MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Study on Factors Affecting Water Mist Cooling Technology in Exhaust Silencer

Ma, Changjian[1]

Zhang, Xinyu[1*]

Zhao, Xiaochen[1]

[1]**College of Power and Energy Engineering, Harbin Engineering University, 150001, PR China**

ABSTRACT

Exhaust silencer is widely used in the engine exhaust system to reduce flow noise. The bandwidth in low-frequency and pressure drop are two engineering issues restricting the performance of a silencer. Lowering the temperature is a method that can simultaneously improve the low-frequency acoustic performance and reduce its hydrodynamic resistance. In this paper, to analyze the water spray cooling mechanism of high-temperature gas in the exhaust silencer system, we establish a numerical model based on the two-phase flow theory to simulate the cooling mechanism. Using the Euler-Lagrange numerical analysis method, the Discrete Phase Model (DPM) is used to simulate the coupling process of the discrete phase and the continuous phase. For the characteristic of the research object, reasonable choices of the additional models in the DPM are made. The influence of the mass flow rate and atomization degree of water spray on the cooling effect is studied considering the evaporation rate. We initially analyze the effect of the spray cooling method on improving the performance of the silencer.

Keywords: silencer, water spray cooling technology, two-phase flow, Discrete Phase Model, evaporation rate
I-INCE Classification of Subject Number: 34

1. INTRODUCTION

Through the study of silencers, researchers found that low-frequency bandwidth and pressure drop are two factors limiting the noise reduction performance of silencers. At the same time, cooling is a method that can improve the low-frequency acoustic performance of silencers and reduce the hydrodynamic drag at the same time. On the one hand, the bandwidth of the silencer depends on the ratio of the size of the silencer to the wavelength. Reducing the temperature of the fluid medium can reduce the speed of sound wave propagation, and then reduce the wavelength of sound wave at the same frequency. Therefore, the silencer can obtain a wider bandwidth without changing the size of the

* zhangxinyu@hrbeu.edu.cn

silencer. On the other hand, reducing the temperature can reduce the volume flow of compressible fluid. This can reduce the average velocity of gas flow in the pipeline and the pressure drop will decrease accordingly (1).

Water spray cooling is a mixed heat transfer mode, which originates from the limitation of air cooling mode. In order to cool the high temperature flue gas, adding cooling water to the flue gas is one of the most effective and easy methods. The cooling water directly contacting the exhaust gas utilizes the latent heat of vaporization (2257KJ/Kg) of water to achieve a significant cooling effect.

In order to study the characteristics of spray cooling in high temperature flue gas, Dr. He et al. carried out experimental research on spray cooling of AIP exhaust gas and high efficiency water absorption theory of CO2 gas. He proposed an experimental method for obtaining the macro mass transfer coefficient and established a mathematical model for predicting the cooling performance of AIP exhaust gas spray (2). In order to improve the cooling effect, Dr. Yuan et al. cooled the high temperature flue gas by spraying cooling water spray into the exhaust pipe of the engine with atomizing atomizer. Experiments show that after spraying a certain amount of cooling water spray, the smoke temperature of diesel engine can be reduced from 358 at the inlet of the pipeline to 120 at the outlet of the exhaust(3,4). The United States, Canada and Japan have spray cooling technology applied to ship exhaust system. The cooling effect of exhaust gas is remarkable (5).

In this paper, the effects of atomization degree and heat transfer space on water spray cooling are studied. Considering the evaporation rate, the influence of mass flow rate of cooling water on cooling effect was studied. Through quantitative calculation, the reason why the exhaust temperature can not be reduced to near the cooling water temperature is explained.

2. NUMERICAL SIMULATION

2.1 Calculation method

This paper establishes a numerical model for simulating the process of water spray cooling. The problem to be studied in this paper is essentially the process of evaporative heat transfer of a small particle discrete phase of liquid water atomization in a high temperature gas. A computational model that can be used to analyze the problem of water spray cooling in the engine exhaust system studied herein is the Euler-Lagrangian method. In the numerical analysis process of water spray cooling, the DPM calculation method is used to bring the calculation parameters of the atomizer into the atomizing atomizer model of FLUENT.

Since the physical processes involved are complex, the fluid phase is separated from the discrete phase to calculate the analysis. According to the actual physical process, the gas continuous phase flow field of the exhaust system is first analyzed and calculated. After the calculation of the continuous phase of the gas is completed, the calculation of the physical processes such as the flow, injection, evaporation, and heat exchange of the droplets of the cooling water is performed on the basis of the flow field of the stabilized exhaust system.

2.2 Calculation domain

In order to facilitate the research, this paper designs two models as the simulation computing domain. One is a straight tube simplified model and the other is a typical silencer model.

The simplified model of the straight pipe is shown in Figure 1. This model omits the silencer structure for the needs of research and the pursuit of universality for different structural silencers. The pipe has a diameter of 0.8m and a length of 13m. The section of the atomizer is 3 meters from the pipe inlet section. This model has enough space to exchange heat between the cooling water and the high temperature flue gas. Basically, it can be considered that a larger heat exchange space cannot be satisfied in engineering applications. In this model, eight pressure swirl atomizers are evenly disposed on the cross section shown in the figure.

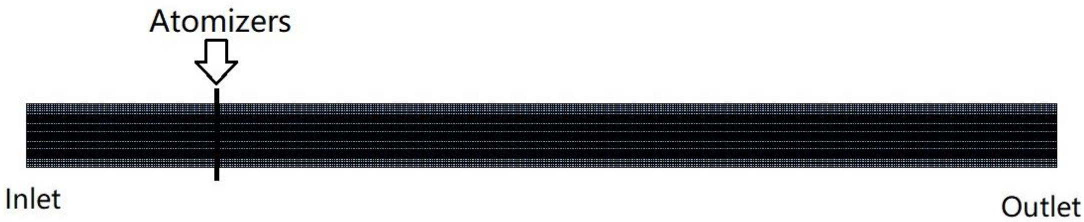


Figure 1 – Straight pipe simplified model diagram

The silencer model is shown in Figure 2. The inlet diameter of this model is 0.5m. The six atomizers of this model are located on the section shown in the figure. The atomizers are evenly arranged on the inner wall surface of the pipe. This article uses a pressure swirl atomizer. The liquid is first accelerated through the cyclone and sent to the flow field, after which the swirling liquid is centrifugally forced into a hollow conical film for further atomization.

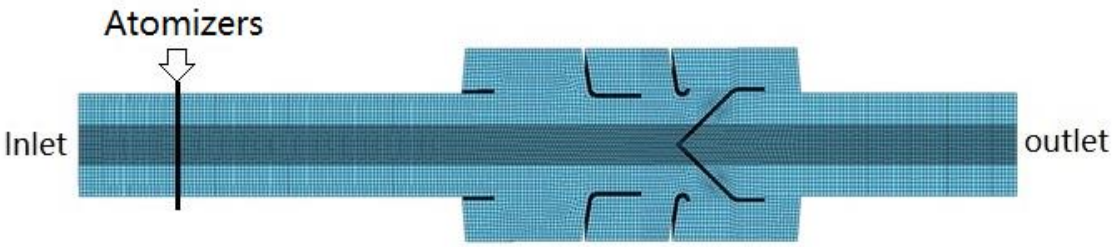


Figure 2 – Schematic diagram of silencer model

2.3 Boundary conditions

During the simulation, the gas is assumed to be the ideal gas. Since the effect of water vapor in the gas on the cooling effect of the water spray is not negligible, it is not possible to simply use air for numerical calculation. According to the law of conservation of mass, the composition of the gas obtained after the diesel is fully burned can be estimated. The calculation results are shown in Table 1.

Table 1 Gas composition, inlet

Composition	Quality score
Water vapor	3.838%
Oxygen	11.257%
Carbon dioxide	10.795%
Nitrogen	74.11%

The wall of the straight tube and the silencer is defined as a heat insulating wall. The sprayy cooling water is defined as a discrete phase in the model. Collision models and fracture models are used in numerical calculations. The droplets bounce when they hit the wall and escape from the computational domain as they flow to the exit. The simulation parameters of the straight pipe simplified model are shown in Table 2. The simulation parameters of the silencer model are shown in Table 3.

Table 2 Simulation parameters of the straight tube model

Parameters	Unit	Value
Mass flow of gas, inlet	kg/s	11.4
Temperature of gas, inlet	K	623
Hydraulic diameter of calculation domain, inlet	m	0.8
Gauge Pressure of gas, outlet	Pa	0
Cooling water mass flow	kg/s	1.2

Table 3 Simulation parameters of the silencer model

Parameters	Unit	Value
Mass flow of gas, inlet	kg/s	2.9
Temperature of gas, inlet	K	773
Hydraulic diameter of calculation domain, inlet	m	0.5
Gauge Pressure of gas, outlet	Pa	0

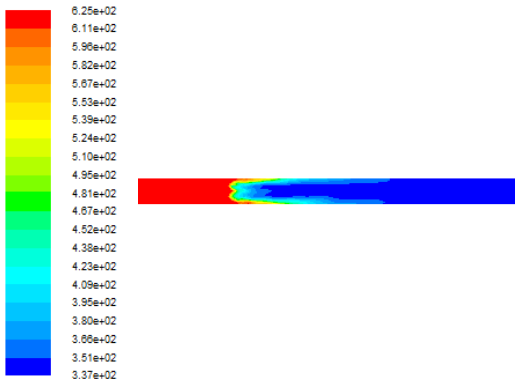
3. SIMULATION AND ANALYSIS

3.1 Effect of atomization degree and heat exchange space on water spray cooling

Since the degree of atomization and the heat exchange space have strong correlations, this paper combines the two for analysis. In order to make the concept of the heat exchange space more intuitive on the temperature profile, this article exaggerates the distance between the atomizer position and the silencer. The subsequent silencer structure is omitted, and the straight pipe model is used to simulate the water spray cooling.

In this paper, different atomization effects are achieved by using atomizers of the same structure but different diameters (1.6 mm, 1.8 mm, 2.0 mm, 2.4 mm). The degree of atomization is convenient for quantitative comparison. The small atomizer diameter represents a high degree of atomization. The results obtained by simulation using four atomizers are shown in Table 4.

Table 4 Simulation results under different atomizers

<table>
<tr><th>Atomizer diameter/ (mm)</th><th>Outlet temperature /(K)</th><th>Particle diameter/(m)</th><th>Axial distribution of gas temperature</th></tr>
<tr><td rowspan="4">1.6</td><td rowspan="4">340</td><td>Minimum</td><td rowspan="4">
</td></tr>
<tr><td>7.523786e-8</td></tr>
<tr><td>Maximum</td></tr>
<tr><td>1.010562e-4</td></tr>
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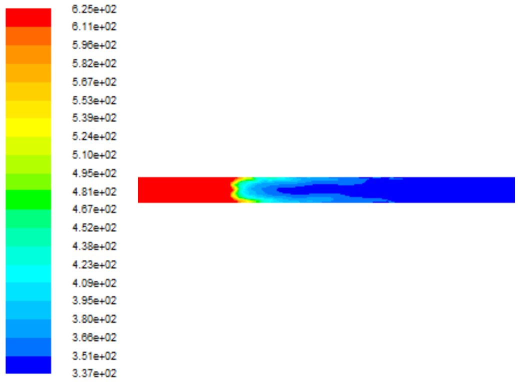
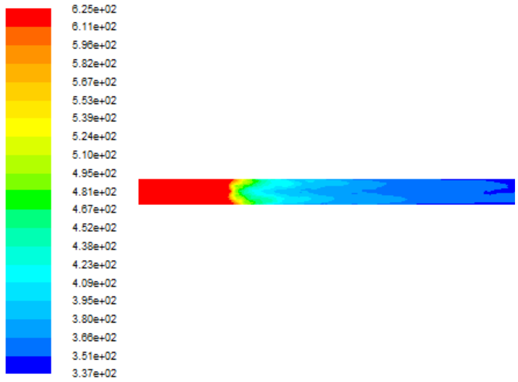
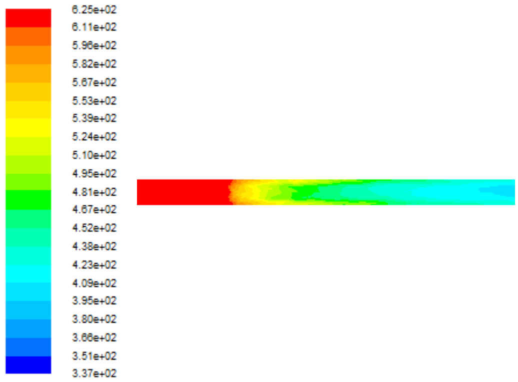
1.8	340	Minimum 1.074252e-7 Maximum 1.423639e-4	
2.0	351	Minimum 3.245458e-7 Maximum 2.171105e-4	
2.4	407	Minimum 7.799376e-7 Maximum 3.454281e-4	

It can be seen from the table that the smaller the atomizer diameter, the smaller the diameter of the atomized particles. This means that the atomization effect is better. The better the atomization effect, the lower the exhaust outlet temperature. However, when the atomization effect is less than a certain degree, the degree of temperature drop does not increase any more. Since the same amount of cooling water is used for the four calculations, their theoretical cooling potential should be the same. Therefore, it can be considered that the heat exchange calculated in the first two times is sufficient, and the heat exchange calculated in the last two times is insufficient.

In the application of water spray cooling technology, selecting the appropriate atomizer type and designing sufficient heat exchange space are important conditions to ensure the cooling effect. On the one hand, the smaller the atomizer diameter, the better the atomization effect. The necessary heat exchange space becomes smaller. However, simply reducing the diameter of the atomizer causes problems such as an excessive number of atomizers and poor anti-blocking performance of the atomizer. This leads to high cost and low reliability of the equipment. On the other hand, designing a larger heat exchange space will make it easier to ensure sufficient heat transfer, but space is a precious resource in engineering design. The above two factors need to be considered comprehensively.

3.2 The influence of different mass flow rates on the temperature field of silencer

This section studies and analyzes the effect of cooling water mass flow on the cooling effect of water spray in the silencer system. The numerical model used in the study was a silencer model with a cooling device. The silencer outlet temperature at different water flows (0.9 kg/s, 1.2 kg/s, 1.5 kg/s, 1.8 kg/s, 2.4 kg/s) was calculated by numerical simulation. As an example, Fig. 3 shows a temperature distribution map corresponding to 2.4 kg/s of cooling water.

Figure 3 – Temperature distribution inside the silencer

It is intuitively judged that increasing the mass flow rate of the spray water will lower the exhaust gas temperature. The temperature of the exhaust gas gradually decreases to a temperature close to the cooling water. But the study found that this is not true. The calculated temperature data is summarized and then plotted as Figure 4.

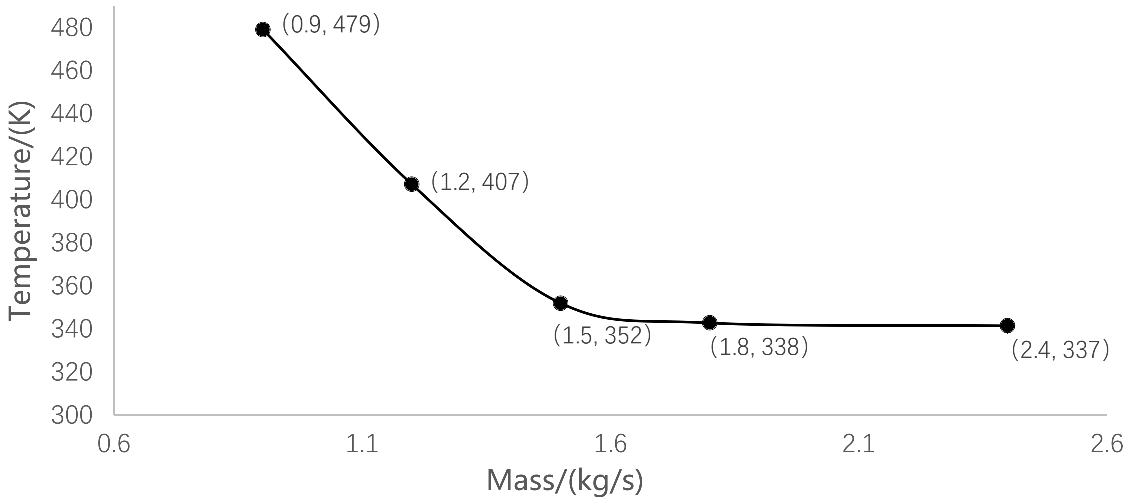


Figure 4 – The relationship between mass flow rate and outlet temperature of the silencer

It can be seen from the figure that the overall silencer outlet temperature gradually decreases as the cooling water mass flow gradually increases. When the cooling water mass flow rate is less than 1.5 kg/s, the relationship between the silencer outlet temperature and the cooling water mass flow rate is substantially linear. However, when the atomization flow rate is greater than 1.5 kg/s, the rate of change of the outlet temperature of the silencer gradually decreases as the mass flow rate of the cooling water increases. When the atomization flow rate is greater than 1.8 kg/s, the silencer outlet temperature almost no changes as the cooling water mass flow rate increases.

Assuming that there is liquid water mixed in the outlet exhaust, the heat balance calculation is performed. The maximum evaporation rate is 100%. The calculated specific values of temperature and evaporation rate are shown in Table 5:

Table 5 Relationship between mass flow rate and evaporation rate of cooling water

Mass flow rate /(kg/s)	Outlet temperature/(K)	Evaporation rate
0.9	479	100%
1.2	407	100%
1.5	352	90.4%
1.8	338	71.7%
2.4	337	53.8%

As the exhaust gas temperature drops below the boiling point of water, the evaporation rate of the cooling water gradually decreases. The cooling water sprayed into the basin can no longer be fully vaporized into water vapor. A liquid spray is mixed in the exhaust gas at the outlet.

In summary, increasing the mass flow of cooling water will increase the degree of water spray cooling in the silencer system. However, when the cooling water increases to a certain extent, the cooling value does not continue to increase.

3.3 Calculation and analysis of the lowest temperature for water spray cooling

This section will explain the phenomenon of “the cooling value does not continue to increase when the cooling water increases to a certain extent” through the heat balance calculation. This paper believes that the key to the problem is to analyze the situation where the outlet temperature has just reached the lowest value. Hereinafter, this state is referred to as a "critical state." First, the necessary calculation parameters are listed in Table 6.

Table 6 Basic calculation parameters

Parameter	Value
Initial gas temperature	773 K
Gas mass flow (M_0)	2.91 kg/s
Mass flow rate of H_2O (M_1)	0.111686 kg/s
Mass flow rate of O_2 (M_3)	0.327579 kg/s
Mass flow rate of CO_2 (M_4)	0.314135 kg/s
Mass flow rate of N_2 (M_5)	2.156601 kg/s
Critical state cooling water mass flow (M_2)	1.8 kg/s
Cooling water temperature	285 K
Critical state outlet temperature	338 K

In order to analyze the characteristics of the critical state, the partial pressure of water vapor in the flue gas at the exit of the system is calculated. The enthalpy values of the components involved in the calculation are listed in Table 7.

Table 7 Enthalpy value of compositions

Composition	Classification	Enthalpy value（kJ/kg）
Water	Cooling water (H_0)	49.876
	Liquid water, outlet (H_1)	250.62
	Water vapor, outlet (H_2)	2608.6
	Water vapor, inlet (H_3)	3488.4
Oxygen	outlet (H_4)	312.42
	inlet (H_5)	737.79

Carbon dioxide	outlet (H_6)	536.8
	inlet (H_7)	993.6
Nitrogen	outlet (H_8)	345.57
	inlet (H_9)	816.42

According to the energy balance equation, the expression of the mass flow (M6) of the gaseous water in the outlet flue gas can be obtained:

$$M_6 = \frac{M_1(H_3 - H_1) - M_2(H_1 - H_0) + M_3(H_5 - H_4) + M_4(H_7 - H_6) + M_5(H_9 - H_8)}{H_2 - H_1} \quad (1)$$

Since the outlet is directly connected to the atmosphere, the outlet pressure is calculated as standard atmospheric pressure. Calculating the molar ratio of the gas components can further give an expression of the partial pressure (Pe) of the water vapor in the outlet flue gas:

$$P_e = \frac{\frac{M_6}{18}}{\frac{M_6}{18} + \frac{M_3}{32} + \frac{M_4}{44} + \frac{M_5}{28}} \times 0.1013 \quad (\text{MPa}) \quad (2)$$

Table 8 shows the relationship between saturated steam and temperature.

Table 8 Saturated vapor pressure gauge for water

Parameter	Value (MPa)
Partial pressure of gaseous water in the flue gas (P_e)	0.024795
Saturated vapor pressure of water at 337K	0.023781
Saturated vapor pressure of water at 338K	0.024874
Saturated vapor pressure of water at 339K	0.026009

The comparison shows that the partial pressure P_e of the gaseous water in the outlet flue gas is substantially equal to the saturated vapor pressure of the water at 338 K. It can be concluded that when the temperature is reduced to a minimum, the water vapor in the outlet flue gas just saturates.

For a certain water spray cooling process, when the water spray volume increases (not reaching the critical state), the water vapor gasification absorbs a large amount of latent heat of vaporization. The partial pressure of water vapor in the outlet flue gas rises, and the temperature of the outlet flue gas decreases. This also causes a drop in the saturated vapor pressure of the flue gas. Therefore, when the rising partial pressure of water vapor and the decreasing saturated vapor pressure are equal, the water spray can no longer continue to vaporize, but can only rely on the heat capacity to cool the smoke. The process of changing 1 kilogram of liquid water at 337K to 338K only absorbs 4.19kJ of heat. The process of changing from 1 kilogram of liquid water at 337K to steam at 338K can absorb 2349.9kJ of heat. Therefore, when the exhaust gas temperature reaches a critical value, the increase in the temperature of the flue gas caused by the increase in the mass flow of the cooling water becomes very low. Continue to increase the amount of water spray will become severely lacking in economic and practical value.

4. CONCLUSIONS

In the application of water spray cooling technology, the cooling effect is limited by at least three factors. They are the cooling water mass flow, the degree of cooling water atomization and the heat exchange space of the exhaust system. The impact of the first factor is limited. The latter two factors are not independent, but are mutually restrictive.

This paper simulates the process of water spray cooling in the exhaust silencer system by establishing numerical models. The following conclusions regarding the degree of cooling are obtained by comparing the calculated data:

(1) When the heat transfer is sufficient, the larger the mass flow rate of the cooling water is, the greater the degree of temperature drops. However, as the mass flow rate of the cooling water increases to a certain extent, the water vapor in the exhaust gas is saturated. The exhaust temperature will never continue to decrease.
(2) When the heat transfer is insufficient, the better the degree of atomization of the cooling water is, the greater the degree of temperature drops.
(3) When the heat transfer is sufficient, the degree of atomization of the cooling water no longer affects the degree of temperature drops.
(4) The relative lack of heat exchange space can result in insufficient heat transfer. The heat exchange space that can be provided in engineering practice is limited. When the degree of atomization of the cooling water is better, the heat exchange space required to achieve sufficient heat transfer is smaller.

5. ACKNOWLEDGEMENTS

This work is supported by the National Natural Science foundation of China (51709058).

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