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The prediction of spray cooling muffler's acoustic characteristics

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ABSTRACT

Water spray cooling in the exhaust system of the diesel engine, as an approach to lower the temperature, has the potential to improve the low-frequency acoustic characteristics and reduce its aerodynamic resistance. Due to the existence of temperature gradient after the injection of cooling water in the muffler, the sound speed and density of exhaust gas changed. As a result, the acoustic performance of the muffler will differ from that of the dry one. Numerical simulation is implemented for gas flow characteristics, cooling effects and acoustic characteristics of the reactive muffler with water spray. The results of temperature distribution after cooling are obtained by calculating and analysing the aerodynamic characteristics of muffler with the finite volume method (FVM). The density and temperature field of the muffler obtained through calculation are coupled with the acoustic finite element method (FEM), so that the acoustic characteristics of the reactive muffler with the injection of cooling water could be predicted, meanwhile, compared with the dry one, and the results in this paper can provide reference for related research on spray cooling muffler.

Keywords: Muffler, Spray Cooling, Transmission Loss
I-INCE Classification of Subject Number: 34

1. INTRODUCTION

The principle of ship side exhaust is to replace the traditional exhaust pipe with a

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transverse transfer pipe and lead the exhaust port to the ship's side. The exhaust pipe and mufflers of the side exhaust system are installed in the cabin. For ships with special requirements on exhaust temperature, which should be reduced as much as possible at the exhaust outlet[1]. In addition, the exhaust system located in the cabin emits a lot of heat, which will also affect the operation of other systems in the cabin[2]. The method of spray cooling the exhaust pipe not only greatly reduces the exhaust gas temperature, but also facilitates the reduction of exhaust noise. Since the water-cooling exhaust system usually works in the harsh conditions of high temperature and gas-liquid mixing, the drastic temperature changes in the system after water spray cooling causes the change of fluid density and other attributes in the exhaust system, and then affects the acoustic performance of the whole system. Therefore, the effect of cooling water spraying on the acoustic performance of exhaust system is studied in this paper.

In order to reduce the exhaust noise and temperature of the marine engine, Li used the finite element method to simulate the internal temperature and flow field of the muffler and analysed the relationship between the acoustic performance and temperature [3].Dong calculated the muffler's acoustic performance according to the muffler temperature field, and explored and discussed the influence of temperature on muffler [4].Huang derived the transfer function of the linear perforated tube muffler with mean flow and temperature gradient, and verifies its correctness through experiments[5]. Brandan studied the control method of exhaust noise under the spray condition[6].

In this paper, the exhaust system is designed to reduce exhaust temperature and noise. The exhaust system is mainly divided into three parts: the primary muffler I, the main muffler II and water spray device. In order to reduce the exhaust temperature effectively, the muffling system adopts the method of cooling by spraying water, and the water spray position is as shown in *Fig 1*. At the same time, in order to control the exhaust noise better, the exhaust muffler adopts the method of grading noise reduction. The primary muffler is a hybrid muffler, which mainly uses the high temperature resistant sound-absorbing material to reduce the high-frequency exhaust noise, and the main muffler is a reactive muffler, which mainly uses the sound-absorbing structure to reduce the low-frequency exhaust noise.

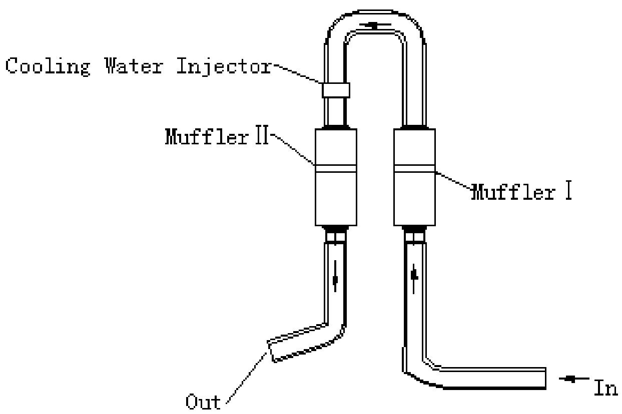
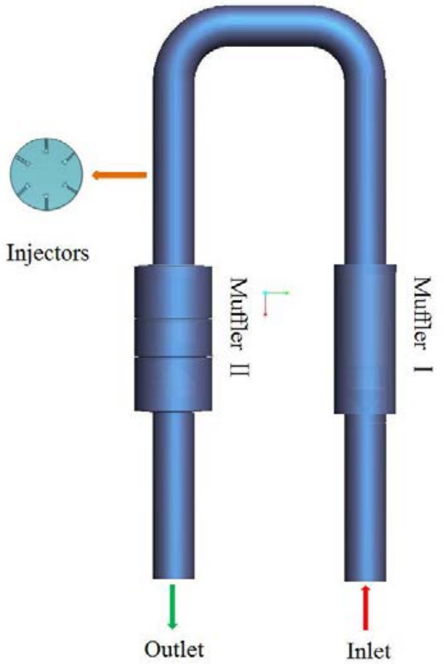


Fig 1 Schematic diagram of exhaust system

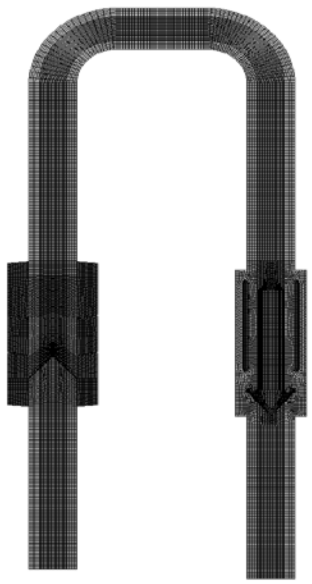
2. NUMERICAL SIMULATION OF WATER SPRAY COOLING

2.1 Numerical Model

The numerical simulation model of the mufflers is shown in *Fig 2*, where water injectors installed in the exhaust pipe injectors are located at upstream of muffler Ⅱ. The spraying water flows with the exhaust gas and has a cooling effect on the downstream field. So the influence of spraying water on the muffler I located at the upstream is negligible. And the wall between the sound absorbing material and the exhaust is established as a rigid wall in the model of water spray cooling, ignoring the interaction between the flow field and the sound absorbing material.



a) Numerical model



b) Computational mesh

Fig 2 Calculation model of CFD

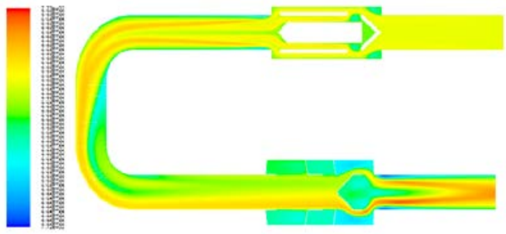
In order to obtain the law of the influence of different flow rates of cooling water on the acoustic characteristics of the exhaust system, the flow field of exhaust system is simulated in four conditions according to different cooling water flow rates: 0 kg/s, 1.2kg/s, 1.8kg/s, and 2.4kg/s. Other parameters such as cooling water temperature, gas flow rate and gas temperature remain unchanged.

Table 1 The coefficients of CFD model

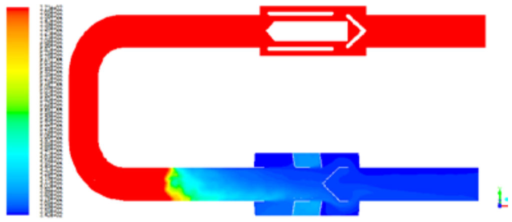
Parameters	*Unit*	*Value*
Flow rates of gas	*kg/s*	*3.0*
Temperature of gas	*K*	*773*
Temperature of water	*K*	*300*

2.2 Results of CFD Calculation

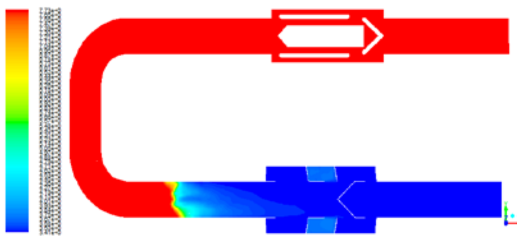
After calculation, the simulation results of temperature field of each working condition before and after cooling can be obtained as shown in *Fig 3*.



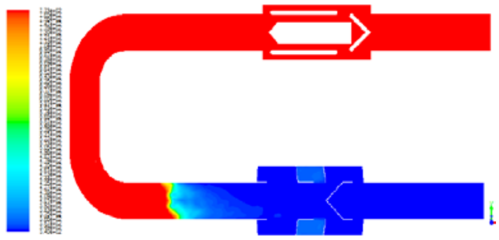
a) water flow rates 0kg/s



b) water flow rates 1.2kg/s



c) water flow rates 1.8kg/s



d) water flow rates 2.4kg/s

Fig 3 Temperature distribution of exhaust system with different water spray rates

It can be seen that when the water is not sprayed into the exhaust system, the temperature of the entire muffler system is about 772K, and there are only minor local differences. The outlet temperature of the exhaust system is reduced to 342K, 341K and 340K respectively when the water injection is 1.2kg/s, 1.8kg/s and 2.4kg/s. Although the exhaust temperature of muffler outlet varies little, it can be seen from the temperature distribution in exhaust pipeline that with the increase of water injection, the temperature of exhaust system decreases more and more rapidly. At this time, the sound velocity of the flue gas in the secondary muffler changes due to temperature gradient. So the influence of temperature gradient should not be neglected when calculating the acoustic characteristics of the muffler.

3. NUMERICAL SIMULATION OF ACOUSTIC PERFORMANCE

3.1 Calculation Method of Transfer Loss

In this paper, the finite element method-based software Virtual Lab is used for acoustic calculation [7].

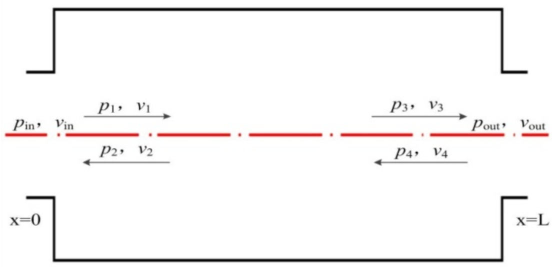


Fig 4 Temperature distribution of exhaust system with different water spray rates

For the pipeline silencing system, there are acoustic wave equations:

$$\frac{\partial^2 p(x,t)}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 p(x,t)}{\partial t^2} = 0 \tag{1}$$

Usually, the solution of partial differential equation form is:

$$p(x,t) = f(ct-x) + f(ct-x) = f(\omega t - kx) + f(\omega t - kx) \tag{2}$$

Where, $k=\frac{\omega}{c}$ is the wave number; c is the speed of sound; ω is the circular frequency.

For the harmonic response, the muffler inlet sound pressure p and the particle vibration velocity v can be written as follows:

$$p_{in}=(p_1e^{-jkx}+p_2e^{jkx})e^{j\omega t} \tag{3}$$

$$v_{in}=\frac{j}{\rho\omega}\frac{\partial p_{in}}{\partial x}=\frac{k}{\rho\omega}(p_1e^{-jkx}-p_2e^{jkx})e^{j\omega t}=\frac{1}{\rho c}(p_1e^{-jkx}-p_2e^{jkx})e^{j\omega t} \tag{4}$$

The time item is ignored and the particle velocity is defined as 1 at the inlet ($x=0$):

$$v_{in}=\frac{1}{\rho c}(p_1-p_2)=1 \tag{5}$$

Therefore $p_1-p_2=\rho c$. since $x=0$ at the entrance, substituting Equation(3):

$$v_{in}=\frac{1}{\rho c}(p_1-p_2)=1 \tag{6}$$

Then:

$$p_{in}=p_1+p_2 \tag{7}$$

At outlet ($x=L$), the sound pressure and particle velocity are:

$$p_{out}=(p_3e^{-jkL}+p_4e^{jkL})e^{j\omega t} \tag{8}$$

$$v_{out}=\frac{1}{\rho c}(p_3e^{-jkL}-p_4e^{jkL})e^{j\omega t} \tag{9}$$

For the calculation of the transmission loss (TL), the boundary is usually defined as a non-reflective boundary condition, and the acoustic impedance is ρc :

$$Z_{out}=\rho c=\frac{p_{out}}{v_{out}}=\rho c\frac{(p_3e^{-jkL}+p_4e^{jkL})}{(p_3e^{-jkL}-p_4e^{jkL})} \tag{10}$$

Because there is no reflected wave, $p_4=0$, so:

$$p_{out}=p_3e^{-jkL}e^{j\omega t} \tag{11}$$

The transmission loss (TL) of the muffler is defined as the difference between the incident sound power level of the muffler inlet and the transmitted sound power level of the outlet, when the muffler outlet has a no-reflection terminal. The area of the muffler inlet cross section is defined as A_{in} , the area of the muffler outlet cross section is A_{out} , and the sound power at the inlet and outlet is expressed as :

$$W_{in}=\frac{p_1^2A_{in}}{\rho c},W_{out}=\frac{p_3^2A_{out}}{\rho c} \tag{12}$$

The transmission loss (TL) of muffler can be expressed as:

$$TL=10\lg(\frac{W_{in}}{W_{out}})=10\lg(\frac{p_1{}^2}{p_3{}^2}\frac{A_{in}}{A_{out}}) \tag{13}$$

Since acoustic pressure p is a complex form in acoustic calculation, therefore:

$$TL=10\lg(\frac{W_{in}}{W_{out}})=10\lg(\frac{p_1\overline{p_1}}{p_3\overline{p_3}}\frac{A_{in}}{A_{out}}) \tag{14}$$

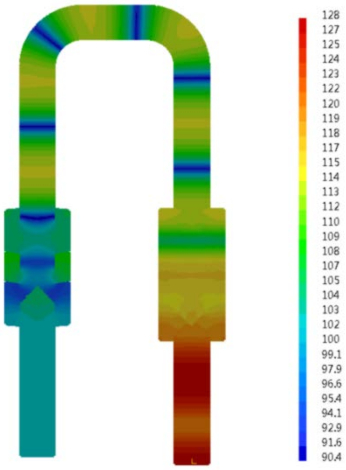
Where, $\overline{p_1}$ and $\overline{p_3}$ are conjugate complex numbers of p_1 and p_3, respectively.

What is obtained in the calculation is the sound pressure p_{in} at the inlet, and the relational expression $p_1 = \frac{1}{2}(p_{in} + \rho c)$ is substituted into Equation(14):

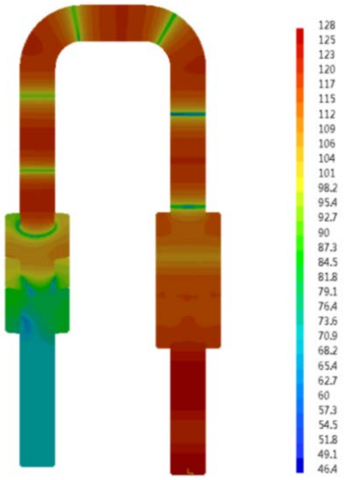
$$TL = 10\lg(\frac{W_{in}}{W_{out}}) = 10\lg(\frac{(p_{in} + \rho c)\overline{(p_{in} + \rho c)}}{4 p_3 \overline{p_3}} \frac{A_{in}}{A_{out}}) \tag{15}$$

3.2 Results of Acoustic Calculation

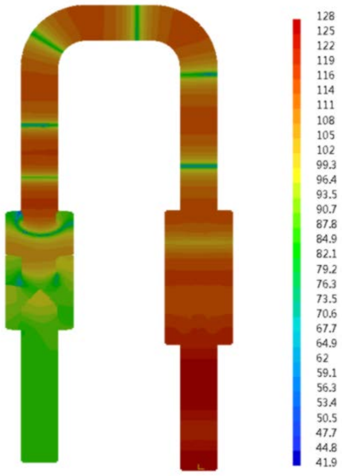
Acoustic performance of the whole system is obtained by using the results of temperature, sound velocity and density calculated by CFD as the boundary conditions of acoustic calculation. *Fig 5* and *Fig 6* show the sound pressure distribution of the system at the typical frequencies of 200 Hz and 2000 Hz.



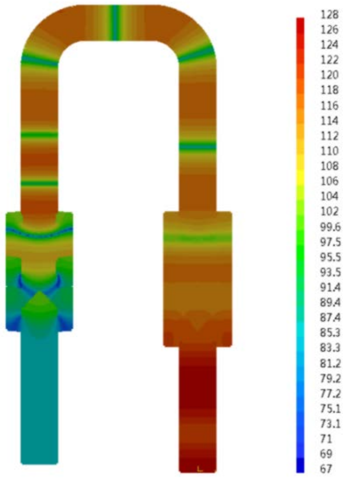
a) water flow rates 0kg/s



b) water flow rates 1.2kg/s



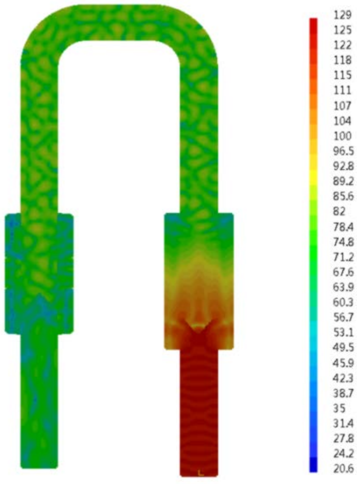
c) water flow rates 1.8kg/s



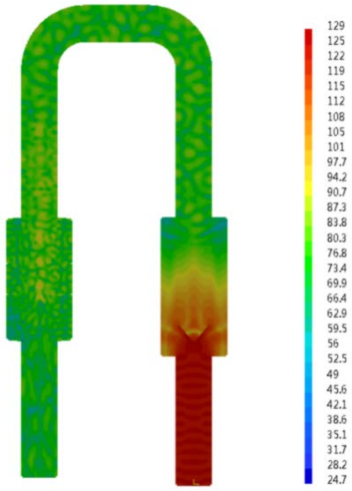
d) water flow rates 2.4kg/s

Fig 5 Sound pressure distribution of 200 Hz with different water spray rates

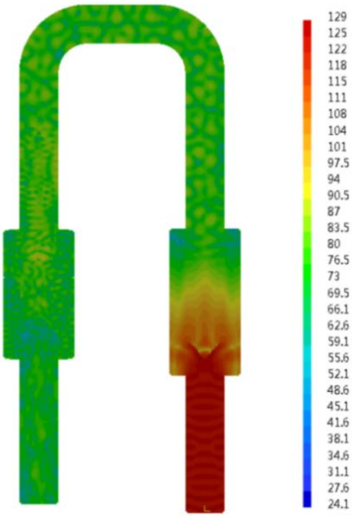
From the sound pressure level distribution of each condition according to *Table 1*, it can be seen that the sound waves propagate in the pipeline in the form of plane wave. The sound pressure has a significant attenuation through the mufflers, especially in the muffler Ⅱ. The sudden change of the medium temperature in pipe yields considerable mismatch of wave impedance, hence the significant reflection. There is another factor is the decrease of gas temperature and volume fraction after water injection, which leads to the decrease of sound velocity. When the exhaust fundamental frequency and harmonic frequencies of diesel remain unchanged, the wavelength of exhaust noise reduces with the decrease of sound speed， Therefore, the ratio of muffler size to acoustic wave length decreases. For muffler design, this is equivalent to the increase of the muffler length-diameter ratio, which can improve the acoustical performance of the muffler in low-frequency region.



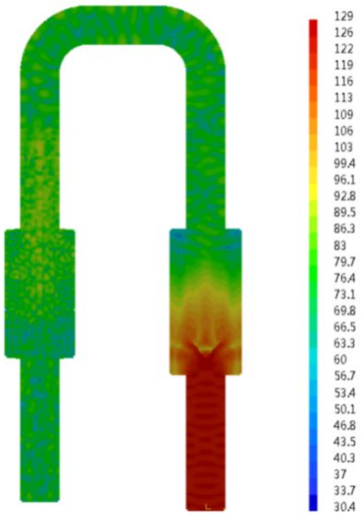
a) water flow rates 0 kg/s



b) water flow rates 1.2kg/s



c) water flow rates 1.8kg/s



d) water flow rates 2.4kg/s

Fig 6 Sound pressure distribution of 2000 Hz with different water spray rates

From the sound pressure level cloud diagram of each condition, it can be seen that the 2000 Hz sound waves in the muffler no longer propagate in the form of plane waves. The sound pressure level at this frequency decreases rapidly in the muffler Ⅰ, and the muffler Ⅱ has almost no noise reduction for higher frequency noise. This is because the sound absorption material in the muffler Ⅰ has a good absorbing effect on the high frequency noise. The muffler Ⅱ mainly works at reducing the low-frequency region, while it has little effect on the high-frequency noise.

Finally, the transmission loss of the exhaust muffler system under different spray rates can be obtained, as shown in *Fig 7*:

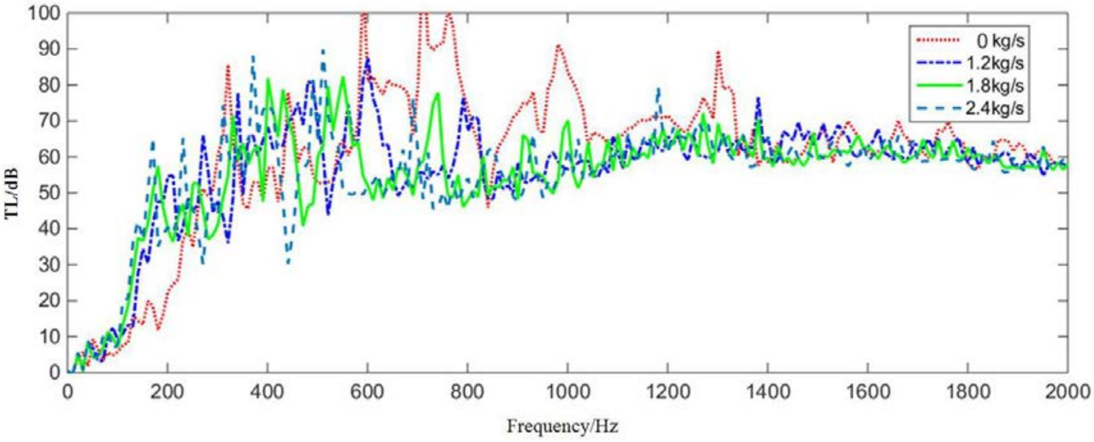


Fig 7 Transmission loss with different water spray rates

It can be seen from *Fig 7* that when the exhaust system is not sprayed with water, the first peak frequency of the mufflers transmission loss(TL) is 320 Hz; when the spray quantity is 1.2 kg/s, 1.8 kg/s and 2.4 kg/s, the peak frequency of the mufflers TL shift to 220 Hz, 180 Hz and 170 Hz, respectively. This indicates that when cooling water is injected into the exhaust pipeline, the transmission loss curve of the mufflers moves to the lower frequencies, which benefits to low-frequency noise control.

4. CONCLUSIONS

In this paper, a numerical model is built to analyse acoustic performance of exhaust muffler system with water spray cooling. The cooling process of the exhaust system by water injection is numerically simulated firstly, and the CFD results are taken as the boundary conditions for acoustic calculation. The acoustic performance of the exhaust system was calculated by the finite element method, and the main factors affecting the acoustic characteristics of mufflers were analysed. It is concluded that transmission loss curve of exhaust system moves to the lower frequency in a certain range with the increase of the amount of water spray. With the improvement of the low-frequency performance of the whole system, it provided a compact exhaust system compared to the traditional dry exhaust arrangement.

5. ACKNOWLEDGEMENTS

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