Flow Analysis and Optimization of the Air channel of Drying Chamber Based on CFD

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Abstract. According to the structure of the air channel in the drying chamber of an automobile factory, a model of the original structure of the drying chamber was established. The airflow of this structure is analyzed based on the CFD simulation, and the velocity at specific points of the car shell being dried is also analyzed. The results show that the original drying chamber structure is optimized, the air flow is uniform in the drying air chamber and short circuit of air between inlet and outlet in the drying chamber is decreased.

1. Introduction

At present, as the competition in the automotive industry continues to increase, the precision of the automotive manufacture needs to be continuously improved to ensure the quality of automobile. The drying chamber plays a vital role in automobile production. If the dry air distribution is uneven in the drying chamber, it will cause uneven temperature in the drying chamber, which will make the dried car unevenly heated and affect the strength of the uniformity of the paint on the surface of the car.

Bai Yun¹ used Autodesk Simulation CFD software to analyze the drying chamber equipment, and moved the air outlet position down by 150mm to make the air pressure and air field in the drying chamber more uniform. Yu Yi² adopted integrated staggered nozzles in the drying chamber to decrease the mutual interference in hot air and improve the efficiency of the drying chamber. Lin Ji³ analyzed the advantages and disadvantages of the drying chamber type and impact on automobile drying by selecting different types of drying chamber methods, and made a guiding significance of the selection of the drying chamber in the automotive industry. Xia Zhong⁴ designed a frequency conversion control system of exhaust fan to achieve the purpose to control the automotive coating production quickly and decrease the maintenance time. Lu Hongping⁵ introduced the principle of drying, and they also analyzed the economics of the drying of the drying chamber and characteristics of the waste heat recovery device. Zhu Bao⁶ analyzed influence the position and air direction of the air inlet and outlet of the car drying chamber to flow field, and gave the control ideas and methods of the drying chamber. Li Chuanzong⁷ used Airpak software to simulate the temperature field and velocity field of the drying chamber, and optimized the airflow organization. Shabbir Ahmed⁸ simulated the operating parameters of the drying chamber based on the air humidity factors.

This paper analyzes the air supply structure of the original drying chamber. A baffle is placed in the air outlet to optimized the tube system. Through two kinds of structure optimization, the velocity of special points of the car shell and the velocity distribution in the drying chamber are analyzed. This
paper provides an effective reference to the design of the inlet and outlet of the automobile drying chamber.

2. Simulation analysis method

2.1 Basic theory of simulation

Because the air velocity in the drying chamber is less than 100m/s, air properties such as compressibility, viscosity are not considered in the calculation. Therefore, the fluid model should be incompressible and ideal gas in mathematical modeling. The equation is as follows:

The equation of continuity is as follows:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]  

(1)

\(\rho\), the fluid density; \(v\), the velocity of a fluid particle; \(t\), time.

The momentum conservation equation of \(x\), \(y\) and \(z\) is as follows:

\[
\frac{\partial (\rho u)}{\partial t} + \text{div}(\rho u U) = -\frac{\partial p}{\partial x} + \frac{\partial (\tau_{xx})}{\partial x} + \frac{\partial (\tau_{xy})}{\partial y} + \frac{\partial (\tau_{xz})}{\partial z} + F_x
\]

(2)

\[
\frac{\partial (\rho v)}{\partial t} + \text{div}(\rho u U) = -\frac{\partial p}{\partial y} + \frac{\partial (\tau_{yx})}{\partial x} + \frac{\partial (\tau_{yy})}{\partial y} + \frac{\partial (\tau_{yz})}{\partial z} + F_y
\]

(3)

\[
\frac{\partial (\rho w)}{\partial t} + \text{div}(\rho u U) = -\frac{\partial p}{\partial z} + \frac{\partial (\tau_{zx})}{\partial x} + \frac{\partial (\tau_{zy})}{\partial y} + \frac{\partial (\tau_{zz})}{\partial z} + F_z
\]

(4)

\(p\), pressure on a fluid microelement; \(F_x\), \(F_y\), \(F_z\), the physical strength of a microelement. If gravity is the only force on the element and the axis is straight up. Then \(F_x\) and \(F_y\) are zero and \(F_z = -p g\).

2.2 Mathematic model

It can be seen that the air is an incompressible, gas-viscous, adiabatic fluid. The standard K-Epsilon model was selected in simulation.

Turbulent kinetic energy \(K\) equation is as follows:

\[
\rho \frac{Dk}{Dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G_k + C_{\mu} - p
\]

(5)

The equation of turbulence dissipation rate \(\varepsilon\) is as follows:

\[
\rho \frac{D\varepsilon}{Dt} = \frac{\partial}{\partial x_i} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + C_{\mu} \frac{\varepsilon}{k} \left( (k + C_{\varepsilon} G_k) - C_{\varepsilon} \rho \frac{\varepsilon^2}{k} \right)
\]

(6)

\(\mu_t\), laminar viscosity coefficient; \(\mu_t\), turbulent viscosity coefficient; \(G_k\), turbulent kinetic energy generated by laminar velocity gradient; \(G_b\), turbulent kinetic energy generated by buoyancy; \(C_{1g}, C_{2g}, C_{3g}, \sigma_\varepsilon, \sigma_k\), empirical constant.

Turbulence viscosity \(\mu_t\) can be expressed as a function of \(K\) and \(\varepsilon\).

\[
\mu_t = C_{\mu} \rho \frac{k^2}{\varepsilon}
\]

(7)

\(C_{\mu}\), fluid constant.

\(C_{1g} = 1.44; C_{2g} = 1.92; C_{\mu} = 0.99; \sigma_\varepsilon = 1.00; \sigma_k = 1.30\).
3. Model establishment of air channel of drying chamber

3.1 Original air channel model and meshing

An uneven drying air around the drying car shell (the car shell) in the drying chamber, leads to the problem that the actual drying time is too long and the drying efficiency is decreased. In this research, the relative position between the car shell and the wall are shown in Fig. 1(a), and the right view is shown in Fig. 1(b).

![Fig. 1. Original chamber and car shell](image)

The original structure of the drying chamber is symmetrical and the top of the wall is folded. Middle and upper circulars are the air inlets which are 5 rows (total number is 138) and the lower squares are the air outlets which is 1 row (total number of is 5), as shown in Fig. 1.

It is pre-processed and meshed by CFD software. The original structure and the car shell are regarded as solid domain, and the area between them was considered as fluid domain. The number of divided grids is 1087245, as shown in Fig. 2.

![Fig. 2. Meshing of the original structure](image)

3.2 Boundary conditions

The circular area is used as the air inlet, and the rectangular area is used as the air outlet. The remaining walls can be set as insulation walls. The specific boundary conditions are set as follows:

- **Inlet**: velocity inlet, 6.5m/s (design requirement).
- **Outlet**: pressure outlet, 0 MPa.

4. Analysis of the original air channel

4.1 Establishment of special planes and special points

In order to analyze the air distribution of the original structure, planes 1-5 are analyzed (as shown in Fig. 3(a)). Points 1-5 on planes 1, 5 and points 1-9 on planes 3, 4 (as shown in Fig. 3(b)) are analysis points, respectively. The air inlet and the air outlet are all on the planes 1-5. These surfaces and points are selected according to the shape of the car shell and the flow line which the drying air sweeps the shell.
Plane 1: points 1, 5 are located on the upper side of the tire; points 2-4 are located on the hood respectively; point 3 located in the center.

Plane 3: points 1,2 are located on the front left door; points 8,9 are located on the front right door; points 3,7 are located on the left and right front glass respectively; points 4-6 are located on the front roof of the vehicle; point 5 located in the center.

Plane 4: points 1,2 are located on the left rear door, points 8,9 are located on the right rear door; points 3,7 are located on the left and right sides of the rear glass respectively; points 4-6 are located on the rear roof; point 5 located in the center.

Plane 5: points 1-5 are located on the rear cover; point 5 located in the center.

4.2 Velocity distribution in the original duct

The velocity profiles of planes 1-5 are shown in Fig. 4(a), 4(b), 4(c), 4(d), 4(e).
The velocity of points in the original structure is shown in Table 1:

| Plane  | P 1  | P 2  | P 3  | P 4  | P 5  | P 6  | P 7  | P 8  | P 9  | MV  | MSE |
|--------|------|------|------|------|------|------|------|------|------|-----|-----|
| Plane 1| 2.52 | 1.09 | 0.36 | 1.02 | 2.49 |      |      |      |      | 1.50| 0.74|
| Plane 3| 2.61 | 2.65 | 2.68 | 1.21 | 0.56 | 1.01 | 2.67 | 2.66 | 2.63 | 2.08| 0.69|
| Plane 4| 2.51 | 2.69 | 2.64 | 1.23 | 0.49 | 1.17 | 2.66 | 2.58 | 2.46 | 2.04| 0.63|
| Plane 5| 1.45 | 0.81 | 0.31 | 0.78 | 1.35 |      |      |      |      | 0.94| 0.17|

P: point; MV: mean velocity; MSE: mean squared error.

In Fig.4, there is an air short circuit in all planes. After the air entering the chamber, it moves directly to the outlets because the inlets are closer to the outlets in the bottom of the wall, the drying air doesn’t fully contact with the car shell.

Table 1 shows that the velocity at the center of the car shell is the lowest in the same plane and the maximum difference in air velocity in plane 4 is 2.2 m/s.

5. Optimization of the structure

5.1 Structure with baffles

By adding baffles on the outlets at an angle of 45° downwards to the outlets on both sides of the original structure (the baffles structure), as shown in Fig. 5.

![Fig. 5. The baffles structure](image)

5.1.1 Velocity analysis of the baffles structure

Three planes (plane A, plane B and plane C) are selected to analyze as shown in the Fig.6, which pass through the central axis of the outlet section. The short circuit of air flow is serious on the three planes. We only analyze the right wall because of symmetry.

![Fig. 6. Three planes](image)

The velocity profile of the original structure and that of the baffles structure are shown in Fig. 7.
Fig. 7. Comparison of velocity profile between original structure and baffles structure

It can be seen from the comparison of velocity profile between the original structure and the baffles structure (as shown in Fig.7 shown with the red arrow), that the baffles structure decreases the short circuit of the air and the disturbance of the drying air is enhanced around the baffles which effectively improves the drying effect.

5.2 Optimal structure based on uniformity

The following two optimization structures are used to decrease the nonuniformity of drying air and increase the velocity of air around the car shell. We research two structures to analyze. The alternative inlets structure: the right wall air inlets are moved forward by 150mm (the distance between adjacent air inlets in the original structure is 300mm), so that the left wall air inlets and the right wall air inlets are arranged alternatively, as shown in Fig.8. The top inlets structure: a row of circular air inlets with a radius of 50mm is added at the top of the original structure (the inlet air velocity is 6.5m/s and the number is 13) to increase the air velocity at the center of the car shell, as shown in Fig.9.

Fig. 8. The alternative inlets structure

Fig. 9. The top inlets structure

The velocity of points of the alternative inlets structure, the top inlets structure and the original structure (shown in Fig.3(b)) are compared as shown in Table 2.
Table 2. Velocity value of special points in the above three structures

|     | unit | P1  | P2  | P3  | P4  | P5  | P6  | P7  | P8  | P9  | MV  | MSE |
|-----|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| (O) | Plane 1 | m/s | 2.52| 1.09| 0.36| 1.02| 2.49|     |     |     | 1.50| 0.74|
| (A) | Plane 1 | m/s | 2.49| 1.15| 0.38| 0.81| 1.23|     |     |     | 1.21| 0.47|
| (T) | Plane 1 | m/s | 2.53| 1.11| 1.16| 1.08| 2.52|     |     |     | 1.68| 0.48|
| (O) | Plane 3 | m/s | 2.61| 2.65| 2.68| 1.21| 0.56| 1.01| 2.67| 2.66| 2.63| 2.08| 0.69|
| (A) | Plane 3 | m/s | 2.62| 2.61| 2.71| 1.25| 0.61| 0.82| 2.13| 2.11| 2.08| 1.88| 0.54|
| (T) | Plane 3 | m/s | 2.63| 2.67| 2.72| 1.23| 1.12| 1.03| 2.69| 2.71| 2.59| 2.15| 0.53|
| (O) | Plane 4 | m/s | 2.51| 2.69| 2.64| 1.23| 0.49| 1.17| 2.66| 2.58| 2.46| 2.04| 0.63|
| (A) | Plane 4 | m/s | 2.55| 2.65| 2.66| 1.26| 0.51| 0.79| 2.02| 2.09| 2.07| 1.84| 0.58|
| (T) | Plane 4 | m/s | 2.51| 2.71| 2.68| 1.25| 1.15| 1.21| 2.72| 2.68| 2.58| 2.17| 0.47|
| (O) | Plane 5 | m/s | 1.45| 0.81| 0.31| 0.78| 1.35|     |     |     | 0.94| 0.17|
| (A) | Plane 5 | m/s | 1.42| 0.78| 0.28| 0.57| 0.98|     |     |     | 0.81| 0.15|
| (T) | Plane 5 | m/s | 1.46| 0.91| 0.99| 0.83| 1.41|     |     |     | 1.12| 0.07|

O: original structure; A: alternative inlets structure; T: top inlet structure; P: point; MV: mean velocity; MSE: mean squared error.

By comparing the velocity of the two optimized structures and the original structure shown in Table 2, we can understand that: (a). The alternative inlets structure decreases the velocity of all points in the right side, the velocity of different points are more uniform, and the actual drying time increases. (b). The top inlets structure decreases the mean squared error of each point, while increasing the average velocity value, shortening the drying time and improving the drying effect.

6. Conclusions
Through the above analysis, the conclusions are as follows.
1. The baffles structure enhances the disturbance between the air inlet and the baffles, the short circuit of air between inlet and outlet is decreased.
2. Although the alternative inlets structure improves the uniform of velocity, air volume is still insufficient for the center of the car shell.
3. The top inlet structure makes the distribution of air velocity more uniform in the drying chamber, and increases the air velocity at the center of the car shell to ensure the drying effect.

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