



Article

Influence of Thickness Effect on Curing Properties of Thick Composites

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Abstract

This work aims to uncover the thermochemical thickness effect mechanism for thick-section composites manufactured via the vacuum infusion molding process (VIMP). Taking the wind turbine blade grade RIMR135/RIMH137 epoxy system as the material subject, dynamic and isothermal curing kinetics were characterized by differential scanning calorimetry (DSC). Autocatalytic and modified autocatalytic models were constructed to describe the respective curing behaviors. Experimental measurements together with finite element analysis were performed to clarify the influences of component thickness and geometric dimensions on curing thermochemistry. The reference pre-curing, curing and post-curing temperatures of the resin were 45 ± 5 °C, 98 ± 5 °C and 134 ± 5 °C. Obvious temperature overshoot arose at the section centre, yielding a maximum internal temperature difference of 30 °C and a 10% discrepancy in the degree of cure. Temperature- and cure degree-related gradients increased linearly with component thickness and volume. This research supplies theoretical support for the process optimization of large, thick-walled composite parts.

Keywords: thickness effect; polymer composites; thermo-chemistry behavior; curing dynamics; thermo-chemistry

1. Introduction

Vacuum infusion molding process (VIMP) is a low-cost liquid composite molding (LCM) technology. Its fundamental principle lies in encapsulating fiber preforms with flexible vacuum bag films; liquid resin is driven by negative vacuum pressure to flow and fully impregnate fiber reinforcements, followed by curing and shaping to form composite components [1–3]. The VIMP process (Figure 1) enables the one-step impregnation and molding of large composite structures integrated with sandwich cores, stiffeners and embedded inserts. Reinforcements can be laid up flexibly according to structural and performance demands. When adopted for manufacturing ultra-large composite components characterized by extensive in-plane dimensions and ultra-thick cross-sections—such as the composite fuselages of large aircrafts and composite wind turbine blades with a projected area up to hundreds of square meters and local cross-sectional thickness ranging from tens of millimeters to nearly one hundred millimeters—VIMP realizes integral one-shot forming. Owing to its outstanding advantages of high performance and low manufacturing cost, this technique has gained extensive popularity for the integral forming of ultra-large composite parts [4,5].



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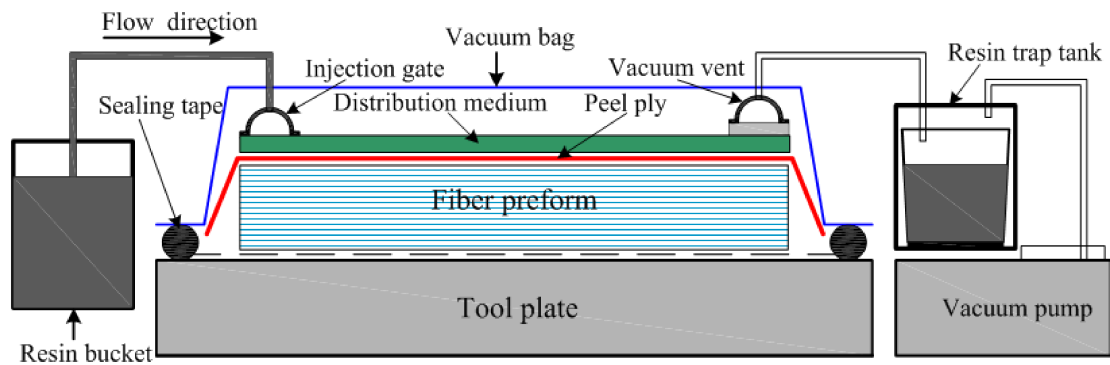


Figure 1. The setup schematic of the vacuum infusion molding process.

Beyond the conventional VIMP approach described above, several alternative manufacturing strategies have been developed to address the challenges of producing thick composite laminates. In industrial practice, flow promoters or high-permeability flow media materials are commonly integrated between fabric layers during the preform lay-up process prior to vacuum infusion. These inter-laminar flow media, typically fabricated with low-performance fibers that yield a low fiber volume fraction and thus high through-thickness permeability, serve to reduce the apparent infusion thickness of the preform and significantly accelerate resin impregnation [6]. For instance, Heider et al. demonstrated that incorporating multiple high-permeability inter-laminar flow media layers can reduce infusion times by 52–68% for glass and Kevlar preform and by 64% for carbon preforms, making the VARTM process viable for much thicker sections. In addition to flow media enhancement, alternative material systems such as epoxy powder and epoxy prepreg laminates have been adopted for thick composite manufacturing. Epoxy powder systems, which are solid at room temperature and exhibit low exothermic reaction, excellent fiber wet out, and low void content, can be partially cured (b-staged) into consolidated subcomponents that are subsequently assembled and co-cured in a single thermal cycle without additional adhesives [7]. This approach has proven particularly suitable for thick composite sections in wind and tidal turbine blade applications. Similarly, epoxy prepreg laminates—pre-impregnated with resin under controlled conditions—provide consistent resin distribution and high fiber volume fractions, enabling precise control over the curing process and superior mechanical properties in thick-section components. The selection among these manufacturing approaches depends on the specific requirements of part geometry, thickness, mechanical performance, and production volume.

The thickness effect is defined as the phenomenon wherein the physicochemical behaviors and mechanical performances of ultra-large composite components fabricated via VIMP vary regularly with cross-sectional thickness. The thickness effect exerts a dominant influence on the curing and shaping stage of VIMP and ultimately determines the final properties of composite materials. Its adverse impacts on curing forming are mainly reflected in two aspects: (1) the coupled heat conduction and curing reaction (i.e., thermochemical mechanism) triggers aggravated temperature spikes and thermal gradients with the increase of component thickness, which readily induces heterogeneous curing and residual thermal stress, thereby deteriorating the overall mechanical performance of composite components; (2) thermos–chemo–mechanical coupling aggravates the volumetric shrinkage and warpage distortion of molded parts as thickness rises, making deformation prediction and suppression far more challenging. A wealth of research focusing on curing kinetics and the thermochemical modeling of thick-section composite curing has been conducted by scholars worldwide, laying solid theoretical and experimental foundations for the present study.

In terms of curing kinetics, differential scanning calorimetry (DSC) is widely adopted by researchers to characterize the dynamic and isothermal curing behaviors of resin systems. Multiple kinetic models, including the *n*th-order reaction model, autocatalytic model and modified Kamal model [8–10], have been established to precisely describe the quantitative correlations among curing rate, degree of cure, temperature and time for epoxy resin matrices. Cruz et al. [11] measured the bimodal curing behaviors of modified epoxy systems via DSC and constructed an autocatalytic kinetic model, which directly correlates curing kinetics with the macroscopic mechanical properties of final composites. On this basis, composite performance optimization can be achieved by regulating curing procedures. Zhang et al. [12] combined DSC measurements with density functional theory (DFT) simulations to verify the intrinsic autocatalytic characteristics of target resin systems. Electrostatic potential (ESP) analysis was further utilized to predict potential reactive sites, bringing the research down to the molecular scale and theoretically elucidating the underlying curing reaction mechanisms. Their work provides theoretical guidelines for the molecular design of novel curing agents and resin matrices.

For research on thermochemical coupling and temperature field evolution, scholars have developed coupled heat transfer–curing reaction models based on finite element methods to numerically predict the spatial distributions of curing temperature and degree of cure. Smith et al. [13] fabricated acrylic resin composite specimens with three distinct thicknesses (9.5 mm, 17.9 mm and 26.4 mm) using VIMP, monitored temperature evolution during polymerization exotherms, and quantified the effects of component thickness on coupled thermochemical behaviors. The established quantitative relationships between thickness and thermochemical/temperature field characteristics offer experimental references for the thermal management and process optimization of thick-section thermoplastic composites. Brouwer [14], Heider [6] and other researchers performed coupled filling–curing analyses of LCM processes for large-scale composite components and optimized resin flow paths and heating schedules; nevertheless, they failed to systematically quantify the regular influences of thickness on thermochemical responses. Although global researchers have investigated curing kinetics and thermochemical modeling for thick-section composite curing, studies specifically focusing on the thickness effect during the VIMP manufacturing of large-size composite structures remain scarce in the existing literature.

This paper aims to investigate the thickness effect on the curing thermochemistry of thick-section composites fabricated by VIMP. The specific objectives are: (1) to characterize the curing behaviors and establish reliable dynamic and isothermal curing kinetic models for the RIMR135/RIMH137 epoxy resin; (2) to reveal the intrinsic mechanisms of the thickness-dependent evolution of temperature and degree-of-cure fields inside thick-section composite parts; (3) to quantify how component thickness and volume affect thermochemical responses during curing. The outcomes of this research can not only enrich the theoretical framework of composite thermochemistry but also provide direct guidance for the determination and optimization of curing schedules for ultra-large composite components, possessing prominent scientific significance and practical engineering value.

2. Experimental

2.1. Raw Materials

The resin system adopted in this work is the high-performance low-viscosity RIMR135/RIMH137 epoxy matrix specially developed for composite wind turbine blades, supplied by Hexion Specialty Chemicals (Iserlohn, Germany). In this two-component system, RIMR135 refers to modified bisphenol A epoxy resin, while RIMH137 serves as a polyamine curing agent. The mass mixing ratio of RIMR135 to RIMH137 is controlled at $100:30 \pm 2$. Key performance parameters including physical state, density, viscosity and

gel time of the mixed RIMR135/RIMH137 resin system at ambient temperature (25 °C) are summarized in Table 1.

Table 1. Properties of RIM135-7 epoxy resin system at room temperature (~25 °C).

RIMR135/RIMH137 Mass Ratio	Density /g·cm ⁻³	Viscosity /mPa·s	Gelation Time /min	Supplier
100:30 ± 2	1.08–1.12	200–300	250–260	Hexion Specialty Chemicals

The reinforcement material used in this study is 300CUD unidirectional carbon fabric supplied by Hangzhou Suqi Advanced Composites Co., Ltd., (Hangzhou, China). The fundamental performance parameters of 300CUD are listed in Table 2.

Table 2. Properties of carbon and glass fiber unidirectional fabrics.

Fabric	Fiber	Type	Superficial Density/g·m ⁻²
300CUD	12k, T700	unidirectional	300

2.2. DSC Analysis

The DSC apparatus adopted in the experiments is the DSC1/700 equipped with a DSC sensor/HC-100 differential scanning calorimeter manufactured by Mettler-Toledo Co., Ltd., (Greifensee, Switzerland). Prior to testing, the instrument was preheated for 1 h, and high-purity indium was utilized to calibrate the energy and temperature signals of the DSC device. All measurements were carried out under a nitrogen atmosphere with a nitrogen purge flow rate of 40 mL/min, and the cooling unit was activated throughout the tests.

DSC measurement enables the continuous monitoring of exothermic heat release during the dynamic and isothermal curing reactions of resin systems. The underlying testing principles and operation procedures are identical for dynamic and isothermal DSC characterization. To guarantee testing accuracy, the optimal mass range of resin specimens for DSC tests is specified as 5–10 mg.

Dynamic DSC tests were implemented under linear temperature ramp curing processes with constant heating rates. A series of heating rates including 3, 5, 8, 10 and 15 °C·min⁻¹ were selected for the dynamic DSC characterization of the target epoxy system. During isothermal DSC measurements, the embedded STARe 9.20 software platform can precisely regulate the heating program. The instrument ramps up to the preset isothermal temperature at the maximum allowable heating rate, which effectively eliminates temperature overshoot and the resultant abrupt exothermic spikes of curing reactions.

2.3. Analysis of Solidification Heat History

Molds for the vacuum infusion molding process (VIMP) generally adopt single-sided rigid molds integrated with heating systems. Fiber preforms are sealed on the mold surface by flexible vacuum bag films to form an enclosed molding cavity connected to the vacuum system. A self-fabricated flat aluminum alloy mold was developed to simulate the VIMP mold system (Figure 2). Its electric heating assembly with programmable intelligent temperature controllers was supplied by Xiamen Yudian Automation Technology Co., Ltd., (Xiamen, China).

To characterize the temperature evolution history inside thick-section composites during curing, commercially available Pt100 thermocouples were utilized to monitor internal temperature distribution. The thermocouples were required to be miniaturized for embedment within fabric preforms, with well-sealed connecting wires to preserve the

airtightness of the VIMP molding cavity after embedding. The temperature measurement accuracy of the thermocouples reaches $\pm 0.1\text{ }^{\circ}\text{C}$.

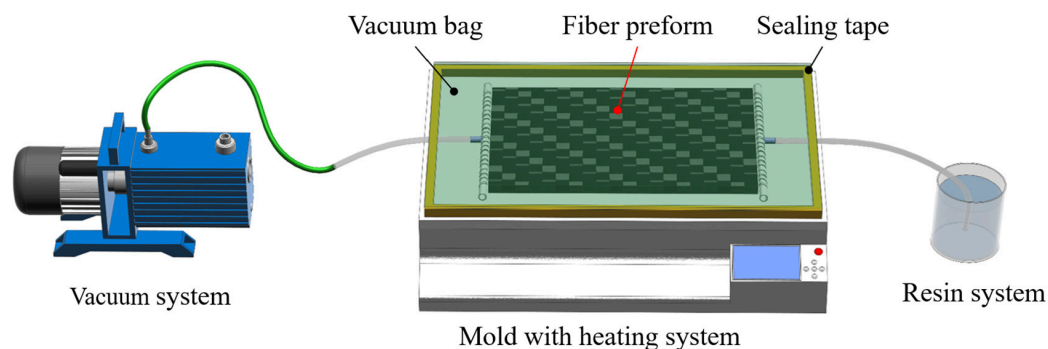


Figure 2. The VIMP mold with heating system.

3. Results and Discussion

3.1. Dynamic Curing Kinetics Behavior of Epoxy Resin System

3.1.1. DSC Analysis and Curing Characteristic Temperature

The dynamic DSC curves of the RIMR135/RIMH137 epoxy resin system at different heating rates of 3, 5, 8, 10, and $15\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ are shown in Figure 3. The exothermic peak of the resin system curing reaction is unimodal, and the temperature difference between the exothermic peaks is more significant at different heating rates. As the heating rate increases, the starting temperature T_i , peak exothermic temperature T_p , and termination temperature T_f of the resin system curing reaction all shift towards higher temperatures, but the difference in the starting temperature T_i of the reaction is relatively small. The faster the heating rate, the sharper the peak shape, and vice versa, the smoother it is.

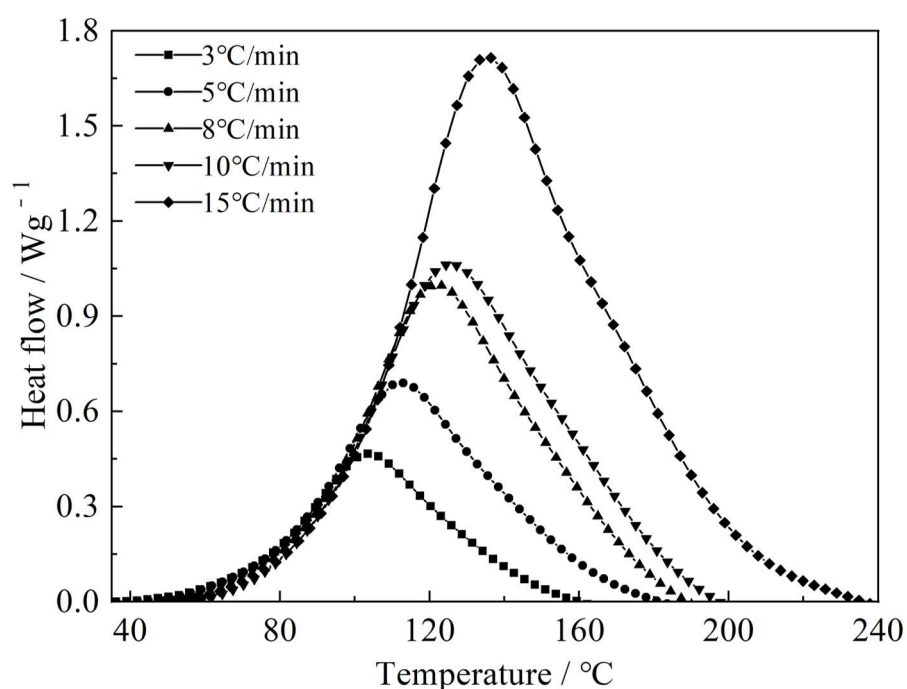


Figure 3. Dynamic DSC curves of the resin system.

This well-documented rate-dependent behaviour originates from coupled kinetic and thermal-lag effects widely reported for epoxy–amine thermosets. At low heating rates, the resin system receives moderate thermal input per unit time, and reactive epoxy–

amine groups have sufficient time to overcome reaction activation barriers at relatively low temperatures. Cross-linking proceeds gradually, and reaction heat can dissipate in quasi-equilibrium with the DSC sensor. Consequently, curing initiates at a lower temperature and spans a broad temperature window [9]. By contrast, high heating rates deliver rapid temperature ramps. Short residence time at intermediate temperatures prevents the chemical system from developing substantial conversion at low-to-moderate temperature ranges. In addition, elevated scanning rates introduce measurable thermal inertia (thermal lag) between sample pans and DSC detectors, so massive exothermic cross-linking is delayed and concentrates within a narrow high-temperature interval, hence yielding sharp peaks and upward-shifted characteristic temperatures T_i , T_p , and T_f [15]. Note that the onset temperature T_i exhibits comparatively weak sensitivity to heating rate, implying that the initial activation of epoxy–amine ring-opening has moderate thermal threshold for this specific formulation.

By comprehensively analyzing and processing the peaks of the dynamic DSC curve, the starting temperature T_i , peak heat release temperature T_p , termination temperature T_f , and heat release rate HR of the resin system curing reaction at different heating rates δ can be obtained. The results are shown in Table 3. The heat release rate (HR) of the curing reaction of the resin system under different heating rates δ was basically similar, and the average HR of the curing reaction was about $474.62 \text{ J}\cdot\text{g}^{-1}$. According to the characteristic temperatures shown in Table 3, the characteristic temperature of the curing system at a heating rate of $\delta = 0$ can be obtained by extrapolation, which is the characteristic temperature of isothermal curing. Its physical significance is to reveal the optimal pre-curing temperature $T_{\text{pre-c}}$, curing temperature T_c , and post-curing temperature $T_{\text{post-c}}$ of the curing system under isothermal conditions. The relationship curve between the dynamic DSC characteristic temperature of the resin system and the heating rate is shown in Figure 4. There is a good linear relationship between characteristic temperature and heating rate δ . By linear fitting and extrapolation to a heating rate of $\delta = 0$, the isothermal curing characteristic temperature of the resin system can be obtained, as shown in Table 4.

Table 3. Characteristic temperature of dynamic DSC curves.

Heating Rate $\delta/^\circ\text{C}\cdot\text{min}^{-1}$	$T_i/^\circ\text{C}$	$T_p/^\circ\text{C}$	$T_f/^\circ\text{C}$	$H_R/\text{J}\cdot\text{g}^{-1}$
3	47.18	103.80	137.81	478.24
5	51.59	112.49	158.36	474.19
8	54.30	122.14	166.80	483.39
10	55.61	125.70	179.01	463.13
15	59.66	135.67	185.57	474.16

Table 4. Characteristic temperature of isothermal curing for resin system.

Resin System	δ	$T_i/^\circ\text{C}$	$T_p/^\circ\text{C}$	$T_f/^\circ\text{C}$	$T_{\text{pre-c}}/^\circ\text{C}$	$T_c/^\circ\text{C}$	$T_{\text{post-c}}/^\circ\text{C}$
RIMR135/RIMH137	0	45.68	98.74	134.58	45 ± 5	98 ± 5	134 ± 5

According to Table 4, the optimal precuring temperature $T_{\text{pre-c}}$, curing temperature T_c , and post curing temperature $T_{\text{post-c}}$ of the resin system are $45 \pm 5^\circ\text{C}$, $98 \pm 5^\circ\text{C}$, and $134 \pm 5^\circ\text{C}$, respectively. The isothermal curing characteristic temperature is an important reference for formulating the curing system of the resin system.

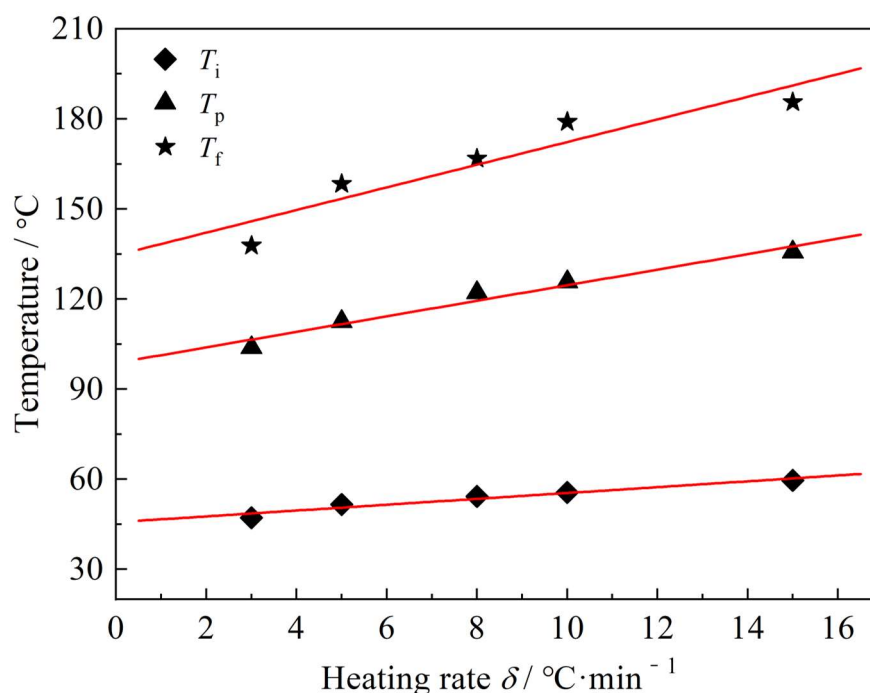


Figure 4. Relationship between characteristic temperature and heating rate.

3.1.2. Conversion Rate of Resin System

The relationship between the conversion rate α (i.e., solidification degree) of the resin system at different heating rates and temperature T during dynamic DSC monitoring is shown in Figure 5. The conversion rate curve α - T shows a clear “S” shape, and as the heating rate increases, the curve gradually shifts towards higher temperatures.

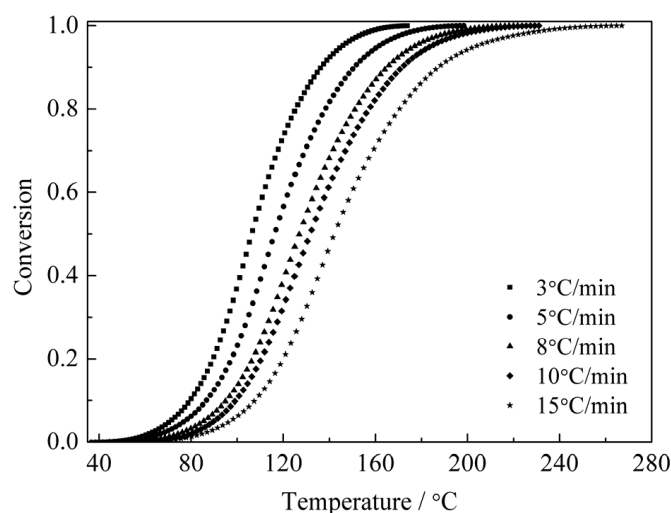


Figure 5. Relationship between conversion and temperature.

The conversion rate α , corresponding to the peak exothermic temperature T_p of the resin system curing reaction at different heating rates, as well as the temperature $T_{\alpha=1}$ and time $t_{\alpha=1}$ corresponding to complete curing, are detailed in Table 5. The conversion rate α_p value corresponding to the peak temperature T_p of the resin system at different heating rates gradually decreases with the increase of heating rate δ , while the curing completion temperature $T_{\alpha=1}$ value gradually increases with the increase of heating rate δ .

Table 5. Results of conversion analysis.

Heating Rate $\delta/^{\circ}\text{C}\cdot\text{min}^{-1}$	α_p	$T_{\alpha=1}/^{\circ}\text{C}$	$t_{\alpha=1}/\text{s}$
3	0.4516	173.80	2977.02
5	0.4328	198.34	2080.98
8	0.4228	221.77	1476.94
10	0.4121	231.03	1236.97
15	0.4095	266.98	968.84

3.1.3. Dynamic Curing Kinetics Model of Resin System

Assuming that the curing reaction rate $d\alpha/dt$ is a function of the reaction rate constant $k(T)$ and the reaction mode $f(\alpha)$, the kinetic equation of the epoxy resin system can be described as [12]:

$$\frac{d\alpha}{dt} = \sum_{i=1}^n f_i(\alpha)k_i(T) \quad (1)$$

In the formula, t is the curing reaction time; $f_i(\alpha)$ is the reaction mode function of the I step reaction; $k_i(T)$ is the rate constant for the I step reaction; T is the absolute temperature, measured in K.

The most widely used model for studying the curing kinetics of epoxy resin systems is the phenomenological model, which includes the n -order reaction model, autocatalytic reaction model, and Kamal model [16–26]. According to the relationship between conversion rate and temperature shown in Figure 4, the curing reaction kinetics of the epoxy resin system used in this article basically conforms to the self-catalytic reaction model. The self-catalytic reaction model $F_{(a)}$ is currently a widely used phenomenological solidification kinetics model, expressed as [18,21]:

$$\frac{d\alpha}{dt} = k_2 \cdot \alpha^m \cdot (1 - \alpha)^n \quad (2)$$

In the formula, m and n are reaction orders; k_2 is the reaction rate constant, follow the Arrhenius equation:

$$k(T) = A \exp\left(\frac{-E_a}{RT}\right) \quad (3)$$

In the formula, A and E_a are the pre-exponential factor and the apparent activation energy of the solidification reaction, respectively, and R is the universal gas constant.

According to Equations (2) and (3), establishing the kinetic equation for the self-catalytic curing reaction of the resin system requires determining the apparent activation energy E_a , pre-exponential factor A , and kinetic parameters m and n . The apparent activation energy E_a of the self-catalytic model is solved using the Kissinger method, while the model parameters A , m , and n are solved using the Malek method [2,3].

(1) Apparent activation energy E_a

According to Kissinger's formula:

$$\ln \frac{\delta}{T_p^2} = -\frac{E_a}{R} \cdot \frac{1}{T_p} + \ln \frac{AR}{E_a} \quad (4)$$

It can be seen that $\ln(\delta/T_p^2)$ and $1/T_p$ have a linear relationship. Based on the peak temperature T_p of the DSC curve at different heating rates, plot $\ln(\delta/T_p^2)$ and $1/T_p$, and linearly fit to obtain the slope q and intercept of the straight line with a value of φ , then:

$$E_a = -R \cdot q \quad (5)$$

The relationship curve between the peak temperature T_p of the DSC curve of the resin system as a function of $\ln(\delta/T_p^2)$ and $1/T_p$ (K^{-1}) at different heating rates is shown in Figure 6. The function $\ln(\delta/T_p^2)$ has a good linear relationship with $1/T_p$.

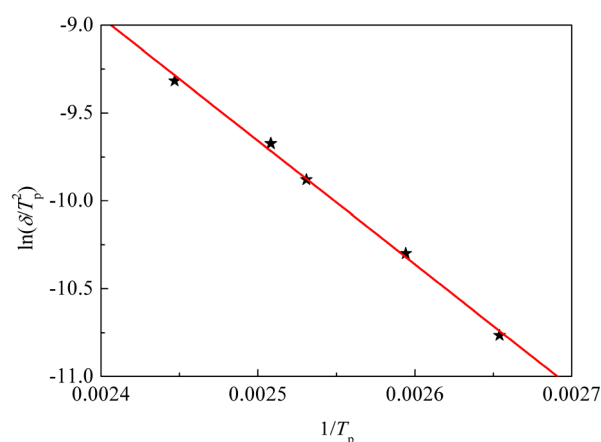


Figure 6. Relationship between function $\ln(\delta/T_p^2)$ and parameter $1/T_p$.

By linearly fitting the relationship curve between the function $\ln(\delta/T_p^2)$ and $1/T_p$, the slope q and intercept φ of the line can be obtained. According to Equation (5), the apparent activation energy E_a of the resin system can be calculated to be $58.44 \text{ kJ}\cdot\text{mol}^{-1}$.

(2) Characteristic function

To solve the parameters of the self-catalytic reaction model using the Malek method, two characteristic functions $y(\alpha)$ and $z(\alpha)$ need to be defined, which are:

$$y(\alpha) = \left(\frac{d\alpha}{dt}\right)e^x \quad (6)$$

$$z(a) = \pi(x)\left(\frac{d\alpha}{dt}\right)\frac{T}{\delta} \quad (7)$$

In the formula, $x = E_a/RT$ is a function of temperature; B is an integral related to temperature, and the approximate expression for the Senum–Yang fourth-order temperature integral of $\pi(x)$ is:

$$\pi(x) = \frac{x^3 + 18x^2 + 88x + 96}{x^4 + 20x^3 + 120x^2 + 240x + 120} \quad (8)$$

According to the apparent activation energy E_a value, the characteristic functions $y(\alpha)$ and $z(\alpha)$ of the resin system can be calculated. After normalization, the characteristic function $y(\alpha)$ and $z(\alpha)$ curves of the resin system can be obtained as shown in Figure 7a,b, respectively.

As shown in Figure 7, the curve shapes of the characteristic functions $y(\alpha)$ and $z(\alpha)$ are convex and have maximum values. The conversion rates corresponding to the maximum values of the characteristic functions $y(\alpha)$ and $z(\alpha)$ are defined as $\alpha_y^{\max}$ and $\alpha_z^{\max}$, respectively. The conversion rates $\alpha_y^{\max}$ and $\alpha_z^{\max}$ values correspond to the maximum values of the characteristic functions $y(\alpha)$ and $z(\alpha)$ of the resin system at different heating rates δ , as well as the conversion rate α_p corresponding to the peak temperature T_p , are shown in Table 6.

Malek's research shows that when the maximum value of the characteristic function $z(\alpha)$ corresponds to a conversion rate $\alpha_z^{\max}$ value less than 0.632, the solidification reaction process of the system can be described using a self-catalytic reaction model.

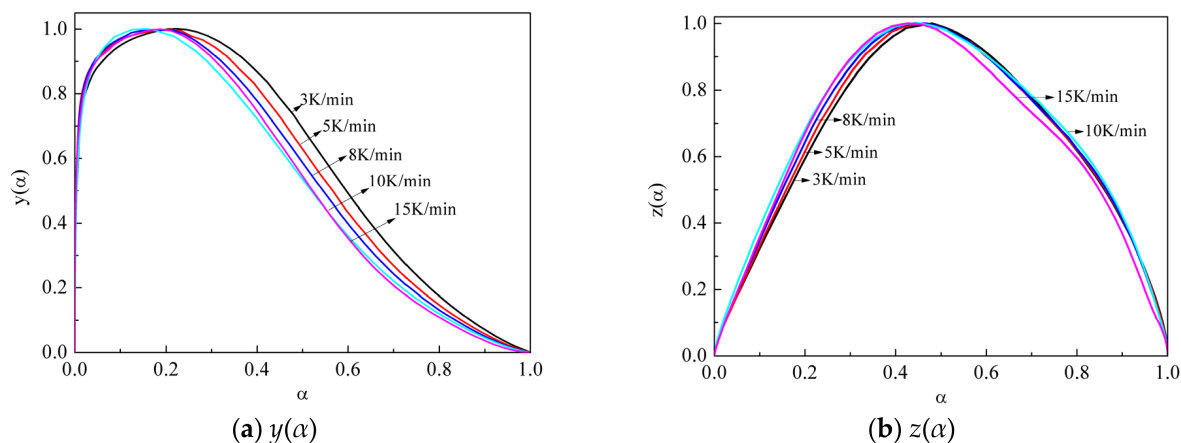


Figure 7. Characteristic functions $y(\alpha)$ and $z(\alpha)$.

Table 6. Parameters of characteristic functions.

Heating Rate $\delta/^\circ\text{C}\cdot\text{min}^{-1}$	$\alpha_y^{\max}$	$\alpha_z^{\max}$	α_p
3	0.1631	0.4800	0.4516
5	0.1127	0.4513	0.4328
8	0.1244	0.4537	0.4228
10	0.1252	0.4545	0.4121
15	0.1284	0.4257	0.4095

(3) Model parameters A, m and n

According to Malek's method, taking the logarithm on both sides of Equation (2) and making a simple transformation yields:

$$\ln[(d\alpha/dt)e^x] = \ln A + n \ln[\alpha^p(1-\alpha)] \quad (9)$$

$$\text{Among them : } m = pn \quad (10)$$

$$p = \alpha_y^{\max} / (1 - \alpha_y^{\max}) \quad (11)$$

According to Equation (9), there is a linear relationship between $\ln[(d\alpha/dt)e^x]$ and $\ln[\alpha^p(1-\alpha)]$. Based on the slope of the line and Equations (10) and (11), the kinetic parameters A, m, and n of the autocatalytic model can be calculated.

The kinetic parameters A, m, and n of the resin system's self-catalytic reaction model are shown in Table 7.

Table 7. Parameters of characteristic functions.

Heating Rate/ $^\circ\text{C}\cdot\text{min}^{-1}$	m	n	lnA	A
3	0.2133	1.0943	12.32	224,134
5	0.1520	1.1971	12.22	202,805
8	0.1642	1.1559	11.88	144,350
10	0.1929	1.3479	12.34	228,662
15	0.2065	1.4019	12.00	162,754
Average	0.1858	1.2394	12.15	189,473

By substituting the apparent activation energy E_a and dynamic parameters A, m, and n into the kinetic model Equation (2) of the self-catalytic reaction, the curing kinetics equation of the resin system can be obtained as follows:

$$\frac{d\alpha}{dt} = 1.89 \times 10^5 \cdot \exp\left(-\frac{58440}{RT}\right) \cdot \alpha^{0.1858}(1-\alpha)^{1.2394} \quad (12)$$

(4) Validation of Autocatalytic Model

To verify the effectiveness of the self-catalytic model, the reaction rate predicted by the self-catalytic curing reaction $d\alpha/dt$ kinetics Equation (12) was compared with experimental values, as shown in Figure 8. As shown in the figure, although there is a certain deviation between the predicted values and experimental values of the self-catalytic reaction model of the resin system under the conditions of heating rates of $10^\circ\text{C}\cdot\text{min}^{-1}$ and $15^\circ\text{C}\cdot\text{min}^{-1}$, the overall trend of the two is basically consistent. Therefore, during the curing process of the resin system, the prediction of the curing degree of the resin system in the dynamic curing process is based on the self-catalytic curing reaction model shown in Equation (12).

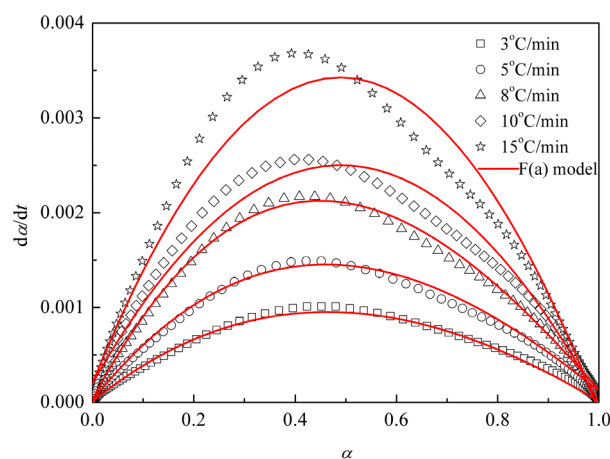


Figure 8. Verification of auto-catalysis reaction model.

3.2. Isothermal Curing Kinetics Behavior of Resin System

3.2.1. Isothermal DSC Curve and Curing Degree of Resin System

A total of seven temperature points including 60, 70, 80, 90, 100, 110, and 120°C were used with DSC to test the isothermal curing DSC curve of the resin system. The results are shown in Figure 9. The exothermic peak of resin system curing increases and shifts forward with the increase of isothermal curing temperature T , indicating that the higher the curing temperature T , the more intense the reaction, the more concentrated the heat release, and the shorter the time t required for complete reaction. The peak heat release occurs after a period of time from the beginning of the curing reaction, which is consistent with the characteristics of the self-catalytic curing model, as the self-catalytic model has an induction period, and the maximum reaction rate only appears after a period of time from the beginning of the reaction.

As mentioned earlier, the curing reaction heat H_R when the resin system is fully reacted is 474.62 J/g . According to the isothermal DSC curve, the relationship between curing degree α and time t at different isothermal curing temperature T can be calculated, as shown in Figure 10. The higher the isothermal curing temperature, the faster the initial reaction rate, the shorter the time to reach the same conversion rate, and the maximum curing degree of the resin system increases with the increase of isothermal curing temperature. The higher the curing temperature, the more obvious the curve (α - t curve) of curing degree with time shows an “S” shape, which indicates from the perspective of dynamic kinetics that the curing reaction of the resin system has the characteristics of a self-catalytic curing reaction.

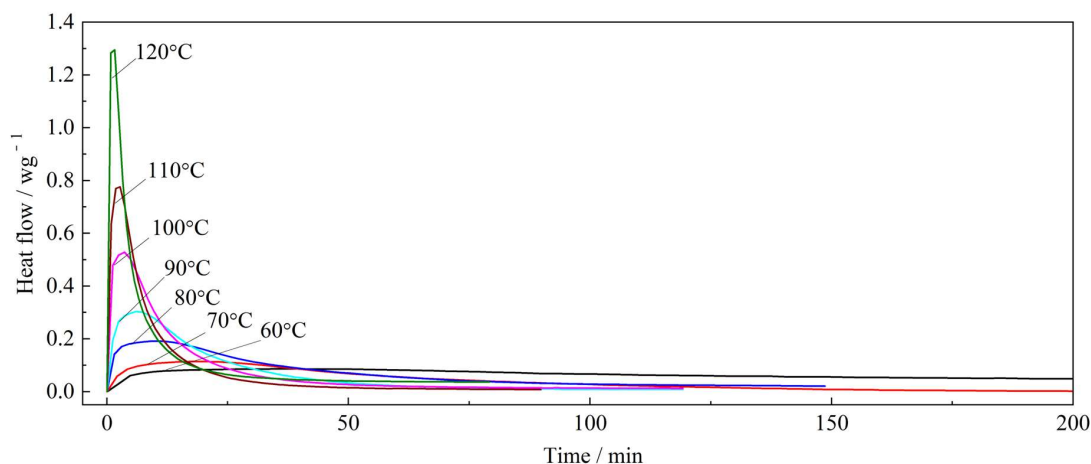


Figure 9. Isothermal DSC curves of RIMR135/RIMH137 resin system.

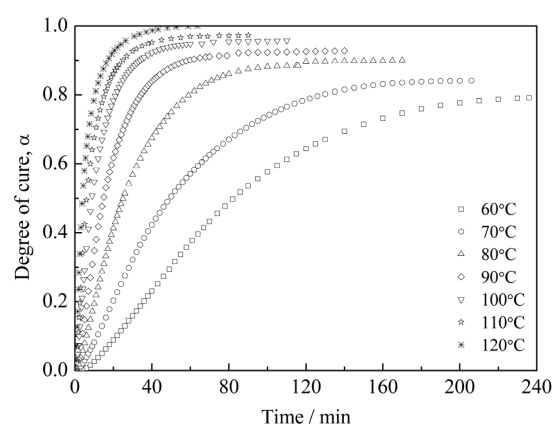


Figure 10. Time dependence of cure degree by isothermal DSC.

As shown in Figure 10, the maximum curing degree $\alpha_{\max}$ of the resin system under isothermal curing system was not equal to 1, indicating that the curing reaction was not completed. The relationship between the maximum curing degree $\alpha_{\max}$ of the resin system at different isothermal temperatures T and the change in curing temperature T is shown in Figure 11. The maximum curing degree $\alpha_{\max}$ has a good linear relationship with the isothermal curing temperature T , which can be expressed as:

$$\alpha_{\max} = -0.3156 + 0.003380 \cdot T \quad (13)$$

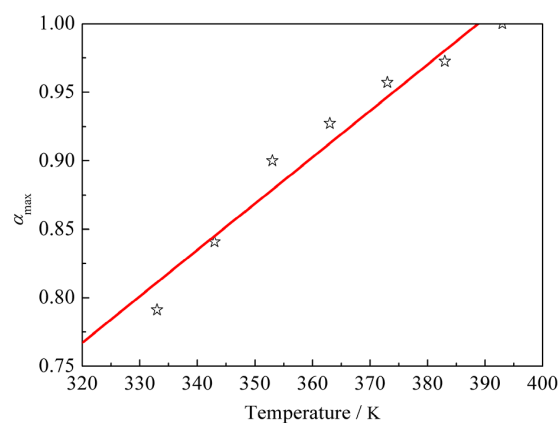


Figure 11. Maximum degree of cure reached at each isothermal cure temperature.

3.2.2. Isothermal Curing Kinetics Model of Resin System

(1) Definition of relative curing degree

According to the analysis of dynamic curing kinetics and isothermal DSC curve characteristics mentioned above, it can be concluded that the curing kinetics of the resin system can be described by a self-catalytic reaction model.

For the convenience of data processing and analysis, the curing degree is normalized, and the normalized curing degree during isothermal curing α_N is defined as relative curing degree:

$$\alpha_N = \frac{\alpha}{\alpha_{\max}} \quad (14)$$

In the formula, α is the degree of solidification at time t ; $\alpha_{\max}$ is the maximum curing degree at a specific isothermal curing temperature.

The relationship between the curing reaction rate $d\alpha/dt$ and the relative curing degree is shown in Figure 12. As the relative curing degree increases, the curing reaction rate of the resin system shows a trend of first increasing and then decreasing, with the maximum reaction rate occurring within the range of relative curing degree $\alpha_N = 0.1 \sim 0.4$; The higher the isothermal curing temperature, the greater the maximum reaction rate, further indicating that the curing process of the resin system has self-catalytic reaction characteristics.

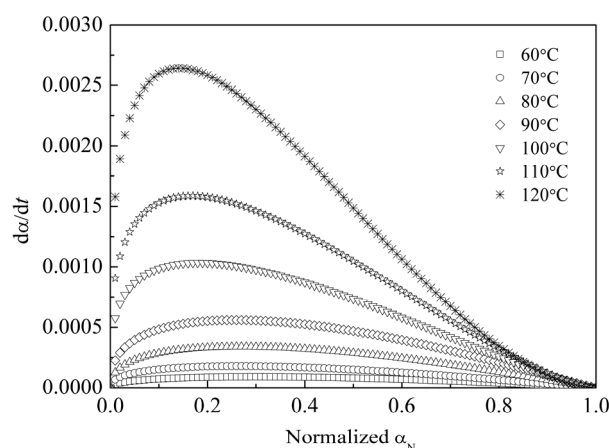


Figure 12. Reaction rate as a function of normalized cure degree.

(2) Application and Verification of Modified Autocatalytic Model

Under isothermal curing conditions, the curing reaction of the self-catalytic resin system can be divided into three stages: the initial stage, which is the induction period of the curing reaction, and the reaction rate slowly increases; in the middle stage of the reaction, the self-catalytic effect becomes prominent, and the reaction rate sharply increases until it reaches its maximum value; in the later stage of solidification, the viscosity of the solid increases, and the solidification reaction gradually shifts from self-catalytic mechanism control of chemical reaction to diffusion control [8]. The solidification reaction rate decreases with the passage of reaction time. In the later stage of solidification reaction, diffusion control plays a major role. When the curing temperature is different, the molecular activity ability and diffusion control effect vary, resulting in different maximum curing degrees at the completion of isothermal curing. The term in the self-catalytic model Equation (2) $(1 - \alpha)^n$ assumes a curing degree of 1 upon completion of curing, but the curing degree at the end of the isothermal curing reaction can only approach 1 as the isothermal temperature increases, rather than 1. This results in the model being unable to simulate experimental results well in the later stages of solidification.

To more accurately simulate the curing reaction of the self-catalytic resin system, this paper uses the modified self-catalytic model M-F (a) Equation (15) to describe the isothermal curing kinetics of the resin system. The M-F (a) model Equation (15) can be simply transformed to obtain:

$$\frac{d\alpha}{dt} = k\alpha^m(\alpha_{\max} - \alpha)^n = k\alpha^m\left(1 - \frac{\alpha}{\alpha_{\max}}\right)^n = k\alpha^m(1 - \alpha_N)^n \quad (15)$$

In the formula, k , m , and n are the parameters of the modified self-catalytic model, which can be obtained through experiments.

According to the modified self-catalytic model M-F(a), the experimental data in Figure 12 were fitted using the least squares method, and the fitted curve is shown in Figure 13. The experimental values at various isothermal curing temperatures are in good agreement with the fitting results of the modified self-catalytic model M-F(a), indicating that the modified self-catalytic model M-F(a) can accurately simulate the relationship between the curing reaction rate $d\alpha/dt$ and the relative curing α_N degree of the resin system. The fitted kinetic parameters of the modified self-catalytic model M-F(a) are shown in Table 8.

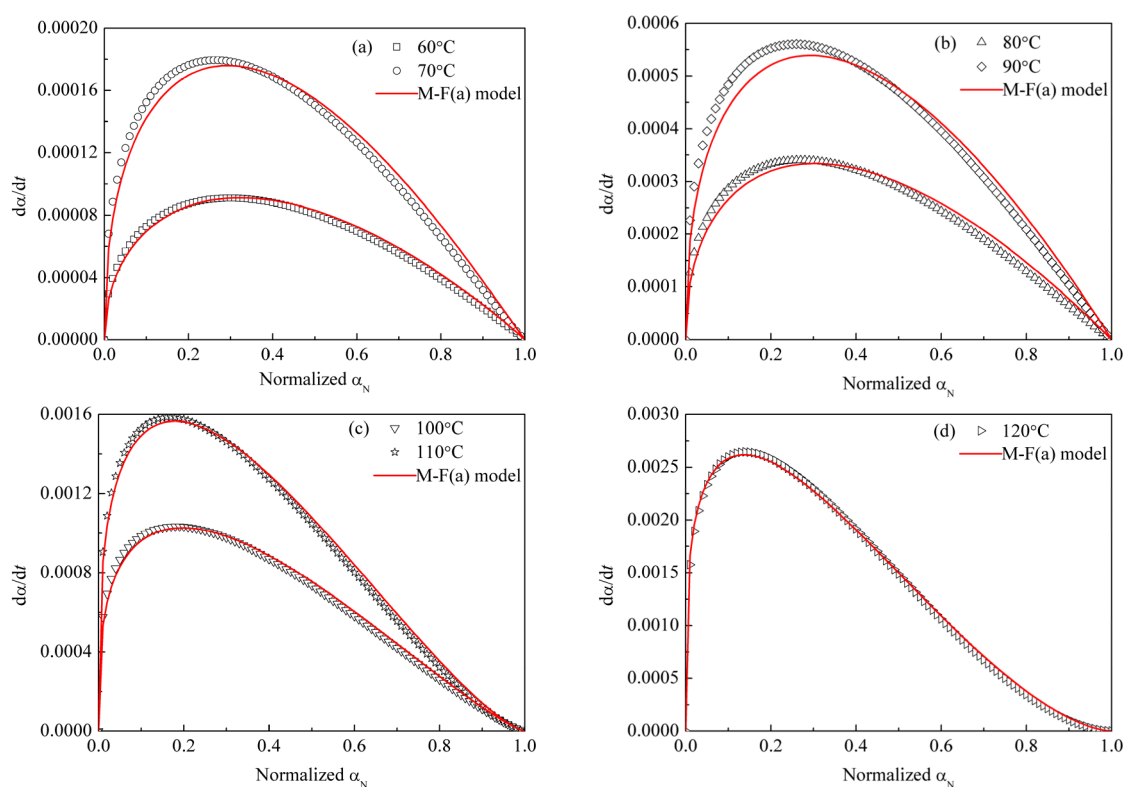


Figure 13. Comparison of experimental data and the simulated results of modified auto-catalyzed model.

Table 8. Kinetic parameters of modified auto-catalyzed model.

Temperature/°C	60	70	80	90	100	110	120
k	0.000227	0.000426	0.000808	0.00126	0.00223	0.00343	0.00558
m	0.4679	0.4290	0.4367	0.4126	0.3084	0.2987	0.2594
n	0.980	1.034	1.001	0.997	1.254	1.370	1.636

The relationship between curing kinetics parameters k , m , n and temperature T can be obtained through linear fitting and quadratic polynomial fitting, as shown in Figure 14.

According to the data in this figure, the relationship between the curing kinetics parameters k , m , n of the modified self-catalytic model M-F (a) and temperature T can be expressed as:

$$k = \exp(12.4474 - 6093.2285/T) \quad (16)$$

$$m = 1.6883 - 0.003620 \cdot T \quad (17)$$

$$n = 33.832 - 0.191 \cdot T + 2.771 \times 10^{-4} \cdot T^2 \quad (18)$$

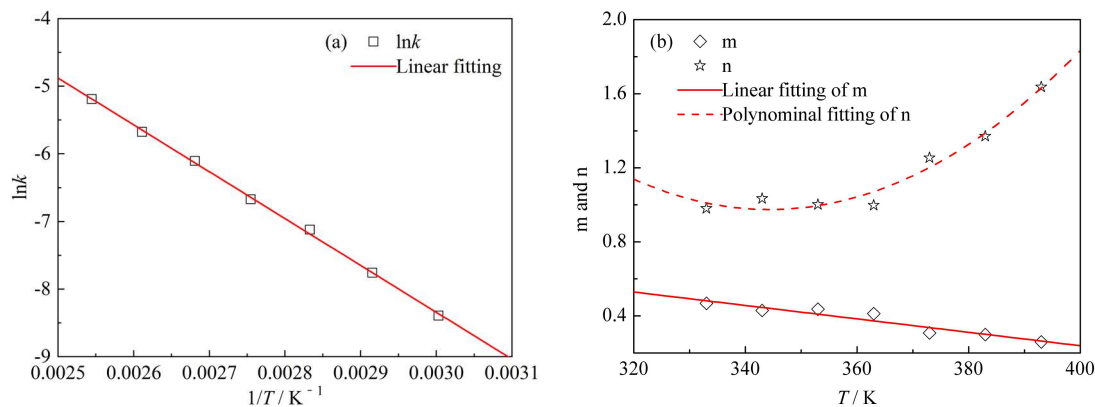


Figure 14. Comparison of experimental data and the simulated results of modified auto-catalyzed model.

Combining Equation (16) to (18), the modified self-catalytic reaction model of the resin system under isothermal curing conditions can be obtained:

$$\frac{d\alpha}{dt} = 2.55 \times 10^5 \cdot \exp\left(-\frac{6093.2285}{T}\right) \cdot \alpha^{1.6883-0.003620 \cdot T} (1-\alpha)^{33.832-0.191 \cdot T+2.771 \times 10^{-4} \cdot T^2} \quad (19)$$

In the formula, T is the isothermal curing temperature.

In summary, the curing degree of the resin system during isothermal curing can be predicted using the modified self-catalytic curing reaction model Equation (19).

3.3. Temperature and Curing Degree Distribution During the Curing Process of Thick-Section Carbon Fiber Composite Materials

3.3.1. Curing Temperature and Degree Distribution in the Thickness Direction

On the basis of the curing kinetic characteristics of the adopted resin system, the two-stage curing schedule consisting of pre-curing and post-curing was formulated by comprehensively taking into account the heat resistance temperature of the manufacturing mold and the curing cycle recommended by the material supplier. The specific curing procedure is described as follows: the temperature was raised to 45 °C at a heating rate of 0.5–1 °C/min within 30 min, followed by an isothermal holding stage for 180 min; afterwards, the temperature was ramped up to 80 °C at a heating rate of 1–2 °C/min over another 30 min and maintained at this temperature for 360 min. The programmed heating temperatures of the curing schedule exhibited favorable consistency with the actual heating temperatures of the mold, as illustrated in Figure 15, which further verifies the temperature control precision of the mold heating system.

To simulate the curing process of thick-section carbon fiber composite materials formed by the VIMP process, the curing temperature and degree distribution along the thickness direction inside the component were investigated. Composite component samples with in-plane dimensions of 200 × 200 mm and thicknesses of 20 mm, 40 mm, and 60 mm were selected to monitor the temperature change history during the curing process. Miniature

Pt100 thermocouples ($\pm 0.1^\circ\text{C}$ accuracy) were embedded inside the fibre pre-form before vacuum-bagging. For each 200×200 mm laminate (20-, 40-, 60-mm thickness), three through-thickness measuring points were placed at the panel in-plane geometric centre (100 mm, 100 mm): 0.8 mm above the mold-contact bottom surface, at the exact thickness mid-plane, and 0.8 mm beneath the free top surface.

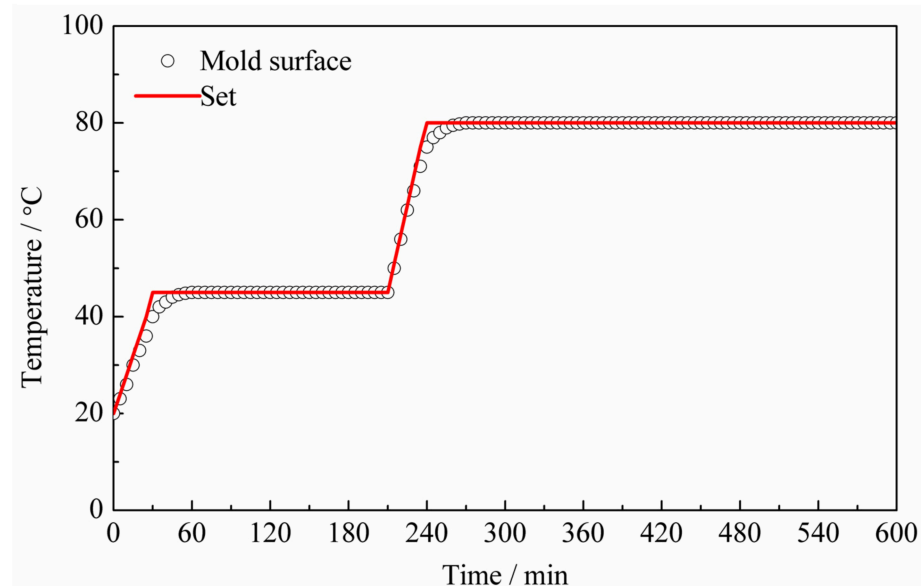


Figure 15. Temperature verification of plate-mold heating system.

The 0.8-mm offset from outer surfaces avoids direct contact with mold or bagging materials to record true internal composite temperature, eliminating boundary-induced measurement bias. Edge regions were excluded due to intensified lateral heat loss. Thermocouple wires were routed sideways and sealed with vacuum-compatible tape to maintain cavity tightness. This arrangement captures full through-thickness thermal gradients arising from the thickness effect. The dimensions and monitoring locations of the composite material model are shown in Figure 16.

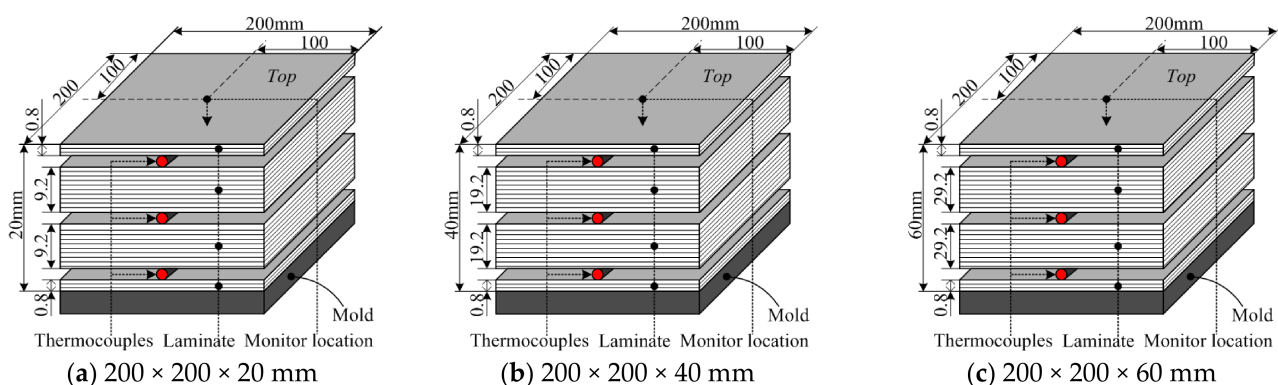


Figure 16. Dimensions and monitoring position of model composites.

During the heating and curing process, insulation treatment was carried out by covering the model composite material with insulation cotton quilts. To minimize heat loss, four layers of cotton quilts were used for insulation. Using the dynamic and isothermal curing degree model Equations (12) and (19) established earlier, the curing degrees during the dynamic and isothermal curing processes were calculated.

Figure 17 presents the temperature evolution histories at internal monitoring positions and corresponding degree-of-cure distribution curves of composite specimens with thicknesses of 20 mm, 40 mm and 60 mm throughout the curing cycle. Distinct temperature spikes can be observed during curing, which originate from the intensive exothermic release of curing reactions within a specific time interval and thereby induce a sharp temperature rise inside the composite parts. The temperature change history of the three monitoring points inside the component sample observed peak temperatures T_p , with the maximum peak temperature T_{p-max} occurring in the middle of the component sample, indicating that the coupling of external heating and curing reaction heat release reached its maximum value in the middle.

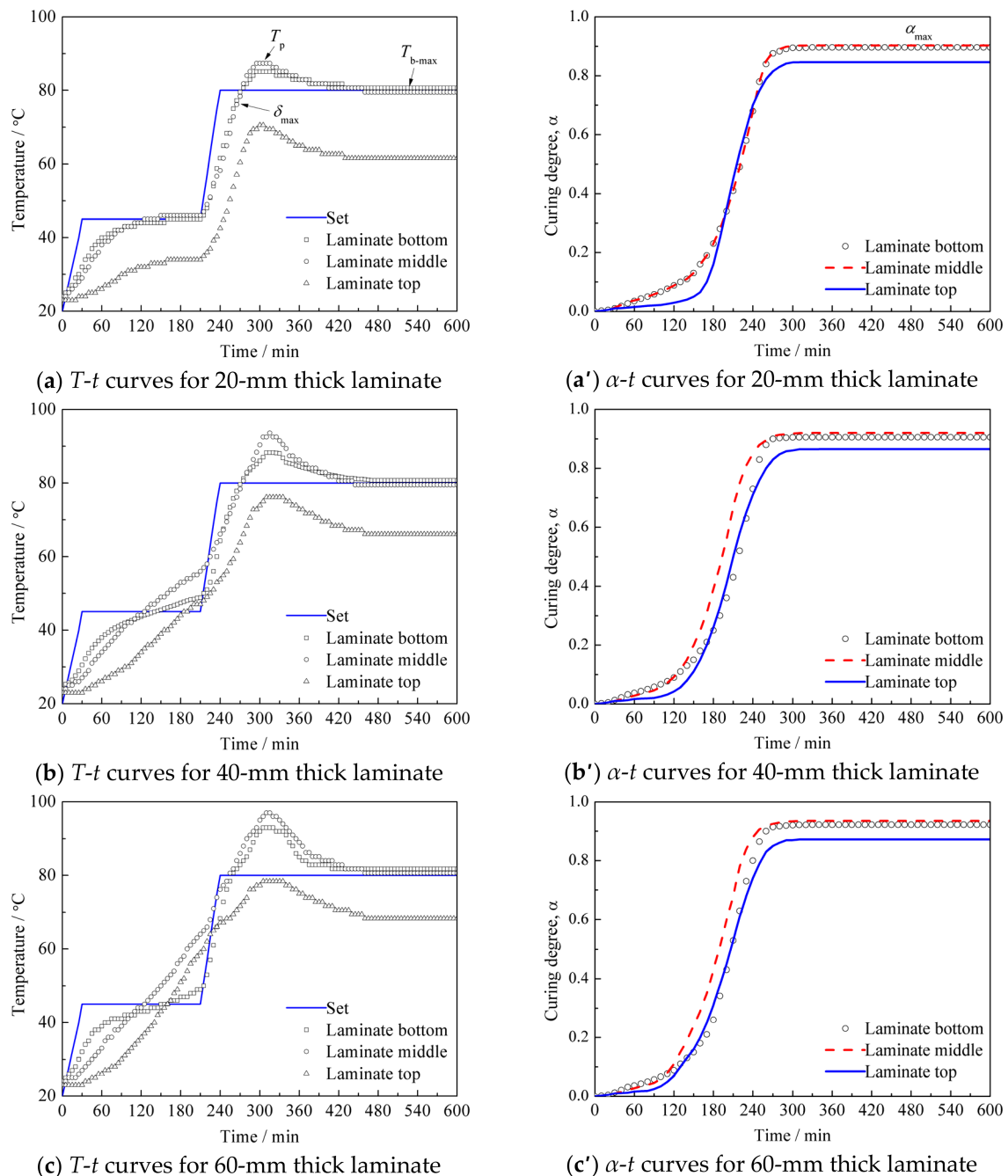


Figure 17. Temperature and curing degree distribution of thick-section composites in curing process.

There was a significant difference in temperature between the surface of the component sample and the bottom and middle surfaces, which is caused by asymmetric heating on

one side. Under the condition of single-sided asymmetric heating, the maximum curing degrees of the bottom $\alpha_{\text{Max}}^{\text{Bottom}}$ and middle $\alpha_{\text{Max}}^{\text{Middle}}$ of thick-section composite materials were basically the same, while the maximum curing degree of the top $\alpha_{\text{Max}}^{\text{Top}}$ was significantly lower than that of the bottom $\alpha_{\text{Max}}^{\text{Bottom}}$ and middle $\alpha_{\text{Max}}^{\text{Middle}}$.

There is a curing gradient in the thickness direction inside the model composite material, which means that there will also be a gradient in the performance of the model composite material in the thickness direction. This gradient in performance is equivalent to a defect inside the product, which can easily lead to premature failure during the service life of the product. This is an issue that needs to be taken seriously and avoided as much as possible in the preparation of thick-section composite materials.

3.3.2. The Influence of Thickness on the Curing Temperature and Degree Distribution of Thick-Section Composite Materials

Figure 18 depicts the evolution of temperature and degree of cure at identical internal monitoring points within VIMP-manufactured composite specimens with an in-plane dimension of 200×200 mm and cross-sectional thicknesses of 20 mm, 40 mm and 60 mm, respectively. The influence of specimen thickness on thermal evolution during curing manifested in two primary aspects. First, the magnitude of temperature spike rose with increasing thickness. Second, the contribution of curing reaction exotherm to temperature elevation inside composite laminates became more prominent as thickness increased. Furthermore, the spatial gradient of temperature distribution formed throughout the curing cycle of thick-section composites intensified with the growth of specimen thickness.

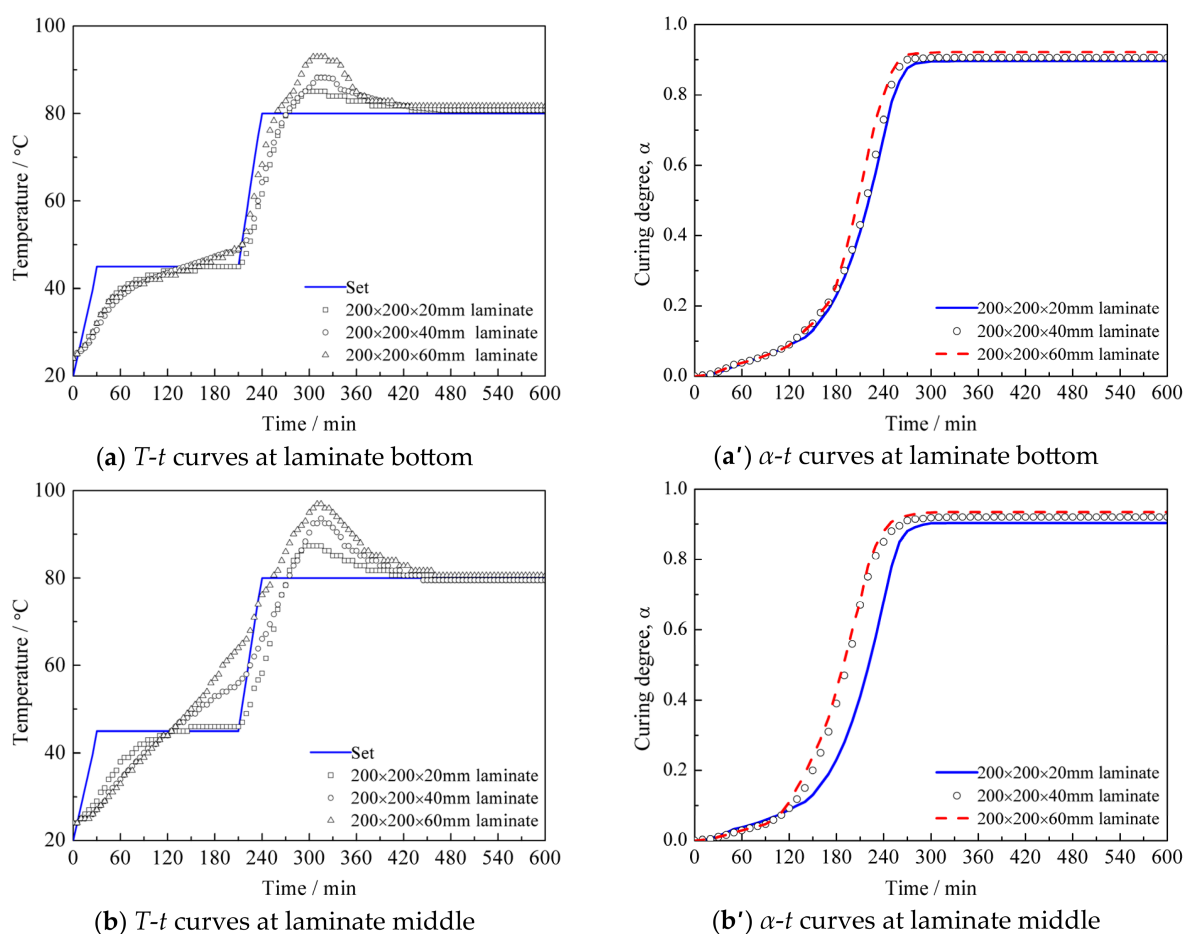


Figure 18. Cont.

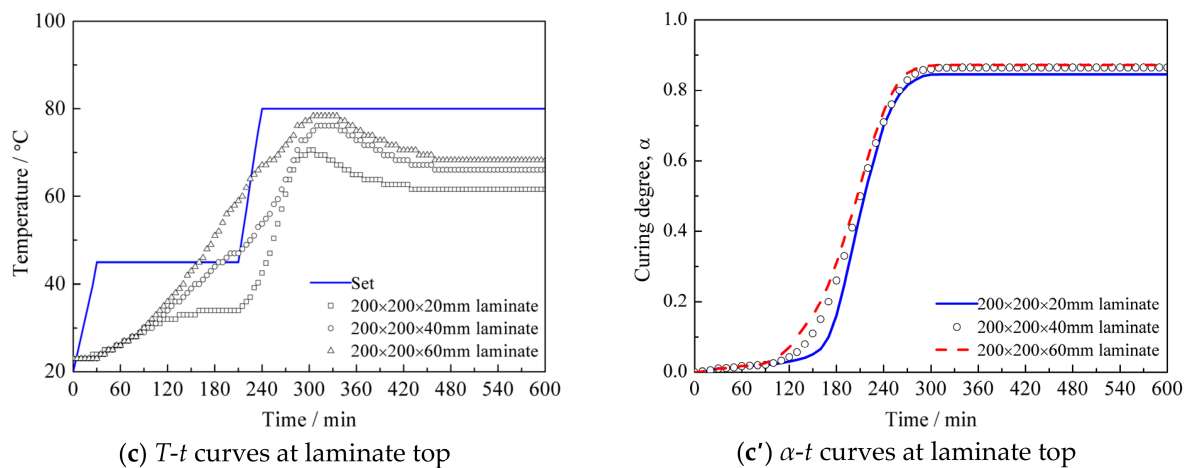


Figure 18. Influence of part thickness on curing temperature and curing degree distribution in thick-section composites.

The curing degree is a function of temperature, and the gradient of curing degree distribution inside thick-section composite materials depends on the maximum peak temperature T_{p-max} during the curing process and the minimum equilibrium temperature T_{min-e} on the surface of the component during the post-curing stage. The relationship between the maximum peak temperature T_{p-max} , minimum equilibrium temperature T_{min-e} , and their difference $\Delta T = T_{p-max} - T_{min-e}$ with the thickness of the composite material in the model is shown in Figure 19. The maximum peak temperature T_{p-max} , minimum equilibrium temperature T_{min-e} , and their difference $\Delta T = T_{p-max} - T_{min-e}$ all increased with the increase of composite material thickness, and they have a good linear relationship.

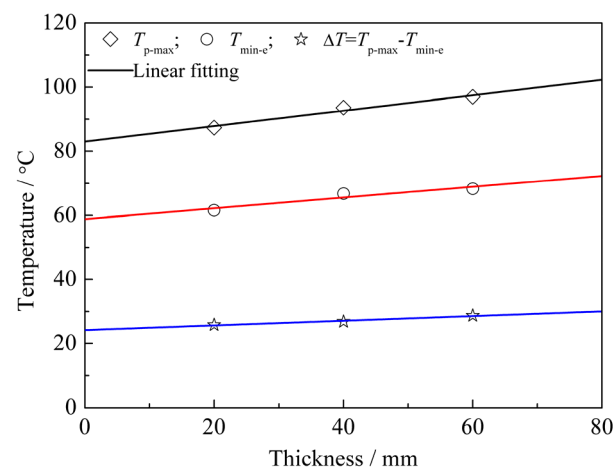


Figure 19. Thickness effect on maximum temperature and minimum equilibrium temperature.

If the temperature change amplitude ΔT_{os} is defined as the difference between the peak temperature T_p and the maximum equilibrium temperature T_{b-max} in the temperature change history $\Delta T_{os} = T_p - T_{b-max}$, the relationship between the temperature change amplitude ΔT_{os} of the bottom, middle, and top surfaces of the model composite material and the thickness h can be obtained as shown in Figure 20. The temperature fluctuation amplitude during the curing process of thick-section composite materials increased linearly with the increase of thickness h , and the growth rate was the highest at the middle position, followed by the heating bottom surface, while the growth rate was the smallest on the upper surface.

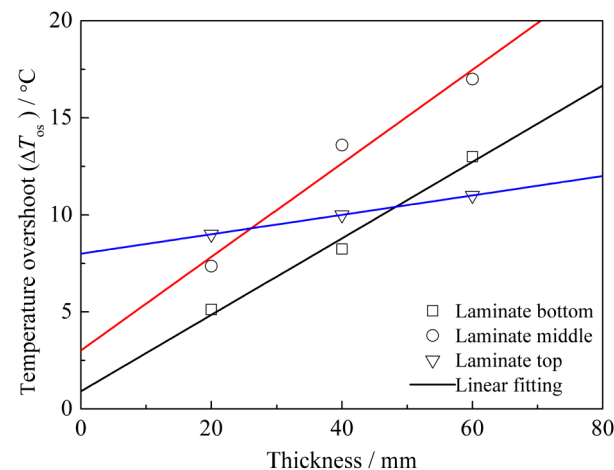


Figure 20. Thickness effect on temperature overshoot extent in the curing process of thick-section composites.

Sudden temperature changes during the curing process can easily lead to residual thermal stress, resulting in product defects. The overall molding of thick-section composite materials requires special attention.

3.3.3. The Influence of Three-Dimensional Dimensions on the Curing Temperature and Degree Distribution of Thick-Section Composite Materials

To investigate the effects of three-dimensional dimensions on the distributions of curing temperature and degree of cure in thick-section composites, three groups of specimens with geometric dimensions of $100 \times 100 \times 20$ mm, $200 \times 200 \times 40$ mm and $300 \times 300 \times 60$ mm were prepared to characterize their temperature and degree-of-cure evolution histories during curing. Schematic diagrams of the composite models with corresponding dimensions and internal monitoring positions are shown in Figure 21.

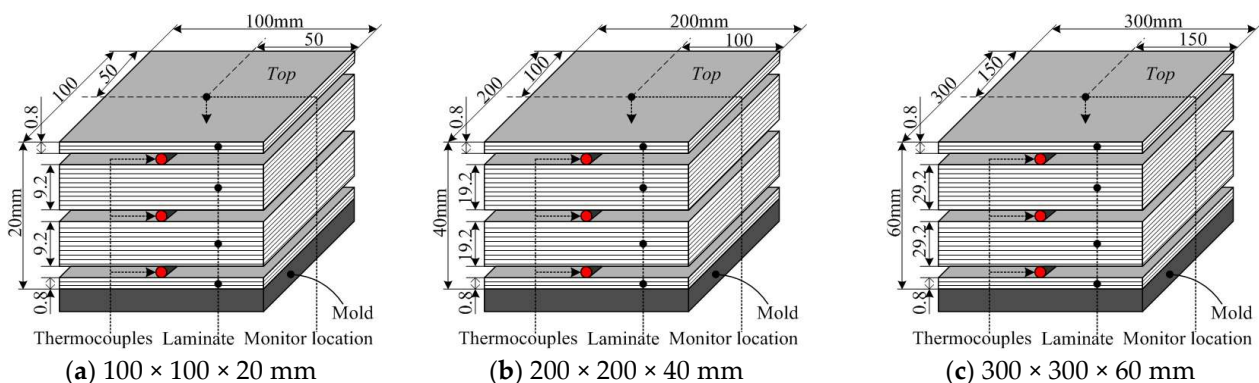


Figure 21. Dimensions and monitoring position of model composites for three-dimensional size effect study.

The temperature change history and corresponding curing degree distribution curves of three component samples with three-dimensional dimensions of $100 \times 100 \times 20$ mm, $200 \times 200 \times 40$ mm, and $300 \times 300 \times 60$ mm during the curing process are shown in Figure 22. The peak temperature and corresponding curing degree of the bottom, middle, and top surfaces of the component during the curing process increased with the increase of the three-dimensional size of the model composite material.

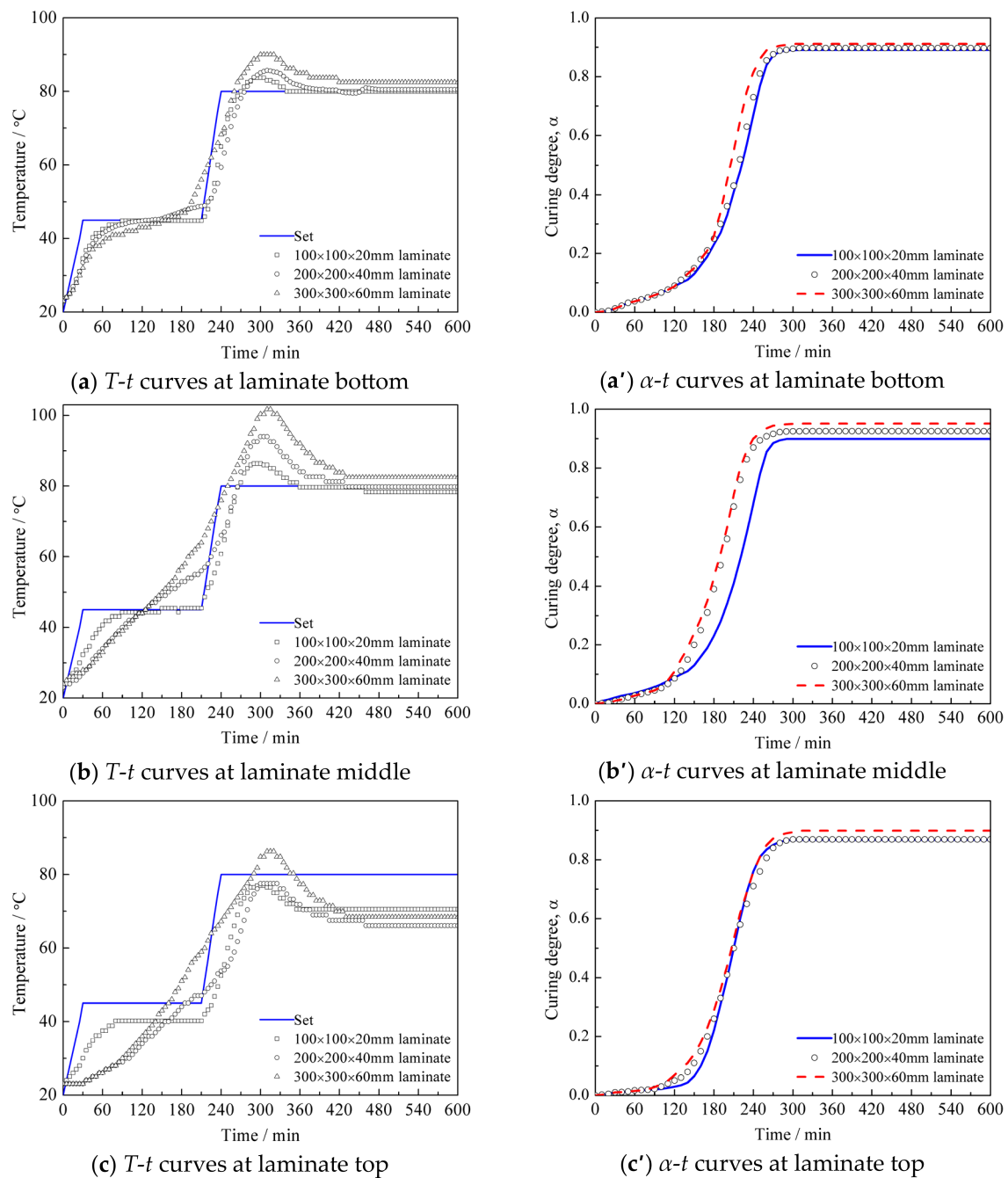


Figure 22. Influence of three-dimensional size on curing temperature and curing degree distribution in thick-section composites.

The relationship between the maximum peak temperature T_{p-max} , minimum equilibrium temperature T_{min-e} , and their difference $\Delta T = T_{p-max} - T_{min-e}$ during the curing process of thick-section composite materials and their volume variation is shown in Figure 23. The maximum peak temperature T_{p-max} , minimum equilibrium temperature T_{min-e} , and their difference $\Delta T = T_{p-max} - T_{min-e}$ all increased with the increase of the volume of the composite material in the model, and they have a good linear relationship.

The relationship between the temperature change amplitude ΔT_{os} of the bottom, middle, and top surfaces of the component sample and its volume change is shown in Figure 24. The temperature change amplitude ΔT_{os} during the curing process of thick-section composite materials increased with the increase of their volume and shows a good linear relationship. The temperature change amplitude ΔT_{os} increased with the increase of

composite material volume, indicating that the larger the volume of thick-section composite materials, the more efforts should be made to avoid or reduce temperature mutation during the curing process.

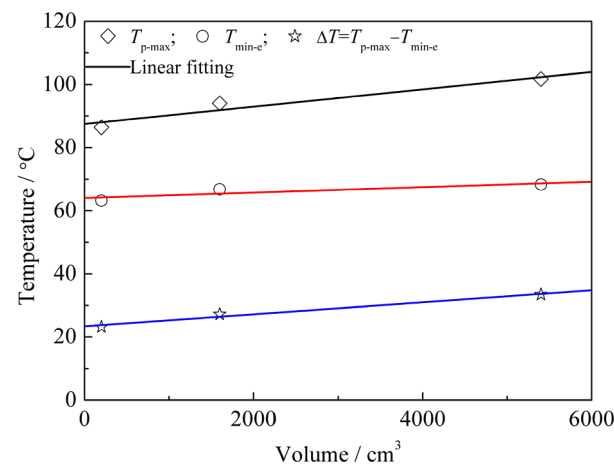


Figure 23. Three-dimonsional size effect on maximum temperature and minimum equilibrium temperature.

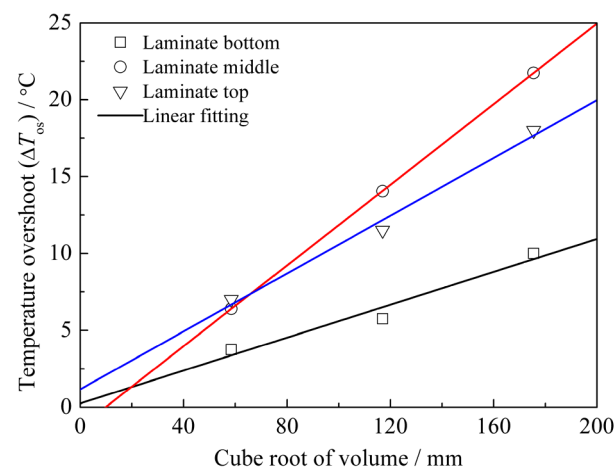


Figure 24. Three-dimensional size effect on temperature overshoot extent in the curing process of thick-section composites.

3.4. Numerical Simulation Analysis of Curing Temperature Field of Thick-Section Composite Materials

3.4.1. Material Parameters and Finite Element Model

Based on the thermal–chemical model of composite materials, the ABAQUS finite element method was used to simulate the temperature change history during the curing process of thick-section (20-mm, 40-mm, 60-mm) composite materials.

(1) Material Property Parameters

The density of composite materials ρ_c can be calculated using the mixing law:

$$\rho_c = (1 - v_f)\rho_m + v_f\rho_f \quad (20)$$

In the formula, subscripts c, f, and m respectively represent composite materials, fibers, and matrix; v for volume fraction; ρ for material density.

Similarly, determining the specific heat of composite materials based on the law of mixing:

$$C_c = \frac{C_f \rho_f v_f + C_m \rho_m (1 - v_f)}{\rho_c} \quad (21)$$

Using the Halpin–Tsai model to calculate the thermal conductivity of composite materials perpendicular to the fiber direction k_z :

$$\frac{k_z}{k_m} = \frac{k_f + k_m + (k_f - k_m)v_f}{k_f + k_m - (k_f - k_m)v_f} \quad (22)$$

In the formula, k is the thermal conductivity of the material.

The fiber volume fraction of carbon fiber composite materials formed by VIMP process is about 60%. The physical parameters such as density, specific heat, and thermal conductivity of the carbon fiber and epoxy resin used are shown in Table 9. According to the calculation formulas (20) to (22) for the physical parameters of composite materials, the physical parameters of the composite materials used in numerical simulations can be calculated, as shown in Table 9.

Table 9. Physical parameters of materials.

Materials	Density /kg·m ^{−3}	Specific Heat /J·kg ^{−1} ·K ^{−1}	Thermal Conductivity /W·m ^{−1} ·K ^{−1}
Resin (RIMR135/RIMH137)	1100	1260	0.24
Fiber (300CUD)	1800	712	2.51
300CUD/ RIMR135/RIMH137	1520	870	0.711

(2) Finite Element Model

The finite element DC3D8 was used for modeling, with an in-plane dimension of 200 × 200 mm. DC3D8 is a thermal analysis three-dimensional finite element in the ABAQUS element database, which is a hexahedral element with 8 nodes, each node having 6 degrees of freedom, as shown in Figure 25.

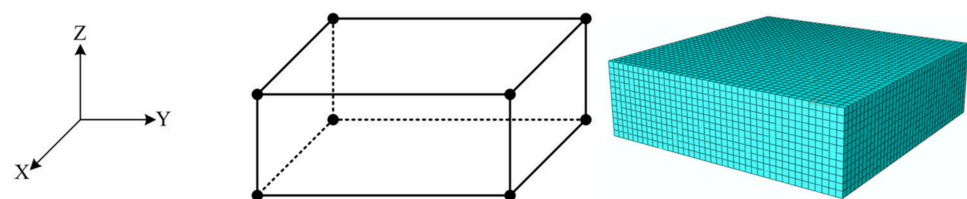


Figure 25. DC3D8 element geometry.

The external heat source originated from the asymmetric single-sided heating system integrated in the molding tool, and a two-stage curing schedule was adopted for thermal cycling: the specimen was heated from ambient temperature to 45 °C at a heating rate of 0.5–1 °C/min over 30 min and held isothermally for 180 min; subsequently, the temperature was raised to 80 °C at a heating rate of 1–2 °C/min within another 30 min, followed by an isothermal dwell of 360 min.

3.4.2. Field Analysis of Finite Element Simulation Results of Temperature Field

Figure 26 shows the temperature field distribution cloud map of a model composite material with a thickness of 20 mm at three critical curing time points: 210 min, 300 min, and 600 min. In this figure, 210 min is the starting point of post-curing heating, 300 min is

the highest peak temperature point, and 600 min is the end point of post-curing; L and h represent the length and thickness of the model composite material, respectively; in the result, 'NT11' represents temperature.

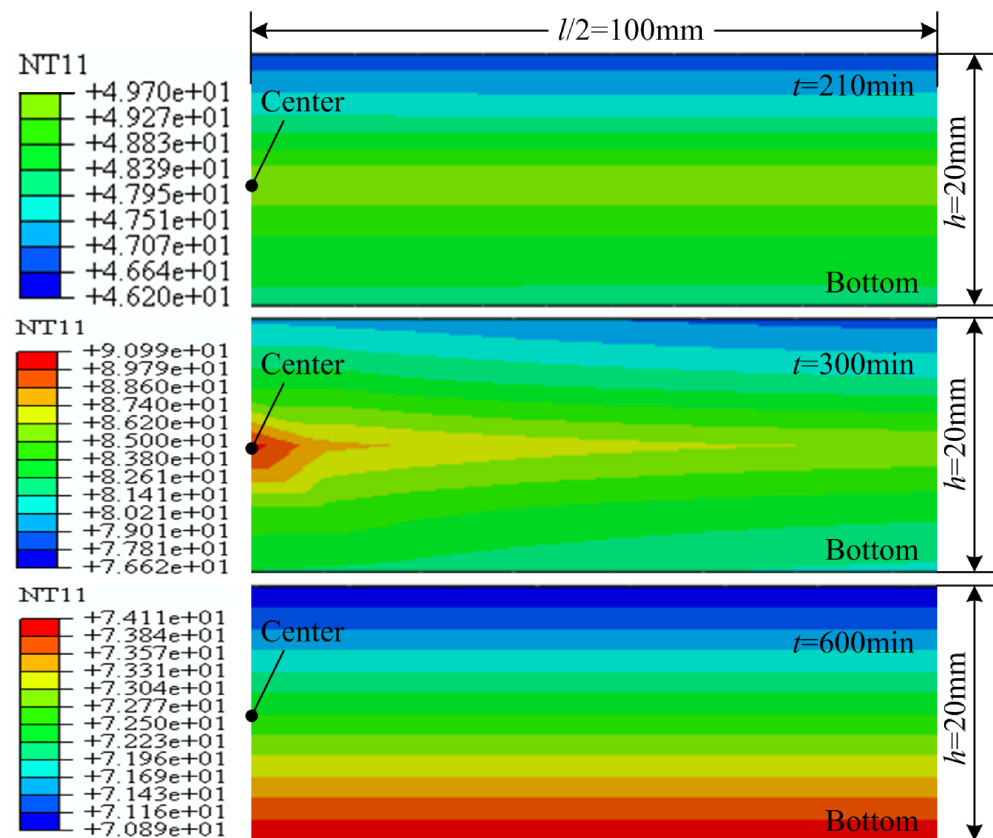


Figure 26. Temperature distribution of 20-mm thick-section composite at 210 min, 300 min and 600 min.

Figure 27 compares the finite element simulation results and experimental measurements of temperature distributions during the curing process. The numerical predictions exhibit satisfactory agreement with experimental data throughout the pre-curing ramp and isothermal holding stages, as well as the late period of the post-curing heating and post-curing isothermal dwell. This validates the reliability of the established numerical simulation framework. Nevertheless, a notable discrepancy exists between the simulated peak temperatures and experimental readings in the early phase of post-curing isothermal holding, and the deviation at the specimen core is considerably larger than that measured at the top surface.

The possible reasons are as follows: first, simplifications of thermal boundary conditions contribute substantially to the deviation. In the finite-element model, the top-surface heat-loss coefficient is assigned as a constant empirical value. In real VIMP experiments, the top surface is covered by a vacuum bag, release fabric, flow media and multi-layer thermal-insulation cotton. The actual heat-loss coefficient is time-dependent; it varies with local temperature, ambient air convection, slight gaps and contact resistance between stacked insulation layers, and the minor local compression of the insulation quilt. These real-world variable boundary conditions cannot be fully captured by a constant heat-transfer coefficient in simulation. Consequently, the simulated top-surface temperature either over-predicts or under-predicts heat dissipation, leading to differences in peak temperature and cure-degree between simulation and experiment, particularly obvious for the non-heated top face.

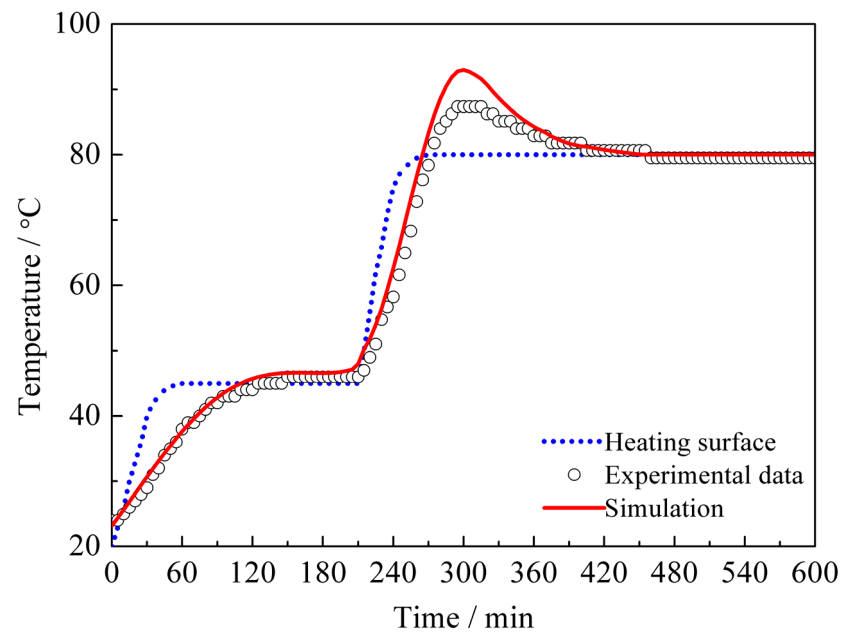
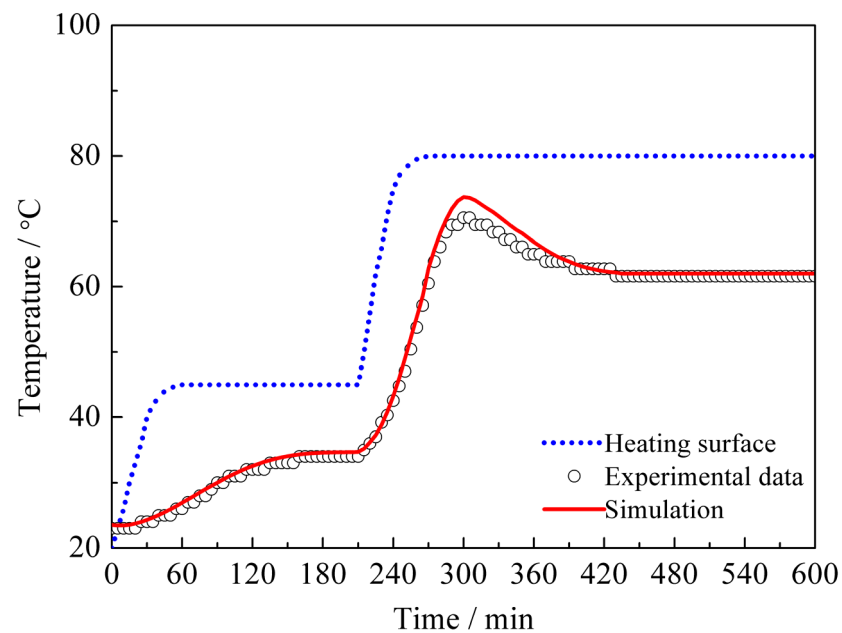
(a) T - t curves for laminate middle(b) T - t curves for laminate top

Figure 27. Simulation results compared to experimental data for temperature distribution in 20-mm thick-section composite.

Second, uncertainties in material property parameters introduce numerical errors. The curing kinetic models (autocatalytic and modified autocatalytic models) are fitted from DSC tests of neat resin samples. In real composite laminates, carbon fiber fabric changes local heat capacity and through-thickness thermal conductivity. Moreover, fiber–resin interfacial effects may slightly alter local curing reaction behaviour. The simulation uses homogenized thermal properties without considering the local spatial variation of fiber volume fraction. Minor spatial fluctuations of fiber content inevitably occur during vacuum infusion, which cause local deviation between modelled and real thermal–chemical responses.

Furthermore, the model does not fully consider chemo-diffusion-controlled curing at late reaction stages. The modified autocatalytic kinetic model achieves good fitting for DSC isothermal data, yet it cannot perfectly capture the diffusion-dominated reaction

slow-down inside thick composite parts under complex transient temperature histories. In the late curing period, increased matrix viscosity restricts molecular mobility; this diffusion limitation causes the experimental cure-degree to rise more slowly than simulation predictions, which explains the growing offset at high conversion.

In general, despite these quantitative discrepancies, the simulation correctly reproduces core physical features: the occurrence of core temperature overshoot, relative temperature ranking among bottom/mid-plane/top positions, and the overall increasing tendency of cure-degree over time. Therefore, the established finite-element model remains suitable for analysing the thickness effect tendency of thick-section VIMP composite components.

Figure 28 shows the temperature field distribution cloud map of a model composite material with a thickness of 40 mm at three critical curing time points: 210 min, 300 min, and 600 min.

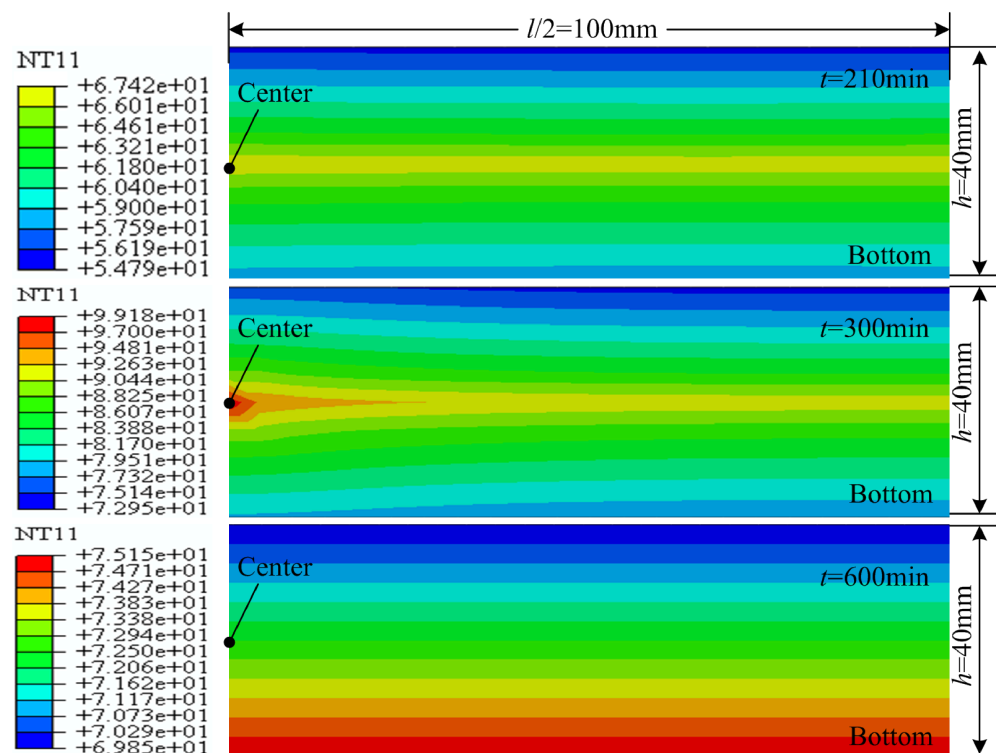


Figure 28. Temperature distribution of 40-mm thick-section composite at 210 min, 300 min and 600 min moment.

Figure 29 illustrates the finite element simulation results and experimental data of temperature distribution during curing. The simulated temperature curves share consistent variation trends with experimentally measured counterparts, while discrepancies between the two sets of data mainly lie in two aspects. Firstly, regarding the heating rate prior to the occurrence of temperature peaks, slight fluctuations in heating rate cannot be captured by numerical simulations. Secondly, there exists a remarkable deviation between the simulated peak temperatures and experimental values.

Figure 30 presents the nephograms of temperature field distribution for the 60-mm-thick composite component at three critical curing time points: namely, 210 min, 300 min and 600 min. The finite element simulation results and experimental measurements of temperature distribution during curing are plotted in Figure 31. The simulated temperature curves basically follow the same variation tendency as the experimentally tested ones, and the discrepancies between simulation and experiment mainly exist in the temperature rising profiles and peak temperatures.

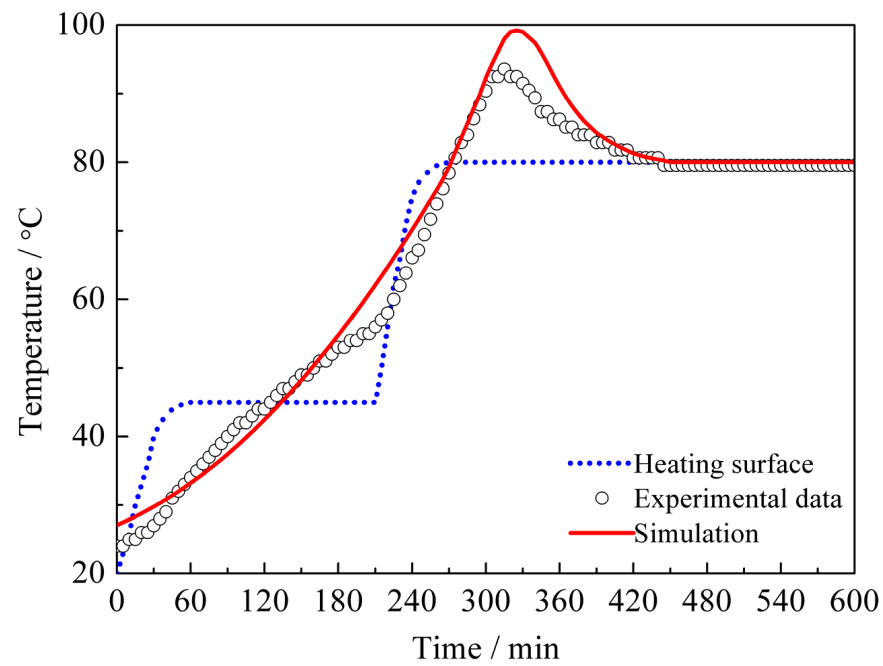
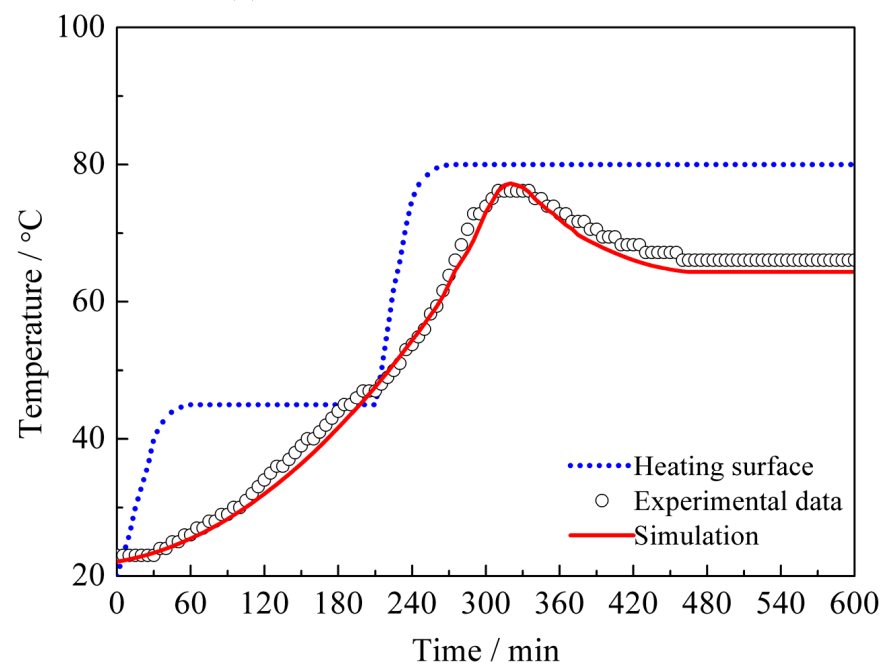
(a) T - t curves for laminate middle(b) T - t curves for laminate top

Figure 29. Simulation results compared to experimental data for temperature distribution in 40-mm thick-section composite.

Comparing the numerical simulation curves of the temperature distribution of composite materials with three different thickness models, it can be seen that the difference between the numerical simulation results of the temperature peak and the experimental values increased with the increase of thickness. However, overall, the numerical simulation results have good reference value for optimizing processes and guiding processes.

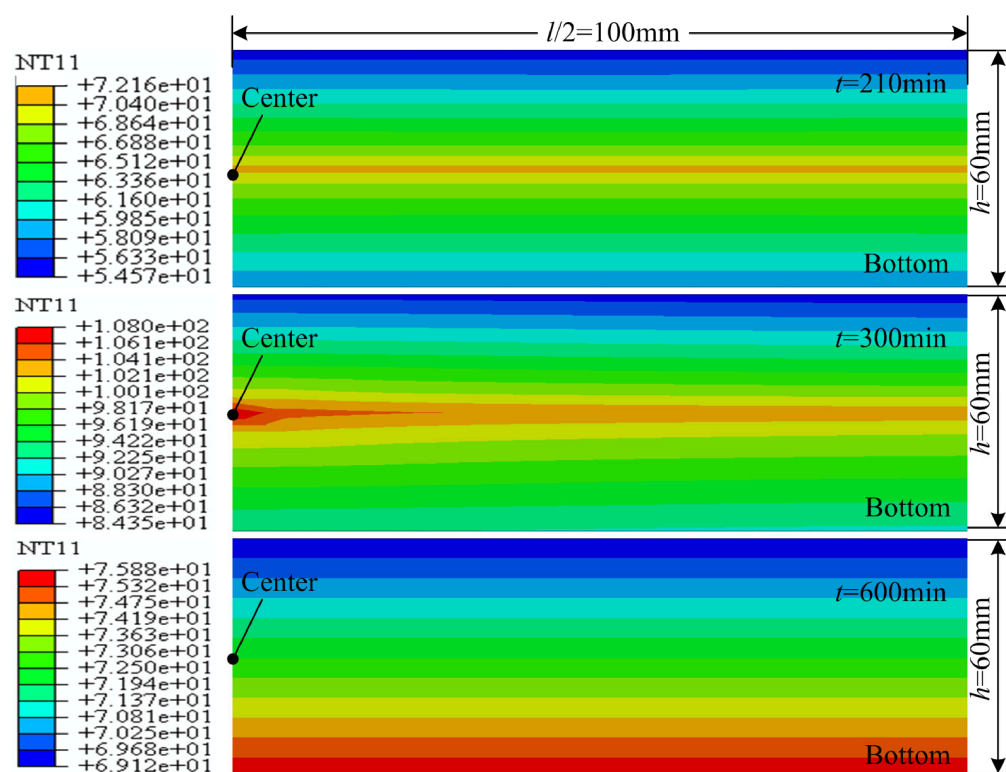
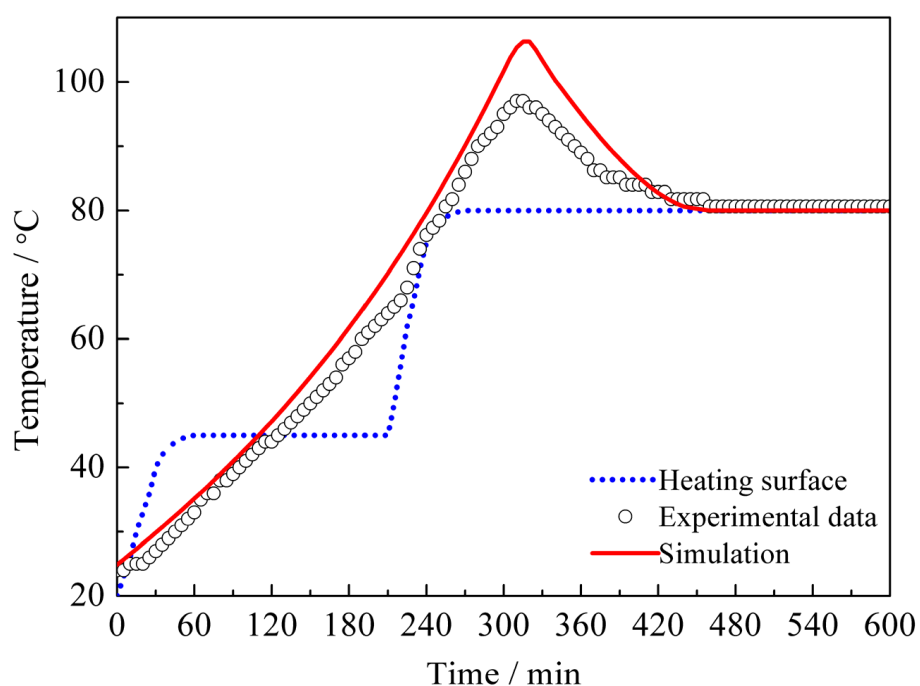
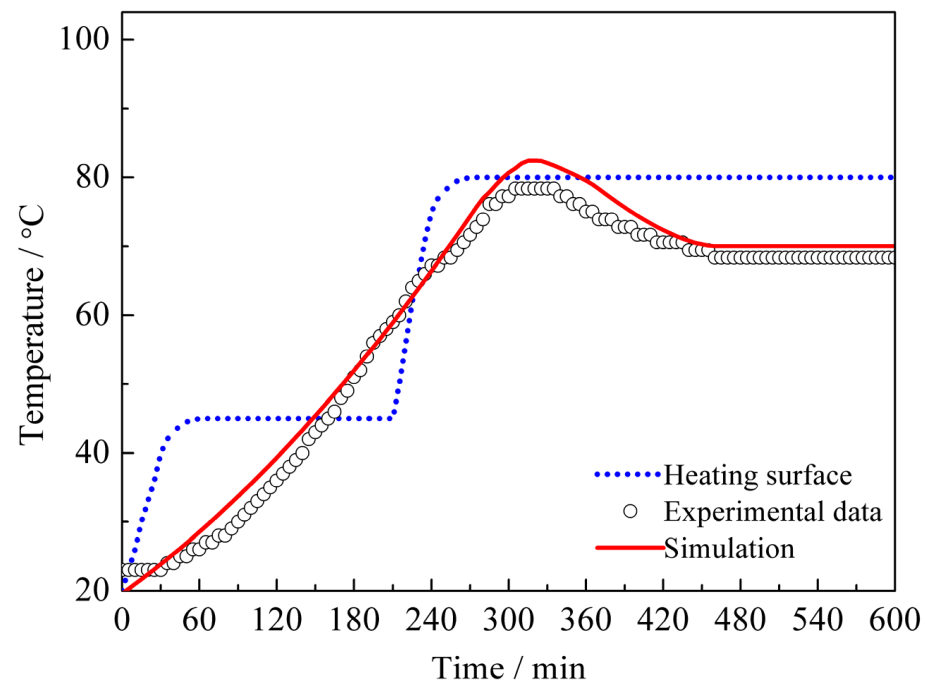


Figure 30. Temperature distribution of 60-mm thick-section composite at 210 min, 300 min and 600 min moment.



(a) *T-t* curves for laminate middle

Figure 31. *Cont.*



(b) *T-t* curves for laminate top

Figure 31. Simulation results compared to experimental data for temperature distribution in 60-mm thick-section composite.

4. Conclusions

This study systematically investigated the thermochemical thickness effect of thick-section carbon-fiber composites manufactured via the vacuum infusion molding process (VIMP) using the RIMR135/RIMH137 epoxy resin system for wind-turbine blades as the research object. Dynamic and isothermal differential scanning calorimetry (DSC) experiments were performed to characterize curing behaviours, and autocatalytic as well as modified autocatalytic kinetic models were established. Combined experimental monitoring and numerical analysis were further implemented to reveal how component thickness governs temperature-field and degree-of-cure evolution inside thick laminates. The main findings are summarised as follows:

- (1) For the RIMR135/RIMH137 epoxy system, extrapolation from dynamic DSC curves yields reference isothermal characteristic temperatures: pre-curing temperature of 45 ± 5 °C, curing temperature of 98 ± 5 °C, and post-curing temperature of 134 ± 5 °C. The dynamic curing process can be well described by the autocatalytic model, whereas the modified autocatalytic model provides superior fitting performance for isothermal curing, especially for capturing diffusion-controlled reaction retardation at the late curing stage. The average total curing enthalpy of the resin system is $474.62 \text{ J} \cdot \text{g}^{-1}$, representing the intrinsic cross-linking heat of this epoxy–amine formulation.
- (2) Obvious temperature overshoot induced by exothermic thermochemical coupling occurs during the curing of VIMP thick-section composites under single-sided heating conditions. The maximum peak temperature consistently appears at the laminate mid-plane. For the tested 20–60-mm-thick laminates, the maximum through-thickness temperature difference reached 30 °C and the maximum difference in degree-of-cure across thickness achieved 10%. The amplitudes of temperature overshoot, peak temperature, temperature gradient and cure-degree gradient increase linearly with component thickness and volume. This trend originates from the reduced surface-to-

volume ratio as thickness increases, which suppresses the heat dissipation of internally generated curing heat.

- (3) Strong asymmetric thermal behaviour exists between the mold-heated bottom side and the top free surface. Constrained by boundary heat loss and the low through-thickness thermal conductivity of uncured composite preforms, the top surface exhibited lower transient temperature, delayed thermal response and lower final cure degree compared with the bottom and mid-plane regions. Such through-thickness heterogeneity is the core manifestation of the thickness effect and constitutes a major source for residual stress and dimensional distortion in large composite parts.
- (4) Comparisons between finite-element simulation and experimental measurements show acceptable consistency in overall evolutionary trends, despite quantitative deviations in peak magnitude and late-stage cure degree. The discrepancies mainly stem from simplified constant thermal boundary parameters, homogenized material properties, thermocouple measurement interference, and the incomplete description of diffusion-limited curing within the kinetic model. The developed modelling framework is still capable of predicting the tendency of thickness-dependent thermochemical responses for VIMP components. Despite the significant differences in geometric complexity, scale dependent thermal boundary conditions, and amplification of multi-physics field coupling effects in actual blade structures from small laboratory samples to the preparation of ultra-large wind turbine blade structures, this study provides experimental datasets and dynamic modeling support for the solidification cycle optimization of ultra-large thick-walled composite material structures such as wind turbine blades.

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