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Application of neural network in the study of combustion rate of natural gas/diesel dual fuel engine*

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Abstract: In order to predict and improve the performance of natural gas/diesel dual fuel engine（DFE），a combustion rate model based on forward neural network was built to study the combustion process of the DFE. The effect of the operating parameters on combustion rate was also studied by means of this model. The study showed that the predicted results were good agreement with the experimental data. It was proved that the developed combustion rate model could be used to successfully predict and optimize the combustion process of dual fuel engine.

Key words: Dual fuel engine，Forward neural network，Rate of combustion
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INTRODUCTION

With the world facing serious pollution of environment and inevitable declining resources of energy，the development of lower pollution and lower energy consumption automobile has become a major research target. The high efficiency and low pollution natural gas-diesel dual fuel engine（DFE）for the city bus can reduce obviously the pollution of the city air，especially for the big cities. So research on the combustion process of DFE is very important.

In general，the combustion process of the engine is a synthesize process of the physics and chemistry（Agrawal et al.，1998；Fei et al.，1992；Karim et al.，1988；Hoekstar et al.，1996；Yan et al.，1992；2001a；Zhang，2000）. The authors do not know if there is a suitable analytic function to describe the complicated combustion process，especially for the DFE. In this paper a new combustion model based on the forward neural network theory is proposed for the DFE.

NEURAL NETWORK COMBUSTION RATE MODEL

Inside the cylinder，the energy absorbed by the medium is the difference between the energy released by fuel and the energy transferred to the wall of the combustion chamber of the engine.

$$\frac{dQ}{d\Phi}=\frac{dQ_f}{d\Phi}-\frac{dQ_w}{d\Phi} \qquad (1)$$

Where $dQ/d\Phi$、$dQ_f/d\Phi$、$dQ_w/d\Phi$ are the combustion rate（heat release rate），heat absorbed by the medium and heat transferred to the wall of the combustion chamber.

The level of engine performance depends on the combustion as quantified usually by the combustion rate. Up to now the quantification of combustion rate of the engine is still dependent on empirical and semi-empirical formulas based on the assumptions. Some common combustion rate formulas cannot satisfactorily be used for calculation of the combustion process during the transitional operating conditions of the engine. In this paper based on experimental data and using the forward neural network theory，a combustion rate model is established for calculating the combustion process of the DFE，especially under transitional operating conditions（Liu，2000；Zhou et al.，2001；Karim，1991）.

The relationship between the input and output in this model is

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$$\mathrm{d}Q/\mathrm{d}\Phi = f(n, M_e, G_m, T_w, G_g) \quad (2)$$

Where, $\mathrm{d}Q/\mathrm{d}\Phi$ is combustion rate (J/CA); n is rotative speed (r/min); M_e is load (Nm); G_m is pilot (kg/h); T_w is temperature of cooling water (K); G_g is quantity of natural gas (butterfly valve open %).

As the number of hidden layer element can arbitrarily assumed in the forward neural network, a three-layer neural network may be used and through certain training cycles it can be approach the arbitrary precision continuous function. A model with three-layer forward neural network was established as shown in Fig.1. The input data are rotative speed, load, pilot, temperature of cooling water, quantity of natural gas and the output is combustion rate $\mathrm{d}Q/\mathrm{d}\Phi$. In Fig.1, $\boldsymbol{P}$ is matrix ($R \times Q$). Where R is the number of parameter (number of input layer element), Q is sampler number of each input parameter, S_1 is the nodes of the hidden layer and a_1 is output of hidden layer or input for the next hidden layer ($S_1 \times R$ matrix). S_2, a_2, $S_2 \times Q$ have similar meaning as above. The impel function $f(\cdot)$ of the model is S function for the hidden layer and the liner function for the output layer. $\boldsymbol{W}_1$, $\boldsymbol{b}_1$ and $\boldsymbol{W}_2$, $\boldsymbol{b}_2$ are the weighted value and threshold value for hidden and output layer respectively. $\boldsymbol{W}_1$ is $S_1 \times R$ matrix; $\boldsymbol{b}_1$ is $S_1 \times 1$ matrix; $\boldsymbol{W}_2$ is $S_2 \times S_1$ matrix and $\boldsymbol{b}_2$ is $S_2 \times 1$ matrix. The number of nodes can be calculated from Eq.(3). For this model the number of nodes is $n_1 = \sqrt{5+1} + 10 \approx 12$ (Omatu et al.,1996)

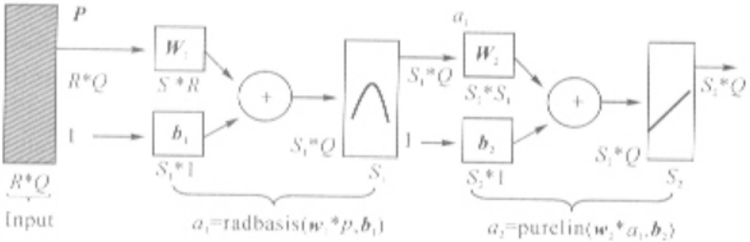


Fig.1 Neural network structure of combustion rate model

$$n_1 = \sqrt{n + m} + a \quad (3)$$

After network training cycle using the experimental data, the error curve is shown in the Fig. 2. The horizontal axis is number of training cycle and the vertical axis is sum-squared error. It can be seen that the sum-squared error can reach up to predicted 2% precision after training 15 000 times.

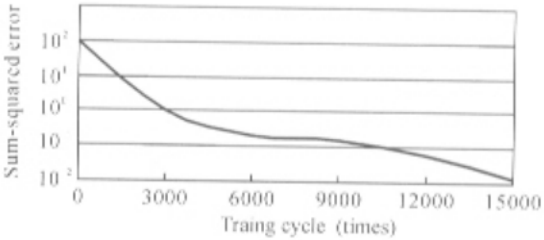
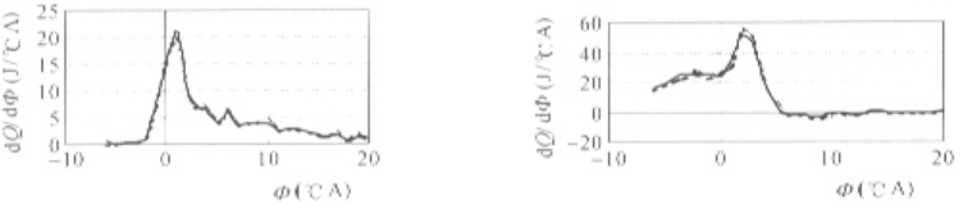


Fig.2 Sum-squared error curve of combustion rate model

VERIFICATION OF MODEL

The combustion rate model was verified for both of the light load and heavy load operating conditions. Comparison of the simulated combustion rate and the test results under the above two operating conditions are shown in Fig. 3. Showing that under light load condition (n = 2100 r/min, $G_g = 20\%$ butterfly valve opening, $M_e = 33.7$ Nm, $G_m = 2.7$ kg/h , $T_w = 79$℃), the simulated results were in good agreement with the test data; which indicated that the model could be much better used to predict the combustion characteristics of the DFE under the light load condition. Under the heavy load condition (n = 2100 r/min, G_g = 95 % butterfly valve opening, $M_e = 382$ Nm, $G_m = 2.8$ kg/h, T_w = 78℃) the simulated results differed much from the test data because only a small number of sample test data was used for the neural network training process. So the model in this is not good enough for training under the heavy load condition. However it was confirmed that the simulation precision could be improved by increasing the sample test data in the case of heavy load of the DFE.



(a)　　(b)

Fig.3　Comparison of simulated result of combustion rate with test data
(a) light load condition　(b) heavy load condition

APPLICATION OF MODEL

The studies of the combustion rate and effect of several main parameters on the combustion process will be introduced by using this model based on forward neural network in this section for an electric control DFE. Engine specifications: $D \times S = 108 \times 125$ mm, rated power/rotation = 112 kW/2800 r/min (Yan et. al., 2001b).

1. Effect of rotative speed

The variation of combustion rate with rotative speed are shown in Fig. 4 for case of light load condition ($M_e = 57$ Nm, $G_m = 2.4$ kg/h, $G_g = 30\%$, $T_w = 77$℃). It can be seen that the combustion delay is prolonged with increasing rotative speed. In other words the main combustion process in the cylinder takes place far away from the TDC. It reduces thermal efficiency. Therefore, when running at high-speed condition, the injection advance timing should be increased. At heavy load, the effect of speed on the combustion rate is similar to that at light load. But the combustion rate is much higher at heavy engine load compared with the lower engine load because of the larger quantity of natural gas.

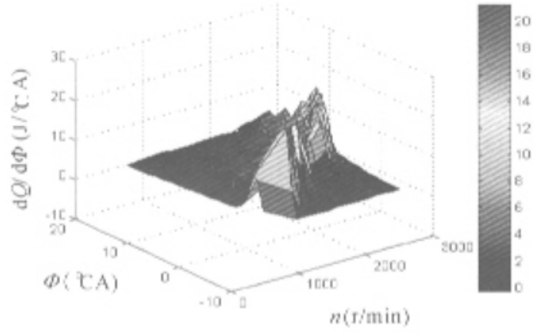


Fig.4　Effect of rotative speed on combustion rate

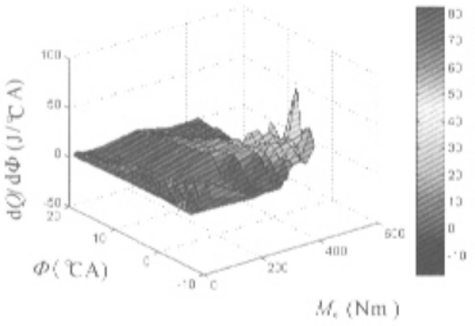


Fig.5 Effect of load on combustion rate

2. Effect of engine load

The effect of the engine load on the combustion rate is shown in Fig. 5. Showing that the combustion rate is lower at light engine load because of the slowly increasing temperature and the reducing of maximum temperature in the cylinder. Meanwhile due to the quite slow flame propagation velocity of natural gas, the combustion process finishes early under the condition still much unburned natural gas in the cylinder. It will exert unfavorable effect on the fuel consumption and emission of the DFE. This is why the DFE appears to be running unstably in the case of light load. With increasing engine load, the temperature and pressure in the cylinder, the combustion rate also increase. Therefore, it is beneficial to the combustion of DFE and the ratio of unburned natural gas reduces as well. Meanwhile the power output, fuel consumption and emissions will be improved, especially for the HC emissions.

3. Effect of natural gas quantity

The variation of combustion rate with natural gas quantity is shown in Fig.6 showing that the combustion rate is lower at light load condition (Fig.6a) because of the smaller quantity of the natural gas and lower temperature and lower flame propagation velocity of the natural gas in the cylinder.

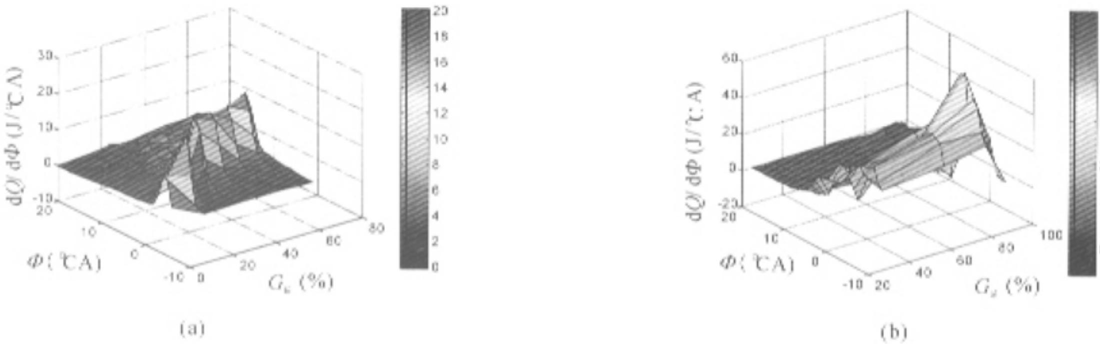


Fig.6 Effect of natural gas quantity on combustion rate
(a) at light load (b) at heavy load

With the butterfly valve opening increasing and the quantity of the natural gas increasing at the same time, the density of the combustible mixture increases in the cylinder. The combustion rate rises rapidly as shown in Fig.6b. The combustion process being finished near the TDC is beneficial for increasing the engine thermal efficiency.

4. Effect of pilot

Fig.7 shows the effect of the smaller quantity of diesel fuel (pilot) on the combustion rate. It can be seen that the variation of the ignition time is not obvious even when the quantity of pilot is increasing. But the combustion rate rises speedily with increasing amount of pilot, because of the increasing ignition energy. And the termination of the combustion process near the TDC will improve the thermal efficiency and fuel consumption of the DFE. But excessively increasing the quantity of pilot will lead to explosive combustion at the heavy load condition of the DFE.

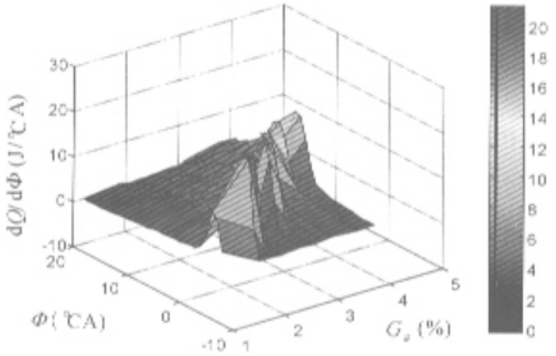


Fig.7 Effect of quantity of pilot on the combustion rate

CONCLUSIONS

1. A combustion rate model for diesel / natural gas dual fuel engine based on the forward neural network was built for analyzing the effect of main parameters on the combustion rate of the DFE. The simulated results agreed quite well with those of the traditional combustion model. It indicates that the model has a certain application value.

2. Verification of the model also proves that the simulated results were good agreement with the test data. Therefore the model can be proposed as theoretical foundation for predicting the performance and emissions. In practice the mod-

el can be used as an important method for improving and optimizing parameters of the DFE.

3. The model still has limitations, because it is highly dependent on the number of the experimental sample data.

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