Project 5 HOU Zhihao

Highlights:

(1) A strategy to improve energy efficiency and sustainability was developed

(2) Overlap rate was correlated to system energy consumption and byproduct generation

(3) Size distributions of particulate matter under different overlap rates were fitted

(4) Identified seven VOCs with health hazards during investigated laser decoating case

(5) A novel integrated extraction shroud was iteratively designed to optimize airflow

The overall project process and content are summarized in Optimization of Energy Consumption and Process Sustainability in Laser Cleaning for Coating Removal.pdf.

1.Project Introduction

With the commercialization of laser cleaning systems, laser decoating has emerged as a robust alternative to conventional removal methods, offering advantages such as high precision and non-contact operation. However, research on optimizing the process for enhanced energy efficiency and sustainability remains limited. In this study, a pulsed Nd:YAG laser (1064 nm wavelength, 10 μs pulse duration) was employed for decoating. Quantitative analysis identified

TVOCs, CO, and PM10 as the primary hazardous byproducts, posing risks to operator health and the environment. To mitigate laser power absorption losses caused by the plume, computational fluid dynamics simulations using Fluent were performed to optimize the airflow design of the integrated extraction shroud. With fixed laser beam parameters, the overlap rate was investigated as a key process variable. Laboratory experiments were conducted to correlate the overlap rate with four critical factors: (1) laser source energy consumption, (2) extraction unit energy consumption, (3) PM10 generation probability, and (4) emitted toxic gas concentrations. An objective function was then formulated by integrating the four correlations mentioned above. By minimizing this objective function, both energy efficiency and sustainability of the laser decoating process were improved simultaneously. This study proposes a practical strategy for energy conservation and emission reduction in laser decoating as shown in Fig.1. Given the large-scale demand for laser decoating across industrial sectors, widespread adoption of this approach could yield significant economic and environmental benefits.

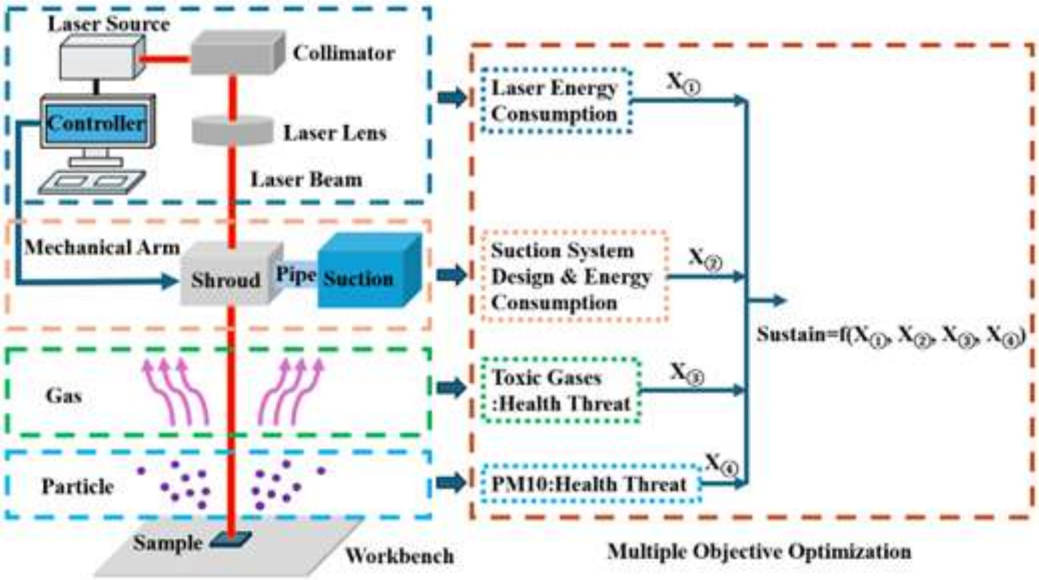

Fig. 1 Schematic representation of process optimization framework.

2. Simulation Ideas

The simulations involved in this experiment are: 1. Simulating the laser's impact on the paint sample during laser paint removal; 2. Simulating the extraction of particles from the dust cover during laser paint removal; and 3. Simulating the extraction of particles from the laser's interior. The focus of this project is on simulations of steps 2 and 3, which are also the subject of my research.

This paper analyses the two-phase flow of particles and air, and the DPM-CFD model is used for simulation. The logic diagram of the model process is shown in Fig. 2.

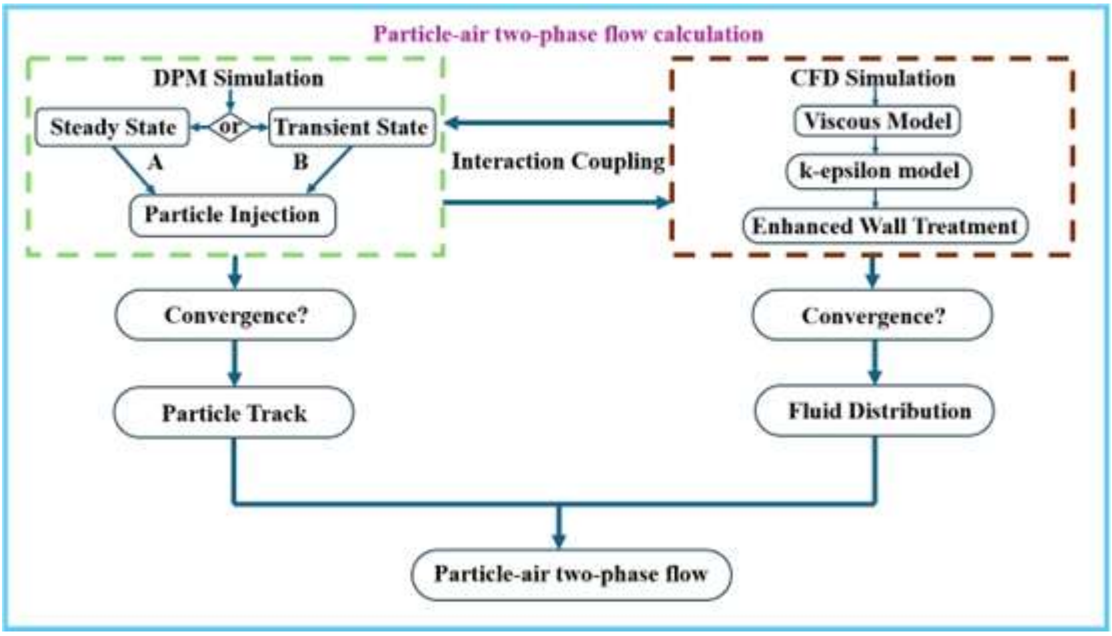

Fig. 2 Particle and air two-phase flow simulation calculation logic diagram.

The aforementioned paper details the design of a two-phase flow model for the DPM model. However, it's important to emphasize that I also conducted preliminary simulations to verify the feasibility of my subsequent simulations. The simulation process is divided into two parts: 1. (Fig.3) The shape design of the dust shield (optimized based on the wind field and particle trajectory under the same conditions); 2. (Fig.4) A comparison of the particle extraction performance of different versions at different particle incidence angles.

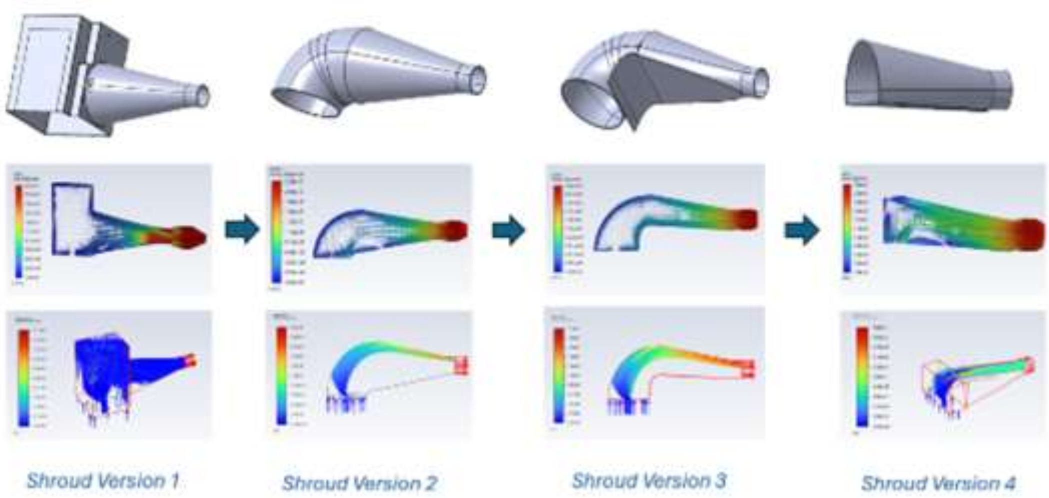

Fig.3 Shroud model design and compare.

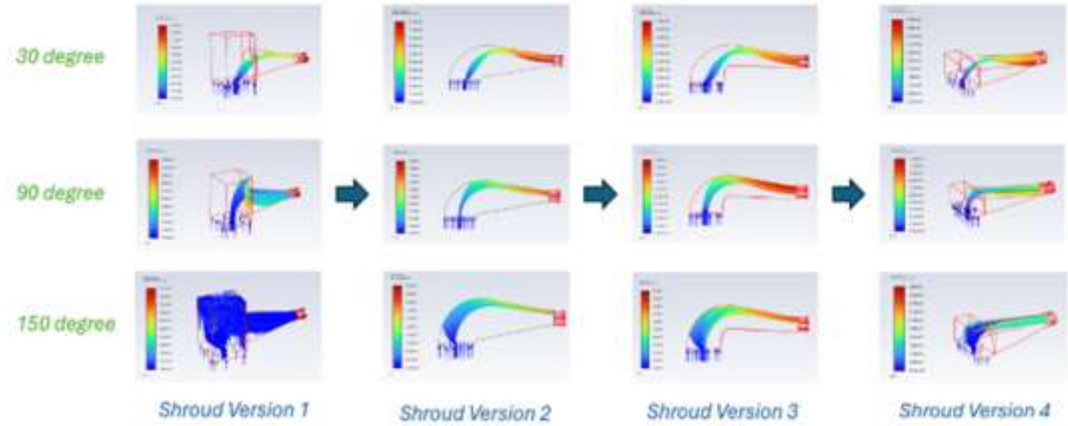

Fig.4. Particle injection angle change.

In addition, when setting up the DPM model, you need to set the diameter distribution of the incident particles. Common choices include R-R distribution and Uniform distribution. In the simulation of this project, I compared the simulation results by changing only the particle diameter distribution parameters and found that the impact on the simulation results was not significant, as shown in Fig.5. Therefore, to reduce the complexity of data processing with the R-R distribution, I chose the Uniform distribution.

(a) (b)

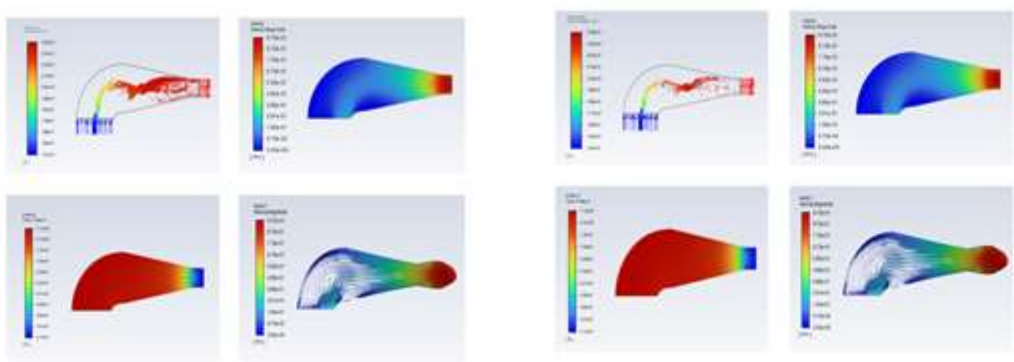

Fig.5 Different distribution of particle diameter. (a) R-R distribution. (b) Uniform distribution.

3. Current Optimization Ideas

Some problems that may exist in the experiment:

1. The laser paint removal has a small action area, and the corresponding number of particles generated is also small, so the particle trajectory observed during the experiment is not very obvious (even if a subsequent experiment was conducted to observe the laser trajectory in a darkroom with a green light, the effect was not obvious). The effect would be better if the sample action amount was increased or an inspection device similar to a photoelectric gate was added;

2. During laser paint removal, the laser action trajectory inside the dust cover is unknown. We can only compare the degree of particle suction by the cleanliness of the wall when cleaning the inside of the dust cover after the experiment (a clean wall means a better suction effect), so if a high-definition high-speed camera can be set up in the dust cover to record the trajectory of particle movement, the experiment will be clearer;

3. Regarding the further settings of the simulation, I have actually completed the second step of the simulation, and the third step of the simulation will be completed soon. Regarding the first step of laser simulation, most existing simulations typically use COMSOL or Fluent for multiphysics simulation, adding user-defined functions (UDFs) to allow users to customize the entire laser action process. However, these simulations only simulate the macroscopic interaction between the Gaussian heat source and the material, such as

thermal deformation and overall laser ablation. They can only simulate a portion of the material that disappears due to the reaction, but cannot achieve particle-level results related to laser ablation or laser spatter. Furthermore, the theory of laser action is not accurate down to the particle level, and existing simulation software is not well-suited to coupling the laser ablation reaction with the resulting particle spatter. This simulation closely resembles reality, but currently, achieving it is challenging. Therefore, to save project time and obtain some preliminary conclusions, I conducted qualitative and quantitative analysis of the second step simulation, referring to numerous publications in the field, by varying the particle incidence angle to approximate the random behavior of particle spatter;

4. My DPM model analysis is the simplest one, which only performs simple fluid-solid interaction. However, due to the lack of detailed data on the detailed parameters of the particles, such as the related forces between the particles, it is impossible to optimize the experimental conditions. This is also a major limitation of particle simulation.

4. Summary and enthusiasm for the UNFoLD lab

This is the product of my Research Associate period. Although immature, it marks a significant milestone for me and has been very beneficial. I was initially drawn to joining the UNFoLD lab by the dynamic video of vortex formation featured on the lab's homepage. The intuitive experimental conditions were captivating (which is exactly what I strive for: clearly presenting project results through visual videos).

I'm constantly learning, constantly challenging myself, and thoroughly enjoying these fascinating experiments. Of course, my years of scientific experience tell me that behind these videos lie countless nights of dedicated research. I hope to hone my theoretical application and problem-solving skills through practical projects. If I am fortunate enough to join the lab, I believe the UNFoLD lab will inspire new ideas and enable me to achieve fruitful research results.