Computation on Infrared Radiation of Side Exhaust Plume under Spraying Water

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Abstract. The high temperature plume of ships has obvious infrared radiation feature. Spraying water-liquid droplets in side exhaust system can effectively reduce the high temperature of the tail gas to reduce the infrared radiation of the exhaust plume. In this paper, ANSYS Fluent is used to establish the concentration field and temperature field of the side exhaust plume after spraying water-liquid droplets. And the statistic narrow band model (Malkmus model) and the C-G approximation method are used to calculate the infrared radiation intensity of the exhaust plume in the normal direction of the exhaust outlet from 3 to 5 μm on this basis. The final results show that spraying water-liquid droplets in side exhaust pipe can reduce the infrared radiation of the side exhaust plume from 3 to 5μm by 88.9% compared with the initial intensity; when the water flow reaches 0.7kg/s, infrared radiation intensity remains unchanged.

Keywords. Side exhaust plume, high temperature, spraying water-liquid droplets, infrared radiation.

1. Introduction
The exhaust gas temperature caused by ship diesel engine can reach more than 300℃, which is much higher than the ambient temperature. Therefore, it’s obvious that the infrared radiation signal of plume formed by ship exhaust gas will attract enemy, which is the primary target of infrared terminal threat and non-terminal threat [1]. Currently, the exhaust ejection technology [2] has little effect on the suppression of the infrared radiation of the plume, so the method of spraying water mist is adopted to directly drop the temperature of exhaust gas to reduce the infrared radiation intensity of the plume. The method of side exhaust can reduce the flow resistance caused by water spraying. Meanwhile, it can also reduce the corrosion of the precision electronic equipment in the superstructure by water mist [3].

The radiation of plume results from gas species, in which CO₂ and H₂O are the main components that affect infrared radiation. Firstly, The most important characteristic of gas radiation is the discontinuity of radiation spectrum, which shows strong radiation properties in a certain band, while the radiation ability tends to zero in other bands [4]. The absorption bands of CO₂ are concentrated in the bands of 2.7μm, 4.3μm and 15μm [5], and the absorption bands of H₂O are concentrated in the bands of 2.7μm and 6.3μm [6]. Secondly, gas radiation is related to the spatial distribution of physical parameters such as temperature, concentration and pressure [7]. In most cases, the distribution of physical parameters is not uniform. The basic unit of gas radiation is the volume element, and the radiation capacity of the element is closely related to the physical parameters. In addition, gas radiation is closely related to the length of the microelement in the detection direction, so the concentration and temperature of the plume in the microelement should be as close as possible.

In this paper, based on the data collected from the test, ANSYS Fluent was used to simulate the plume
field before and after spraying water. Based on this, the intensity distribution model of the exponential tail reciprocal line in the narrow band model (Malkmus model) and the C-G approximation method \cite{4} were used to calculate the infrared radiation intensity of the plume in the normal direction of the exhaust outlet in the band of 3-5 μm. In addition, the influence of the mass flow of water jet on the infrared radiation intensity was explored, and the corresponding water jet flow rate was obtained when the radiation intensity decreased the most.

2. Numerical Simulation of Exhaust Plume Field

The geometric model of the exhaust plume includes the pipe wall, the internal flow field and the outer space of the expelled atmosphere, as shown in figure 1. The inner and outer basins were replaced by cylinders, whose axial length and radial length ratios were 1:3 and 1:10.

Assume conditions required for flow field calculation:
(1) Complete combustion of fuel in the combustion chamber of the diesel engine;
(2) Pipe wall insulation;
(3) The waste gas is desulfurized and contains only gas components;
(4) The influence of wind speed is not considered.

The general form of the basic equations for flow and heat transfer control is \cite{8}:

\[
\frac{\partial (\rho \varphi)}{\partial t} + \text{div} (\rho \vec{V} \varphi) = \text{div} \left( \Gamma \varphi \text{grad}(\varphi) \right)
\]  (1)

The turbulence model of ANSYS Fluent adopts Realizable k-ε model \cite{9}.

Discrete Phase Model \cite{10} is used in the calculation process of water spray, and atomizing nozzles are used for spraying. The flow ratio between the main nozzle and the auxiliary nozzle is 5:1, and the calculation process assumes that the water mist has completely evaporated.

The input parameters were obtained from the side exhaust water cooling test. Under the test conditions, the exhaust gas input flow of a diesel engine under the rated power condition was 2 kg/s, the temperature was 580K, and the mass fraction of CO2 and H2O was 10.795% and 3.838%. The ambient temperature is set at 300K, the spray water temperature is 303K, and the spray water flow rate is 0.84kg/s. The simulation results of temperature field before and after water spraying are shown in figure 2 and figure 3:
3. Calculation of Infrared Radiation Intensity of Exhaust Plume

3.1. Calculation Principle of Infrared Radiation Intensity

Radiative transfer equation is a basic equation for studying the radiation characteristics of targets. It indicates that the process of radiation energy transmission along a certain direction in the medium is affected by the absorption, emission and scattering of the medium. It is an energy balance equation in the direction of ray transmission, and the equation is expressed as [11]:

$$\frac{dI_{\lambda}(s, \bar{s})}{ds} + (\kappa_{\lambda}(s) + \sigma_{\lambda}(s))I_{\lambda}(s, \bar{s}) = \kappa_{\lambda}(s)I_{b\lambda}(s) + \frac{\sigma_{\lambda}(s)}{4\pi} \int_0^{4\pi} I_{\lambda}(s, \bar{s}, \vec{s}) \Phi_{\lambda}(\vec{s}, \bar{s}) d\Omega_i$$

(2)

In the formula, $I_{\lambda}(s, \bar{s})$ is the spectral radiation intensity at position $s$ and along the direction of $\bar{s}$ bit in the transmission process; $I_{b\lambda}(s)$ is the blackbody spectral radiation intensity at position $s$; $\Omega_i$ is the solid angle of space; $\kappa_{\lambda}(s)$ and $\sigma_{\lambda}(s)$ denotes the spectral absorption coefficient and spectral scattering coefficient of the medium. $\Phi_{\lambda}(\vec{s}, \bar{s})$ is the scattering phase function.

Since the plume calculated in this paper contains only the gas medium, the scattering effect of the medium is ignored in the calculation process, that is, the spectral scattering coefficient is determined to be zero. Then the radiation transfer equation is simplified as:

$$\frac{dI_{\lambda}(s, \bar{s})}{ds} + \kappa_{\lambda}(s)I_{\lambda}(s, \bar{s}) = \kappa_{\lambda}(s)I_{b\lambda}(s)$$

(3)

The spectral radiation intensity of the gaseous medium along the total path $L$ along the direction of the transmission path is [12]:

$$I_{\lambda} = -\int_0^L I_{b\lambda}(s) \frac{dr_{\lambda}}{dl} dl$$

(4)

Where $dl$ is the length of the gas element along the direction of the transmission path, and $r_{\lambda}$ is the spectral transmittance of the gas medium at the distance from the detection point [12]. In discrete form, it is:

$$I_{\lambda} = -\sum_{i=1}^{N} I_{b\lambda}(i) (r_{\lambda,i} - r_{\lambda,i-1})$$

(5)

In the formula, $N$ is the total number of gas elements along the path, and $r_{\lambda,i}$ is the transmittance from the first element to the $i$th element along the path.
The calculation methods of gas radiation characteristic parameters can be divided into line by line, band model and integral model according to the wavenumber spacing [13]. In this paper, the Malkmus model in the statistical narrow band model is adopted. The wavenumber interval is 5cm⁻¹, and the average spectral transmittance of the mixed gas within each wavenumber interval is [5]:

$$\tau_\lambda = \exp\left\{-2 \frac{\bar{\gamma}}{\sigma} \left[1 + \bar{\kappa} c_p l \frac{d}{\bar{\gamma}} - 1\right]\right\}$$

(6)

Where, $c$ is the mole fraction of gas; $p$ is the total pressure of the mixture; $l$ is the length of propagation path; $\bar{\kappa}$ is the average absorption coefficient, $\bar{\gamma}$ is the half-width of the average spectral line, and $d$ is the average spectral line spacing. HITEMP2010 database was used to calculate spectral parameters [14].

The gas with radiation characteristics in the band of 3-5 μm studied in this paper is CO₂, so it is assumed that the half-width of the average spectral line is only related to the concentration, pressure and temperature of the widened gas composition [5] when calculating the half-width of the average spectral line. The formula of the half-width of the average spectral line of CO₂ is [15]:

$$\bar{\gamma}_{CO_2} = \frac{p}{p_0} \left(\frac{T}{T_0}\right)^{0.7} \left[0.07c_{CO_2} + 0.058(1 - c_{CO_2} - c_{H_2O}) + 0.01c_{H_2O}\right]$$

(7)

In the formula, $p_0$ is standard atmospheric pressure, and $T_0=296$K.

3.2. Calculation Examples and Analysis of Results

![Figure 4. Spectrum radiation intensity of the plume from 3 to 5μm](image)

Table 1. Exhaust plume radiation intensity record before and after spraying water (Export normal direction).

| Temperature T/K | Intensity I/(W/sr) (vertical to outlet) |
|-----------------|----------------------------------------|
| No spraying water | 580 | 16.38 |
| Spraying water   | 330 | 1.81 |
| diff/ordinary    | 43.1% | 88.9% |

The spectral radiation intensity distribution in the normal direction of the exit before and after sprinkling is shown in figure 4, which indicates that the radiation suppression of plume radiation in the band of 2325cm⁻¹ (4.3μm) by sprinkling is very obvious. The infrared radiation intensity before and
after water spraying was calculated in table 1, and the results showed that the infrared radiation intensity in the tail normal direction of the exhaust outlet could be reduced by 88.9% by the method of water spraying, indicating that the method of water spraying can effectively reduce the infrared radiation of the plume.

![Figure 5](image5.png)

Figure 5. Relationship between water flow rate and outlet average temperature.

![Figure 6](image6.png)

Figure 6. Relationship between water flow and exhaust plume radiation intensity.

Comparing figure 5 and figure 6, we find that there is a negative correlation between outlet temperature and water mass flow while the radiation intensity does not accord with this relationship. There will be a maximum of infrared radiation intensity when water mass flow was about 0.6kg/s. The reason is that the water vapor will also produce infrared radiation. And the increased infrared radiation intensity of H2O is greater than the decrease value of the infrared radiation intensity of CO2. When the water mass flow increases to a certain amount and evaporates to a saturated state, the concentration and temperature of water vapor tend to be stable, and the corresponding infrared radiation intensity will not change.

In the field of engineering calculation, the outlet of the exhaust pipe will be regarded as a gray-body disk with a spectral emissivity of 0.9, and the radiation intensity will be calculated by using Planck's black body radiation formula. The advantage of this method is that the calculation process is simple and
efficient, and the disadvantage is that the calculation accuracy is low. It is not suitable for the calculation of infrared radiation intensity under other detection angles. As shown in figure 6, there will be an intersection between the two methods of calculation. When water mass flow is greater than the intersection corresponding value, the result calculated by Malkmus model is greater than Graybody radiation model. It confirmed that the reduction of infrared radiation caused by water mist is less than ideal.

4. Conclusion
In this paper, the infrared radiation intensity of the exhaust plume in the normal direction of the exhaust outlet at 3~5μm before and after spray is calculated. The maximum decrease of the infrared radiation intensity before and after spray is 88.9%. It is theoretically proved that the water spray cooling device can effectively reduce the infrared radiation intensity of the plume. On the relationship between the water flow rate and radiation intensity are discussed, and the radiation intensity is reduced to the minimum is obtained when the corresponding water flow rate, temperature and radiation intensity and water flow rate and radiation intensity are discussed, and the radiation intensity i can effectively reduce the infrared radiation intensity of the plume.

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