Temperature optimization of mold for autoclave process of large composite manufacturing

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Abstract. In autoclave processing, the temperature distribution of mold is important to the curing quality and performance of composite. The scale and complex structure of the mold have a great influence on heat transfer efficiency, which result in no uniform temperature field of the mold. Therefore, a method of heat transfer compensation is proposed, in which a "heat conducting fin" with high heat conductivity is installed in the section with slower heating process of the mold to improve the heat transfer efficiency of the mold and hot air, and to determine the structural size, quantity and reasonable installation position of "heat conducting fins" by combining CFD with heat transfer calculation. The results show that, combined with the typical panel mold, the heat transfer efficiency of the local section of the mold can be effectively improved by optimizing "heat conducting fin", the maximum temperature difference of the mold surface is reduced by 15.1%, and the temperature gradient along the axial direction of the mold is decreased.

1. Introduction

Advanced composite materials are widely used in the field of aerospace, due to high specific strength and stiffness, excellent corrosion resistance [1-3]. The autoclave process is one of the ways for preparing high-quality composite components. In the autoclave process, composite components are mainly laid on the mold surface for curing. But due to excessive mold size and complex mold structure lead to the non-uniformity of temperature distribution, which result in residual stress and affect the curing quality and assembly accuracy of the composite components [4,5]. Therefore, it is significance to optimize the uniformity of mold temperature field.

The optimization of mold and composite component temperature fields in autoclave process has been studied extensively. Gniatczyk [6] investigated that the "egg frame" structure of mold can effectively improve the heat transfer efficiency and improve the uniformity of the temperature field of the mold. Yunwang Lin [7] proposed to install a local isolation structure under the mold to change the overall heat
transfer coefficient of the mold, which combined numerical with genetic algorithm to optimize the installation of the diaphragm structure to improve the overall synchronization of the mold heating process. Qing Wang [8] analyzed the optimization of mold structure design parameters by introducing genetic algorithms in numerical models to effectively improve the uniformity of the mold temperature field. Xusheng Zhang [9] used CFD to analyze the "straight", "cross" and "T" type air ducts, and concluded that the "T" air ducts had the best effect on the optimization of the mold temperature field. Dios M and Maffezzoli A [10, 11] established objective function by different models to optimize the placement of mold in autoclave to improve the thermal performance of mold. Jiaguan Lin [12] used fluent analysis to install a fan at the frame mold vent to enhance the convective heat transfer strength between the mold and the hot air and improve the uniformity of the mold temperature. Based on the principle of heat compensation, Chengyang Fu [13] proposed to install a heater in the slow heat rising section of the mold based on the principle of thermal compensation to improve the uniformity of the mold temperature. Although many researches have been done to improve the uniformity of the temperature field of the mold, the temperature gradient in the local area still cannot be eliminated due to the difficult to improve the flow field of the complex mold shape and the difficult to adjust the structure. The addition of external equipment and external heat source equipment will result in more complex working conditions of the curing process. Therefore, a method of heat transfer compensation is proposed [14], in which the heat transfer efficiency is improved by installing heat conduction fins (HCF) with high heat conductivity under the mold surface. In this research method, the temperature field distribution of the mold is accurately predicted by comparing CFD numerical model with experiment, and optimizes the installed heat conduction fins (HCF) by CFD combined with heat transfer calculation formula, and finally improves the uniformity of the mold temperature field.

2. Optimization numerical of mold temperature field

2.1. Modeling of the autoclave process and mesh

In the autoclave system shown in Figure 1. There are three heat transfer ways in the autoclave process: heat conduction, heat convection and heat radiation. The curing temperature of the autoclave is not more than 180°C, so the heat radiation can be neglected. Therefore, forced convection is the major heat transfer mode between the heat air and the mold. The mold adopts the mold of the scaled wing panel of COMAC, the basic dimension of the mold is 1730mm × 1398mm × 412mm, the material is Q235, and the material parameters are shown in Table 1. The mold adopts frame structure, which is not conducive to the heat exchange efficiency of air and mold, but also can reduce the weight of mold. Different meshes are used for the fluid and solid domains in the calculation model. Due to the complex structure of the mold, tetrahedral meshes are used, while mixed tetrahedron and hexahedron meshes are used for the fluid domain, as shown in Figure 1.

![Figure 1. Schematic diagram and grid generation of autoclave process.](image-url)
2.2. **Construction of heat conduction fin structure**

According to the heat transfer compensation and the of temperature field, the HCF with high thermal conductivity is added to the lower mold surface to improve the heat transfer efficiency in the slow region of the heating process and improve the temperature field no uniformity in the local region of the mold. The technical roadmap and Schematic diagram are shown in Figure 2 and Figure 3(a). The HCF can be designed and installed before or after the mold manufacturing, without changing the structure of the original mold. Moreover, the mold temperature field can be further improved by optimizing and modifying the fin structure.

![Schematic workflow of the optimization process. (HFC: heat conduction fin)](image)

The position of local "low temperature region" is roughly determined by thermal compensation combined with numerical of temperature field of panel mold. Then, the relative compensation temperature difference in this area is taken as $T_{\Delta k}(t)$, and the compensation heat flux required for unit time in this area is set as $\Phi_{\Delta k}$, the heat exchange between fin side and mold surface is set as $\Phi_{\Delta k}$, and the heat exchange between fin surface and air is set as $\Phi_{\Delta k}$.

According to the above assumption, the heat of the heat conduction fin is transferred to the mold surface through heat conduction, and the heat flux function is

$$\Phi_a = A_a \frac{\lambda}{\delta} (t_1 - t_2) = \eta_w \Phi_b$$  \hspace{1cm} (1)

There is strong heat convective between the heat conducting fins and the fluid in the autoclave, the heat convection function is

$$\Phi_c = h_i \eta_f A_f (t_0 - t_1) = \Phi_b$$  \hspace{1cm} (2)

Then, by combining (1) and (2), eliminate $t_1$

$$\Phi_a = \frac{(t_0-t_f)}{A_b \eta_f h_i \eta_w}$$  \hspace{1cm} (3)
Where $t_0$ is the air temperature, $t_1$ is the fin temperature, $t_2$ is the mold surface temperature, $A_1$ is the contact area between the mold and the fin, $A_2$ is the contact area between the fin and the air, $\delta$ is the mold thickness, $\lambda$ is the heat transfer coefficient, $h_5$ is the fin surface heat transfer coefficient, $\eta_w$ is the heat transfer efficiency between the mold and the fin, $\eta_f$ is the fin efficiency.

The temperature distribution equation of the temperature distribution in the rectangular fin (Figure 3(b)) is

$$\frac{d^2t}{dx^2} = \frac{HUt^2}{\lambda A} (t_0 - t_1)$$ (4)

Boundary condition: $x = 0, t = t_1; x = H, t = t_0$

The heat transfer efficiency function of the heat conduction fin is

$$\eta_f = \frac{th(mH')}{mH'}, m = \frac{2h}{\lambda \delta}$$  \hspace{1cm} (1)

$$H' = H + \delta/4$$ (5)

Where $A$ is the cross-sectional area of the fin, $H$ is the height of the fin, $d$ is the diameter of the fin, $U$ is the circumference of the fin, $\lambda$ is the thermal conductivity of the fin, $h$ is the heat transfer coefficient, $t_0$ is the temperature of the autoclave, $th(mH')$ is the hyperbolic function.

According to the mold temperature field numerical combined with the heat transfer calculation formula, the structure size, installation quantity and reasonable installation position of the HCF are obtained, and optimize the fin spacing and structural form.

**Figure 3.** Schematic diagram: (a) The HCF structures; (b) Rectangular fin.

2.3. governing equations

The numerical of fluid flow and heat exchange in the autoclave process dominated by three energy equations, including mass conservation, energy conservation and momentum conservation.

Mass conservation equation

$$\text{div} \nu + \frac{1}{\rho} \frac{\partial \rho}{\partial t} = 0$$  \hspace{1cm} (6)

Momentum conservation equation
\[ \frac{\partial (\rho v)}{\partial t} + \text{div}(\rho v \otimes v) = \text{div}(\mu \cdot \text{grad}v) - \frac{\partial p}{\partial y} + S \] (7)

Where \( \rho \) is the density of fluid, \( \mu \) is the dynamic viscosity, \( p \) is the pressure of fluid, \( S \) is the generalized source term of the momentum equation, \( v \) and is the component of velocity in \( x, y, z \) directions.

Energy conservation equation

\[ \frac{\partial (\rho h)}{\partial t} + \text{div}(\rho hU) = \text{div}(k \cdot \text{grad}(T)) - P \cdot \text{div}(U) + \Phi + S_T \] (8)

Where \( \partial (\rho h) / \partial t \) is the transient term, \( \text{div}(\rho hU) \) is the thermal convection term, \( \text{div}(k \cdot \text{grad}(T)) \) is the thermal conduction term, \( P \cdot \text{div}(U) \) is the pressure work term, \( \Phi \) is the viscosity work term, and \( S_T \) is the source term.

In the autoclave process, the mold belongs to the solid domain, compared with the fluid domain, there is no flow in the solid domain, so the energy conservation equation in the solid domain can be expressed as follows:

\[ \frac{\partial \rho c T}{\partial t} = \nabla(\lambda \nabla T) + S_T \] (9)

Where \( T \) is the solid temperature, \( \rho \) is the solid density, \( c \) is the specific heat of the solid, and \( S_T \) is the internal heat source term of the solid.

2.4. Boundary conditions and calculation parameters

The numerical calculation is based on Fluent 15.0 to simulate the temperature field of the mold during the autoclave process. The size of the autoclave is \( \Phi 2.25 \times 4 \text{m} \), the air flow rate is \( 2 \text{m/s} \), and the physical properties of the air are shown in Table 1. Moreover, according to the calculation formula of Reynolds number, \( R_e = \rho u_d / \mu, R_e > 2000 \) can be obtained. Therefore, the air flow in autoclave is turbulent, and the turbulence model includes many models. Based on the accuracy of the model, the k-epsilon turbulence model is recommended in this paper [15].

| Material     | Density P/kg·m³ | Specific heat capacity \( C_p/J \cdot \text{kg} \cdot K \) | Thermal conductivity K/W · (m · K)⁻¹ |
|--------------|-----------------|-------------------------------------------------|----------------------------------|
| Air          | 1.225           | 1006.43                                         | 0.0242                           |
| Q235         | 7850            | 470                                             | 49.8                             |
| Aluminum alloy | 2710           | 902                                             | 236                              |

Set the boundary conditions according to the autoclave process:

(1) The inlet of autoclave is set as velocity inlet, the UDF is used to define the temperature process curve as the air temperature at the inlet, as shown in Figure 4.

(2) The outlet of the autoclave is set as pressure outlet, and the pressure and reflux temperature at the outlet are specified.

(3) The symmetrical surface of fluid and mold is set as the symmetry.

(4) The wall of autoclave is heat insulation wall, and the interface between fluid and solid is coupling wall.
3. Optimization and result analysis of mold temperature field

3.1. Numerical and verification of mold temperature field in the autoclave process

As shown in Figure 5(b), the temperature of the windward end of the mold is higher than the temperature of the leeward end. The main reason is that the blocking effect of the mold frame structure and the boundary layer lead to the decrease of the air velocity at the end of the mold, which results in the weakening of the jet impact heat transfer strength, causing the non-uniform temperature field of the mold. In order to verify the accuracy of the numerical mold, six thermocouples are set on the mold surface, and their positions are shown in Figure 5(a). The comparison between the experimental thermocouple test data and numerical data collected through the test is shown in Figure 5(b). The average error between the thermocouple monitoring points 1, points 2, points 3, points 4, points 5, points 6 temperature data and numerical results are 0.5%, 0.38%, 0.43%, 0.42%, 0.73%, 0.98%, and the results show that numerics are good agreement with the experimental results. It is verified that the numerical model can effectively predict the distribution of mold temperature field.

Figure 5. Mold temperature: (a) Monitoring points; (b) Comparison between CFD curve and experiment curve
3.2. Analysis of mold temperature field optimization results

According to the temperature field numerical of the mold in the previous section, the area where the mold has a slow course in the heating stage is obtained. From Figure 8 (a), it can be seen that this local section accounts for about 10% to 20% of the overall mold surface area, and mainly occurs in the middle area of the leeward end of the mold. The frame structure hinders the blocking of the fluid medium, and the structure is difficult to adjust. Therefore, based on the mold temperature field numerical model constructed above, a numerical model for optimize mold temperature field by installing the HFC is established, and the structural size, quantity, and installation position of the HFCs are roughly determined by the above heat transfer calculation formula. To determine the optimum reference model, three different fin structures (HCF1, HCF2, and HCF3) are analyzed [16], as shown in Figure 6.

The optimization result of the mold temperature is shown in the figure below. Figure 7 (a) is the comparison of the temperature difference data of different mold profiles. In the process of forming large-scale composite component autoclave, the temperature difference of the mold is increasing in the rising and cooling stage, while in the heat preservation stage, the temperature difference of the mold is decreasing. By comparing and analyzing the temperature field of the mold with different structure heat conduction fins and the original mold, it can be seen that the temperature field optimization effect of the structure mold with HFC3 is the best. Fig. 7 (a) shows that the maximum temperature difference of the mold surface with the HFC3 is relatively reduced by 3.5k, which is 15.1% lower than that with the original mold.

Figure 7 (b) is the temperature gradient curve along the axial direction of the mold at 78min for different molds. It can be seen that the slowest temperature rise region is mainly concentrated in the leeward region of the mold. In section where the mold without equipping with heat conductive fins, the distribution of temperature gradient is approximately equal, while for areas where the mold is applying with HFC, the temperature increase effect compared to the original mold is obvious. The temperature gradient along the axial direction at the leeward of the mold is reduced. Figure 8 is the temperature field of different mold at 78min. It is more intuitive to understand that the temperature field optimization

![Figure 6. Installation diagram and structure dimension of HFC](image-url)
effect of the mold "low temperature area" with the HFC3 is obvious. Therefore, the method of installing HFCs can effectively improve the temperature of the "low temperature area" of the mold.

**Figure 7.** Curves of mold surface temperature: (a) temperature difference; and (b) temperature along mold axis at 78min.

In order to illustrate the optimization effect of different HFCs on the temperature field of the mold, it can be seen from the local velocity and temperature distribution of Figure 9 and Figure 10, the distance between HFC2 is larger than that HFC1. Due to the viscous effect of the fluid, the structure of HFC2 is more conducive to the flow of the medium and increases the heat transfer efficiency in this area. The structure of HFC3 adopts the form of small fins. It can be seen from Figure 9 and 10 that the flow velocity of the fluid medium in the fin area is relatively uniform compared to HFC1 and HFC2. The form of the small fins increases the heat transfer area and further improves the heat transfer efficiency. Therefore, through comparative analysis, it is possible to adopt a reasonable distance for the heat conductive fins and adopt the structure form of small fins to effectively improve the heat transfer efficiency and further improve the heating process in the "low temperature region".
Figure 8. Temperature field of the mold and at 78min: (a) Original mold; (b) HFC1 type; (c) HFC2 type; (d) HFC3 type.

Figure 9. Velocity of air with different molds: (a) Original mold; (b) HFC1 type; (c) HFC2 type; (d) HFC3 type.
Figure 10. Temperature field of heat conductive fins with different molds: (a) Original mold; (b) HFC1 type; (c) HFC2 type; (d) HFC3 type.

4. Conclusion
In order to improve the heat transfer efficiency and the curing synchronism of composite components, a high thermal conductivity heat conduction fin is installed in the slow region of the mold heating process based on the principle of heat transfer compensation.

The numerical model of mold temperature field in the autoclave process is built by using fluent software, and the validity of the numerical model is verified by comparing the CFD and experiments. According to the above numerical model, the temperature field numerical analysis of the mold installed with HFCs is constructed. Through the optimization results, the maximum temperature difference of the mold surface is reduced by 3.5K, which is 15.1% lower than the original mold, effectively improving the heat transfer efficiency of the "low temperature area" of the mold. Compared with the results of the temperature field of the mold by applying different HFCs, the flow field form has a great influence on the heat transfer efficiency of the heat transfer rib. Therefore, by optimizing the structure of HFCs, the heat transfer efficiency of the section can be effectively improved, and the uniformity of the temperature Field of the mold can be improved. It is concluded that the small fin form can effectively improve the heat transfer efficiency of the HFC.

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References
[1]  Yao S S, Jin F L, Rhee K Y, et al. Recent advances in carbon-fiber-reinforced thermoplastic composites: A review [J]. Composites Part B: Engineering, 2017: S1359836817322692.
[2]  Soutis C. Fibre reinforced composites in aircraft construction [J]. Progress in Aerospace Sciences, 2005, 41 (2): 143 - 151.
[3]  Baran I Cinar K, Ersoy N, et al. A Review on the Mechanical Modeling of Composite Manufacturing Processes [J]. Archives of Computational Methods in Engineering, 2017, 24
[4] Wang X, Zhang Z, Xie F, et al. Correlated Rules between Complex Structure of Composite Components and Manufacturing Defects in Autoclave Molding Technology [J]. Journal of Reinforced Plastics and Composites, 2009, 28 (22): 2791 - 2803.

[5] Ding A, Li S, Wang J, et al. A three-dimensional thermo-viscoelastic analysis of process-induced residual stress in composite laminates [J]. Composite Structures, 2015, 129: 60 - 69.

[6] Gniatczyk J L, Aquilina G R, Deaver D T, et al. Composite molding tools and parts and processes of forming molding tools: US 2001.

[7] Wang Q, Wang L, Zhu W, et al. Design optimization of molds for autoclave process of composite manufacturing [J]. Journal of Reinforced Plastics and Composites, 2017: 073168441771826.

[8] Lingyun W, Weidong Z, Qing W, et al. A heat-balance method for autoclave process of composite manufacturing [J]. Journal of Composite Materials, 2018: 002199831878891.

[9] Xusheng Zhang, Zhong Gan, Haiyan Zhang, Research on optimization of mold temperature fields in autoclave age forming, Manufacture Information Engineering of China, Vol.40, No. 10, 2011, pp. 30 - 37.

[10] Maffezzoli A, Grieco A. Optimization of Parts Placement in Autoclave Processing of Composites [J]. Applied Composite Materials, 2013.

[11] Dios M, Gonzalez-R P L, Dios D, et al. A mathematical modeling approach to optimize composite parts placement in autoclave [J]. International Transactions in Operational Research, 2016.

[12] LIN Jiaguan, Yang Rui, et al. Large-scale composite curing temperature analysis and improvement in autoclave process[J]. Fiber Reinforced Plastics/Composites, 2016 (05).

[13] FU cheng yuan, Li ying guang, et al. Temperature Uniformity Optimizing Method of the Aircraft Composite Parts in Autoclave Processing [J]. Journal of Materials Science and Engineering 2013 (02): 121 - 124 - 152.

[14] Yang Shiming, Tao Wenji. Heat Transfer. 4th edition [M]. Higher Education Press, 2006.

[15] Wang Q, Lu J, Yin W, et al. Numerical study of gas solid flow in a coal benefication fluidized bed using kinetic theory of granular flow [J]. Fuel Processing Technology, 2013, 111: 29 - 41.

[16] Yu S H, Lee K S, Yook S J. Optimum design of a radial heat sink under natural convection[J]. International Journal of Heat and Mass Transfer, 2011, 54 (11-12): 2499 - 2505.