http://ansinet.com/itj

ITJ

ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 13 (9): 1648-1655, 2014
ISSN 1812-5638 / DOI: 10.3923/itj.2014.1648.1655

Visualization Simulation Research of Fuel Common Rail System of Marine Intelligent Diesel Engine

Shen Haosheng, Zhang Jundong and Cao Hui
Marine Engineering College, Dalian Maritime University, No. 1, Linghai Road, Dalian, 116026, China

Abstract: To better improve the ability and skill of operating marine electronically controlled diesel engine for marine engineers, chosen 7RT-FLEX60C diesel engine as the study object, a kind of visualization simulation system is developed for its fuel common rail system. The working principle of fuel common rail system is analyzed and its mathematical model is established based on the continuity equation and motion equation of fluid mechanics, the mathematical model is simulated and analyzed by applying MATLAB/Simulink. Based on the mathematical model, the 2D visualization simulation system is developed by using high-level computer programming language visual C# which can provide man machine interactive function and main parameters are real-time refreshed based on the mathematical model. The results showed that the visualization simulation system can be used to train marine engineers effectively and systematically.

Key words: Marine electronically controlled diesel engine, visualization simulation system, mathematical model, engine room simulator, fuel common rail system

INTRODUCTION

Introducing electronically controlled technique into the field of marine high-power low-speed two-stroke diesel engine is another major revolution for marine diesel technique which makes marine internal combustion engine enter a new stage. Marine electronically common rail engine is widely used for low fuel consumption, intelligence, low pollution, compact structure, safety, reliability and other advantages (Lin *et al*., 2012) which needs marine engineer get a full understanding for the working principle and working process of electronically controlled common rail engine, so it is necessary to develop a kind of simulation system of electronically controlled common rail engine to train marine engineers and students of maritime colleges.

This study gives a two-dimensional visualization system for fuel common rail system of 7RT-FLEX60C diesel engine developed by Wärtsilä. Firstly, the mathematical model is built for fuel common rail system including high-pressure fuel pump, intermediate fuel accumulator, fuel common rail, ICU (Injection Control Unit), injector. Secondly, the mathematical model is calculated by using MATLAB/Simulink to get the changing trend of main parameters, such as plunger chamber pressure, plunger lift displacement, intermediate accumulator and common rail fuel pressure, ICU fuel quantity piston displacement, nozzle chamber pressure, etc. Finally, the 2D visualization simulation system is developed according to the mathematical model we have built. This simulation system can not only be used for training but also be used for the researching and optimizing of common rail system.

System framework: The whole visualization simulation system consists of two parts: Mathematical models, 2D visualization simulation interface, as shown in Fig. 1 (Gan *et al*., 2012a). Mathematical model is the core of the whole simulation system which is used to simulate the

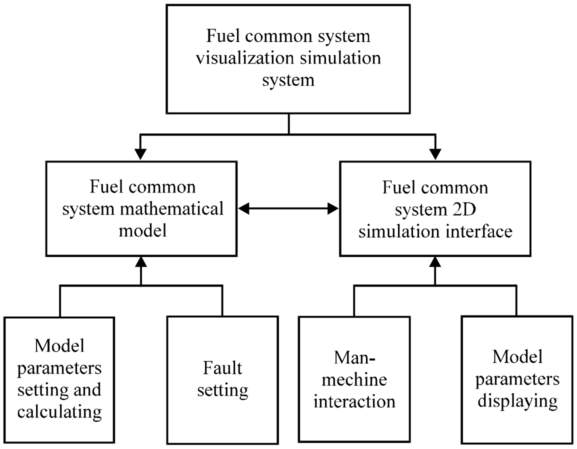

Fig. 1: System frame diagram

Corresponding Author: Shen Haosheng, Marine Engineering College, Dalian Maritime University, No. 1, Linghai Road, Dalian, 116026, China running process or fault condition of fuel common rail system to provide data to the 2D visualization simulation interface. A 2D visualization simulation interface is the implementation of the mathematical models established which provides the function of operating and the function of setting and displaying main parameters of the system. At the same time, the initial conditions and faults can also be set in the 2D visualization system.

Working principle of fuel common rail system: The specific marine electronically controlled diesel engine concerned in this study is SULZER 7RT-FLEX60C developed by Wärtsilä which is widely used on board. Its whole common system consists of fuel oil common rail system, servo oil common rail system (Cao *et al*., 2013). In this study only the fuel common rail system model is derived in detail.

Figure 2 and 3 show the schematic diagram offuel common rail system (Wang *et al*., 2013). The whole system mainly consists of high-pressure fuel pump, intermediate fuel accumulator, fuel rail, ICU (injection control unit) and injector. The gear located in the crankshaft output side drives the camshaft to implement the boost process of fuel, the cam is a kind of 3-lobe cam

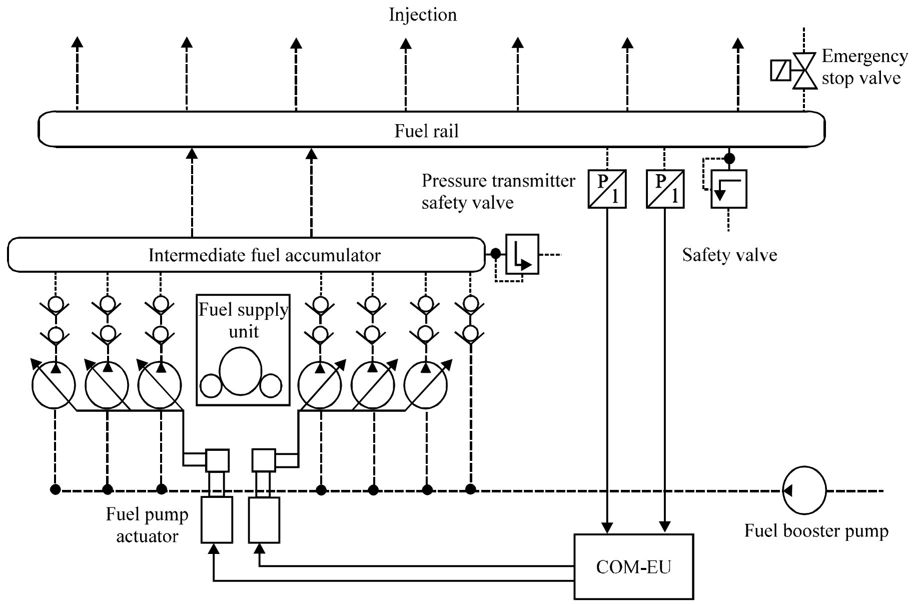

Fig. 2: Working principle of fuel common rail system

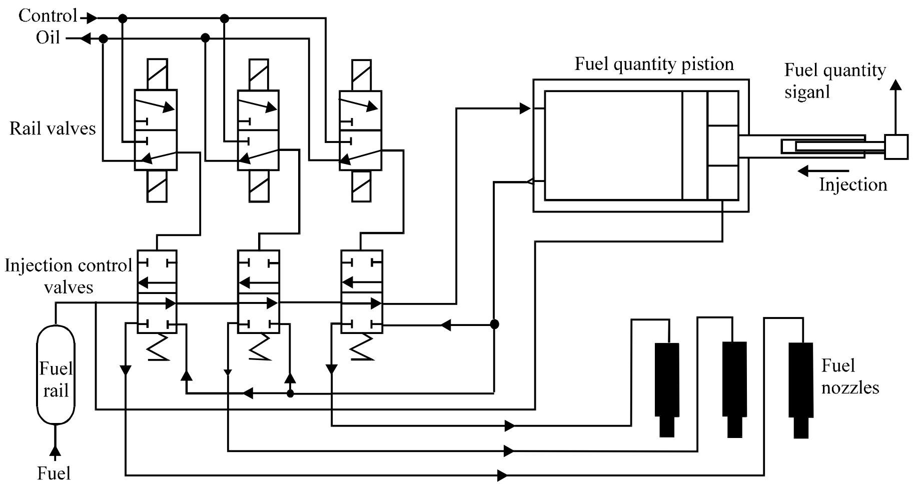

Fig. 3: Working principle of injection control

which means the fuel boost process is implemented by three times when the cam rotates a period, this kind of designation can reduce the fuel pressure fluctuations and the driving torque fluctuations, then the fuel by boosting flows into the intermediate fuel accumulator, the intermediate fuel accumulator is set as a pressure buffer to absorb the fuel pressure fluctuations, at the same time, a safety valve is set on the intermediate fuel accumulator, making the fuel flows into the overflow tank once the fuel pressure in the intermediate fuel accumulator is higher than regulation value, the intermediate fuel accumulator and fuel rail are connected by two standpipes, then fuel supplied by the intermediate fuel accumulator in the fuel rail is distributed to each ICU, when the ICU fuel rail valve gets the injection signal, the rail valve will open to implement the set-timing, set-quantitative fuel injection.

Mathematical model: During mathematics description of the physical model, this paper gives some suppositions as follows (Cao *et al*., 2013; Seykens *et al*., 2005):

- At the start of simulating, each volumetric chamber is full of fuel and has a certain initial pressure value Because the mathematical model of fuel common rail valve is relatively complicated, we consider its motion as instantaneous motion which can be treated as a switching value
- As the return stroke of the quantity piston of the ICU has no influence on the injection process, so we assume that the quantity piston will return the initial position instantaneously when the injection signal disappears
- The chamber volume is centralized, ignoring the pressure propagation time, everywhere has an equal pressure under the same moment
- Ignoring the leakage between the mating surface and the local loss in the outlet and inlet. The mathematical model of fuel common rail system developed in this study is based on the continuity equation and the motion equation of the fluid mechanics

High-pressure fuel pump: The high-pressure fuel pump (7RT-flex60C diesel engine has six high-pressure fuel pumps, these pumps are divided into two rows which can be named “AA row” and “B row”, the two rows are located separately at the each side of the intermediate fuel accumulator), is an single plunger pump which is driven by the crankshaft via two intermediate gears to provide the camshaft the power, at the same time, the displacement can be adjusted by changing the position of the rack:

$$h(a) = C_0 + C_1\beta^2 + C_2\beta^6 + C_3\beta^8 + C_4\beta^{10} \tag{1}$$

$$\beta = 1 - a/a_B \tag{2}$$

where, $h(\alpha)$ is cam lift displacement; α is cam angle; C_0 is maximum lift displacement of the cam; α_B is cam half wrapping angle; C_1, C_2, C_3, C_4 is undetermined coefficient of the equation, determination mathematical equation refers to literature (He and Li, 2008).

The flow of fuel within single high-pressure fuel pump meets the requirement of continuity equation:

$$\frac{V_{plu}}{E}\frac{dP_{plu}}{dt} = A_{plu}\frac{dh_{plu}}{dt} - Q_{plu\_out} \tag{3}$$

$$Q_{plu\_out} = u_{ifa\_in}A_{ifa\_in}\sqrt{\frac{2}{\rho}\left|P_{plu} - P_{ifa}\right|} \tag{4}$$

where, V_{plu} is a single plunger cavity volume; E is fuel elastic model; P_{plu} is the fuel pressure in the plunger chamber; A_{plu} is the cross-sectional area of the plunger; h_{plu} is the plunger lift displacement; Q_{plu_out} is the flow from single plunger into intermediate fuel accumulator; μ_{ifa_in}, A_{ifa_in} is inlet flow coefficient and area of the intermediate fuel accumulator; ñ is fuel density in the plunger chamber; P_{ifa} is the fuel pressure in the intermediate fuel accumulator.

Intermediate fuel accumulator: Supposing that the intermediate fuel accumulator is full of fuel, the inflows and outflows of fuel meet continuity equation as:

$$\frac{V_{ifa}}{E_{ifa}}\frac{dP_{ifa}}{dt} = \sum Q_{plu\_out} - Q_{ifa\_out} - Q_{ifa\_osv} \tag{5}$$

$$Q_{ifa\_out} = u_{ifa\_out}A_{ifa\_out}\sqrt{\frac{2}{\rho}\left|P_{ifa} - P_{fcr}\right|} \tag{6}$$

$$Q_{ifa\_osv} = du_{ifa\_osv}A_{ifa\_osv}\sqrt{\frac{2}{\rho}P_{ifa}} \tag{7}$$

$$d = \begin{cases} 1, & P_{ifa} > P_{set} \\ 0, & P_{ifa} < P_{set} \end{cases} \tag{8}$$

where, V_{ifa} is the volume of intermediate fuel accumulator; E is fuel elastic model; Q_{ifa_out} is the flow from intermediate into the fuel common rail; Q_{ifa_osv} is the flow out of the intermediate fuel accumulator via safety valve; μ_{ifa_out}, A_{ifa_out} is the outlet coefficient and area of the intermediate fuel accumulator; P_{fcr} is the fuel pressure in the fuel common rail; μ_{ifa_osv}, A_{ifa_osv} is the discharge coefficient and area of safety valve; ñ is fuel density in the intermediate fuel accumulator; P_{set} is the open pressure of the safety valve.

Fuel common rail: As same as the intermediate fuel accumulator, the fuel common rail is also supposed to be full of fuel and then the inflows and outflows of fuel meet continuity equation as:

$$\frac{V_{fcr}}{E}\frac{dP_{fcr}}{dt} = \sum Q_{ifa\_out} - \sum Q_{fcr\_out} \tag{9}$$

where, V_{fcr} is volume of fuel common rail; Q_{fcr_out} is the flow from fuel common rail into ICU.

Injection control module: The injection control module in fuel common rail system, as shown in Fig. 2, including ICU (injection control unit) and injector.

The displacement equation of ICU fuel quantity piston:

$$m_{icu\_fqp}\frac{d^2h_{icu\_fqp}}{dt^2} = P_{fcr}A_{icu\_fqp\_b} - P_{icu}A_{icu\_fqp\_f} \tag{10}$$

where, m_{icu_fqp} is mass of the fuel quantity piston; h_{icu_fqp} is displacement of fuel quantity piston; P_{icu} is the fuel pressure in the front chamber; $A_{icu\_fqp\_b}$, $A_{icu\_fqp\_f}$ is the back and front area of the quantity piston.

The continuity equation of the front chamber of the ICU fuel quantity piston:

$$\frac{V_{icu}}{E}\frac{dP_{icu}}{dt} = A_{icu\_fqp\_f}\frac{dh_{icu\_fqp}}{dt} - Q_{icu\_out} - d_1\mu_{icu\_osv}A_{icu\_osv}\sqrt{\frac{2}{\rho}P_{icu}} \tag{11}$$

$$Q_{icu\_out} = d_2\mu_{fiv}A_{fiv}\sqrt{\frac{2}{\rho}\left|P_{icu} - P_{fiv}\right|} \tag{12}$$

$$d_1 = \begin{cases} 1, & P_{icu} > P_{set} \\ 0, & P_{icu} < P_{set} \end{cases} \tag{13}$$

$$d_2 = \begin{cases} 1, & \text{Injection signal exists} \\ 0, & \text{Injection signal not exists} \end{cases} \tag{14}$$

where, V_{icu} is volume of the front chamber; P_{icu} is the fuel pressure in the front chamber; Q_{icu_out} is the flow from ICU into nozzle chamber of the injector; μ_{icu_osv}, A_{icu_osv} is the outlet coefficient and area of safety valve of the ICU; ñ is the fuel density in the front chamber; μ_{fiv}, A_{fiv} is the inlet coefficient and area of nozzle chamber of the injector; P_{fiv} is fuel pressure in the nozzle chamber of the injector.

The displacement equation of the needle valve of the injector (Gauthier *et al*., 2005; Seykens *et al*., 2005):

$$m_{fiv}\frac{d^2h_{fiv}}{dt^2} = (A_{fiv\_up} - A_{fiv\_down})P_{fiv} - k_{fiv}(h_{fiv} + h_{fiv\_pre}) \tag{15}$$

where, m_{fiv} is mass of the needle valve; h_{fiv} is displacement of the needle valve; A_{fiv_up}, A_{fiv_down} is the upper and lower side are of the needle valve; P_{fiv} is the fuel pressure in the nozzle chamber; k_{fiv} is stiffness coefficient of spring of the injector; h_{fiv_pre} is pre-compression quantity of the spring.

The continuity equation of the nozzle chamber of injector:

$$\frac{V_{fiv}}{E}\frac{dP_{fiv}}{dt} = Q_{icu\_out} - A_{fiv\_down}\frac{dh_{fiv}}{dt} - eN_{fih}\mu_{fih}A_{fiv}\sqrt{\frac{2}{\rho}\left|P_{fiv} - P_{cyl}\right|} \tag{16}$$

where, V_{fiv} is volume of the nozzle chamber; N_{fiv} is the number of nozzle hole; μ_{fih}, A_{fih} is the flow coefficient and area of the nozzle hole; P_{cyl} is the combustion gas pressure in the cylinder.

Calculation of simulation: Parameter Initialization. Ode4 algorithm is applied when simulating in MATLAB/Simulink, the calculating step length is 0.00001, the load of the engine is 99.97%, the rack position of the high-pressure fuel pump is 66.66% of full range, the rotation speed of camshaft is 570 rpm, the initial fuel pressure in intermediate accumulator and common rail is 98.75 and 89.6MPa.

Analysis of simulation results: Figure 4 is the simulation curve of plunger pressure and plunger lift displacement of a single high-pressure pump in the "A row". We can see that the lift and return stroke curve is relatively soft and stable which meets the requirements of high efficiency and fuel supplying for the high-pressure pump. When the plunger is at the beginning of lifting, the fuel pressure in the plunger chamber increases at a relatively fast speed. The delivery valve will open when the fuel pressure in the plunger chamber is greater than in the intermediate accumulator as the lifting of plunger. But the plunger is still at the stage of lifting at the same time, so the fuel pressure in the plunger chamber will still increase until the flow into intermediate accumulator via the delivery valve is greater than the flow generated by the lifting of plunger. When the plunger is at the stage of return stroke, the delivery valve will close with the decreasing of fuel pressure in the plunger chamber, at last the pressure will decrease gradually to initial pressure.

Figure 5 shows the injection pulse of each cylinder, the injection sequence is 1-3-5-7-2-4-6. Figure 6 is the

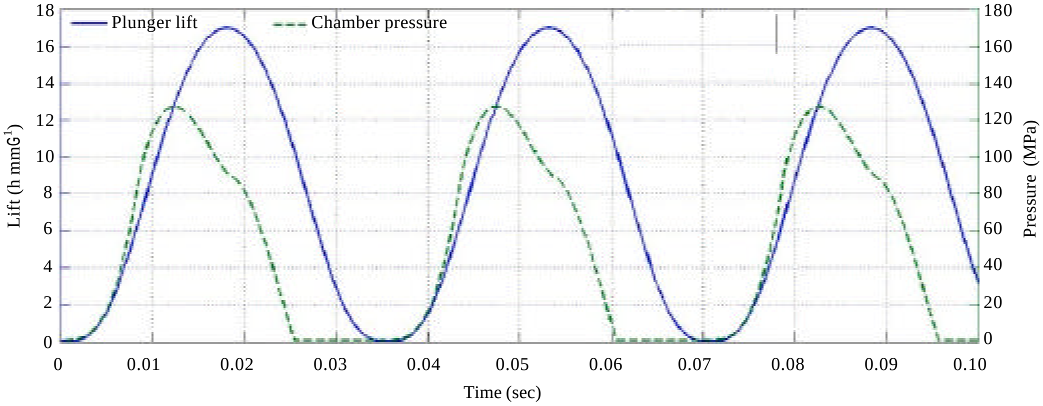

Fig. 4: Plunger lift and chamber pressure of single fuel pump in the “A row”

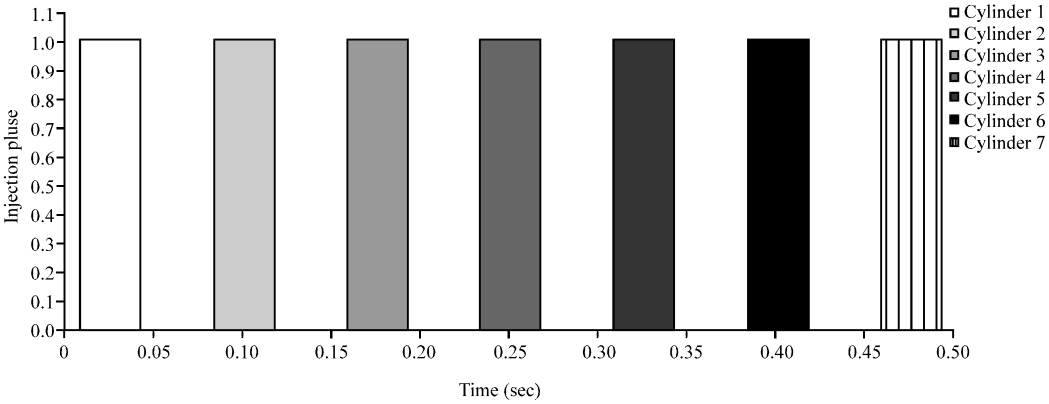

Fig. 5: Injection pulse of each cylinder

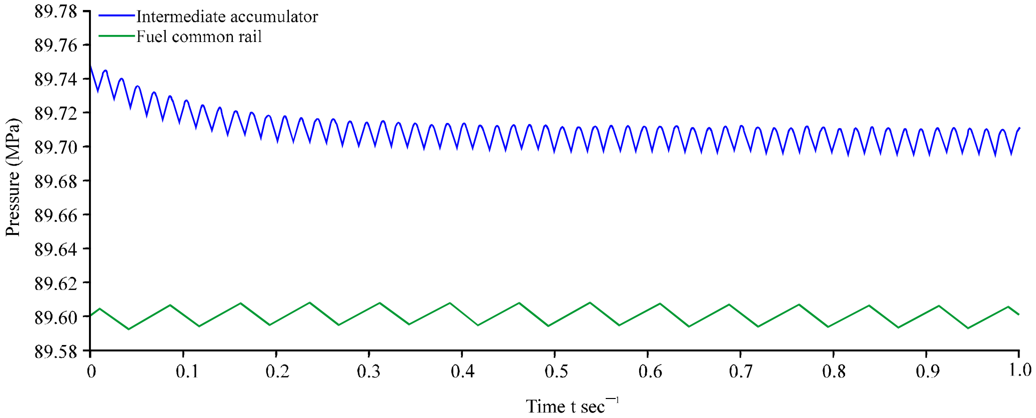

Fig. 6: Pressure in intermediate accumulator and fuel common rail

simulation curve of fuel pressure in the intermediate accumulator and fuel common rail, in the figure we can see that the pressure fluctuation frequency in the intermediate accumulator is as same as the fuel supplying frequency of the high-pressure and the pressure fluctuation frequency in the fuel common rail is as same as the injection pulse

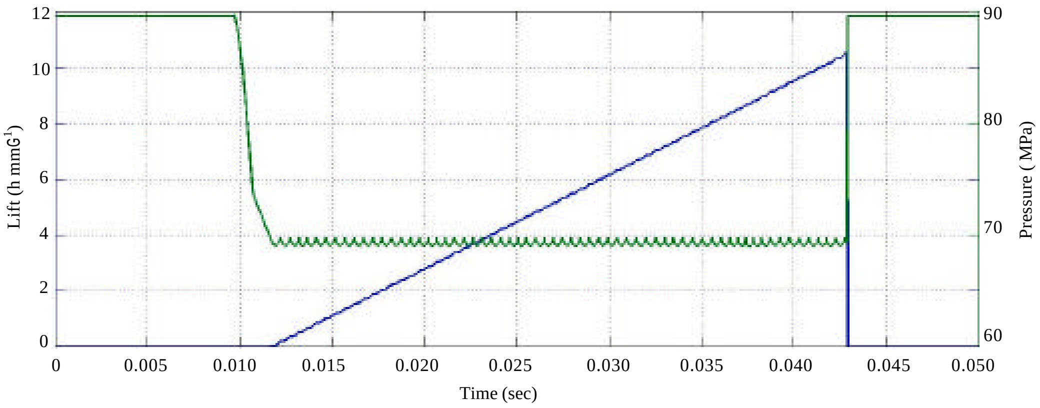

Fig. 7: Fuel quantity piston displacement and fuel pressure in the front chamber of single ICU

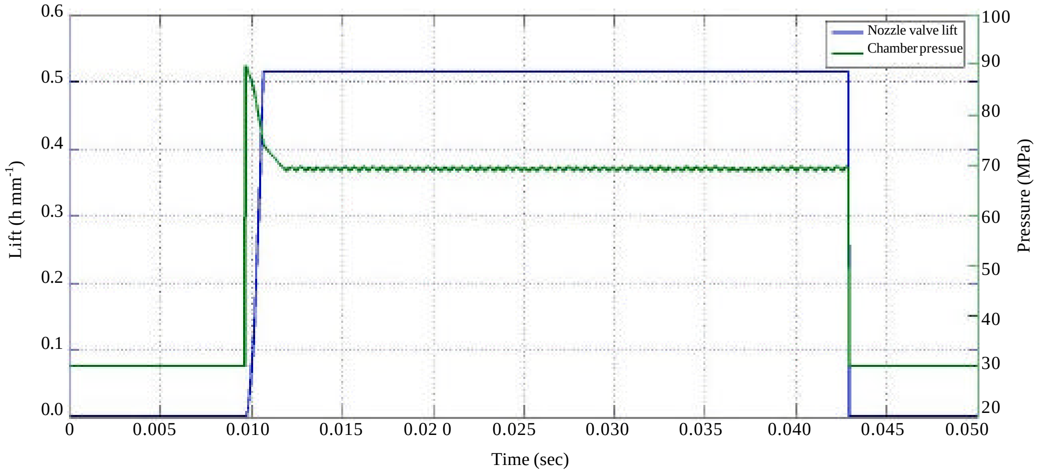

Fig. 8: Nozzle valve lift displacement and chamber pressure of single injector

frequency. At the same time, the Fig. 6 shows that the fuel pressure fluctuation in the intermediate accumulator and fuel common rail is less than 0.02 MPa when the whole system is stable which meets the requirements that the pressure fluctuation of common fuel rail should be less than 5%.

Figure 7 is the result of simulating the displacement of single ICU fuel quantity piston and the fuel pressure in the front chamber. As the return stroke of the fuel quantity piston has no influence on the injection process, so we just take the pushing stroke into consideration when modeling the pressure in the front chamber which is showed in Fig. 7 that the fuel quantity piston will instantaneously return to its initial position as soon as the injection pulse ends. When the first injection pulse arrives at 9.7 msec, the fuel common rail valve moves to make the control lubrication oil act on the button of the injection control piston which leads the front chamber of the fuel quantity piston connects with nozzle chamber of the injector, so the fuel pressure in the front chamber will decrease rapidly which leads the fuel pressure in the front chamber less than that in the back chamber and then the fuel quantity piston will move with the exist of pressure difference. In addition, in the figure the fuel quantity piston does not move instantaneously when the fuel pressure decreased in the front chamber, that is because the back and front area of the piston is different.

Figure 8 is the simulation curve of nozzle valve lifting displacement and nozzle chamber pressure of the injector. When modeling the fuel pressure in the nozzle chamber, we ignore the influence of the return stroke of the nozzle valve on the injection process which is shown in Fig. 8

that the nozzle valve will return its initial position instantaneously when injection pulse ends. In the Fig. 8 we can see that when the first injection pulse arrives at 9.7 msec, the fuel common rail valve moves to make the control lubrication oil act on the button of the injection control piston which leads the front chamber of the fuel quantity piston connects with nozzle chamber of the injector, so the fuel pressure in the nozzle chamber will increase rapidly. When the fuel pressure in the nozzle chamber is greater than 37.5 MPa (valve lifting pressure of the nozzle valve), the nozzle valve will be lifted at 9.9 msec and then will gradually reach to the full-opening state with increase of fuel pressure in the nozzle chamber. In the Fig. 8, we can also find that the pressure fluctuation in the nozzle chamber is as same as that in the front chamber of the ICU when the nozzle chamber and the front chamber of the ICU are connected.

Development of 2D visualization simulation software: After establishing the mathematical model of the fuel common rail system and analyzing the simulation result, the mathematical model established is programed and the whole system is displayed in the terms of 2D visualization interface by using Visual C# computer programming language, the layout of the interface is reasonable which can demonstrate the working process and main system parameter of the system clearly. Using the technique support-GDI+ (Graphics Development Interface Plus) specially for graphic creation supplied by. NET 2010 to develop controls such as instrument button, light, pipe, rail valve, etc. (Gan *et al*., 2012b; Yan and Chang, 2006) which can be used for man machine interactive and dynamic displaying of the parameter.

Figure 9 shows the fuel common rail system simulation interface, in which the valves, fuel oil supply pump, emergency stop valve can be operated for opening or closing. Fuel common solenoid valve can open or close according to the injection pulse sent from the control system. The circle in the top left corner can show which injectors are injecting. The pipes in this system are drawn in the form of controls which can show the flow state of fuel dynamically. The main parameters are refreshed real-time according to the calculation of models. The functions of fuel oil transfer, starting and stopping of pumps, emergency stop of main engine, injection control and safety protection are realized and simulated likely to the real ship. Fault setting is also realized by adding parameters to the simulation models which can be used to train and promote the ability of fault detecting, fault solving, fault reset for students and marine engineer (Sun *et al*., 2005).

As the Fig. 10, a kind of common rail simulation system in the forms of hardware is also developed it is connected with the software interface by establishing communications protocol. Trainers can operate either the

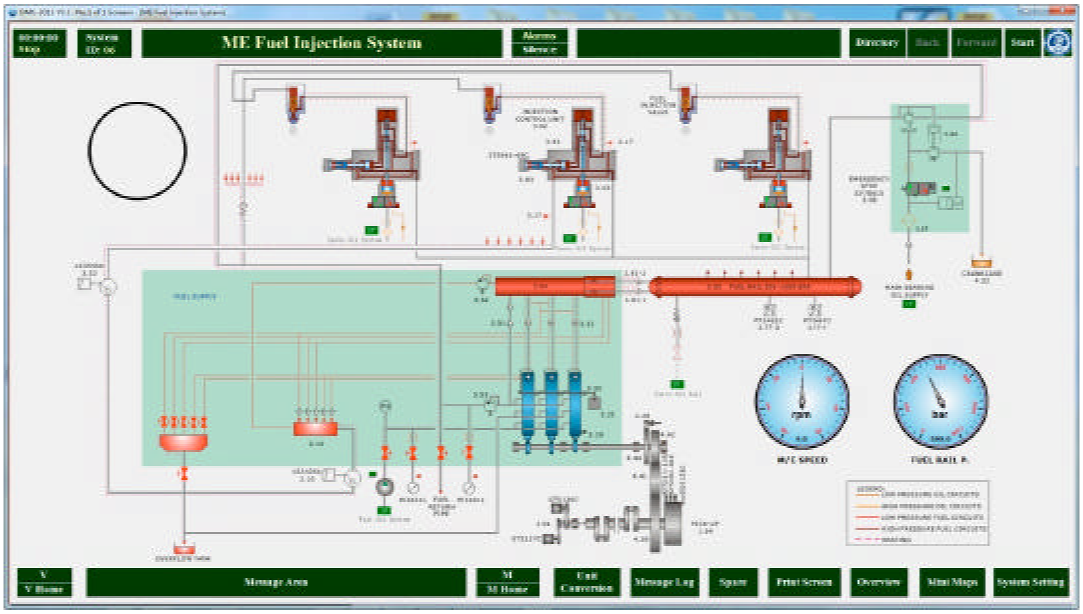

Fig. 9: Interface of fuel common rail system

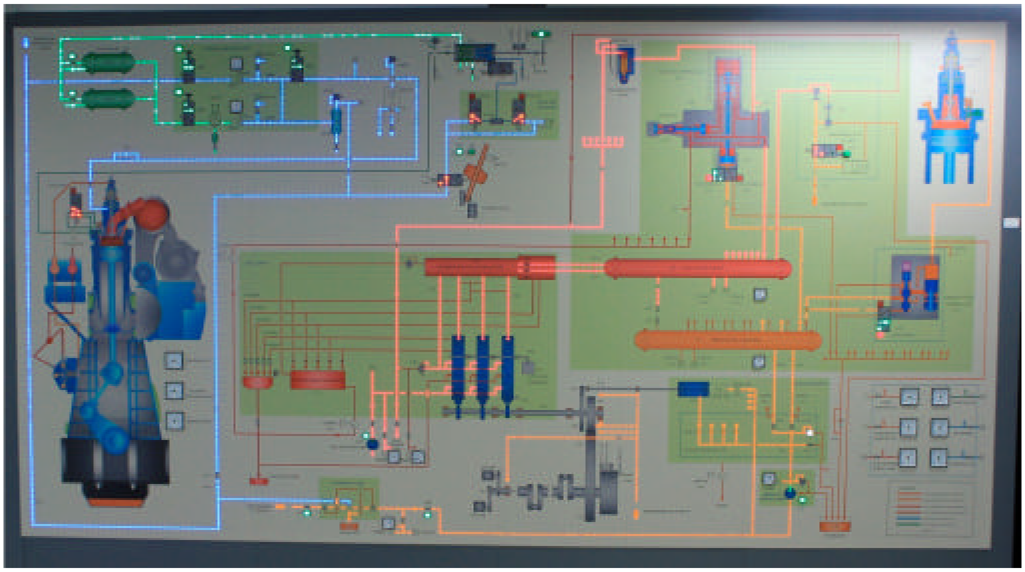

Fig. 10: Common rail simulation in the forms of hardware

software interface or the hardware simulation system which can achieve the effect of synchronous display and operation.

CONCLUSION

In this study the working principle of fuel common rail system of 7RT-Flex60c diesel engine is researched. The mathematical model of the fuel common rail system is established by using modular method, including high-pressure fuel pump, intermediate accumulator, fuel common rail, ICU, injector. Simulation results show that the model established can reflect the working process of fuel common rail sys tem and the change trend of main parameters. Based on the models, a kind of two-dimensional visualization simulation system is developed. From the study, we can find that the interface is friendly and professionally which is suitable for the training of students in the maritime college and marine engineers in the ships. What is important is that the simulation system has already been applied in the VLCC (very large crude carrier) full mission engine room simulator.

ACKNOWLEDGMENTS

The study is supported by the National Natural Science Foundation of China under Grant No. 51179102. The authors are grateful for these supports.

REFERENCES

Cao, H., B. Jia and J. Zhang, 2013. Modeling and analysis of servo oil common rail system of marine intelligent diesel engine. J. Applied Sci., 13: 5012-5019.

Gan, H., J. Zhang and H. Zeng, 2012a. A novel marine auxiliary boiler simulation system integrated three-dimensional simulation. Int. J. Digital Content Technol. Appl., 6: 561-571.

Gan, H., J. Zhang and H. Zeng, 2012b. Development of main boiler simulation system for LNG ship. Int. J. Adv. Comput. Technol., 4: 466-475.

Gauthier, C., O. Sename, L. Dugard and G. Meissonnier, 2005. Modelling of a diesel engine common rail injection system. IFAC, 16: 188-193.

He, Z. and X. Li, 2008. Optimization design of the cam profile of a High-order polynomial using MATLAB. Mech. Sci. Technol. Aerospace Eng., 27: 1141-1144.

Lin, K., P. Wu and P. Li, 2012. Volumetric model simulation for common rail electronically controlled marine diesel engine. J. Dalian Maritime Univ., 38: 69-72.

Seykens, X.L.J., L.M.T. Somers and R.S.G. Baert, 2005. Detailed modeling of common rail fuel injection process. MECCA, 3: 30-39.

Sun, C., D. Zhao and C. Zhang, 2005. Researching and implementation of fault simulation of marine power station in DMS-2002 marine power plant simulator. China Shiprepair, 4: 8-10.

Wang, Y.J., J.F. Chen and S.Q. Li, 2013. Fuel common rail injection system of RT-Flex marine intelligent diesel engine and its simulation dynamic model. Adv. Mater. Res., 732-733: 23-28.

Yan, Y.H. and X. Chang, 2006. Implementation of dynamic graphical display using GDI+ in C#. Comput. Technol. Dev., 16: 117-118, 232.