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SIMULATION OF IN-CYLINDER RADIATIVE HEAT TRANSFER OF DIESEL ENGINE WITH MONTE-CARLO METHOD*

YAN Zhao-da(严兆大), LIU Zhen-tao(刘震涛), RUI Yang(芮阳),
CHEN Jie(陈捷), YU Xiao-li(俞小莉)
(*Dept. of Energy Engineering, Zhejiang University, Hangzhou 310027, China*)
Cheung, C. S(张镇顺)
(*Dept. of Mechanical Engineering Hong Kong Polytechnic University, Hong Kong*)

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Abstract: A multi-zone (multi-dimensional) model is used to model the in-cylinder radiative heat transfer of a direct injection diesel engine. The space and the surface of the ω-combustion chamber are approximated by simple geometric shapes and discretized. The model takes into consideration the complexity of the structure of the combustion chamber and the non-uniform distribution of the radiation medium, and uses the Monte-Carlo method to simulate the in-cylinder radiative heat transfer.

Key words: simulation, radiative heat transfer, monte-carlo method
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INTRODUCTION

Following the progress in research on in-cylinder heat transfer processes of diesel engines, the analytical evaluation of the radiative heat transfer is becoming more and more important. Many researchers proposed models and developed corresponding approaches for evaluating the in-cylinder radiative heat transfer of a diesel engine (Chen, 1998; Shen, 1999; Chapman, 1983; Chang, 1983; Zhou, 1990; Zhang, 1994). But till now, there are still few studies on the multi-dimensional modeling of in-cylinder radiative heat transfer.

The multi-zone (multi-dimensional) radiative heat transfer model (Chen, 1998) is adopted in this paper. The effect of the complex structure of the combustion chamber, and the effect of non-uniform distribution of radiative medium, on the surface heat flux in the cylinder of the engine are taken into consideration. The combustion chamber and surface are approximated by simple geometrical shapes and discretized into a number of volume and surface elements. As the Monte-Carlo method can deal with both non-uniform radiation media and the complex structure of the combustion chamber, it was chosen for simulating and analyzing the in-cylinder radiative heat flux of a G4135 direct injection diesel engine.

MONTE-CARLO METHOD

The Monte-Carlo method (Xie, 1995; Siegel, 1981) is a kind of probability simulation method, in which the object of investigation is specified as a probability model and solved with a probability method. For the radiative heat transfer processes in the combustion chamber, the probability model assumes that the radiative energy emitted by an element of the radiating medium is composed of many energy bundle's. The direction of each energy bundles radiation is random, and can be characterized by three random quantities with a definite distribution density function. By tracing each of the energy bundles until all of them have been absorbed, the number of energy bundles absorbed by each of the surface elements can be obtained.

The radiative heat flux Q_{A_j} at the surface element A_j of the combustion chamber can be defined as expressed below:

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$$Q_{Aj} = \int_{Aj}\int_V \frac{k_{ai}}{\pi r r^2}\exp\left(-\int_0^r k_{ai} r dr\right)\sigma T_{gi}^4 dV_i dA_j + \int_{Aj}\int_A \frac{\cos\eta_i \cos\eta_j}{\pi r^2}\exp\left(-\int_0^r k_{ai} r dr\right)\cdot \varepsilon_{si}\sigma T_{si}^4 dA_i dA_j \qquad (1)$$

In the Eq.(1), the first term is the radiative heat transfer between all volume elements V and the surface element A_j, while the second term is the radiative heat transfer between all surface elements and the surface elements A_j; K_{ai} is the absorption coefficient of a volume element, η is the angle between the normal to the surface and the direction of radiation, ε is the absorption coefficient of a surface element, r is the distance from the radiation source to the surface, σ is Boltzmann's constant and T the temperature of an element. The subscripts i and j refer to the zones, g to a volume element and s a surface element.

If the volume element dV_i emits n energy bundles of which n_1 are absorbed by dA_j, then the fraction of the energy bundles emitted by dV and absorbed by dA_j is:

$$P_{gij} = n_i / n$$

Similarly, P_{sij} represents the fraction of the energy bundles emitted by all surface elements absorbed by dA_j. Then Eq.(1) can be rewritten as:

$$Q_{Aj} = \sum_{i=1}^{M_g} P_{gij} Q_{gi} + \sum_{i=1}^{M_s} P_{sij} Q_{si} \qquad (2)$$

Where M_g and M_s are the number of volume elements and the number of surface elements respectively, while Q_{gi} and Q_{si} are the energy emitted by the volume element and the surface element respectively.

The steps for evaluating the radiative heat flux to the cylinder head, the cylinder liner surface, the piston bowl and the global radiative heat flux are shown below.

1) At any crank angle during the stage of diffusion combustion, the combustion chamber is divided into M_g volume elements and M_s surface elements.

2) Determine the extinction coefficient, radiation temperature, absorption coefficient and emission coefficient (or the emissivity ε) of the volume elements and the surface elements based on the diesel engine multi-zone (multi-dimensional) in-cylinder radiation model developed in (Chen, 1998).

3) The radiation energy emitted by each element is divided into N energy bundles. Apply the Monte-Carlo method to simulate the direction and the trajectory (including the reflection part) of each energy bundle and determine the position at which it is absorbed.

4) Sum up the number of energy bundles absorbed by each surface element. From Eq.(2), the distribution of radiative heat flux through the surfaces can be calculated and hence the averaged global radiative heat flux.

DISCRETIZATION OF THE COMBUSTION CHAMBER

1. Discretization of the combustion chamber

To apply the Monte-Carlo method for calculating the radiative heat flux, the space and the surfaces of the combustion chamber must be discretized into a number of volume elements and surface elements. Since the space geometry and values of the parameters (such as the shapes of the burned zone and the unburned zone, the distribution of soot concentration) of the radiating medium vary with time, the zonal division of the volume cavity should also vary with time. Except for the cylinder liner surface, other surface elements will not change with time. The surface elements of the cylinder head and the piston surface are hence fixed in size. Thus the volume elements and the surface elements are independent of each other.

The combustion chamber is divided into seven independent surfaces, numbered from 0 to 6, as shown in Fig. 1. The surfaces 0,2,3,4,5,6 are fixed surfaces, whose surface elements are numbered 0 – 12, 25 – 29, 23 – 24, 21 – 22, 19 – 20, 13 – 18 respectively. Actually surface 0 refers to the cylinder cover, surface 2 refers to the piston crown and the other surfaces, 3,4,5 and 6, refer to the piston bowl surface. Surface 1 refers to the cylinder liner, whose elements are numbered 38 – 47, while the length of an element is determined by the piston stroke. The space of the combustion chamber is divided into 8 volume elements, numbered 30 – 37. They are either solid or hollow cylinders.

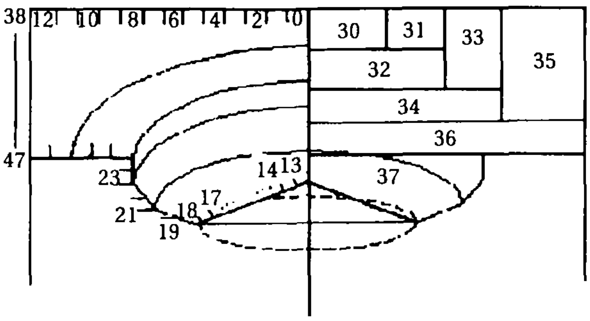

Fig.1 **Division of the volume elements and surface elements of the combustion chamber**

2. Determination of zonal radiation parameters

Based on the multi-zone (multi-dimensional) radiative heat transfer model (Chen, 1998), the burning zone is divided into a fuel core zone C, two combustible mixing zones B_1, B_2 and an air zone A, as shown in Fig.2. Element 30 is located in the fuel core zone, elements 31 and 32 are located in the rich mixture zones B_1, elements 33 and 34 are located in the lean mixture zones B_2, while the rest are air zones. The values of the characteristic parameters of each zone are shown in Table 1.

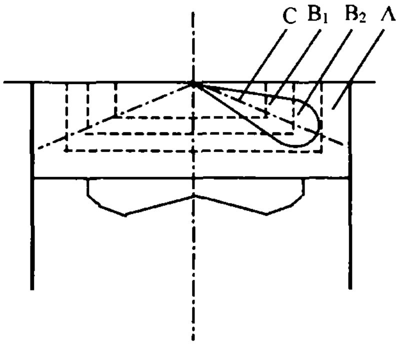

Fig.2 **Division of combustion model zones**
A-Zone; B_1-Zone; B_2-Zone; C-Zone

Table 1 **Characteristic parameters of each zone**

ATDC ℃A	Extinction coef. (1/m)				Radiation temp. (K)			
	C	B_1	B_2	A	C	B_1	B_2	A
10U	600	380	450	0	1980	1980	2450	2450
10S	680	380	450	0	1980	1980	2450	2450
20U	100	180	240	0	2300	2700	2600	2600
30U	80	20	120	0	2500	2800	2600	2600
30S	110	20	120	0	2500	2800	2600	2600

U: unscattering, S: scattering

SIMULATED RESULTS AND ANALYSES

1. The heat release rate of a diesel engine with ω-combustion chamber shows that in general the heat release occurs from 8 – 10 ℃A (Crank Angle) before top dead center (BTDC) to 40 – 60 ℃A after top dead center (ATDC). The initial period is a stage of premixed combustion, which rises to a peak value near the TDC. After the TDC, diffusion combustion begins and the amount of heat released in this stage is 70 – 80 percent of the total amount of heat released. Fig. 3 and Fig. 4 show that the peak radiative heat flux on the bottom of the cylinder head and the top of the piston occurs at 20℃A ATDC. Diffusion combustion is not yet fully developed at 10 ℃A ATDC, so the radiative heat flux at this crank angle is lower than that at 20℃A ATDC. While at 30℃A ATDC, diffusion combustion is nearly completed, so the radiative heat flux drops significantly. In-cylinder radiative heat flux is directly related to the temperature and soot concentration. Experimental data on the G4135 engine (Xu, 1996) show that the peak flame temperature and soot concentration occurs around 20℃A ATDC, which agree with the simulated results.

2. At any crank angle, the peak radiative heat flux on the piston crown comes into contact with the flame front first, and always occurs at the apex (element 13) of the ω-combustion chamber bowl. The simulation indicates that this location can absorb more energy bundles coming from all directions. On the other hand, the peak

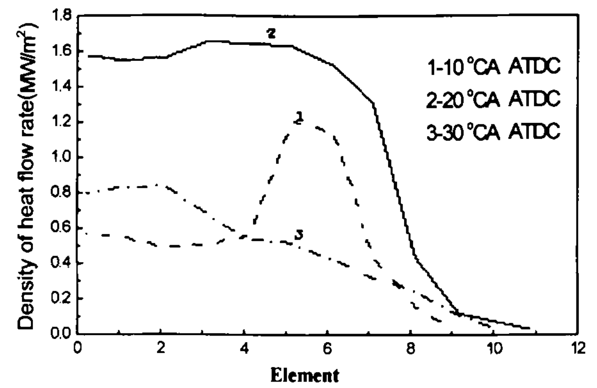

Fig. 3 Radiative heat flux on the bottom of cylinder head

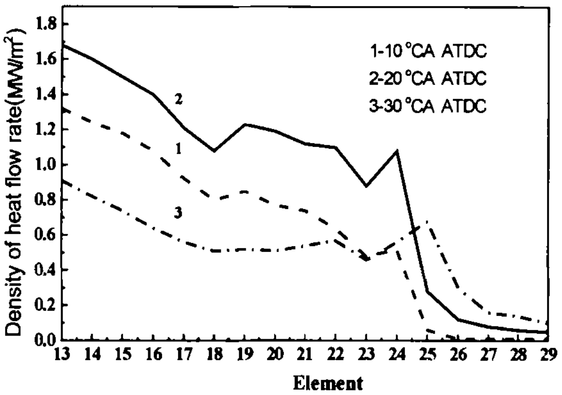

Fig. 4 Radiative heat flux on the top of the piston

radiative heat flux on the cylinder head does not appear at its center, but close to element 5. The reason is that at the center of the cylinder head, which is the location of the fuel injector and the fuel core zone C, the temperature is relatively low. Combustion starts at the combustible fuel-air mixture zone B, which is at the tip of the spray bundles around element 5. As the optical thickness from the flame to the center of the cylinder head is large and the unburned fuel droplets tend to reduce the radiation energy of the energy bundles, the radiative heat flux is relatively low. As shown in the curve 2 of Fig. 3, at 20℃A ATDC, there is a significant increase in the radiative heat flux at the center of the cylinder head due to the intense diffusion combustion. This figure also shows that there is fluctuation in the distribution of radiative heat flux, which is due to the difference in the values of the various parameters in the different zones.

3. As shown in Fig. 4, the radiative heat flux bounces at the edges joining the piston crown and the piston bowl of the ω-combustion chamber, at elements 24 and 25. The main reason is that when the radiation energy bundles emitted by the soot and the gas radiation sources arrive at these elements, most of them are absorbed and few of them are reflected. On the other surfaces, there are reflections of the energy bundles. So the bounce occurs. As the piston moves, the distances and directions of the energy bundles to these elements are also changed; the level of bounce in the radiative heat flux at these elements hence changes with crank angle.

4. The scattering effect of the fuel droplet on the radiative heat transfer is a controversial issue. In this paper, the scattering effect of fuel droplets is taken into consideration. The simulated results with and without fuel droplet scattering are shown in Fig. 5. The effect on the radiative heat flux is not significant, except around the fuel core region where the fuel droplet density is high.

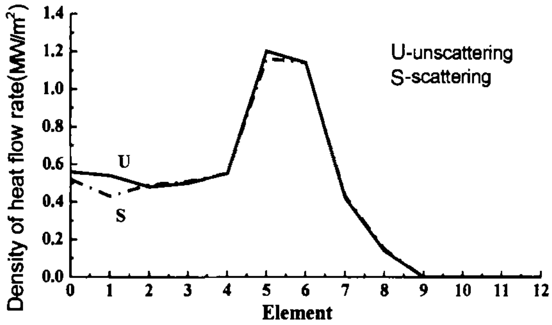

Fig. 5 Scattering effect of fuel droplets on cyl. head radiative heat flux at 10℃A ATDC

5. The distribution pattern of radiative heat flux simulated in this paper is similar to the results obtained by Mengul (Mengul, 1985) with a spherical harmonics approximation method. Fig. 6 shows the radiative heat flux peak values on the top of piston and bottom of cylinder head and the average values of whole surfaces of the combustion chamber. It indicates that the magnitudes of the heat fluxes also agree with experimental data obtained from similar engines. Hence, the mathematical model established in

this paper can be used for predicting the radiative heat flux of similar engines.

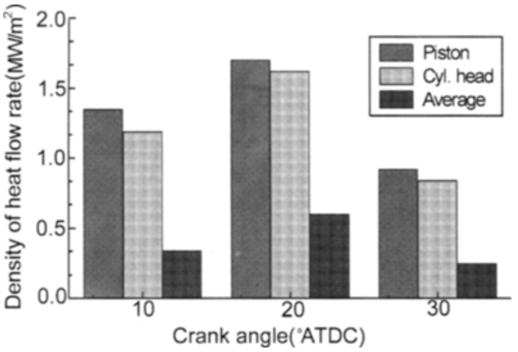

Fig.6 **Radiative heat flux peak values on top of piston and bottom of cylinder head and average values of wholesurfaces.**

CONCLUSIONS

In this study based on a multi-zone spray combustion model and a multi-zone (multi-dimensional) radiation model, the in-cylinder radiative heat flux of a diesel engine was calculated with the Monte-Carlo method. The ω-combustion chamber and the surfaces were geometrically simplified and discretized into a number of elements. The effect of non-uniform distribution of the radiation medium was taken into account. The numerical results indicated that the pattern of distribution and magnitude of the radiative heat flux agree with the combustion processes and experimental data. The results accorded with those obtained by Mengul. The scattering effect of fuel droplets on the radiative heat flux was also investigated. It can be concluded that the probability model for describing the radiation mechanism can be an effective method for simulating the in-cylinder radiative heat flux of similar diesel engines.

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