pressure of throttling inlet and outlet respectively.

3.3. Model of injector orifice

When the fuel is ejected through injection orifice, the increase of fuel kinetic energy at the outlet of the injection orifice cannot be ignored. Assuming that there is no exchange work in other parts of the injection system and nozzles, the enthalpy of the fuel in the injection orifice is always stable, and the enthalpy needs to change the balance kinetic energy. The enthalpy balance equation of the upstream and downstream ends of the injection orifice is followed.

$$h_{dw} (T_{dw}, p_{dw}) = h_{up} (T_{up}, p_{up}) - \frac{1}{2} \Delta u_o^2$$  \hspace{1cm} (7)

Where: $h_{dw}$ and $h_{up}$ are the enthalpy at the downstream and upstream end of the orifice respectively, $\Delta u_o$ is the actual speed difference between the upstream and downstream end of the orifice, $T_{dw}$, $p_{dw}$ is fuel temperature and pressure at the downstream end of the orifice, $T_{up}$, $p_{up}$ is fuel temperature and pressure at the upstream end of the orifice.

When considering the adiabatic fluid theory of velocity variation, the fuel temperature at the outlet of the orifice can be determined by the following formula [12]. Because of the existence of friction, the actual velocity is smaller than the theoretical velocity, and the velocity coefficient is related to the flow coefficient and the regional coefficient.

$$u_o = C_v C_a u_{th}$$  \hspace{1cm} (8)

Where: $C_v$ is the speed coefficient, $C_a$ is the orifice area contraction coefficient, $u_{th}$ is the Bernoulli theoretical speed

$$u_{th} = \sqrt{\frac{2 \Delta p}{\rho_f}}$$  \hspace{1cm} (9)

Where: $\Delta p$ is the fuel pressure difference between the upstream and downstream ends of the orifice, $\Delta p = p_{up} - p_{dw}$, $\rho_f$ is the fuel density.
When there is no cavitation in the nozzle orifice, \( C_d \) is the flow coefficient, \( C_d = C_v C_a \), the contraction coefficient of orifice area \( C_a = 1 \).

\[
\frac{1}{2} \rho_o v^2 = C_d^2 \frac{p_{up} - p_{dw}}{\rho_f} \quad (10)
\]

Substituting Equation (10) into Equation (7) is gotten

\[
h(T_{dw}, p_{dw}) = h(T_{up}, p_{up}) - C_d^2 \frac{p_{up} - p_{dw}}{\rho_f} \quad (11)
\]

3.4. Model of fuel thermodynamics

In order to express fuel enthalpy as a function of temperature and pressure, the relationship between enthalpy and internal energy is followed:

\[
h = e + \frac{p}{\rho_f} \quad (12)
\]

The general relationship between enthalpy and fuel temperature and pressure is followed:

\[
dh = c_p dT + \frac{1-\beta T}{\rho_f} dp \quad (13)
\]

Where: \( \beta \) is the elastic modulus of fuel.

4. Simulation modelling

It is necessary to establish a fine simulation model of the injector which covers the structure of each component, with the aid of AMESim (advanced modeling environment for performing simulation of engineering systems) simulation platform [13], which includes mechanical library, signal control library, hydraulic component library and thermal hydraulic component library, users can extract the smallest unit of the engineering system from the relevant component library, and describe the functions of all systems and components in the model. Electronic controlled injector with solenoid valve of Bosch company is used as simulation injector, a fine thermal simulation model of ECI is established by AMESim, as shown in Figure 2 of Page two.

In simulation model, the main parameters of injector are orifice diameter 0.188mm, orifice number 8, fuel inlet and outlet orifice diameter 0.23, 0.30mm, control plunge diameter 6mm, needle lift 0.3mm, injection pressure 50-145MPa. Injection pressure is set in parameter list of pressure source P, injection duration 0.7-1.5ms is given in electrical components Mod, environmental temperature is set as 20°C.

Injection temperature is measured on the high pressure common rail injection system test bench, test fuel is -20# diesel, test instrument includes Akribis II injection regularity instrument, pressure sensor, temperature sensor, oscilloscope, etc. Among these, the measuring range of Akribis II injection regularity instrument is 0-500mm³, the fuel temperature range is 20-160 °C, the resolution is 0.1mm³/s, and the accuracy is less than ± 0.1% of the full range.

**Table 1.** Fuel temperature between measurement and simulation of injector orifice/(°C).

| Pressure/MPa | 1.5ms measurement | 1.5ms simulation | relative error | 1.0ms measurement | 1.0ms simulation | relative error | 0.7ms measurement | 0.7ms simulation | relative error |
|-------------|------------------|------------------|---------------|------------------|------------------|---------------|------------------|------------------|---------------|
| 140         | 98.5             | 100.5            | 2.0%,         | 96.9             | 99.3             | 2.4%          | 92.5             | 96.6             | 4.4%          |
| 90          | 70.2             | 76.3             | 8.6%          | 69.4             | 74.8             | 7.5%          | 67.7             | 73.6             | 8.7%          |
| 55          | 56.8             | 60.2             | 6.0%          | 54.1             | 59.4             | 9.7%          | 53.7             | 58.3             | 8.6%          |

When the initial fuel temperature is 25 and 40 °C, the injection duration is 1.5, 1.0 and 0.7 ms, and the common rail pressure is 140, 90 and 55 MPa respectively, fuel temperature at the outlet of injector orifice is measured. The fuel temperature between the measurement and simulation at the injector orifice outlet is shown in Table 1 in the initial fuel temperature 40 °C, the relative errors in Table 1 are less than 10% [14]. It shows that the calculation result of the thermal model of ECI is reasonable.
5. Fuel temperature analysis

5.1. Fuel temperature of needle valve chamber
In the conditions of inlet fuel temperature of 40 °C and injection duration of 1.5ms, fuel temperature change in needle valve chamber corresponding to different injection pressure is shown in Figure 3. Figure 3 shows that under the terms of 140MPa injection pressure, when the injector does not inject, fuel temperature drops gradually from 40 °C to 30 °C, when the injector starts to inject fuel, fuel temperature in the needle valve chamber rises rapidly to 88.6 °C, then drops to 52.3 °C, the fuel temperature rises rapidly to 105.2 °C when the injection ends, finally drops gently to 78.8 °C. The change trend of fuel temperature in 90MPa is basically the same as that of 140MPa except that the maximum fuel temperature and stable temperature are reduced, which is 76.1 °C and 56.5 °C respectively, different injection pressure has a great influence on the maximum temperature and stable temperature in needle valve chamber. The reason is that the friction heat generated by the high-speed fuel in the needle valve cavity increases, the friction heat caused by the continuous reduction of the flow area through the needle clearance makes fuel temperature increase rapidly, fuel temperature drops with low-temperature fuel flowing in, the fuel in the needle valve chamber is compressed in a short time when the needle valve is seated, it makes the fuel temperature rise a little again, fuel temperature drops gently due to the effect of heat transfer.

When inlet fuel temperature is 40 °C and injection pressure is 140MPa, fuel temperature change of needle valve chamber under different injection duration is shown in Figure 4. Figure 4 shows that when injection duration is 1.5ms, the maximum fuel temperature in the needle valve chamber is 105.2 °C, and the final stable temperature is about 80 °C. When the injection duration is 1.0ms, maximum temperature and stable temperature of fuel have little change comparing with injection duration 1.5ms, fuel temperature difference corresponding to the two injection duration is about 3.6 °C, it indicates injection duration change has little effect on fuel temperature.

![Figure 3](image3.png)
**Figure 3.** Fuel temperature of needle chamber in different pressure.

![Figure 4](image4.png)
**Figure 4.** Fuel temperature of needle chamber in different injection duration.

5.2. Fuel temperature of control room
When injection pressure is 140MPa and injection duration is 1.5ms, fuel temperature change corresponding to different inlet fuel temperature is shown in Figure 5. Figure 5 shows that in the conditions of inlet fuel temperature 40 °C, fuel temperature is about 44 °C when the injector does not inject, fuel temperature rapidly drops from 44.0 °C to 40.7 °C when the injector starts to inject, and the plunger moves upward to raise the fuel temperature to 65.7 °C, fuel temperature slowly drops to 55.5 °C at the end of injection. In the terms of inlet fuel temperature 25°C, change trend of fuel temperature is similar with that of 40 °C. When the inlet fuel temperature is higher, fuel temperature in the control room will rise more. The temperature rise of the highest fuel temperature corresponding to the temperature of 25 °C and 40 °C is 24.9 °C and 25.7 °C respectively. The changes of two
temperature curves reflect that the fuel temperature in the control room experiences a process of rising first and then falling. The reason is that rapid fuel draining in the control room makes the plunger move up and the temperature in the control room rise. When fuel return orifice is closed, more fuel through inlet fuel orifice to enter the control room and make fuel temperature drop slowly.

Under the conditions of inlet fuel temperature of 40°C and injection duration of 1.5ms, the simulation curve of fuel temperature change in control room corresponding to different injection pressures is shown in Figure 6. Figure 6 shows that the stable temperature of the fuel in the control room corresponding to the injection pressure of 90MPa and 140MPa is 52.5 °C and 63 °C respectively, indicating that the high injection pressure makes the fuel temperature rise significantly.

5.3. Fuel temperature of return chamber

In the conditions of pressure 140MPa and injection duration 1.5ms, change curve of fuel temperature in return chamber is shown in Figure 7. Figure 7 shows that when the inlet fuel temperature is 25 °C and 40 °C, the fuel temperature rises to 65.7 °C and 90.9 °C respectively in the beginning of injection, and then slowly drops to 59.1 °C and 80.4 °C. The reason is that fuel temperature will continue to rise when the fuel leaks through the fuel return orifice, and then drops due to the heat exchange between the fuel and its wall.

6. Temperature effect

The variation of fuel temperature and pressure will directly cause the change of fuel density, when fuel pressure and temperature in different positions are in transient state, the fuel density in different areas will be different. According to density change with pressure and temperature, the fuel density is expressed as follow [15]:

\[ \rho = \rho_0 \left( \frac{P}{P_0} \right)^{\frac{1}{\gamma}} \]
\[ \rho(p,T) = (C_6 + C_7 T + C_8 T^2) \exp \left[ C_5 (p + C_4 - C_7 T)^{C_6} \right] \]  
(14)

Where:  
\( C_6 = 199.26971, \quad C_7 = -0.101948, \quad C_8 = 0.00019149, \quad C_5 = 0.5431, \quad C_4 = 111061456.8, \quad C_3 = 469742.34, \quad C_2 = 0.053, \)  
T is fuel temperature, °C; \( p \) is fuel pressure, Pa.

When the temperature is 50-100 °C and the injection pressure is 55-140mpa, the density of -20 diesel oil is shown in Table 2. Data in Table 2 shows that the density of fuel increases with the increase of pressure at a certain temperature, the higher the pressure, the less the increasing trend, the density of fuel decreases with the increase of temperature under a certain pressure.

### Table 2. Density of -20 diesel in part temperature and pressure/(kg·m⁻³).

| Pressure/MPa | Temperature/°C | 50  | 60  | 70  | 80  | 90  | 100 | 110 |
|--------------|---------------|-----|-----|-----|-----|-----|-----|-----|
| 55           |               | 845 | 840 | 835 | 829 | 824 | 820 | 816 |
| 75           |               | 854 | 849 | 843 | 838 | 833 | 827 | 821 |
| 95           |               | 862 | 857 | 851 | 846 | 841 | 835 | 829 |
| 100          |               | 864 | 859 | 853 | 848 | 844 | 838 | 833 |
| 110          |               | 867 | 863 | 858 | 852 | 847 | 842 | 837 |
| 120          |               | 871 | 866 | 860 | 856 | 851 | 845 | 840 |
| 140          |               | 878 | 872 | 868 | 863 | 857 | 852 | 844 |

7. Conclusions

1) In the injection process, fuel temperature of the needle valve chamber experiences a stable change process after fast up and down, fuel temperature rises rapidly due to the heat-releasing of throttling action, fuel temperature drops rapidly with the subsequent low-temperature fuel flowing in, injection pressure decrease only affects maximum fuel temperature and stable temperature.

2) In the injection process, fuel temperature in the control room experiences a change process of first rising and then falling, return orifice opening makes the plunger move up and temperature in the room increases, fuel temperature slowly drops with return orifice closing and fuel entered control room increasing.

3) Temperature directly affects the change of fuel density under different pressures, the density of fuel decreases with the increase of temperature under a certain pressure.

References

[1] Francesco Concetto and Umberto Ferrara *SAE 2018-01-0282* (Warrendale: American SAE) pp 5
[2] Qiu T, Song X and Lei Y 2016 *Fuel* 01779
[3] Zhong W X, He Z X, Wang Q and Tao X C 2015 *Transactions of CSICE* 03 238
[4] He X, Li Y K and Shi Y H 2018 *Transactions of Mechnanical Engineering* 02 89
[5] He Z X, Zhang X and Tao X C 2017 *Transactions of CSICE* 05 399
[6] Zhao J H, Wei K B and Yue P F *SAE 2019-01-0276* (Warrendale: American SAE) pp 8
[7] Su H F, Zhang Y T and Zhang J W 2013 *J Beijing Institute of Technology* 33 1027
[8] R Payri, F J Salvador and M Carreres *SAE 2018-01-0275* (Warrendale: American SAE) pp 16
[9] G Strotos, P Koukouvounis and A Theodorakakos 2015 *Int. J. Heat Fluid Fl.* 51 257
[10] Park Junlyu, Jang Ji Hwan and Park Sungwook 2015 *Oceans Engineering* 104 580
[11] Tao W Q 2006 *Heat Transfer Theory* (Xi’an: Northwestern Polytechnical University Press) pp 210
[12] F J Salvador, J Gilmero and M Carreres 2016 *Energy conversion & management* 114 364
[13] Fu Y L and Qi X Y 2011 Reference manual of LMS Imagine.Lab AMESim system modeling and simulation (Beijing: Beihang University Press) pp 125
[14] John D Anderson 2010 *Computational Fluid Dynamics. The Basics with Applications* (Beijing: China Machine Press) pp 120
[15] Zhang J M, Zhang W G and Wang Y W 2005 *Chin. J. High Press. Phys.* 19 41