Numerical simulation of mesoscopic bubble defect and optimization of process parameters in fiber wetting process of high voltage post insulator resin

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Abstract. Based on the method of fluid volume function, the two-phase flow model of mesoscopic resin and air between unit cell fiber bundles was established. The causes of mesoscopic bubble defects were discussed and the controllable process parameters were analyzed. A near-real mono-cell mesoscopic geometry model of strut insulator was constructed and meshed. The solution of the resin and air two-phase flow model was completed by adopting the finite volume method and using the Fluent software. The numerical simulation of the mesoscopic resin air two-phase flow and the air bubble defect was applied. The relationship between process parameters and air bubble defect was studied, and process parameters were optimized. Through the contrastive analysis of the capillary number, the correctness of the numerical simulation and parameter optimization was theoretically verified. Further, the effectiveness of the method in this paper was verified through the experiment.

1 Introduction

High-voltage strut insulator adopts vacuum assisted resin impregnated fiber forming process, which is widely used in the manufacture of composite materials. However, the determination of its process parameters still relies mainly on a large number of tests and experiences. This design method is of high cost and low efficiency. With the development of numerical simulation technology, the method of simulating the resin in the mold to infiltrate the fiber, predicting the defects that may occur during the infiltration process and optimizing the process parameters [1, 2], can reduce the cost, improve the design efficiency, and provide theoretical guidance for the actual infiltration process design. In the study of numerical simulation, Vanegas [3] established the resin flow model in the Resin Transfer molding (Resin Transfer Moulding, RTM) mold filling process based on Darcy’s law. They simulated the RTM mold filling process, and verified the validity of the algorithm by experiment. According to Stokes and Brinkman equations, Verleye and Wei yajun established a two-scale RTM resin flow model for fiber unit cell. Resin simulation and calculation were carried out for mold filling process and permeation process, and the validity of the model was verified by experimental results. De Valve C et al. [4] simulated the entrapment process of bubbles in the fiber bundle in RTM process by VOF method, and analyzed the relationship between the bubble content and size, Reynolds number and capillary number. Yang bo analyzed the flow of resin in the two-scale pores of preformed body and the formation mechanism of bubbles, established a prediction model for bubble formation in the mold.
filling process, and verified the correctness of the prediction model through experiments. Jin tianguo established the control equation of single-cell resin and air flow in the process of RTM mold filling by using the VOF two-phase flow method, and realized the simulation and prediction of air inclusion process, and compared with the experimental values in previous research results, verified the correctness of bubble prediction model. In the application of numerical simulation, researchers have carried out numerical simulation of resin charging and resin infiltrated fibers on actual products [5]. Also, molding process was optimized by the simulation, such as sprue gate and vent port layout, etc., and used to guide the practical production.

The above numerical simulation research had greatly promoted the development of resin mold filling and resin infiltration fiber technology, but these researches mainly focus on the fields of machinery and ships, and it is still rare in the field of electrical insulation, especially in the field of high voltage insulation. In order to improve the optimization efficiency of resin infiltrating fiber molding process of high-voltage insulation parts, the numerical simulation of meso-bubble defects and the optimization of controllable process parameters was carried out for the vacuum-assisted resin-infiltrating fiber process of high-voltage pillar insulators in this paper.

2 Construction of mono-cellular two-phase flow model of post insulator resin impregnated fiber
In the process of fiber infiltration by vacuum assisted of high-voltage strut insulator, the resin flows in the mold cavity where the fiber is laid, which can be regarded as the seepage process of the viscous Newtonian fluid in the porous medium. Due to the complex structure of fiber preforming parts, it is difficult to describe the flow process of resin in the fiber at one time. Therefore, the whole fiber is considered to be composed of multiple single cells, and the resin flow in the preforming body is studied by analyzing the resin flow in the fiber unite cell according to the periodic characteristics of fiber preforming parts. Among them, monocellular mesoscopic flow, that is, resin flow in mesoscopic pores between fiber bundles, is prone to produce large bubbles, which has a fatal impact on the electrical insulation performance of strut insulators. Numerical simulation method was used to simulate the flow of resin, bubble generation and the effect of process parameters on bubble defects in the infiltration process, further optimizing the process parameters and eliminating bubbles, which can improve the process design efficiency and reduce the design and experiment cost.

Bubble formation process is a typical two-phase flow process of gas-liquid (air and resin). In order to effectively simulate the infiltration of mesoscopic resin flow, the generation of large bubbles and the influence of process parameters on bubble defects, it is necessary to establish a correlation model for tracking the interface of the two-phase flow for resin and air to correctly reflect the unsaturated flow of the resin. Among the methods to build the model, the VOF method is currently the most widely used multi-phase fluid interface tracking technology [6]. Therefore, in this paper we build a single-cell mesoscopic resin two-phase flow interface tracking model based on the VOF method for high-voltage strut insulators, as follows:

The VOF method determines the free surface through the resin and mesh volume ratio function F, and tracks the change of the resin. When F=1, the resin fills the unit; When F=0, there is no resin in the unit; When 0≤F≤1, the unit is a resin-air interface unit. In the unicellular mesoscopic region, that is, the inter fiber bundle region, it can be considered that there is only pure fluid flows, and the corresponding momentum equation of two-phase flow for resin and air can be expressed by navier-stokes equation and surface tension term:

\[
\frac{\partial (\rho_m v)}{\partial t} + \nabla \cdot (\rho_m v \times v) = \rho_m g - \nabla P + \nabla \left[ \mu_m \left( \nabla v + \nabla v^T \right) \right] + F_s .
\]  (1)

Where \(\rho_m\) is the density of the unit, P is pressure, v is velocity of resin at time t, g is acceleration of gravity, \(\mu_m\) is viscosity of the unit, and \(F_s\) is surface tension term of the unit. \(\rho_m\) and \(\mu_m\) are as follows:

\[
\rho_m = F \rho_r + (1 - F) \rho_a = 0 .
\]  (2)
\[ \mu_m = F \mu_r + (1 - F) \mu_a = 0, \quad (3) \]

Where \( \rho_r \) and \( \rho_a \) are the density of the resin and air, respectively, and \( \mu_r \) and \( \mu_a \) are the viscosity of the resin and air, respectively. The transport equations of two-phase flow continuity equation and volume ratio function \( F \) are shown in Eq. (4) and (5) respectively.

\[ \frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m v) = 0. \quad (4) \]

\[ \frac{\partial F}{\partial t} + \nabla \cdot (\mu_m F) = 0. \quad (5) \]

According to literature [7], the element surface tension \( F_{st} \) is reflected in the form of pressure difference on both sides of the resin-air interface. According to the divergence theorem, \( F_{st} \) can be expressed as volume force, specific as follows:

\[ F_{st} = \sigma_{ra} \frac{\rho_a \kappa F}{2 \left( \rho_r + \rho_a \right)}. \quad (6) \]

Where, \( \sigma_{ra} \) is the tension coefficient at the air interface of the resin, \( \kappa \) is the curvature of the air interface of the resin, and the \( \nabla F \) is the gradient of the volume fraction of the resin unit.

3 An overview of mesoscopic bubble formation and analysis of controllable process parameters

3.1 An overview of the origin of meso-large bubbles

According to the literature [4,7], the mesoscopic flow of resin between fiber bundles is mainly driven by dynamic pressure due to the large mesoscopic space between fiber bundles (millimeter-level) and small capillary effect. While the micro voids in the fiber bundles are small (micron scale), and the flow of resin in the fiber bundles mainly depends on the capillary force. When the flow rate is low, the microcosmic flow of the resin is ahead of the mesoscopic flow. When the front the microcosmic flow meets the braiding knot of the fiber or the transverse fiber, the resin flows laterally, thus forming a larger microscopic bubble between the fiber bundles.

3.2 Analysis of controllable process parameters

Resin type, fiber type, fiber laying method, fiber layer number, resin feeding port, discharging port, feeding mode and discharging mode have been determined in the process of high-voltage post insulator resin infiltration fiber. The pressure applied the feed port during infiltration is small and negligible compared to vacuum negative pressure. Therefore, the adjustable process parameters are vacuum degree and resin viscosity. Insulation rod resin wetting fiber process requires more than 97% vacuum, so only the resin viscosity can be adjusted Resin viscosity is not a directly controllable process parameter, but viscosity is related to temperature. The corresponding relationship between the resin viscosity and temperature is shown in Figure 1. Meanwhile, the change of temperature will cause the change of resin surface tension and the corresponding relationship between the surface tension and temperature is shown in Figure 2. Therefore, the wetting temperature can be adjusted to change the viscosity and surface tension of the resin, thereby the infiltration process can be indirectly controlled to minimize the negative effect of the bubble.
Figure 1. The curve of the viscosity-temperature of a certain type of resin.

Figure 2. The curve of the surface tension-temperature of a certain type of resin.

4 Construction and mesh generation of cellular geometry model

The corresponding geometric model was built according to the real cellular structure, which was used as the structural matrix for simulation. The mesh division of the structural matrix was used as the basis for solving the resin air two-phase flow model. The cellular mesoscopic geometric model and mesh division process were as follows.

4.1 Construction of geometric model of single cell

In order to reduce the intensity of simulation calculation, the two-dimensional section of the model was adopted, and the two-dimensional section geometric model of the intercellular fiber bundles was constructed. Transverse fiber bundle width was 0.9 mm; longitudinal dimension bundle width was 1.8 mm; and the distance between transverse and longitudinal fiber bundles was 0.2 mm.

4.2 Mesh generation

The model is divided into small simple geometric unit, which provides a basis for solving the resin air two-phase flow model. The mesh size is 0.02 mm, and the total mesh number is 25,000.

5 Discretization and solution of governing equations

In this simulation, the discrete model of resin air two-phase flow model was established by FVM method. FVM divides the calculation area into a series of control volumes, which are interrelated and isolated. All of them contain a grid node as the representative. Through the method of control volume integration, the two-phase flow model in the form of conservation is transformed into a discrete model. This model is widely used in numerical simulation of incompressible flow, because of the conservation of integral in the whole computational domain. The basic idea of FVM is simple and understandable. The core of FVM is regional discretization. In essence, it replaces continuous space by a finite number of discrete points.

In the numerical solutions of incompressible fluid flow field, the pressure correction method is the main method, and the semi-implicit method of pressure coupled equations is the most widely used pressure correction method. It is the most popular algorithm in various CFD software. The method is adopted to solve the discrete model.

6 Microscopic bubble defect simulation and process parameter optimization

The mono-cellular infiltration process of vacuum-assisted resin infiltrating fiber of high-voltage strut insulator was numerically simulated and the controllable process parameters were analyzed by Fluent software. Which is based on the mono-cellular geometric model of strut insulator and mesh division results, and dispersion model of resin and air two-phase flow.

Boundary conditions: the left side of the cellular mesoscopic view was the inlet, and the inlet boundary conditions were the velocity inlet; The right side of the cell is the outlet, and the boundary
condition of the outlet is the pressure outlet. Considering the fact of multilayer fiber coating, the upper and lower boundary of a single cell is set as symmetrical boundary. The axial permeability of fiber bundles of a certain type of fiber is $2.246 \times 10^{-9} m^2$ and the radial permeability is $4.776 \times 10^{-10} m^2$. The resin viscosity was set at 300 mPa·s. According to the viscosity - temperature and surface tension - temperature relationship in section 3, the temperature was 65°C and the surface tension was 0.024N/m. The flow rate was set at 0.472mm/s. The simulation results of mesospheric infiltration between fiber bundles were shown in Figure 3. The blue area was resin, and the red area was air. According to the literature [6], the capillary number less than 0.007 is prone to produce mesoscopic large bubbles. However, between 0.007 and 0.008, resin infiltration of fibers has the best effect. The capillary value $Ca=0.0059$ was obtained according to the capillary number calculation method [7], indicating that the simulation results of microscopic infiltration between fiber fascicles were consistent with the theory.

![Figure 3. Cellular mesoscopic bubble wrap simulation.](image)

On the basis of the above simulation, this paper carried out a series of simulations on the process of a certain type of resin infiltrating a certain type of fiber at different temperatures. The results showed that there was no microscopic bubble defect when the temperature was 50°C, and the resin viscosity was 450mPa.s. The surface tension was 0.028N/m, and the flow rate was 0.472mm/s. The corresponding capillary number is calculated based on the process conditions of series simulation, which are shown in table 1. As can be seen from the table, when the temperature is 50°C, the capillary value $Ca$ is between 0.007 and 0.008, which theoretically verifies the effectiveness of the simulation.

| No. | Temperature (°C) | Viscosity (mPa.s) | Surface tension (N/m) | Flow velocity (mm/s) | Capillary number |
|-----|-----------------|------------------|-----------------------|----------------------|-----------------|
| 1   | 50              | 450              | 0.028                 | 0.472                | 0.0076          |
| 2   | 55              | 370              | 0.027                 | 0.472                | 0.0065          |
| 3   | 60              | 340              | 0.025                 | 0.472                | 0.0064          |
| 4   | 65              | 300              | 0.024                 | 0.472                | 0.0059          |
| 5   | 70              | 260              | 0.023                 | 0.472                | 0.0053          |

On the basis of the above series of simulation, the effectiveness of simulation is further verified by experiments. The temperature process parameters in No. 1 and 4 in table 1 and the flow rate is 0.472mm/s. The corresponding prop insulator test pieces are obtained by vacuum assisted resin fiber
infiltration process. Sample pieces are cut for the test pieces respectively and siphon experiments are conducted. It can be seen from the figure 4 that the large bubble defect was produced at 65°C, while the product had no defect at 50°C. This result is consistent with the numerical simulation results, which further verifies the effectiveness of the numerical simulation, which indicates that the numerical simulation method can provide theoretical guidance for the actual infiltration process design.

![Figure 4](image)

**Figure 4.** The siphon test results of the molded strut insulator samples at different temperatures.

**7 Conclusion**

In this paper, the numerical simulation method of bubble defect of vacuum assisted resin wetted fiber of high voltage strut insulator is studied. Specific conclusions include: the resin and air two-phase flow model of vacuum assisted resin infiltration fiber of high-voltage post insulator was established based on VOF method, taking the single-cell mesoscopic view of high-voltage post insulator as the object. The causes of mesoscopic bubble defects were summarized, and the controllable process parameters were analyzed. Finally, the wetting temperature was determined as the main control parameter. Closing to the real high-voltage insulating rod unit cell mesoscopic geometrical model is built. With the help of the Fluent software and by FVM method, single cell in the process of mesoscopic infiltration bubble defect series numerical simulation, and combining with capillary number infiltration temperature are studied. The results show that the temperature of 50 °C, the capillary number Ca between 0.007 and 0.008. Infiltrating effect is best. Ca is less than 0.007 is easy to produce large bubbles. Thus, theoretically, the correctness of the numerical simulation and temperature parameter optimization are verified; The siphon experiment was carried out based on the process parameters of numerical simulation to process the strut insulator test pieces. The experimental results were consistent with the numerical simulation results, which further verified the effectiveness of the method and provided theoretical guidance for the design of actual infiltration process.

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