Numerical Study on Particle Deposition Characteristics of Impingement Effusion Cooling Structure

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Abstract. The paper investigates the effect of impingement velocity and particle diameters on the flow and solid-phase deposition characteristics of the impingement effusion cooling structure by numerical simulation of gas-solid two-phase flow using DPM with UDF. The results show that under the same condition of the particle diameter, both the particle deposition flux and the particle deposition rate become increase with the increasing of the impingement velocity while the dimensionless particle deposition rate increases first and then decreases; Under the same condition of the impingement velocity, with the increase of the particle diameter, the particle deposition flux increases, while the particle deposition rate and the dimensionless deposition rate of the particle both increase first and then decrease. Taken together, Brownian motion of particles, turbulent diffusion, and particle inertia and flow characteristics is the main factors that affect the solid-phase particle deposition behaviour.

Keywords. Impingement effusion structure, Gas-solid two-phase flow, Particle deposition rate, Dimensionless particle deposition rate, Numerical simulation. The first section in your paper.

1. Nomenclature

| Symbol | Description | Unit |
|--------|-------------|------|
| \( D \) | The diameters of impingement hole and film hole | [mm] |
| \( H \) | Impingement spacing | [mm] |
| \( L \) | Spanwise spacing of impingement chamber | [mm] |
| \( W \) | Streamwise spacing of film hole | [mm] |
| \( P \) | Spanwise spacing of film hole | [mm] |
| \( W_i \) | Spacing between row of impingement holes | [mm] |
| \( P_i \) | Spacing between impingement holes in the same row | [mm] |
| \( S_t \) | Particle stokes number |
| \( \mu \) | Dynamic viscosity | [N·s/m²] |
| \( u_\infty \) | The velocity of flow | [m/s] |
2. Introduction

During the operation of an aviation gas turbine engine, solid particle impurities entrained in the air entering the engine will affect the normal operation of the engine [1]. Especially when working in a dusty geographic environment or encountering a dusty climate, aero engines will inhale a large amount of sand with a particle size ranging from 1 to 1000 μm [2-3]. Sand particles intrude into the cooling passages of the turbine blades, which are prone to deposition and blockages in the narrow internal cooling passages, causing the cooling effectiveness of the turbine blades to decrease, thereby increasing the temperature of the turbine blades. These will affect the service life, working performance and safe operation of aero-engines [4].

With the adaptability of aircraft flying in volcanic and desert environments, the deposition of particulate matter on the turbine blade wall has attracted the attention of researchers from various countries, so the more systematic basis and engineering application research have been carried out. Foreign research started early, and the main research methods include experimental research and numerical simulation. Jenson et al. [5] designed a High Temperature Accelerated Deposition Device (TADF) to perform accelerated experiments on particle deposition by increasing the particle concentration in the turbine environment. Ai [6] used accelerated deposition equipment to experimentally study the dust deposition of turbine blades using film cooling, and obtained the dust deposition under different blowing ratios. Shah et al. [7] used large eddy simulation to simulate the impingement of particle diameter on the distribution of particle impingement velocity and angle on the wall surface of ribbed channels and the law of particle energy transmission. Jonathan et al. [8] studied the erosion and deposition characteristics of particles in the channels of a cross-arrangement cylindrical array. The gas-solid two-phase flow model was used to investigate the particle erosion and deposition characteristics in the spoiler channel under different particle Stokes numbers and different softening temperatures. Zhou et al. [9-11] numerically simulated the particle deposition near the turbine cascade and the film hole, studied the particle motion and deposition characteristics, and revealed the flow and heat transfer laws. Yang et al. [12-13] studied the deposition of particulate matter on the surface of turbine blades and cascades and the effect of deposition on film cooling. Pei et al. [14] proposed a new deposition model based on the critical viscosity model and critical velocity model, and studied the effect of mainstream temperature and inlet/outlet pressure ratio on the deposition behavior for the non-film-cooling blade channel model.

From the current point of view, research on the phenomenon of particle deposition is mainly concentrated on the surface of the turbine cascade and the exit of the film hole. In this paper, the particle deposition mechanism of the impingement effusion internal cooling channel structure of the turbine blade is studied, and the deposition laws of different impingement velocities and different particle diameters in the impingement effusion internal cooling structure are analyzed. It has important theoretical guiding significance for avoiding the particle deposition in the cooling channels in turbine blades.

3. Computational physical model and meshing

The computational physical model is based on a simplified impingement effusion cooling structure of a certain type of turbine guide vane structure, as shown in Figure 1. The diameter of the film hole and the diameter of the impingement hole are $D$, and the impingement spacing is $H / D = 50$. There are two rows of impingement holes, with the spacing between the impingement holes in the same row is $W / D = 14$, and the spacing between the impingement holes in each row is $P / D = 8$. There are two
rows of film holes. The streamwise spacing of film holes is $W / D = 14$, the spanwise spacing of film holes is $P / D = 8$.

Structural meshing was performed on the computational domain using the ICEM CFD software, as shown in Figures 1. The number of grid cells in the entire computational domain is about 3.6 million. Among them, the grid is encrypted at the wall surface and near the wall of the film hole and the impingement hole. The grid size gradually increases from the wall surface and is enhanced according to the near-wall surface model. The requirement is that the first layer of grids near the wall surface should be below the cohesive sublayer, $y+$ is about 1.

![Figure 1. Computational Model and Meshing](image)

4. Numerical simulation method

4.1. El-Batsh Particle Deposition Impingement Criteria

The impingement model mainly includes two physical processes: one is the interaction between particles and the wall surface, which mainly includes two phenomena of adhesion and rebound; the other is the interaction between the adherent particles and the wall surface and the surrounding flow field to determine whether the particles are finally will deposit.

For the former physical process, the judgment criterion is the critical capture velocity, which is defined as:

$$V_{ce} = \left( \frac{2E}{d_p} \right)^{10/7}$$  \hspace{1cm} (1)

In the equation: It is related to the Poisson's ratio of particles and the wall surface of spoiler and Young's modulus.

When the normal velocity of the particles relative to the wall surface is greater than the critical capture velocity, the particles rebound, otherwise they adhere to the wall surface.

Particles adhering to the wall are affected by the flow near the wall, and secondary suspension may occur. Only when the fluid wall friction velocity is less than the critical shear velocity, the particles will eventually deposit on the wall

$$u_{wc}^2 = \frac{W_A}{\rho d_p} \left[ \frac{9\pi^2 W_A (k_s + k_p)}{8 d_p} \right]^{1/3}$$  \hspace{1cm} (2)

4.2. Numerical Simulation Settings and Boundary Conditions

This paper uses the Realizable k-ε model for the numerical turbulence calculation of the two-phase flow in the impingement effusion cooling channel structure. The near-wall area is treated with enhanced wall surface. The particle phase is bidirectionally coupled by DPM and the random walk model is selected. The UDF based on the El-Batsh impingement criterion is used to perform steady calculations using the SIMPLE algorithm. Momentum, turbulent kinetic energy, turbulent dissipation rate, and energy all uses the second-order QUICK format.
Inlet boundary: inlet gas temperature is 733K; The inlet velocity is matched and calculated by a given engine blade inlet Reynolds number, and the impingement Reynolds number is 300-3000, so we select the inlet velocity(impingement velocities)that meets this Reynolds number range: 5m/s, 20m/s, 32m/s, 50m/s.

Outlet boundary: the outlet is a pressure outlet condition, and the pressure is given by the working atmospheric pressure.

4.3. Mesh independence verification
At the same time, we also conducted a mesh independence verification to eliminate the effect of grid division on the simulation process and results. By adjusting the global mesh parameters and the number of near-wall nodes, we divided three kinds of mesh with different numbers of grids (mesh 1, mesh 2 and mesh 3), the number of mesh are 1609621, 3125567, 7853282 respectively. We selected four different working conditions to achieve four different dimensionless relaxation times and corresponding dimensionless deposition rates as shown in Figure 2. It can be seen that there is no obvious change in the numerical results obtained by the continuous refinement of grid 2, so grid 2 meets the requirements of grid independence.

![Figure 2. Mesh independence verification](image)

4.4. Verification of Particle Deposition on Two-Dimensional Channel Wall
In order to verify the availability of the numerical simulation method, a two-dimensional channel wall structure is used for modeling, and the above numerical method is used for numerical simulation. The two-dimensional channel model is 800mm long and 12.7mm wide, and still uses structural grid division. Figure 3 shows the channel model and grid division.

![Figure 3. 2D channel meshing](image)

Numerical simulation of particle deposition on the wall with an initial velocity of 5.3 m/s ($u_\tau = 0.342$ m/s) and a diameter in the range of 1-50μm. To verify the rationality of the particle deposition calculation method used in this paper, the numerical simulation results are compared with the experimental results of Liu and Agarwal [15] and Sehmel [16], which have obtained experimental data, are compared. The comparison result is shown in Figure 4. Among them, within the range of $\tau_p^+ < 10$, the
dimensionless deposition rate of particles increases with $\tau_p^+$ increasing; while at $\tau_p^+ > 10$, with the $\tau_p^+$ increase, the growth of the dimensionless deposition rate of particles slows down and shows a downward trend, which is the same as the change trend in the literature, indicating that the particle deposition calculation method used in this paper can better reflect the particle deposition trend, thus proving its rationality.

**Figure 4.** Numerical simulation and verification of 2D channel wall

### 4.5. Verification of Particle Deposition on Two-Dimensional Channel Wall

Particle deposition flux $R_{dep}$ (kg/s²) is the total particle deposition per unit area per unit time and is defined as:

$$R_{dep} = \sum_{p=1}^{N} \frac{m_p}{A_{face}}$$  \hspace{1cm} (3)

The particle deposition rate $V_d$ (m/s) is a measure of how fast particles are deposited on the wall and is defined as:

$$V_d = \frac{J}{C_0}$$  \hspace{1cm} (4)

In the equation 4: $J$ (kg/m³·s) represents the average deposition flux of particles on the wall surface; $C_0$ (kg/m³) represents the average particle concentration.

Considering the shear environment of the near-wall flow field, the ratio of particle deposition rate to wall friction velocity is defined as a dimensionless deposition rate, which is used to measure the deposition capacity of particles in different wall environments. Its expression is:

$$V_d^+ = \frac{V_d}{u_\tau}$$  \hspace{1cm} (5)

In the equation 5: $u_\tau$ is wall friction velocity.

Considering the interaction of particle deposition and fluid vortex near the wall, the dimensionless relaxation time based on the flow time scale is defined as:

$$\tau_p^+ = \frac{C_d \rho \alpha d_p u_\tau^2}{18 \mu v}$$  \hspace{1cm} (6)
In the equation 6: $C_c$ is Cunningham coefficient.

5. Results and analysis.

5.1. Flow Characteristics

In the simplified impingement effusion cooling structure channel, the particle deposition is greatly affected by the channel impingement hole and the film hole structure. During the flow of cooling gas carrying particles in the channel, the impingement on the wall surface will change the fluid streamline in the near-wall area, and vortices will form in the square impingement cavity channel, which will affect the deposition.

Figure 5 shows the streamline distribution and velocity of Y direction distribution of the cooling gas flow field at four different inlet velocities with a particle size of 10μm.

![Figure 5. Velocity streamline and velocity of Y direction distribution of gas flow field at different inlet velocities (d_p=15μm)](image)

It can be seen from the velocity streamline distribution that the gas enters from the impingement hole, and the velocity of Y direction distribution pattern of upward impingement is formed after the gas enters the square channel. When the velocity changes from 5m/s to 20m/s, the upward impingement velocity region expands significantly. When the velocity changes to 32m/s, the upper wall recoil velocity region appears, which weakens the impingement velocity region. When the velocity changes to 50m/s, the upper wall recoil velocity region increases, and the impingement velocity region is further weakened. At the same time, it can be seen from the streamline distribution that as the inlet velocity increases, the smaller the size of the eddy current cluster in the square channel, the larger the area of the fluid domain.

Based on the Euler-Lagrange model, and considering both the effect of continuous fluid on particles and the reaction of particles on continuous fluid, the flow direction of gas-solid two-phase fluid in the square channel is opposite to the direction of particle gravity. Therefore, changes in particle gravity caused by changes in particle size will have a certain effect on the fluid velocity flow field.

Figure 6 shows the velocity of Y direction distribution of the cooling gas flow field at four different intake particle diameters and an inlet velocity of 32 m/s.
Figure 6. Velocity of Y direction distribution of gas flow field under different particle size conditions (v=32m/s)

It can be obtained from the velocity of Y direction distribution that the particle diameter has a great effect on the gas velocity flow field of the cooling channel. When the particle size is changing, the increase of particle size causes the impingement velocity region continuously decrease, and the impingement of the flow is continuously weakened due to the effect of the particle gravity. When the particle size is greater than 15μm, the gas at the outlet of the impingement hole has almost no ejection, the impingement velocity region almost disappears, and the upper wall recoil velocity region in the negative Y direction increases continuously, the velocity region in the negative Y direction with increase in particle size continuously occupies the middle area of the square channel. And under the condition of larger particle size, the size of the eddy current is increased, and the backflow with large area eddy current suppress the ejection of the impingement hole.

5.2. Effect of Channel Inlet Velocity of Gas-Solid Two-Phase Flow on Deposition

The difference in channel inlet velocity of gas-solid two-phase flow greatly affects the fluid flow state in the impingement effusion cooling structure, and then also affects the particle deposition characteristics and deposition morphology in the internal cooling channel structure. At the same time, as the change of the incident velocity of the particles will affect the followability to fluid of the particles and the determination parameters in the El-Batsh deposition model, these will change the probability that the particles are deposited on the wall.

Figure 7 shows the effect of the average gas-solid flow inlet velocity on the particle deposition rate and the dimensionless deposition rate of the cooling channel when the particle diameter is 10μm and the working temperature is 733K. Figure 8 shows the relationship between the frictional velocity of the wall of the channel, the dimensionless relaxation time, and the inlet velocity of the two-phase flow.
As shown in Figure 7, for the particle deposition rate, as the average velocity of the inlet increases, the deposition rate of particles on the wall as a whole increase, and the dimensionless deposition rate increases first, then flattens and decreases; combined with the change of friction velocity with the average inlet velocity, the increase in the average velocity of gas-solid two-phase flow leads to a constant increase in wall friction velocity, according to the definition of dimensionless deposition rate, the increase in dimensionless deposition rate is continuously slowed until it is flat or even reduced.

For the simplified impingement effusion cooling structure channel, the inlet and outlet are both holes with a relatively small size relative to the rectangular cross section of the channel. As the velocity increases, the dimensionless relaxation time of the particles increases, the Stokes number increases, and the inertial effect of particle continues to increase, which is continuously reduced by the effects of fluid flow lines and eddy currents, and decreases with followability to fluid of the particles, reduced the probability of particles escaping from the channel when the outlet is relatively small compared to the rectangular cross-sectional size of the channel, the probability of interaction between particles and the channel wall surface is increased, and the deposition capacity of the particles on the wall surface is increased, so that the deposition rate increases with the inlet velocity rise. At the same time, due to the particle-wall collision criterion of the EI-Batsh deposition model and the increase in particle velocity, the interaction time of solid particles staying in the channel is reduced, and the deposition capacity of particles on the wall is reduced, making the growth of the dimensionless deposition rate gradually slow down until it starts to decrease.

Figure 9 shows the deposition morphology of the four inlet average velocities for the cooling channel in the case of relatively small particles ($d_p=1\mu m$) when the working temperature is 733K.
It can be seen in the results of the deposition morphology of the four different inlet velocities of relatively small particles ($d_p=1\,\mu m$): There is relatively less deposition on the side of the impingement hole and the lower wall of the model; but as the inlet velocity continues to increase, the average deposition flux on the inner wall of the impingement hole is increased, which is due to the relatively high probability of particles contacting the wall surface during the flow of the relatively narrow channel at the inlet impingement hole; according to the channel velocity distribution, the velocity inside the impingement hole is larger, and the increase of the particle velocity increases the particle dimensionless relaxation time, the followability to fluid of particles are weakened, which increases the deposition ability of the inner wall of the impingement hole.

Besides, a certain deposition occurs on the inner wall of the film hole, and as the velocity increases, the inner wall of the film hole decreases in deposition, which is due to an increase in dimensionless relaxation time and an increase in the Stokes number due to an increase in velocity, which reduces the flowability to fluid of the particles and decreases the number of particles transported into the film hole with the gas flow, resulting in a decrease in the average deposition flux on the inner wall surface of the film hole.

As the inlet velocity continues to increase, the average deposition flux on the lower wall surface continues to decrease. According to the definition of the Stokes number, the characteristic velocity of particles has a linear relationship with the Stokes number. An increase in velocity means an increase in the Stokes number of particles, that is, the inertia effect of large particles has continuously played a leading role, causing a large number of particles to be deposited on the upper wall surface during the impingement process, thereby reducing the average deposition flux on the lower wall surface.

The deposition concentration area on the upper wall surface shifts from the entrance of the film hole to the area with the same Y coordinate of the impingement hole as the velocity increases; the same reason is that as the velocity increases, the inertia effect of the particles starts to be greater than the diffusion effect, and particles are less affected by the effects of gas vortices and streamlines; when the velocity is small, the flowability to fluid of the particles is better, and the particles are easy to follow the gas flow and deposited at the inlet of the film hole. When the velocity is large, the particles are easily
affected by the impingement velocity and are deposited on the upper wall surface consistent with the Y coordinate of the impingement hole.

Figure 10 shows the deposition morphology of the four inlet velocities for the cooling channel in the case of relatively large particles ($d_p=20\mu m$) when the operating temperature is 733K.

![Deposition morphology](image)

**Figure 10.** Deposition distribution of cooling channels at different inlet velocities ($d_p=20\mu m$)

In the impingement hole side deposition morphology of four different inlet velocities of relatively large particles ($d_p=20\mu m$), compare the impingement hole side deposition morphology of small particle diameters and different inlet velocities: under the working conditions of 5m/s, 20m/s, the deposition on side of the impingement hole and the lower wall of the model is relatively small; and under the conditions of 32m/s and 50m/s, the deposition on the lower wall and the surrounding wall increases sharply; on the one hand, in the channel, the gas flow recirculation velocity region along the negative Y direction appears, and the impingement velocity region continues to disappear as the particle size increases. The recoil recirculation velocity region continues to increase, resulting in the case of large particle diameters and high velocity, massive deposition appears on the lower wall surface and surrounding wall surfaces; on the other hand, due to the increase in particle size, the critical capture velocity of the wall surface for particle size decreases, and the critical shear velocity also decreases at the same time, resulting in an increase in the probability of the physical state of particles peeling and rebounding. Part of the deposited particles on the upper wall surface is eventually deposited on the lower wall surface due to vortex peeling or rebound. At the same time, as the velocity increases, the amount of deposition area on the upper wall consistent with the Y-coordinate of the impingement hole increases significantly, which is also the result of the increasing inertia effect of the particles.

5.3. Effect of Particle Size on Deposition

Figure 11 shows the effect of particle diameter on the particle deposition rate and dimensionless deposition rate of cooling channel when the working temperature is 733K and the average inlet velocity of the gas-solid two-phase flow is 32m/s. Figure 12 shows the relationship between dimensionless relaxation time and wall friction velocity with the change of particle diameter.
As for the particle deposition rate, as the particle diameter increases, both the particle deposition rate on the wall surface and the dimensionless deposition rate change trend increase first and then decrease, and the peak value of the dimensionless deposition rate takes precedence over the peak value of the deposition rate change. In the case of relatively small particle sizes, the dimensionless relaxation time and particle Stokes number caused by the increase in particle size continue to increase, and the probability of collision between particles in the channel and the wall surface increases due to the increase of inertia of particles, and the decrease in the probability of escaping from the outlet of the film hole leads to an increase in the deposition capacity; at a relatively large particle size according to the particle-wall collision criterion of the EI-Batsh deposition model, the critical capture velocity decreases with increasing particle size, making more particles unable to meet the adhesion conditions and rebounding, resulting in a weakening of the deposition ability. From 12, it can be seen that as the particle size increases, the wall friction velocity increases but the increase is relatively limited, but the critical shear rate gradually decreases with the increase in particle size, making more particles have a wall friction velocity greater than the critical shear velocity makes the deposited particles peel off the wall surface, so that the deposition ability is weakened with the increase of the particle size in the case of a larger particle size.

It is worth noting that in the case of relatively small particle diameters, the wall friction velocity decreases with the increase of the particle diameter, which suppresses the physical peeling of the particles. Therefore, the deposition rate can be maintained and climbed due to the flow shearing environment near the wall, which makes the change peak of dimensionless deposition rate takes precedence over the change peak of deposition rate.

Figure 13 shows the influence of the four particle diameters on the deposition morphology of the impingement hole side and the film hole side when the working temperature is 733K and the inlet velocity is 32m/s.
Figure 13. Deposition distribution of cooling channels at different particle diameters (d_p=20μm)

In the deposition morphology results of different particle diameters under the condition of 32m/s, it can be seen that the deposition on the inner wall of the impingement hole gradually decreases with increasing particle size; the reason is that the increase in particle diameter reduces the critical adhesion velocity and the critical shear rate makes the physical state of the particles rebound and peel gradually increase, and the deposition ability is limited. At the same time, the inner wall of the film hole is deposited under the condition of the particle size of 1μm, as the particle size increases, the inner wall of the film holes gradually becomes almost non-depositing; the deposition in the film holes is mainly related to the followability to fluid of the particles, which are limited in the case of 32m/s, so the particles appear in the film holes when the particle size is small. With the increase of the particle size, the deposition of the lower wall surface and surrounding wall surface decreases first and then increases, and the deposition morphology changes greatly during the change to 10μm to 15μm. When the particle size is less than 10μm, that is, a relatively small particle size, the impingement of the gas flow is intense, and the reflow effect is weak, the increase in particle size causes more particles to maintain their own movement and deposit on the upper wall surface, resulting in the ability of deposition in lower wall surface gradually decreases. When the particles are larger than 15μm, that is, in the case of a relatively large particle size, according to the definition of the Stokes number, the particle diameter greatly affects the change of the Stokes number, the increase of the particle size means that the Stokes number of the particles increases sharply, that is, the followability to fluid of particles decreases, the larger the particle size, the inertial effect of the particle continues to play a leading role, making a large number of particles unable to escape the channel, and during the effect of eddy current and rebound, the particles constantly weakens its own velocity, so that the particles meet the deposition conditions and finally deposited on the surrounding wall and the lower wall. At the same time, with the increase of the particle size, the deposition of the upper wall area which is consistent with the Y-coordinate of the impingement hole increased significantly and the deposition area became more concentrated, which was also the result of the increasing inertia effect of the particles.
6. Conclusions
In this paper, the Euler-Lagrange method is used to simulate the deposition rule of particles in the impingement effusion cooling structure under different conditions including different inlet velocities and particle diameters of the gas-solid two-phase flow. The rules and mechanisms of deposition in the cooling channel are summarized as follows:

1. The gravity of particles can affect fluid flow under different working conditions. The impingement of gas flow in the cooling channel is continuously weakened due to the effect of particle gravity.

2. When changing the inlet velocity and particle diameter of gas-solid two-phase flow, particle deposition still conforms to the deposition mechanism with Brownian motion, turbulent diffusion, and particle inertia as the main reasons for deposition.

3. The inlet velocity of gas-solid two-phase flow has a great effect on particle deposition. Increasing the inlet velocity on the one hand increases the inertia effect of the particles, thereby reducing the escape of particles from the film holes which are relatively small compared to the rectangular cross section of the channel, allowing more particles to stay inside the channel, and eventually depositing in the channel under the condition of continuous weakening of the velocity of particles, which improves the deposition ability; On the other hand, the wall friction velocity and normal velocity of hitting wall are increased, which weakens the particle deposition ability. In general, for the velocity interval conditions studied in this paper, the increase in inlet velocity enhances the particle deposition ability. At the same time, the velocity affects the flowability to fluid of the particles. The larger the inlet velocity, the worse the flowability to fluid of the particles;

4. Particle diameter has a great impact on particle deposition. The increase in particle diameter on the one hand increases the particle inertia effect to allow more particles to stay inside the channel, which promotes the particle deposition ability, on the other hand, the critical capture velocity and the critical shear velocity near the wall are reduced, which weakens the particle deposition ability; meanwhile, the particle size affects the flowability to fluid of the particles. The larger the particle size, the worse the flowability to fluid of the particles.

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