

Article

Optimization Design of a Recovery System for an Automatic Spray Robot and the Simulation of VOC Recovery

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Abstract: A recovery system for an automatic spraying robot to conduct the spraying operation outdoors for ships is designed in this paper, which addresses the pollution problem of volatile organic compounds (VOCs) by employing the vacuum recovery method. The recovery system consists of the recovery hood, nozzle, and vacuum tubes. The recovery hood is the critical part of the recovery system and is designed with internal and external cavities, as well as four vacuum tubes for recycling VOCs. Based on the computational fluid dynamics (CFD) method, simulation in the time domain of the gas–liquid interaction, droplet evaporation, and wall impingement is conducted. To identify the better recovery performance, three vacuum recovery-hood schemes are designed, and their performance is compared. The numerical results show that the distance between the vacuum tubes and the intake gap has a significant impact on the VOCs' recovery effect. One of the main reasons for the escape of VOCs is that the swirling airflows in the baffle plane act as vortices which may capture VOCs, causing the accumulation of VOCs beyond the capacity of the external cavity. Dividing the external cavity into four chambers with deflectors (with each chamber equipped with one vacuum tube only) can significantly reduce the leakage rate of the recovery system. The recovery system provides a theoretical solution for implementing the prevention and control of VOCs in shipyards as soon as possible.

Keywords: CFD simulation; Lagrangian multiphase model; recovery-hood design



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1. Introduction

Painting and coating operations [1] are major operations in the shipbuilding and repair industry, which are essential ways to prevent the corrosion and deterioration of ships. Traditionally, the coating and painting operations are performed manually by staff equipped with manual spraying devices on prefabricated scaffolding or elevated vehicles; these tasks are intense, tedious, and potentially dangerous [2]. Those aerial working platforms require operators to adjust them at any time to assist spray workers in moving. Not only does this require a large number of workers, but it is also not very efficient. What is more, some health-risk assessment must be carried out for the workers engaged in the close-up spraying operations. It poses a serious health risk to the painting workers, leading to central nervous system anesthesia, hematopoietic damage and respiratory lesions, white blood cell production, thrombocytopenia [3], etc. To tackle the health crisis that the workers suffer, developing automatic and intelligent equipment for the construction of hull spraying in shipyards seems like a feasible way.

Since automation and robotics are gradually becoming essential for increasing safety, productivity, and quality in the shipbuilding industry, the coating and painting operations have shown great potential for the application of wall-climbing robots. With the gradual implementation of intelligent manufacturing strategies and the in-depth development of technology, extensive research has been carried out, and prototypes of an automatic

spraying robot have been proposed to replace manual labor. Wall-climbing robots begin with simple systems equipped with adhesion mechanisms like electromagnets [4], suction cups [5], or slide rails [6]. Those robots were originally intended to replace workers in completing hazardous and/or costly tasks performed by humans due to harsh environments [7]. These systems were designed to fit exactly one application or object at the beginning of the research. Thanks to new locomotion types and adhesion mechanisms, which have been developed in the last few decades, this limitation has decreased. The wall-climbing robots are now also employed for tasks such as inspection, maintenance, and construction tasks everywhere. The commercial applications of climbing robots can be found in [8–17].

In the shipbuilding industry, the integration of automatic spraying robots and the wall-climbing system can easily meet the needs of spraying operations and moving. Urakami Research Institute developed a wall-climbing robot for fully automated blast cleaning in a double-hulled block [17], and Palfinger proposed a non-contact spraying robot based on the track layout [18]. Li et al. [19] designed a magnetic-adsorption-type robot to replace workers in spraying operations. Wang et al. [20] applied a parallel-adjustment algorithm to an intelligent spraying robot for building walls. Yuping et al. [21] designed a wall-climbing robot for hull-plate spraying in the dock (WCR-HPSD). Xu et al. [22] integrated the climbing robot and spraying mechanism together for the maintenance and damage repair of bridge cables. Most of them are designed to perform the spraying operation as well as possible. When manual labor is replaced by spraying robots, the workers no longer need close contact with the pollutant emissions during the spraying process. However, the process of untreated pollutant emissions entering the atmosphere has not been stopped, as the spraying operations for ships are often conducted outdoors, such as in large outfitting docks. Those operations are of large scale and complex, and they may generate significant amounts of multimedia emissions (solid, liquid, and air) [22,23], which may cause environmental pollution. It is incompetent in tackling the pollution problem.

The concepts of environmental protection and sustainable development are gradually becoming rooted in the public. Employing the concept of ESG (environment, society, and governance) proposed by UNPRI and its related practices at the firm level has become a new international trend [24]. The American Advanced Manufacturing Partnership [25], Germany Industry 4.0 [26], Made in China 2025 [27], and other national strategies have put forward prospects and objectives for reducing environmental impact. Environmental protection, energy saving, and high efficiency of those operations are the bottlenecks of the shipbuilding industry. Therefore, technological innovations for painting and coating operations need to be promoted to meet the requirements of environmental protection and economic benefits. Some research has focused on pollutants in the shipbuilding and repair industry and has presented information on major shipyard processes and the associated pollutant emissions resulting from the construction and maintenance of ships. The research indicated that the painting of ship external surfaces generates significant emissions of VOCs into the atmosphere. It is reported by USEPA (1994) [28] that more than one-third of all organic HAPs are VOCs in the shipping industry. Lin and Kenny L. [29] studied the control of volatile organic air pollutants from industry. Nevertheless, the emission treatment generally is not involved in shipyards when the spraying operation is being conducted. The environmental pollution problem caused by ship spraying remains unresolved, while the pollutant emissions during the operation are inevitable. It is proposed to figure out an efficient way to reduce the emissions of pollutants to an acceptable range or to develop a recovery system that can capture the noxious emissions once they are produced. However, it is not an easy task to reduce the noxious emissions because of the strict painting requirements of ships. Therefore, we should shift our focus to recovery, developing a robot with a VOC recovery function.

Currently, there are four main mainstream recovery methods for pollutant emissions: carbon absorption, vacuum recovery, water-curtain recovery, and electrostatic recovery. Adsorption methods such as activated carbon are relatively common. Li and Shen et al. [30] studied the adsorption and desorption behaviors of VOCs on activated carbon in tempera-

ture swing adsorption (TSA) and temperature–vacuum swing adsorption (TVSA) processes. Nevertheless, the excellent adsorption performance causes a low reuse rate and also creates difficulties for the separation of paint mist. William B. et al. [31] recover overspray mist by circulating water in a water-curtain spray booth. Sauro et al. [32] suggested an innovative sustainable process for VOC recovery from water-wash spray-paint booths, which may be used in the shipbuilding industry. Nonetheless, it is a complex process to separate and collect pollutants using the water-curtain recovery method. A well-grounded recovery system and resistance characteristics of the paint are required when using the electrostatic recovery, making it unsuitable for the recovery on the ship hull. Among those methods, the working principle of vacuum recovery is the simplest. The diffused pollutant produced in the process of spraying can be easily collected by a vacuum pump. The vacuum pump can be equipped with other devices to integrate the different functions so that recycling while carrying out the spraying operation can be achieved. Sanghvi H. et al. [33] proposed a methodology for collecting the paint mist by a vacuum recovery process and converting it into renewable lacquers through catalysis.

During the numerical simulation, there are several key physical processes that are worthy of our attention. Firstly, multiphase flows are found in the simulation, which is a liquid phase (paint particles) interacting with a gas phase (air and VOCs). Tracking the flow path of dispersed particles (paint particles) in a continuous phase (air), as well as capturing the associated heat and mass-transfer phenomena (droplet evaporation), requires precise grid division. Secondly, the interaction between the liquid phase and gas phase affects the pressure field, while the pressure gradient has a great impact on the movement of the liquid phase and the gas phase. Thirdly, collision and fusion between droplets can occur, and various possible outcomes may arise after collision with the wall boundary. Apart from that, the optimization design of the recovery hood for the automatic spray robot also faces challenges. Eddy currents are prone to occur in the cavity, resulting in the accumulation of VOCs inside the recovery hood. The flow field of a spray gun integrated with a single-layer recovery hood was first discussed by Yi et al. [34], and the flow field caused by vacuum recovery suction was also studied. The characteristics of the recovery hood were optimized to improve the efficiency of paint misting to 83.4%, meeting the engineering needs of paint-mist recovery during spraying operations. As only a single-layer recovery hood was used, the vacuum recovery suction may have affected the spraying operation directly. The flow field generated by vacuum recovery suction can not only recycle the overspray paint mist but also have a significant impact on the paint mist that should be deposited on the ship hull. In addition, the physical phenomenon of VOCs evaporation was not considered by Yi et al. [34]. Although the aforementioned research studies have made a lot of conceptual improvements in the ship painting system with the recovery function, some functions of the prototype production are still unsatisfactory and need to be further improved.

In this paper, a VOC recovery system with the vacuum recovery method is integrated into the automatic spraying robot. Aimed at recycling noxious gases as much as possible under the premise of ensuring the normal operation of painting for the ship, the spray gun is integrated with a recovery hood with internal and external cavities in the present paper. The analysis and preliminary design of the recovery hood and the simulation of the vacuum recovery system are carried out utilizing CFD technology. The flow field is simulated by Eulerian numerical methods. The Lagrangian numerical method is used in conjunction with the Eulerian numerical method to describe the dispersed particles in a continuous phase. The associated heat- and mass-transfer phenomena (droplet evaporation) are simulated by the droplet evaporation model. A more accurate understanding of the technical performance of the recovery system can be obtained, which provides ideas and directions for optimizing and improving the design of the prototype before trial production and testing.

2. Numerical Methodology

The spraying and recovery system is one of the key technologies in the design of automatic spraying robots. The physical processes inside the spraying and recovery system

mainly involve the spraying process; the multiphase flow process for air, VOCs, and paint droplets; and the interaction between different phases, including the transport of paint droplets caused by air, the evaporation of paint droplets, and the wall impingement of the paint droplets. To research the spraying and recovery system, a numerical model based on a Lagrangian–Eulerian approach that can effectively predict complex physical phenomena is employed in the simulation. The mass conservation for the droplets is written in Lagrangian form, while the governing equations for the continuous phase are expressed in Eulerian form. The spraying process is simplified as the process in which the droplets enter the computational domain through an injector in the simulation. The size and the velocity vector distribution of the paint particles are defined by a distribution function. During the evaporation process of VOCs, the mass transfer that occurs between the paint droplets and VOCs is described by the droplet evaporation model. The results of the droplets' impact on impermeable boundaries (walls) are predicted by the Bai–Gosman wall impingement model.

2.1. Governing Equation for the Gas Phase

The flow of the continuous phases (air and VOCs) is resolved by Reynolds-averaged Navier–Stokes equations (RANS). The standard k – ε model is employed to calculate the turbulent parameters because of its low computational cost and high accuracy for a broader range of flows [35,36]. The governing equations are as follows [35]:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{u}) = 0 \quad (1)$$

where $\bar{u}$ represents the average air velocity over time and ρ is the density.

Momentum equation:

$$\frac{\partial}{\partial t}(\rho \bar{u}) + \nabla \cdot (\rho \bar{u} \otimes \bar{u}) = -\nabla \cdot \bar{p}_{\text{mod}} + \nabla \cdot (\bar{T} + T_{\text{RANS}}) + f_b \quad (2)$$

In which $\bar{T}$, T_{RANS} , and f_b represent the mean viscous stress tensor, Reynolds stress tensor, and gravity, respectively. $\bar{p}_{\text{mod}} = \bar{p} + \frac{2}{3}\rho k$ is the modified mean pressure, where $\bar{p}$ is the mean pressure and k is the kinetic energy.

The transport equations for the kinetic energy k and the turbulent dissipation rate ε are as follows [37]:

$$\frac{\partial}{\partial t}(\rho k) + \nabla \cdot (\rho k \bar{v}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k + G_{nl} + G_b - \gamma_M - \rho \varepsilon + S_k \quad (3)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \nabla \cdot (\rho \varepsilon \bar{v}) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{\varepsilon 1} \frac{\varepsilon}{k} (G_k + G_{nl} + C_{\varepsilon 3} G_b) - C_{\varepsilon 2} \frac{\varepsilon^2}{k} + S_\varepsilon \quad (4)$$

where $\bar{v}$, S_k , and S_ε represent the mean velocity and the user-specified source terms of k and ε , respectively. G_k , G_{nl} , and G_b are the turbulent production, the buoyancy production, and the nonlinear production, respectively.

2.2. Governing Equations for the Droplets

The Lagrangian multiphase flow model is designed to simulate and track the flow path of paint droplets in a continuous phase, including the associated heat- and mass-transfer phenomena (droplet evaporation). The two-way coupling method is employed to describe momentum exchange between the gas phase and the droplets. The influence of not only gas flow on the droplet trajectory, but also droplet motion on gas flow, is considered using this method [38]. The change in momentum is balanced by surface and body forces that act on the droplet, which can be written as:

$$m_p \frac{dv_p}{dt} = F_s + F_b \quad (5)$$

where v_p denotes the instantaneous particle velocity. $F_s = F_d + F_p$, and $F_b = F_g + F_c + F_{MRF}$ is the resultant of the surface forces and the body forces, where F_d , F_p , F_g , F_c , and F_{MRF} are the drag force, pressure gradient force, gravity force, contact force, and moving reference frames forces, respectively.

The size and the velocity vector distribution of droplets, as well as their temperature and composition, are specified by the injector. A range of droplet sizes generated by the injector are represented statistically by a size distribution. The log-normal size distribution is a normal (Gaussian) distribution that uses the logarithm of the size as the independent variable. Its cumulative distribution function can be written as:

$$F(D) = \frac{1}{2} \left[1 + \operatorname{erf} \left(\frac{\ln D - \ln \bar{D}}{\sigma \sqrt{2}} \right) \right] \quad (6)$$

where D and σ is the diameter and standard deviation.

2.3. Droplet Evaporation Model

As paint droplets are volatile, mass transfer occurs from liquid to air. The mass transfer is accompanied by interphase heat transfer caused by temperature differences. The mass conservation equation of a paint droplet can be written as:

$$\frac{dm_p}{dt} = \dot{m}_p \quad (7)$$

where $\dot{m}_p$ is the mass transfer rate for the particles, which is zero unless mass transfer occurs, like in evaporation. Droplet evaporation assumes the droplets to be internally homogeneous, consisting of an ideal mixture of liquid components. The change rate of droplet mass due to quasi-steady evaporation $\dot{m}_p$ is given by [39]:

$$\dot{m}_p = -\varepsilon_i g^* A_s \ln(1 + B) \quad \left(\sum_i \varepsilon_i = 1 \right) \quad (8)$$

where B is the Spalding transfer number and g^* is the mass transfer conductance. The index i refers to each component of the mixture of components and ε_i is the fractional mass transfer rate.

2.4. Wall Impingement Model

The impact of droplets on rigid solid surfaces produces a variety of effects, which may depend on the size, velocity, material, and nature of the surface. To model the behavior of droplets impacting on a wall, the Bai–Gosman wall impingement model [40] is used in the present paper. The Bai–Gosman wall impingement model categorizes possible outcomes as being in one of six possible regimes (adhere, rebound, spread, break-up and rebound, break-up and spread, and splash).

For a given impingement event, the regime is determined by the following three parameters: the incident Weber number We_I , the boundary temperature T_w , and the wall state (wet or dry).

The incident Weber number:

$$We_I = \frac{\rho_p v_{r,n}^2 D_p}{\sigma} \quad (9)$$

in which $v_{r,n} = (v_p - v_w) \cdot \vec{n}_w$ represents the normal component of the particle velocity v_p relative to the wall. $\vec{n}_w$ is the unit vector normal to the boundary. ρ_p , D_p , and σ represent the density, diameter, and surface tension of the droplet.

Three ranges are separated by two transition temperatures (T_{12} and T_{23}). T_{12} , which is expected to be the boiling temperature of the droplet, separates range 1 from range 2. T_{23} is expected to be approximately the Leidenfrost temperature of the droplet, separating range

2 from range 3. In range 1, adhere ($We_l \leq 2$) and rebound ($2 \leq We_l \leq 20$) regimes may occur on a wet wall, but not on a dry wall. The regimes are determined by two characteristic Weber numbers (We_{T1} and We_{T2}), including rebound, break-up and rebound, break-up and spread, as well as splash.

3. Automatic Spraying and Recovery Robot

The automatic spraying and recovery robot is expected to conduct the recovery operation to recycle VOCs as much as possible during the spraying process. Without any restrictions or controls, the escape of VOCs is bound to occur. Therefore, recovery hoods with vacuum recovery methods need to be designed to ensure the generation of a recovery flow field. The recovery flow field is required to have the ability to prevent VOCs from escaping.

3.1. Design Scheme of the Spray and Recovery System

The recovery system is comprised of two parts: the recovery hood for recycling the diffused pollutant and the nozzle for spraying. To meet the requirements of spraying and recycling VOCs, the automatic spraying robot is equipped with a recovery hood with a built-in spraying system and double-layer cavities in the design scheme. The recovery hood, which is axially symmetric, consists of an external and internal cavity and four vacuum tubes. The nozzle and the recovery hood are situated 320 mm and 20 mm, respectively, distant from the hull. The diameter of the vacuum tube, internal cavity, and external cavity is defined as 100 mm, 350 mm, and 600 mm, respectively.

To facilitate the understanding of the characteristics of the device, the parameters of three vacuum recovery-hood schemes are provided. The models of these schemes are created by a CAD software named CAESSES 5.0. The schematic diagrams of these are shown in Figures 1–3. Scheme A is a recovery hood consisting of an internal cavity and an external cavity with a height of 0.32 m, as well as four vacuum tubes. Scheme B is a modification based on Scheme A. Considering that the velocity of airflow may decrease with distance, Scheme B adopts a shorter external cavity, as shown in Figure 2. To tackle the problems caused by the vortices mentioned in Section 4.1.2, Scheme C is designed. Based on Scheme B, Scheme C adds deflectors to the baffle planes of the recovery system to separate the external cavity, which is expected to further improve the recovery efficiency and reduce the leakage rate. The geometric parameters of the deflectors are shown in Figure 3.

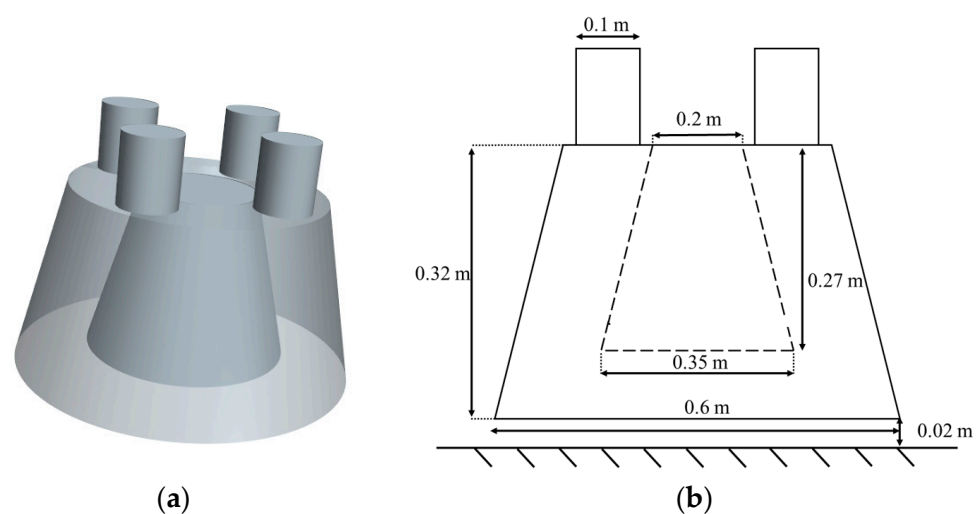


Figure 1. Schematic diagram of Scheme A. (a) Front view. (b) Dimensional diagram.

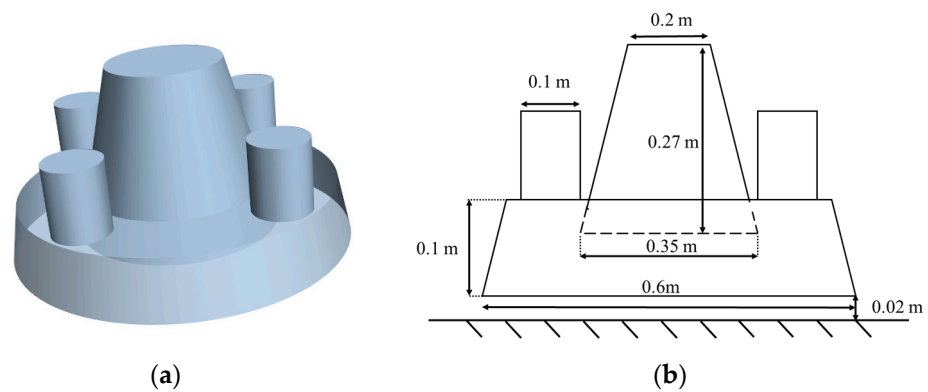


Figure 2. Schematic diagram of Scheme B. (a) Front view. (b) Dimensional diagram.

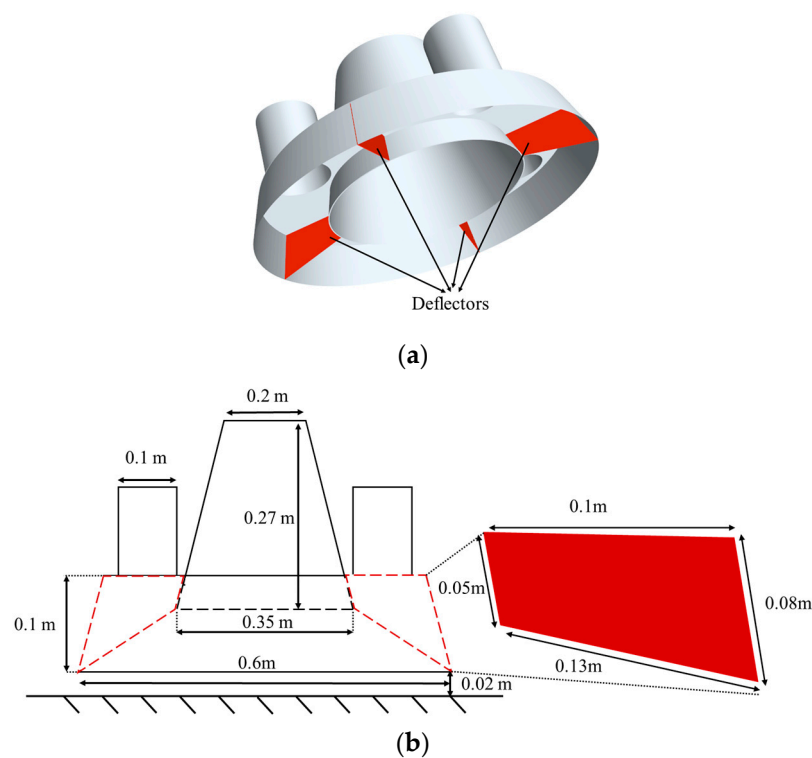


Figure 3. Schematic diagram of Scheme C. (a) Front view. (b) Dimensional diagram.

3.2. Working Principle

The bold arrows in Figure 4 indicate the expected flow direction of the flow field inside the recovery hood of Scheme A, which is consistent with Scheme B and Scheme C. The negative pressure suction is generated by the vacuum recovery method at the position of the vacuum tubes. When affected by the negative pressure suction, the VOCs or overspray paint mist can be recycled into the vacuum tubes, and the air flows into the recovery hood in the intake gap, which may prevent the VOCs and overspray paint mist from escaping from the device. When affected by the flow field, the VOCs evaporated from the paint mist are expected to flow into the vacuum tubes rather than escape from the recovery hood into the external atmospheric environment. Under the protection of the internal cavity, the paint is sprayed in a conical shape around a specified axis from the nozzle with an airless spraying method, as shown in Figure 5.

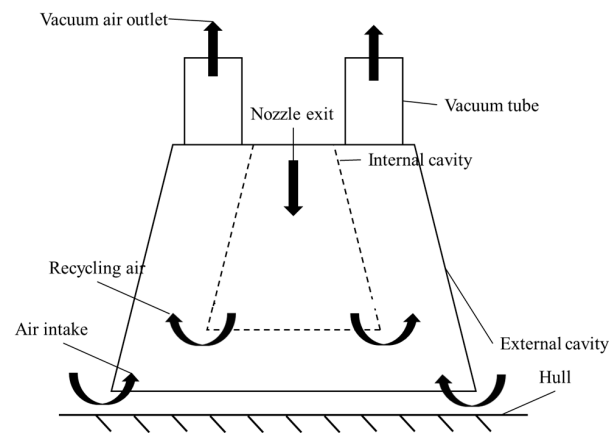


Figure 4. Schematic diagram of the recovery hood.

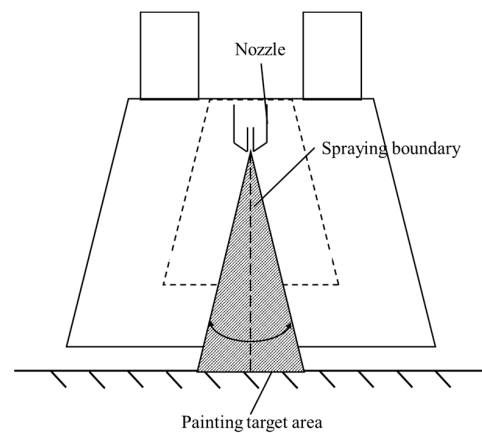


Figure 5. Schematic diagram of the recovery hood with nozzle.

The recovery performance of these is investigated and analyzed in the present paper. The technical parameters of the existing industrial vacuum blower are combined to determine the working conditions of the simulation, as shown in Table 1. The parameters of the paint and nozzle are determined by the technical data of the phenolic/novolac epoxy Jotaprim 510 product [13], as shown in Table 2.

Table 1. Parameters of the recovery hood.

Parameters	Performance
Volume flow rate	960 m ³ /h
Total suction area (four vacuum tubes)	0.0314159 m ²
Critical flow Reynolds number	8000~10,000 mm
Distance of recovery hood from the hull	20 mm
Distance of nozzle from the hull	320 mm
Taper angle of spraying	20 deg
Average spraying velocity	10 m/s

Table 2. Parameters of the paint.

Parameters	Jotaprim 510 Comp A	Jotaprim 510 Comp B
Surface tension	0.0456 N/m	0.0287 N/m
Density	1170 kg/m ³	861 kg/m ³
Molecular weight	340.413 kg/kmol	106.165 kg/kmol
Specific heat	\	1200 J/kg·K
Critical pressure	\	3.51 MPa
Critical temperature	\	359 °C

3.3. Computational Domain and Mesh Generation

The spraying operation is simulated by means of the hollow-cone injector model, as the internal cone angle, injector diameter, and velocity of particles are defined. The computational domain of the numerical model used in this study is depicted in Figure 6. To better capture the phenomenon of the VOCs escaping from the recovery system, the area between the hull and the recovery system is also added to the computational domain and expanded, as shown by the cylinder below the recycling system in Figure 6. The top and sides of the cylinder are set as velocity inlets to simulate the process of the device inhaling air from the external atmospheric environment, while are also regarded as the boundaries to detect any escape of VOCs. The bottom of the cylinder represents the painted surface of the hull. The tops of those vacuum tubes are defined as outlets, while the remaining boundaries are set as walls. Planes of the vacuum tube and the baffle are established to show the flow field inside the recovery system, as shown in Figure 7. To ensure that a stable recovery flow field has been generated when the paint mist is sprayed out of the nozzle, the process of spraying is set for 1 s after the start of the suction caused by the vacuum tubes.

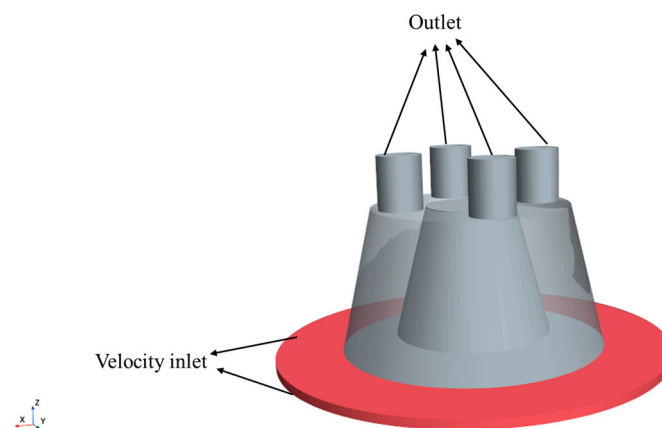


Figure 6. Computational domain.

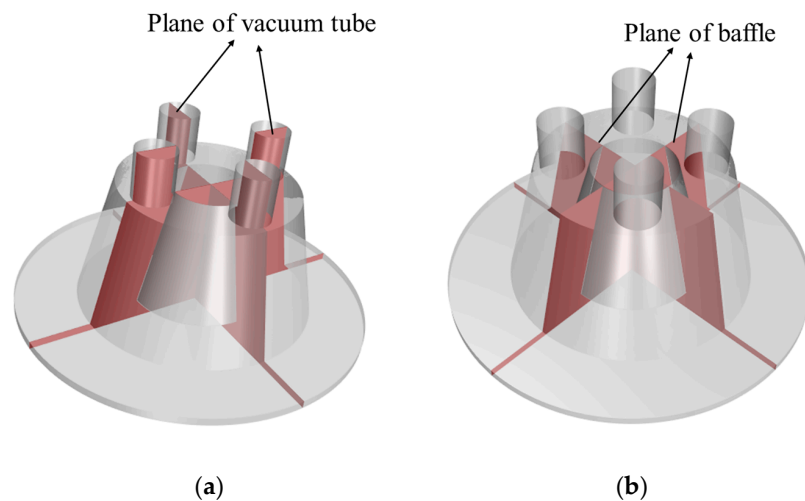


Figure 7. (a) Vacuum tube planes. (b) Baffle planes.

For the paint spraying and recovery simulations of the recovery system, the domain is discretized in a grid system, and finite volume mesh is generated entirely with trimmed cells, as shown in Figure 8. To ensure that the features of complex flow and the intense atomization of the paint during spraying are appropriately captured, the mesh is refined in the spray fan area. The area near the intake gap is also refined to better identify whether VOCs and overspray paint mist have escaped from the device. The refined mesh in these zones is achieved by using volumetric controls. Considering the complexities and effects

of the regimes when the droplets impact a wall, a prism layer model is also applied to produce refined orthogonal prismatic cells of four layers adjacent to the object surface. The details of the refinement can be seen in the mesh slice of the recovery hood in Figure 8. The base size of the mesh is set as 0.004 m, and the cell sizes in the refined mesh areas are defined as 60% relative to the base size.

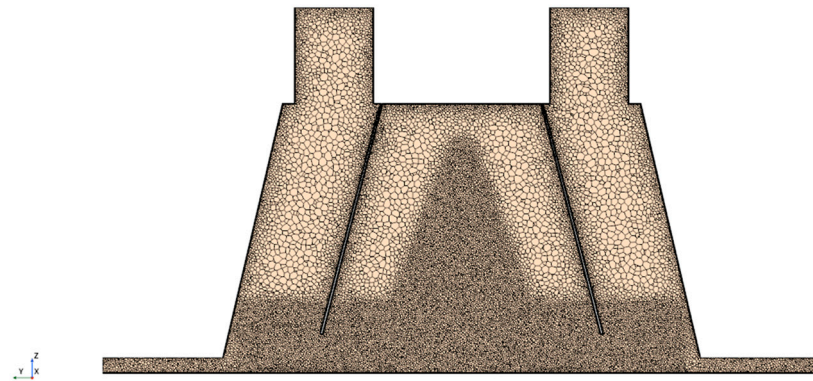


Figure 8. Mesh slice in the vacuum-tube plane of the recovery hood.

To verify the accuracy of the simulation, the convergence study of the mesh size and the time step is carried out in the present study. Five models of Scheme A (model 1, model 2, model 3, model 4, and model 5) with different meshes ($\Delta x = 0.004$ m, $\Delta x = 0.00525$ m, and $\Delta x = 0.0065$ m) and different time steps ($\Delta t = 0.00025$ s, $\Delta t = 0.0005$ s, and $\Delta t = 0.00075$ s) are investigated, with the details of the meshes and the time steps shown in Table 3. As seen from Figure 9, the results of model 2 and model 3 with the mesh refinement agree well, while the results of model 4 are different, especially at the beginning. The results of model 1, model 2, and model 5 as shown in Figure 10 are almost identical, while the results of model 5 with time step $\Delta t = 0.00075$ s are different compared with the results in the other two cases. It is concluded that the model generating the cells with 0.004 m and a time step of 0.0005 s is sufficiently accurate.

Table 3. Time-step and mesh-size details for the convergence study.

Model	Time Step	Mesh Size
1	$\Delta t = 0.00025$ s	$\Delta x = 0.004$ m
2	$\Delta t = 0.0005$ s	$\Delta x = 0.004$ m
3	$\Delta t = 0.0005$ s	$\Delta x = 0.00525$ m
4	$\Delta t = 0.0005$ s	$\Delta x = 0.0065$ m
5	$\Delta t = 0.00075$ s	$\Delta x = 0.004$ m

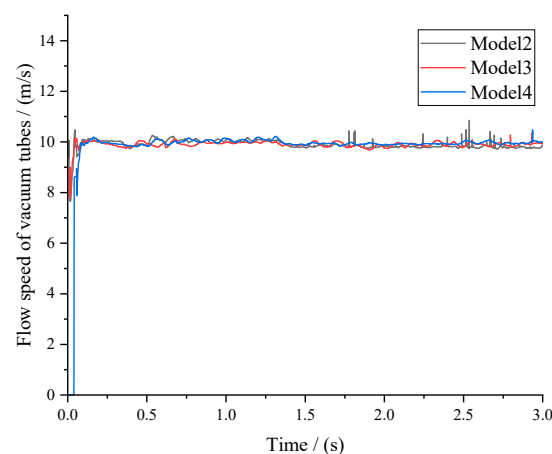


Figure 9. Flow speed of vacuum tubes with different meshes.

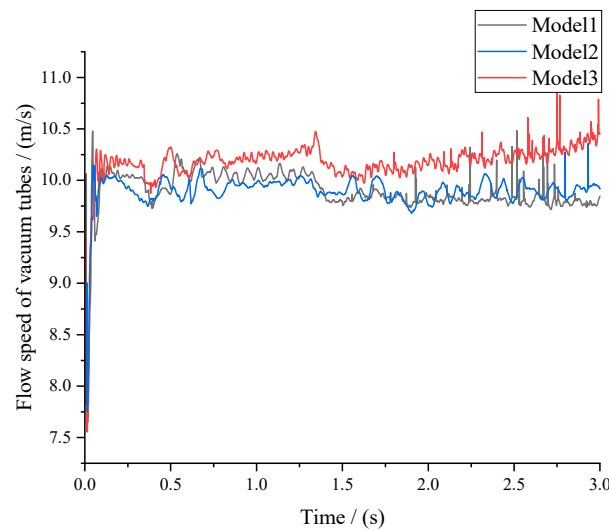


Figure 10. Flow speed of vacuum tubes with different time steps.

4. Discussion of Results

4.1. Analysis of the Flow Field Inside the Recovery Hood

As shown in Figure 11, the suction of the vacuum tubes has a great impact on the flow field in the area near the hull and the intake gap, as well as on the area near the external cavity. The air-phase flow speed caused by the suction of the vacuum tubes decreases with the increase in the distance from the vacuum tubes. The velocity of the intake gap caused by the suction of the vacuum tubes can reach 2 m/s. The reason why the air-phase flow speed drops sharply from 10 m/s in the vacuum tubes to 5 m/s in the external cavity is that when entering the external cavity from the vacuum tubes, the surface area increases. As we can see from the velocity vectors shown in Figure 11, the air-phase flow direction at the end of the internal cavity undergoes a significant angular deflection due to the wall friction. The impact of the flow field on the internal cavity is minimal, resulting in the air-phase flow speed not exceeding 0.5 m/s in the internal cavity. The conical velocity component inside the recovery system shown in Figure 12 is caused by the spraying of paint mist from the nozzle. The velocity of the paint mist sprayed from the nozzle reaches 9.9 m/s, which equals the initial spraying speed defined earlier. It means that the spraying process is not affected by the flow field and conducts normally under the protection of the internal cavity. However, when affected by the geometric shape of the internal cavity and external cavity, the flow direction of the airflow from the intake gap and internal cavity entering the external cavity changes greatly. When the airflow enters the external cavity, it moves along the wall of the external cavity toward the vacuum tubes, causing a zero-velocity region near the surface of the internal cavity. It indicates that the space of the external cavity has not been fully utilized.

The average air-phase flow speed in the area of the vacuum tubes is 10 m/s, as we can see from Figure 13. Figure 14 illustrates that the air-phase flow speed of the air intake exhibits periodic fluctuations, with an equilibrium position of 1.5 m/s and an amplitude of 0.5 m/s. The periodic fluctuations may be caused by the airflow generated by the periodic spraying of paint particles. The peak velocity of 12 m/s in the vacuum tubes and intake gap is caused by the paint particles flowing to the above areas. Since the boundaries of the suction surface and intake gap have detected paint particles flowing to those areas, paint particles and VOCs can escape from the recovery system. Therefore, it is necessary to try to further improve the structure of the recovery hood.

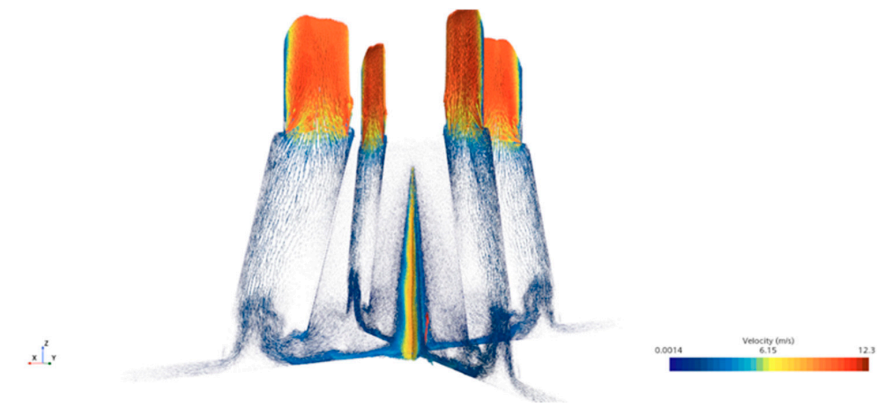


Figure 11. Velocity vectors of the flow field in the vacuum-tube planes.

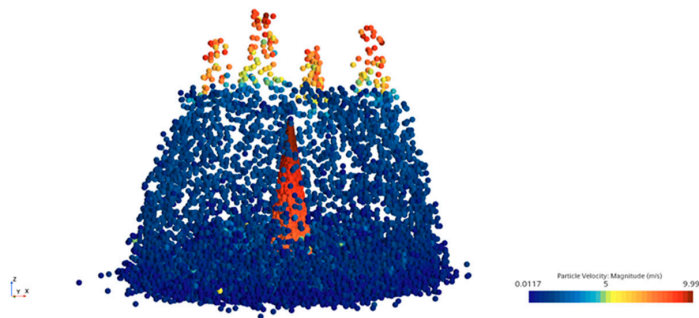


Figure 12. Velocity of the paint particles inside the recovery system.

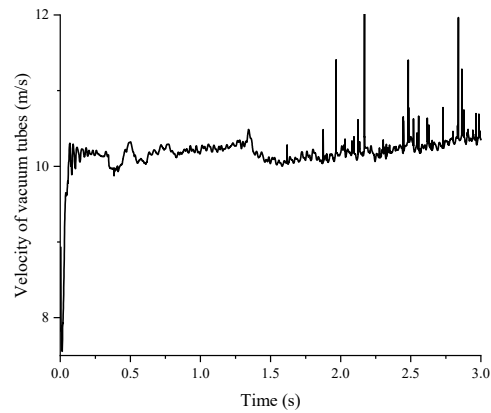


Figure 13. Velocity in the vacuum tubes.

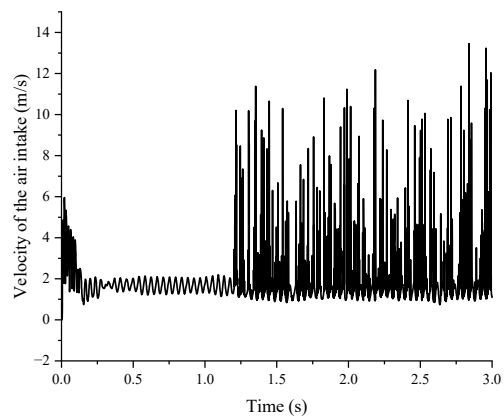


Figure 14. Velocity of the air intake.

4.1.1. Improvement in Velocity Attenuation

To solve the problem of velocity decrease without changing the recovery parameters, the recovery hood is modified as in Scheme B, as shown in Figure 2. The main optimization in Scheme B is that the height of the external cavity is reduced, directly shortening the distance from the vacuum tubes to the bottom of the recovery hood. The height of the external cavity is set as 0.1 m, while the other geometric parameters of the recovery hood are the same as for Scheme A.

The parameters for the mesh are also the same as for Scheme A. The definitions of the refined zones continue to follow those of Scheme A, as the regions that require refinement to capture complex phenomena are consistent. As we can see from Figure 15, the air-phase flow speed in the area of the intake gap and external cavity increases since the distance between the vacuum tubes and the intake gap is shortened. The significant change in the airflow direction in the external cavity is still present, while the zero-velocity zones in the external cavity surface disappear. The impact on the spraying process is small under the protection of the internal cavity, as shown in Figure 16.

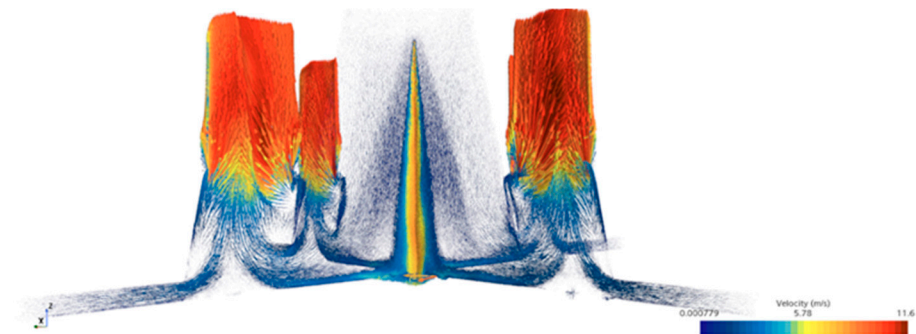


Figure 15. Velocity vectors of the flow field on the vacuum-tube planes of Scheme B.

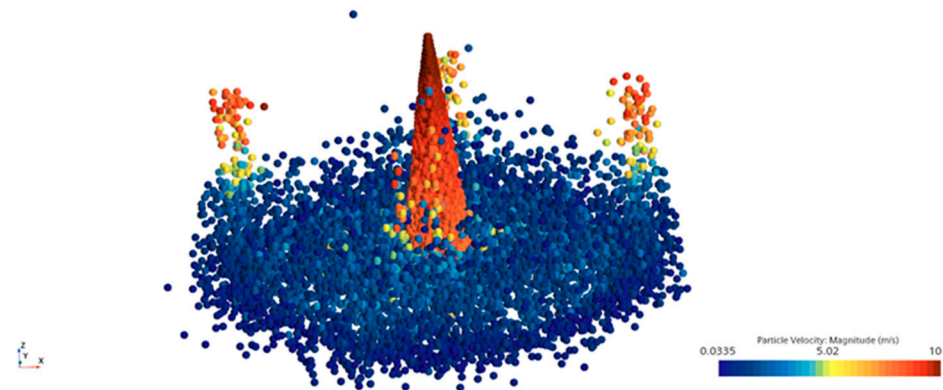


Figure 16. Velocity of the paint particles inside the recovery system of Scheme B.

Figure 17 shows that the velocity of the air intake in Scheme B also exhibits periodic fluctuations, with an equilibrium position of 2.8 m/s and an amplitude of 0.1 m/s. The average velocity of the air intake increases as expected, while the vacuum tubes are deposited closer to the intake gap. The smaller amplitude compared with Scheme A illustrates that the velocity of the air intake becomes more stable. The peak velocity of 13 m/s records the velocity of paint particles flowing to those areas. The peak value of the air-intake velocity in Scheme B shows the same tendency as in Scheme A, which indicates that the leakage situation may not differ significantly from that in Scheme A. The improvement of the flow field in the vacuum-tube plane may have little impact on the leakage situation since the leakage situation remains unchanged. Therefore, we should focus on areas where the escape of VOCs may occur, such as the baffle planes of the recovery system, where VOCs may accumulate.

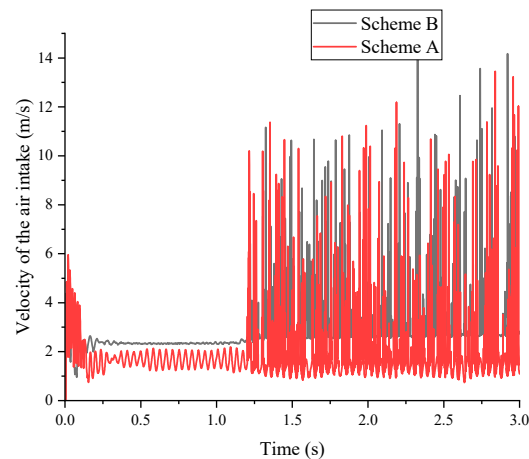


Figure 17. Velocity of the air intake (Scheme A vs. Scheme B).

Figure 18 shows the flow-field velocity vectors on the baffle planes of Scheme B, where the vortices highlighted by a red box on the baffle planes are worthy of our attention. Those vortices may capture the VOCs, causing the accumulation of VOCs in those areas until they escape. After optimization, the fluctuation of airflow velocity in the recovery system becomes smaller, as shown in Figure 18, and the flow field becomes more stable. In addition, the baffle plane is placed between two vacuum tubes, and the vacuum tubes on both sides of the baffle plane have the same effect on it. It illustrates that the suction on both sides of the baffle plane is equal, and the vortices will not be forced to flow into one of the vacuum tubes, which allows the vortices to remain stable in the region for a long time.

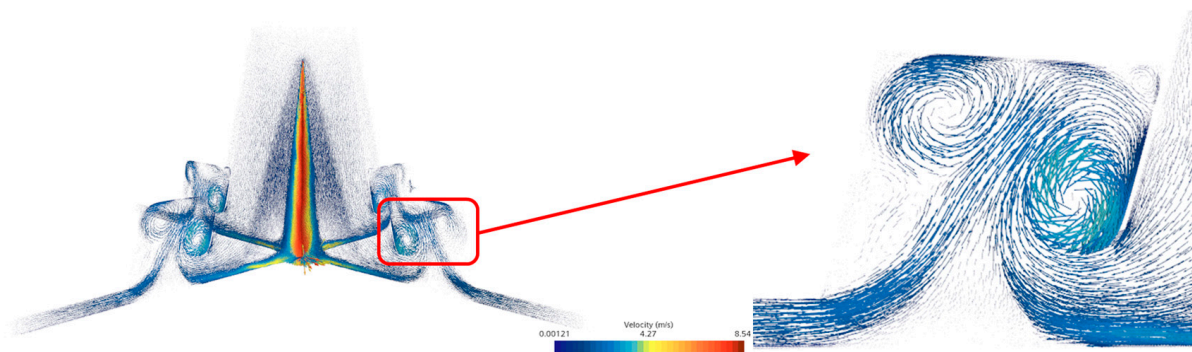


Figure 18. Velocity vectors of the flow field on the baffle planes of Scheme B.

4.1.2. Improvements for Swirling Airflow

As we can see from Figure 18, the airflows entering the baffle planes come from the intake gap and the internal cavity. When these airflows collide with the baffles, the flow direction is forced to change, forming vortices. Since we cannot avoid the generation of the vortices, guiding the airflows to the vacuum tubes seems to be the most promising way to weaken the vortices in the baffle planes. As the recovery system is symmetrical along the baffle plane, the flow field in the baffle planes is also symmetrical. The suction on both sides of the baffle planes is balanced, which is the main reason why the vortices will not flow to any vacuum tubes. To guide the vortices to the vacuum tubes, Scheme C adds deflectors to the baffle planes of the recovery system to separate the external cavity, based on Scheme B. The geometric parameters of the deflectors are shown in Figure 3.

The external cavity is divided into four chambers by the deflectors, each equipped with a vacuum tube. By doing so, the vortices in the baffle planes will not remain stationary, while the airflow in any chamber will flow toward the only vacuum tube in its chamber.

The trajectory of airflows in the baffle planes can be observed through the velocity vector within the recovery system, as shown in Figures 19 and 20.

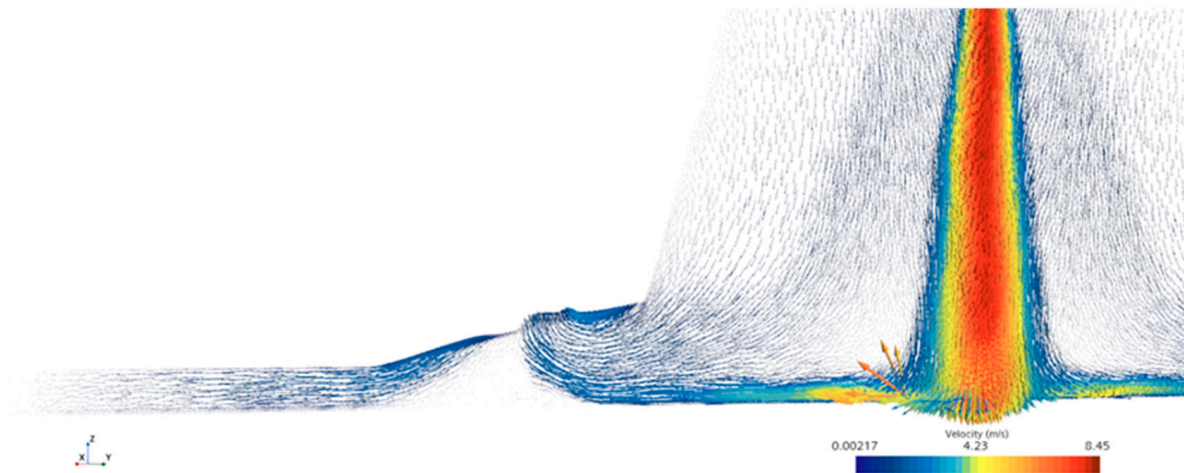


Figure 19. Velocity vectors on the baffle plane of the recovery system with deflectors.

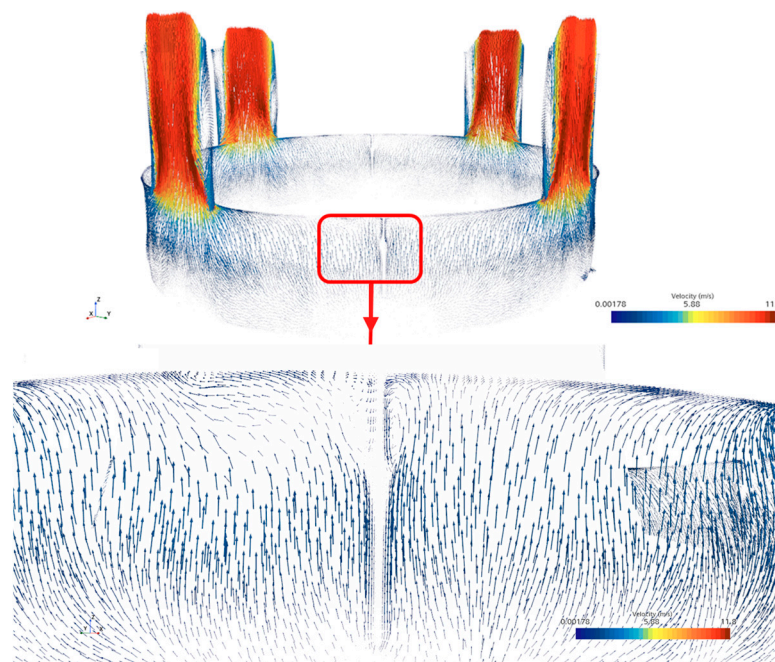


Figure 20. Velocity vectors on the cylinder plane of the recovery system with deflectors.

The vortices in the baffle plane disappear when the deflectors are added. Figure 20 shows the velocity vectors in the cylinder plane (radius = 0.24 m), which is orthogonal to the deflectors. After adding the deflectors, the airflow separates near the surface of the deflector and moves away from it, ultimately being recovered by the vacuum tubes. As we can see from Figure 21, the average air-intake speed in Scheme C is smaller than that in Scheme B, while their trend is similar. Furthermore, the number of times the air-intake speed reaches a peak of 12 m/s (the velocity of paint particles) in Scheme C is less than that in Scheme B, which indicates an improvement in its leakage rate. So, it is necessary to figure out the recovery performance of the recovery system by analyzing the distribution of the VOCs.

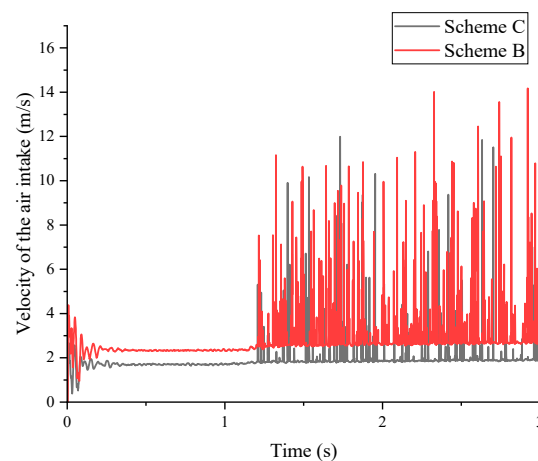


Figure 21. Velocity of the air intake (Scheme B vs. Scheme C).

4.2. Analysis of VOC Distribution Inside the Recovery Hood

As we have modified the flow field inside the recovery hood, it is necessary to figure out its influence on the VOCs by analyzing the distribution of the VOCs. The VOCs and air-component distribution of Scheme A in the plane of the vacuum tube (X-axis) are well presented in Figures 22 and 23. The color depth in Figure 22 represents the size of the VOC mass fraction and reflects the concentration of VOCs. The results of the vacuum-tube plane (Y-axis) are omitted since the physical phenomena are symmetrical about the centerline of the model. The morphology of partial VOCs in the external cavity shows that the flow direction of VOCs would change on the way to the vacuum tubes. During the propagation of VOCs to the vacuum tubes, there are directional changes rather than movement directly along the direction of the vacuum tubes. Those directional changes will lead to a longer propagation distance, resulting in a significant discount in the recycling capacity. Figure 23 records the maximum VOC mass fraction at each X-coordinate. It can be seen that the evaporation process of VOCs from paint mist mainly occurs in the area near the spray path and the painted surface of the ship. When affected by the flow field, the VOCs generated from the paint mist move toward the vacuum tubes. Figure 23 shows that the mass fraction of VOCs is not zero at 0.32 m on the X-axis, which means that the VOCs escape to the areas outside the recovery system (the maximum radius of the external cavity of the recovery system is 0.3 m). The distribution of VOCs shows that most VOCs are concentrated inside the internal cavity, with a small portion scattered at the vacuum tubes and the hull. As the absolute value of the X-coordinate increases, the VOC mass fraction shows a decreasing trend, and only when the absolute value of the X-coordinate reaches 0.2 does the VOC mass fraction increase. The peak of the VOC mass fraction reaches 1.0 in the center of the recovery system since the VOCs have evaporated from the paint mist during the spraying process. A second peak of the VOC mass fraction appeared near the vacuum tubes, with a size of 0.38.

The VOCs and air-component distribution of Scheme B in the vacuum-tube plane (X-axis) are well presented in Figures 24 and 25. Figure 24 shows that as the distance between the vacuum tube and the intake gap shortens, volatile organic compounds move directly along the direction of the vacuum tubes. The shorter the propagation distance, the better the recycling efficiency. The area where the X-coordinate is zero is the place with the highest VOC concentration, where the evaporation and spraying processes occur most fiercely. Compared with the mass fraction of VOCs inside Scheme A, the mass fraction of VOCs decreases to 0 at the edge of the recovery hood (X-coordinate > 0.3 m) after optimization. The mass fraction of VOCs reaches 0.1 near those areas in Scheme A. It indicates that the diffusion of VOCs at the edge of the recovery hood is suppressed as the vacuum tubes are deposited closer.

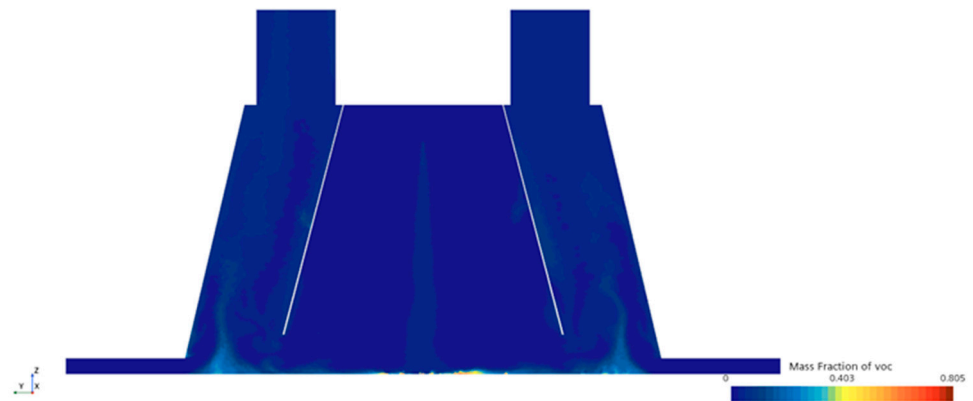


Figure 22. Distribution of the VOCs on the plane of the vacuum tube (X-axis).

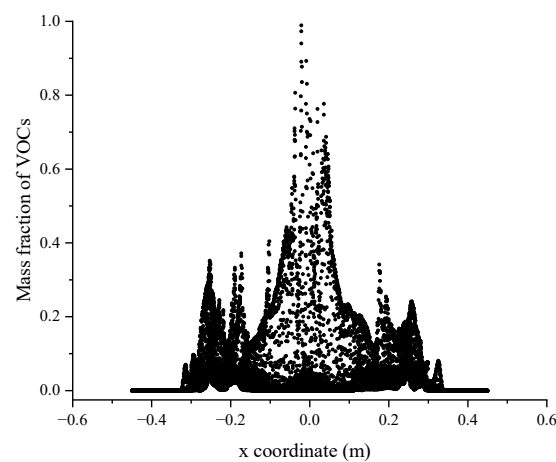


Figure 23. Mass fraction of VOCs on the plane of the vacuum tube (X-axis).



Figure 24. Distribution of the VOCs on the vacuum-tube plane (X-axis) of Scheme B.

As we seen from Figures 26 and 27, the distribution of VOCs also exhibits characteristics similar to vortex velocity vectors. The VOCs move together with vortices and roll over in this region. The negative effects caused by the vortex have been described in Section 4.1.1. As shown in Figure 27, when the absolute value of the X-coordinate nears 0.3 m (the edge of the recovery hood), the mass distribution of VOCs reaches a peak of 0.8. It is obvious that the accumulation of VOCs is caused by vortices. In addition, due to the absence of vacuum tubes in these areas, those accumulated VOCs cannot be recovered completely. Most of them may escape from the device. It is clear that the method of optimizing the

recovery system is to minimize the vortices in the baffle planes as much as possible since they are the main cause of VOCs accumulating in the external cavity and escaping.

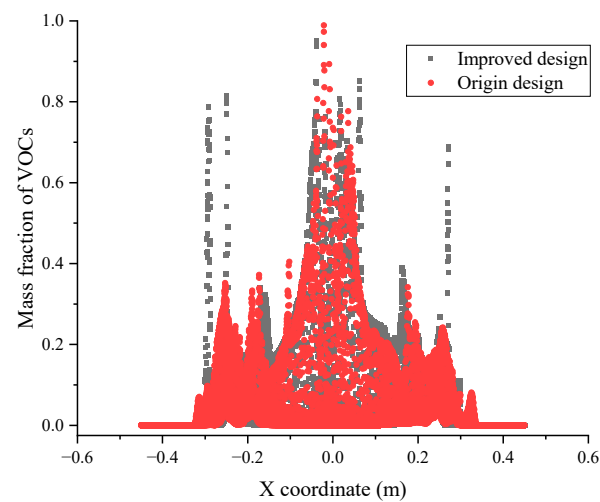


Figure 25. Mass fraction of VOCs on the vacuum-tube plane (Scheme A vs. Scheme B).

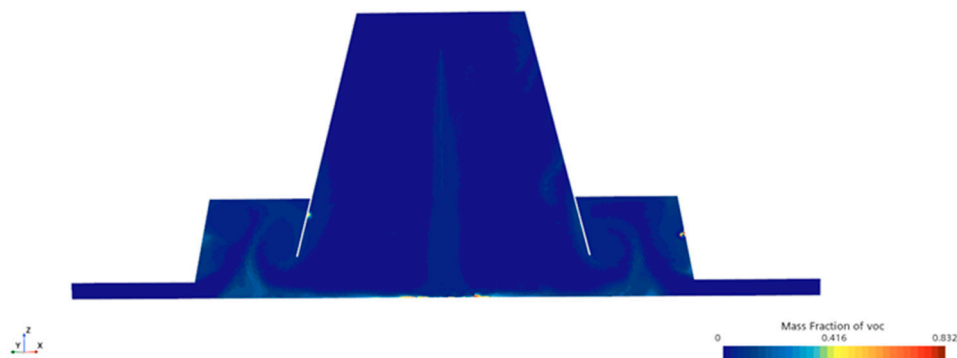


Figure 26. Distribution of the VOCs on the baffle plane of Scheme B.

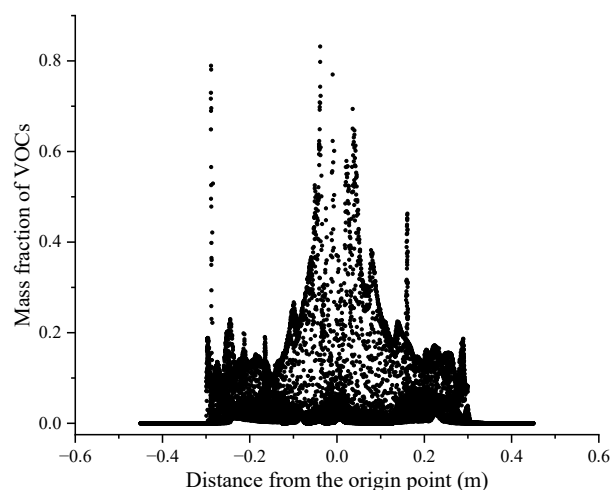


Figure 27. Mass fraction of VOCs on the baffle plane.

As the flow field changes after adding the deflectors, the distribution of VOCs also changes accordingly, as shown in Figure 28. After adding the deflectors, the peak of the VOC mass fraction at the edge of the external cavity on the baffle plane decreases from 0.81 to 0.32. It means that the accumulation of VOCs on the baffle plane is reduced. Compared

with the recovery system without deflectors, the mass fraction of VOCs increases when the absolute value of the distance from the origin point is less than 0.2. It illustrates that more VOCs move to the vacuum tubes rather than accumulate in the external cavity, which confirms the expected role of the deflectors. Next, let us focus on the performance indicators of the recovery system, such as leakage rate, recovery rate, and trapped rate.

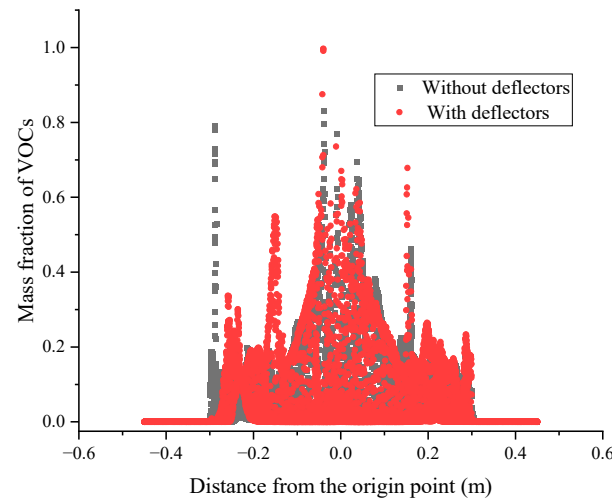


Figure 28. Mass fraction of VOCs on the baffle plane (Scheme C vs. Scheme B).

4.3. Analysis of the VOC Recovery Effect

In order to evaluate the efficiency of the recovery system, the recovery rate η_r and leakage rate η_l are defined as shown in Equations (10)–(12).

$$\eta_r = \frac{m_r}{m_{total}} \times 100\% \quad (10)$$

$$\eta_l = \frac{m_l}{m_{total}} \times 100\% \quad (11)$$

$$\eta_t = \frac{m_t}{m_{total}} \times 100\% \quad (12)$$

where m_{total} is the total mass of VOCs in the device, which can also be written as $m_{total} = m_r + m_l + m_t$. m_r , m_l , and m_t represent the VOC recovery mass, VOC escape mass, and VOC trapped mass, respectively. From the statistics of the escape of VOCs in the recovery system, the recovery rate η_r and leakage rate η_l are shown in Figure 29.

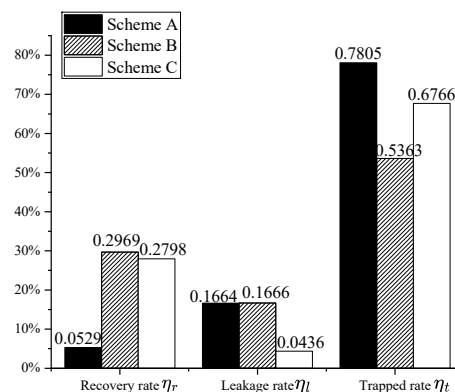


Figure 29. The efficiency of the recovery system.

As for Scheme A, although the leakage rate of VOCs is less than 20%, the recovery rate can only reach 5.29%. The low recovery rate means that even if the spraying operation

is stopped, a significant cost (such as time or a larger negative pressure for suction) still needs to be paid to recover the VOCs captured in the device. In order to improve the recovery efficiency, the defect in the current design needs to be corrected. According to the flow-field analysis, there is a main design defect that may cause the low recovery efficiency. The defect is that the vacuum tubes are deposited too far from the intake gap, resulting in a significant velocity attenuation of the air-phase flow. Due to the speed of the VOCs evaporated from the paint mist, a low-speed air-phase flow may not effectively force the VOCs to move toward the vacuum tubes. Meanwhile, the long distance from the vacuum tubes to the bottom of the device becomes a channel for capturing VOCs, which may cause a high trapped rate.

The recovery rate of Scheme B improves to 29.69% after optimization, while the leakage rate remains unchanged. Although the diffusion of VOCs at the edge of the recovery hood in the vacuum-tube plane (X-axis) is suppressed, it has a small impact on the leakage rate. Therefore, the diffusion of VOCs in the vacuum-tube plane (X-axis) may be not the main cause of the leakage of VOCs. The task of optimizing the recovery system requires an understanding of how the VOCs escape and their distribution characteristics within the hood. As we know, the main leakage is not in the area near the vacuum tubes, so we should focus on the areas less affected by the vacuum tubes, like the baffle planes. Figure 25 shows the velocity vectors of the flow field on the baffle planes of Scheme B, where the vortices highlighted by a red box on the baffle planes are worthy of our attention. Those vortices may capture the VOCs, causing the accumulation of VOCs in those areas until they escape. After optimization, the fluctuation of airflow velocity in the recovery system becomes smaller, as shown in Figure 22, and the flow field becomes more stable. In addition, the baffle planes are placed between two vacuum tubes, and the vacuum tubes on the left side and right side have the same effect on the baffle planes. This allows the vortices to remain stable in the region for a long time. From the statistics of the escape of VOCs in Scheme C, the recovery rate of the recovery system remains invariant compared with Scheme B, while the leakage rate is greatly reduced to 4.36%.

5. Discussion

The recovery system consists of two parts: (1) A recovery hood equipped with vacuum tubes, which can ensure the normal operation of painting for the ship while also recovering VOCs; (2) A nozzle arranged at the center of the recovery hood. Three vacuum recovery hood schemes are designed as follows: Scheme A, with a recovery hood consisting of an internal cavity and an equally high external cavity, as well as four vacuum tubes; Scheme B, with a shortened external cavity; and Scheme C, with the deflectors. The recovery vacuum suction remains the same in the vacuum recovery-hood schemes. During the simulation process, the parameters for the spraying operation, as well as the mesh definition and boundary conditions in different schemes, are the same.

The simulation process of Scheme A shows that the airflow generated by negative pressure suction decreases sharply with increasing distance. In addition, governed by the structure of the recovery hood, the flow direction is forced to change. When the airflow enters the external cavity, it is limited by the steering angle of the flow direction, and the airflow can only move along the wall of the external cavity toward the vacuum tubes, causing a zero-velocity region in the external cavity. The zero-velocity region in the external cavity indicates that the air phase stays still in this region, which means that the space of the external cavity has not been fully utilized. The recovery rate can only reach 5.29%, while the leakage rate is 16.64%.

The simulation process of Scheme B indicates that the recovery efficiency of the recovery system can be significantly improved by shortening the distance between the vacuum tubes to the intake gap. Compared with Scheme A, the recovery rate of Scheme B increases from 5.29% to 29.69%, while the leakage rate remains basically unchanged and reaches 16.66%. It indicates that once the spraying operation is stopped (no more VOCs are produced), the VOCs inside the recovery system can be recovered in a short period.

The simulation process of Scheme C finds that the most promising way to weaken the vortices on the baffle planes is to guide the vortices to the vacuum tubes. By dividing the external cavity into four chambers with the deflectors, each chamber is affected by only one vacuum tube, so that the vortices that once still stayed on the baffle planes can be eliminated. The leakage rate of Scheme C can be reduced to 4.36%, and the recovery rate can remain at 27.98%.

It is evident that Scheme C can achieve the recovery of VOCs without affecting the spraying process, which is suitable for painting and coating operations in shipyards. The simulation of the recovery system provides a theoretical solution for the implementation of VOC emissions control in shipyards as soon as possible.

6. Conclusions

In this paper, we design a recovery system for a spraying robot with a vacuum recovery method to address the VOCs produced in the spraying operation. Three vacuum recovery-hood schemes are designed to meet the requirements of spraying and recycling VOCs. The CFD method is applied to estimate the efficiency of these schemes, leading to the following conclusions:

- (1) The flow direction of the airflow is affected by the structure of the recovery hood. Limited by the steering angle of the flow direction, a zero-velocity region may be formed in the channel from the external cavity to the vacuum tubes. The zero-velocity region narrows the space from the external cavity to the vacuum tubes, which is not conducive to the recovery of VOCs.
- (2) The recovery rate of Scheme B increases from 5.29% to 29.69% compared with Scheme A. The distance between the vacuum tubes and the intake gap has a significant impact on the VOC recovery effect. Shortening the distance between the vacuum tubes to the intake gap can significantly improve the recovery efficiency of the recovery system.
- (3) The deceleration of the airflow occurs due to the friction at the wall. The vortices are generated in the corner of the recovery hood. Those vortices deserve more attention from us, especially the vortices on the baffle planes, since they may capture VOCs. As VOCs are continuously captured by vortices, the concentration of VOCs will continue to rise. In the area where vacuum tubes are absent (baffle plane), the accumulation of VOCs is easily beyond the capacity of the external cavity and escapes.
- (4) By adding deflectors to guide the vortices to the vacuum tubes, the leakage rate of Scheme C can be reduced to 4.36%, and the recovery rate can remain at 27.98%. Dividing the external cavity into four chambers with the deflectors (such that each chamber is affected by only one vacuum tube) can eliminate the vortices that once still remained on the baffle planes.

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