Optimized Design of Internal Mixing Nozzle for Asphalt Oil Based on Fluent

Weiheng Tai¹, Rongyu Ge¹*, Xiuli Fu¹ and Liwen Chen²

¹ School of Mechanical Engineering, University of Jinan, Jinan, Shandong, China
² Shandong Roadway Construction Machinery Manufacturing Co., LTD, Jining, Shandong, China
* me_gery@ujn.edu.cn.

Abstract. The design of the nozzle has an important influence on the atomization effect of asphalt oil in the road maintenance process. Fluent is used to numerically analyze the atomization process of asphalt oil in an internal mixing nozzle. The physical model of the nozzle was established, and the influence of the gas inlet pressure on the atomization cone angle and the SMD of atomized droplets was discussed. At the same time, the SMD of atomized droplets in different cross-sections downstream of the nozzle was studied. The results show that with the increase of the gas inlet pressure, the atomization cone angle of the asphalt oil gradually increases first and then decreases, and the SMD of the droplets gradually becomes smaller. As the distance between the cross-section and the nozzle outlet becomes larger, the SMD of the droplets on the cross-section first gradually becomes smaller and then remains basically unchanged. According to this rule, it provides a reference for the design of the internal mixing nozzle.

1. Introduction
In the road maintenance process, the asphalt material newly generated from the old asphalt material through the thermal regeneration technology. Before paving again, it is necessary to spray a layer of asphalt oil with viscosity on the working pavement, so that the pavement can have a certain viscosity, the asphalt material and the working pavement can achieve a better bonding effect. The process of spraying asphalt oil needs to be realized by nozzles. The structure and working parameters of nozzles determine to a large extent the effect of asphalt oil spraying. Therefore, numerical simulation of the internal and external flow field of the nozzle by CFD technology to match the appropriate structural parameters and working parameters is important to improve the atomization effect of asphalt oil.

Air-assisted atomizing nozzle is widely used in companies because of their ability to produce liquid-phase particles with small diameters under low pressure conditions. According to the structure type, it can be divided into internal mixing nozzle and external mixing nozzle. Haijun Liu used the Euler-Lagrange two-phase flow model to analyse the atomization process of an air-assisted atomization nozzle with threaded channels, and obtained the velocity, pressure and temperature distribution of the gas phase in the nozzle [1]. Lin Zhang discussed the influence of the length of the internal mixing nozzle atomization chamber and the gas-liquid ratio on the atomization particle size [2]. Fangbo Li simulated the gas-phase flow field and the gas-liquid two-phase flow field of the air nozzle when the pressure of the fan control hole was selected as a variable [3]. The internal structure of the nozzle in this study is shown in Figure 1. Air flows into the mixing chamber from the two gas phase inlets, and the asphalt oil
flows into the mixing chamber from the middle liquid phase inlet. After being fully mixed inside the mixing chamber, the gas-liquid mixture flows into the outside atmosphere from the outlet.

Figure 1. Schematic diagram of the internal structure of the internal mixing nozzle

2. Materials and Methods

2.1. Model parameters and meshing

The nozzle flow field is numerically simulated with Fluent. The calculation area is the internal flow field of the nozzle and the external flow field of atmospheric environment. Considering the internal flow situation of the nozzle and calculation efficiency, the internal flow field of the nozzle is simplified and only retains the mixing chamber part in the nozzle. The length of the mixing chamber is 5mm, the diameter of the liquid flow channel is 3mm, the diameter of the gas flow channel is 2mm, and the outlet diameter of the nozzle is 2mm. A cylindrical area of 300×300mm is constructed as the external flow field of the atomization. The unstructured grid is used to divide the overall computing domain, and the area near the nozzle is locally encrypted. Through the verification of grid independence, the final total number of grids in the computing domain is 70472, as shown in Figure 2.

Figure 2. Schematic diagram of grid division of nozzle flow field calculation domain

2.2. Selection of multiphase flow model

The present study is on the process of air-assisted asphalt oil atomization. In the atomization process, air is regarded as a continuous phase, while asphalt oil should be regarded as a discrete phase, so the DPM model is chosen for the simulation of the atomization process. The simulation process requires a steady-state solution for the continuous air phase, using the results of the steady-state solution as the initial conditions for the discrete-phase asphalt oil, and then coupling the discrete and continuous phases to calculate and perform the transient solution. The DPM model uses the air-blast-atomizer model provided in Fluent, turns on the droplet stochastic collision and breakup model, and the droplet breakup model uses the Wave model. The dynamic drag force model is used to consider the influence of droplet deformation on the drag coefficient. Select inert for the type of injected particles and modify the
parameters of the discrete phase particles. The momentum equation is not selected during the simulation process, and the relevant parameters of the asphalt oil are shown in table 1.

| Density (kg/m³) | Viscosity (kg/m.s) | Surface Tension (n/m) |
|----------------|-------------------|----------------------|
| 1013           | 0.02              | 0.04                 |

2.3. Selection of turbulence model
Since the asphalt oil acts as a discrete phase during the atomization process, only the continuous air phase needs to be selected for the turbulence model. The turbulence models provided in Fluent mainly include standard $k-\varepsilon$ turbulence model, RNG $k-\varepsilon$ turbulence model, realizable $k-\varepsilon$ turbulence model and $k-\Omega$ SST turbulence model. In this case, the standard $k-\varepsilon$ turbulence model is chosen, its turbulent kinetic energy equation:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right) + G_k + G_b - \rho \varepsilon - Y_m$$ (1)

Where, $\rho$ is the fluid density, $u$ is the fluid velocity, $\mu$ is hydrodynamic viscosity, $\sigma_k$ is turbulent Prandtl number of turbulent kinetic energy, $\sigma_k=1.0$. $G_k$ is the turbulent kinetic energy caused by average velocity gradient, $G_b$ is the turbulent kinetic energy caused by buoyancy, $Y_m$ is the influence coefficient of compressible turbulent pulsating expansion on the total dissipation rate.

Dissipation rate equation:

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left(\mu + \frac{\mu_t}{\sigma_k}\frac{\partial \varepsilon}{\partial x_j}\right) + C_1 \frac{\varepsilon}{k} (G_k + C_3 \varepsilon G_b) - C_2 \varepsilon \rho \frac{e^2}{k}$$ (2)

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}$$ (3)

Where, $\sigma_\varepsilon$ is Prandtl number of turbulent energy dissipation rate, $\sigma_\varepsilon=1.3$. $C_1$, $C_2$, $C_3$ and $C_\mu$ are empirical constants whose values are 1.45, 1.91, 1.0 and 0.09 respectively.

2.4. Solver settings
Fluent is used to perform simulation of nozzle atomization flow field. Taking asphalt oil and air as the working medium, the gas phase is first simulated and solved using the density-based steady state, and after convergence in the gas phase, the liquid phase is inserted using the DPM model and solved using the unsteady state. The momentum component, turbulent kinetic energy component and dissipation rate all adopt the second-order upwind difference format with second-order accuracy, which is conducive to the convergence of the DPM model. Pressure-velocity coupling adopts SIMPLEC algorithm. In the iterative process, the relaxation factors are appropriately reduced to 0.3, 0.5, 0.5, 0.3, 0.3, 0.3, 0.4 and 0.3 respectively, and the time step of discrete phase is 0.001s.

2.5. Boundary conditions
The inlet of gas phase adopts the pressure inlet boundary, and the gas phase is set as the ideal gas. The pressure values of gas phase are taken as 0.1Mpa, 0.2Mpa, 0.3Mpa, 0.4Mpa, 0.5Mpa and 0.6Mpa respectively. The equivalent hydraulic diameter of the gas phase inlet is 2mm. The flow rate of the liquid phase inlet is 0.1kg/s, and the equivalent hydraulic diameter of the liquid phase inlet is 3mm. The outlet of nozzle adopts the pressure outlet boundary, the pressure value is standard atmospheric pressure, and the equivalent hydraulic diameter is 300mm. Select the non-slip wall condition. The interface between the nozzle outlet and the external environment is selected as the jet source of the discrete phase particles.

Calculation of asphalt oil related parameters:

Asphalt oil mass flow

$$Q_a = 100g/s$$

Inlet diameter of asphalt oil

$$D_a = 3mm$$
Density of asphalt oil

\[ \rho_a = 1013 \text{kg/m}^3 \]

Dynamic viscosity

\[ \mu_a = 0.2 \text{Pa} \cdot \text{s} \]

Asphalt oil inlet area

\[ A_a = \frac{\pi d_a^2}{4} = 7.065 \text{mm} \]

Asphalt oil inlet volume flow

\[ Q_{va} = \frac{Q_a}{\rho_a} = 9.87 \times 10^{-5} \text{m}^3 \]

Asphalt oil inlet speed

\[ V_a = \frac{Q_{va}}{A_a} = 13.97 \text{m/s} \]

3. Simulation results and analysis

3.1. The influence of gas phase inlet pressure on atomization cone angle

Figure 3 shows the position distribution of asphalt oil atomized droplets under different gas phase inlet pressures.

Figure 3. Position distribution of droplets of asphalt oil under different gas phase inlet pressure

The figure 3 is processed by Image Pro Plus that is a professional image processing software, and the nozzle atomization cone angle under different gas phase inlet pressures can be obtained [4]. Figure 4 shows the relationship between the atomization cone angle and the gas phase inlet pressure.

Figure 4. The relationship between the atomization cone angle and the gas phase inlet pressure
It can be seen from Figure 4 that the atomization cone angle curve shows a trend of gradually increasing first and then decreasing with the increase of the gas phase inlet pressure. This is due to the fact that the relative velocity between the air and asphalt oil inside the nozzle becomes progressively larger during the initial phase as the gas phase inlet pressure increases. The continuous asphalt oil surface accelerates the rupture under the impact of air, which promotes the initial atomization process of the asphalt oil in the mixing chamber inside the nozzle, and the atomization cone angle gradually becomes larger. When the pressure of the gas phase inlet is too high, the velocity difference between the gas and liquid phases will no longer change significantly. In addition, the air will squeeze the asphalt oil in the mixing chamber, so that the nozzle outlet out of the asphalt oil mass reduced, resulting in the atomization cone angle becomes smaller. Therefore, in the process of designing the working conditions of the nozzle, it can get a better atomization working range when the gas inlet pressure is selected to be 0.5Mpa.

3.2. The influence of gas phase inlet pressure on atomized droplet size

The droplet size is a variable that describes the size of the droplets produced by the liquid after the atomization process. In practical applications, the Sauter mean diameter (SMD) and the mass median diameter are usually used to describe the droplet size. The Sauter mean diameter is the average particle diameter of the surface area, and its calculational expression [5] is:

$$D_{32} = \frac{\sum N_i D_i^3}{\sum N_i D_i^2}$$

Where, $N$ is the total number of droplets on a certain surface, $D_i$ is the diameter of the i-th droplet.

The number and diameter of droplets distributed on a certain plane can be obtained by using the report sample function in post-processing, and the SMD on a certain plane can be obtained by bringing it into formula 7. Taking the cross-sections that are 10, 60, 110, 160 and 210mm respectively distance from the nozzle outlet along the axial direction in the nozzle downstream. The SMD of the liquid phase on each cross-section is shown in Figure 5.

As it can be seen from Figure 5, the SMD of the droplets gradually becomes smaller as the inlet pressure of the gas phase gradually increases in a cross-section of equal nozzle downstream distance. This is because the increase of gas phase inlet pressure will accelerate the relative velocity between gas and liquid phases. The liquid phase is broken into smaller droplets under the impact of gas phase, which reduces the SMD of droplets. Under the equal air inlet pressure, the droplets are ejected from the nozzle to the cross-section 160mm downstream of the nozzle, the amount of change of the SMD is obvious, and the amount of change of the SMD at the cross-section above 160mm is no longer obvious, indicating that the secondary atomization process of the droplets mainly occurs 0-160mm away from the nozzle.

During the use of the nozzle, the atomization range of asphalt oil shall be given priority. Although the SMD of the atomized droplets obtained at 0.6Mpa is smaller, the atomization cone angle is not as good as the atomization cone angle at 0.5Mpa. Comprehensive consideration, in the design process of the nozzle operating conditions, the gas inlet pressure is selected as 0.5Mpa, which can achieve a better atomization effect on the asphalt oil. Asphalt oil can be atomized more fully through the secondary.
atomization process. During the construction process, the distance between the nozzle and the working pavement is above 160mm, which can ensure a better atomization effect of the asphalt oil.

4. Conclusion
(1) With the increase of gas phase inlet pressure, the atomization cone angle first gradually becomes larger and then becomes smaller. For the asphalt oil material in this study, the atomization cone angle is the largest when the inlet pressure is 0.5MPa.

(2) On the section at the same distance downstream of the nozzle, the SMD of droplets gradually becomes smaller with the increase of gas phase inlet pressure. In the working process of the nozzle, priority is given to the atomization cone angle. There is little difference in SMD of droplets between 0.5MPa and 0.6MPa, so it is more appropriate to select 0.5MPa for gas phase inlet pressure in the design of nozzle working conditions.

(3) The SMD of droplets on the downstream cross-section of the nozzle first becomes smaller and then remains basically unchanged with the increase of distance. The secondary atomization process of the nozzle mainly occurs at a distance of 0-160mm downstream from the nozzle. During the construction process, the distance between the nozzle and the working pavement is above 160mm, which can ensure a better atomization effect of the asphalt oil.

Acknowledgments
This paper is one of the stage results of the major science and technology innovation project of Shandong Province, China, "Multi-functional road maintenance intelligent equipment development and industrialization demonstration" (No. 2019JZZY010451).

References
[1] Liu, H.J., Song, L.W., Wu, H. (2015) Numerical simulation study of air-assisted atomization nozzle. Energy Conservation Technology, 03: 207-210+215.
[2] Zhang, L., Wang, L.K., Xue, L., Wang, H.Q. (2012) Numerical simulation study of internal mixing nozzle flow field. Journal of Chemical Engineering of Chinese Universities, 06: 959-963.
[3] Li, F.B., Zhang, Z.D., Li, S.L., Ding, L. (2018) Numerical study on the atomization characteristics of air nozzles based on spray amplitude pressure. Agricultural Equipment & Vehicle Engineering, 04: 59-62.
[4] Zhang, K., Liu, R.H., Wang, P.F., Wang, J. (2019) The effect of internal mixing air atomization nozzle internal flow on spray effect. Mining Technology, 01: 107-109.
[5] Ai, J.W., Gao, Z.X. (2019) Experimental and simulation study on the atomization performance of internal mixing air atomizing nozzles. Computers and Applied Chemistry, 06: 645-651.