Research on Vacuum Pressure Impregnation of Nb_3Sn Superconducting Coil

Junsheng Cheng, Guang Zhu, Wanshuo Sun, Lankai Li, Yi Li, Shunzhong Chen, Jianhua Liu, Xinning Hu, Yinming Dai, Luguang Yan, Qiuliang Wang

Institute of Electrical Engineering, Chinese Academy of Sciences

Key Laboratory of Applied Superconductors, Chinese Academy of Sciences

中国科学院电工研究所 INSTITUTE OF ELECTRICAL ENGINEERING, CAS

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Background

To accurately describe the process of resin transfusion and infiltration in superconducting coils, fluid mechanics in porous media can be adopted. As for the specific geometrical conditions and boundary conditions of the impregnation process for superconducting magnets, certain adjustments to the fluid mechanics in porous media should be made. These adjustments allow the derivation of the mathematic model applicable for magnet simulation during the VPI process. Through this mathematic model, impregnation data can be calculated, and impregnation time can be estimated.

Objectives

This study focuses on the VPI process of solenoid coils. To improve the practicality of the model, we tested the feature of the resin for impregnation and the practical permeability of the coils through experiments. Then the corresponding models were built. The influence of parameter during impregnation was discussed and analyzed according to the calculation results. Finally, the epoxy impregnated Nb_3Sn coil fabrication technology was also introduced in the conduction-cooled NbTi/Nb_3Sn split magnet system referring to the modeling results.

Conclusion

- On the basis of Darcy's law of fluid mechanics in porous media, an equation for the dynamic VPI of a superconducting magnet was developed. A model of the rheological behavior of resins for impregnation and the fitting relationship of A15 coil permeability was introduced. A 1D equation of dynamic impregnation was proposed, and the impregnation process was simulated in 3D.
- The VPI process could be divided by three stages based on the features of impregnation. A method for estimating the overall impregnation time with the axial and linear impregnation time is proposed.
- Finally, four Nb_3Sn superconducting coils for application of a conduction-cooled split magnet were processed by the flood-filling type VPI technique referring to the modeling results. The cryogenic test results show that the steady current of the Nb_3Sn coil in the magnet was 100 A and the central magnetic field of the magnet reached 8.07 T. The maximum field in the Nb_3Sn coils reached 11.7 T.

VPI Dynamic Model

VPI steady seepage equation

Under low seepage velocity condition, the VPI process conforms to Darcy's law. Without consideration of the compression of fluid, the steady seepage equation can be written as follows under cylindrical coordinates

$$\begin{cases} \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 p}{\partial \theta^2}+\frac{\partial^2 p}{\partial z^2}=0 \\ V_r=-\frac{K_r}{\eta}\frac{\partial p}{\partial r} \\ V_z=-\frac{K_z}{\eta}\frac{\partial p}{\partial z} \\ V_\theta=-\frac{K_\theta}{\eta}\frac{\partial p}{\partial \theta} \end{cases}$$

Where, r, θ, and z denote the cylindrical coordinates of the calculating point. p is the intensity of pressure at all directions; V_r, V_z, V_θ are the seepage velocity of different directions; K_r, K_z, K_θ are the permeability, which can be obtained through experimental measurement; and η is the viscosity of the fluid for impregnation.

Model of the Rheological Behavior of Resin

During isothermal curing, the relationship between viscosity and curing time can be represented by the formula below

$$\ln\eta = \ln\eta_0 + kt$$

Where, η_0 is the viscosity of the resin, η is the initial viscosity, k is the apparent dynamic factor, and t is the curing time. η_0 and k under certain temperatures can be obtained by fitting the curing curve.

According to the classical four-parameter Arrhenius Class 1 reaction rheological model, a relationship exists between η0, k, and curing time t, as shown below

$$\eta_0 = \eta_\infty \exp\left(E_\eta / RT\right)$$

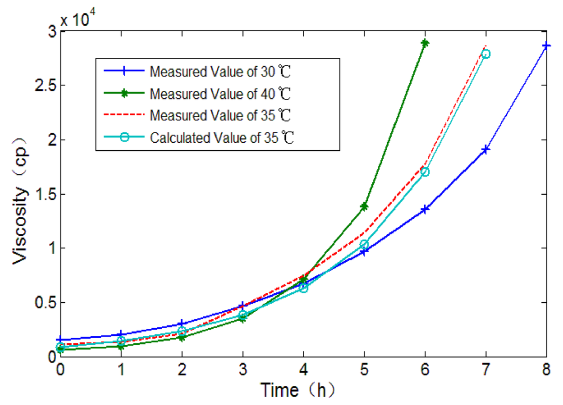
$$k = k_\infty \exp\left(-E_k / RT\right)$$

$$\ln\eta = \ln\eta_\infty + E_\eta / RT + tk_\infty \exp\left(-E_k / RT\right)$$

the relationship between viscosity, time, and temperature.

TABLE I
PARAMETERS OF THE RHEOLOGICAL PROPERTIES OF THE DW3 AND CTD101K EPOXY RESINS

	η_∞ (Pa s)	k_∞ (1/s)	E_k (kJ/mol)	E_η (kJ/mol)
CTD101K	3.23×10^{-18}	1.31×10^{19}	1.50×10^{5}	1.22×10^{5}
DW3	1.11×10^{-11}	5.89×10^{3}	4.50×10^{4}	8.19×10^{-4}



Isothermal curing curve of DW3

Permeability

axial permeability can be expressed as:

$$K=-\frac{\eta VL}{(P_s-P_m)}=-\frac{\eta QL}{(P_s-P_m)\Delta t\pi(r_2^2-r_1^2)}$$

Where Ps is the inlet pressure, pm is the pressure in the vacuum tank, r_1, r_2 are the outer/inner diameters respectively, Q is the volume of the resin flow into the counting cup during Δt, and L is the length of the coil. Gravity can be ignored since the height difference is quite small.

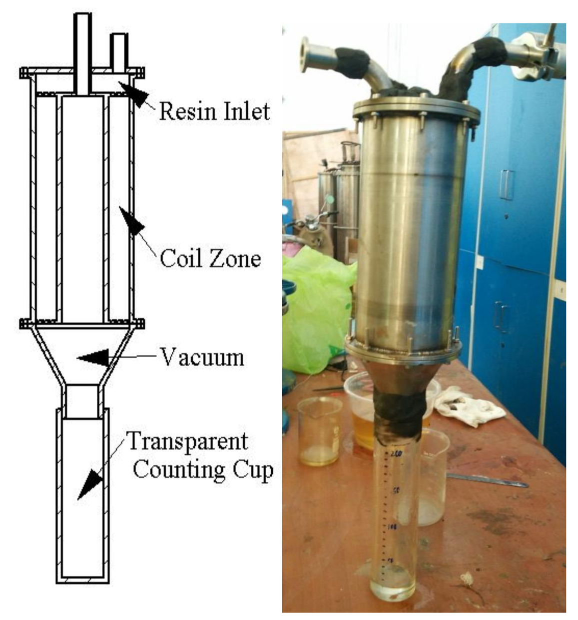


TABLE II
PERMEABILITY UNDER DIFFERENT WIRE DIAMETERS

Wire Diameter +Insulating Layer (mm)	Length (m)	Axial Permeability (m^2)	Radial Permeability (m^2)	Hoop Permeability (m^2)
0.5+0.15	1200	9.43×10^{-11}	1.23×10^{-10}	5.61×10^{-10}
1+0.15	400	6.15×10^{-11}	1.17×10^{-10}	3.83×10^{-10}
1.5+0.15	240	4.29×10^{-11}	6.26×10^{-11}	2.61×10^{-10}

VPI Dynamic Model

The flood-filling type process was considered in the vertical solenoid coil VPI Dynamic Model. The steady seepage equation can be simplified into a 1D equation

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right)=0$$

the pressure distribution of the impregnating area can be obtained as follows:

$$p(r) = C_1 \ln r + C_2$$

When impregnation is conducted from the outside, constants C_1 and C_2 in the formula can be expressed as:

$$C_1=\frac{P_s-P_m}{\ln r_2-\ln r_1} \qquad C_2=P_s-C_1 r_2$$

equation of radial impregnation velocity under steady impregnation

$$V_r=-\frac{K_r}{\eta}\frac{dp}{dr}=-\frac{C_1 K_r}{r\eta}$$

the seepage velocity at r, that is, v(r), can be represented by the following formula:

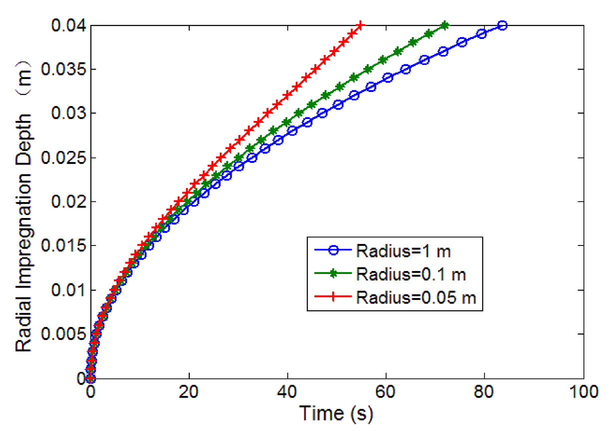
$$v(r)=-\frac{K_r}{r\eta}\frac{P_s-P_m}{\ln(r_2/r)}$$

where P_r was replaced by P_m, since at r P_r can be approximately be P_m. Hence, the overall impregnation time can be obtained by integration:

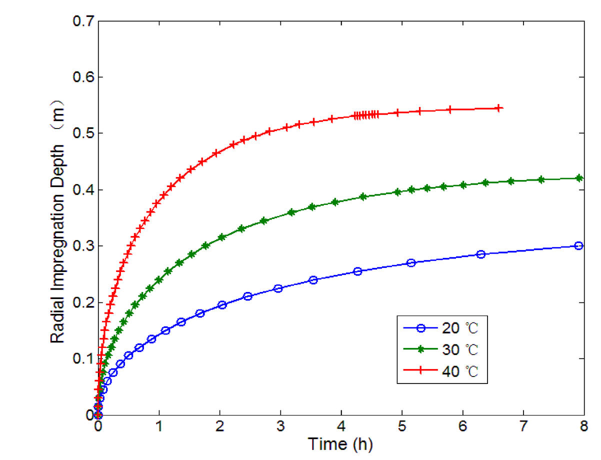
$$\tau=\int_{r1}^{r2} 1/v(r)\,dr$$

We can derive a differential equation that describes the relationship between impregnation time and depth, that is, the VPI dynamic model under constant temperature.

$$\dot{r}+\frac{K_r}{r\eta_\infty e^{E_\eta/RT+tk_\infty\exp(-E_k/RT)}}\frac{P_s-P_m}{\ln(r_1/r)}=0$$

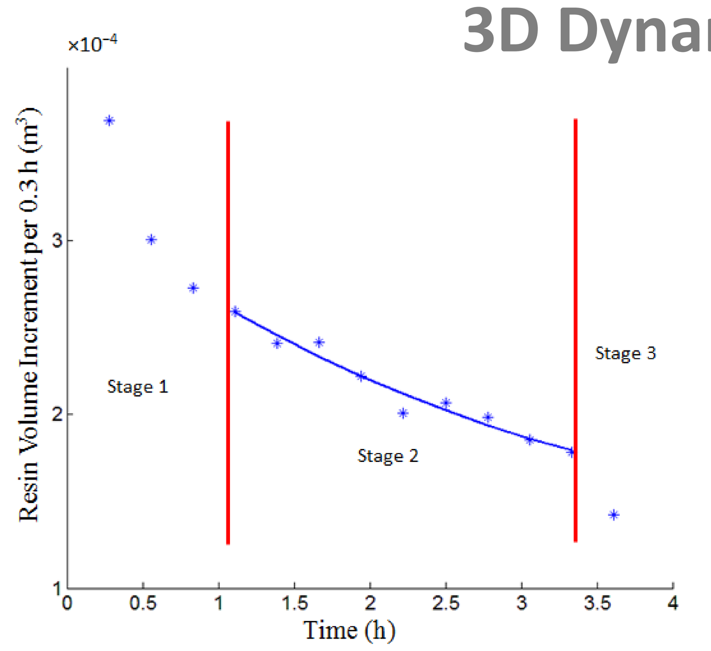


Influence of Coil Radius (curvature) on Impregnation

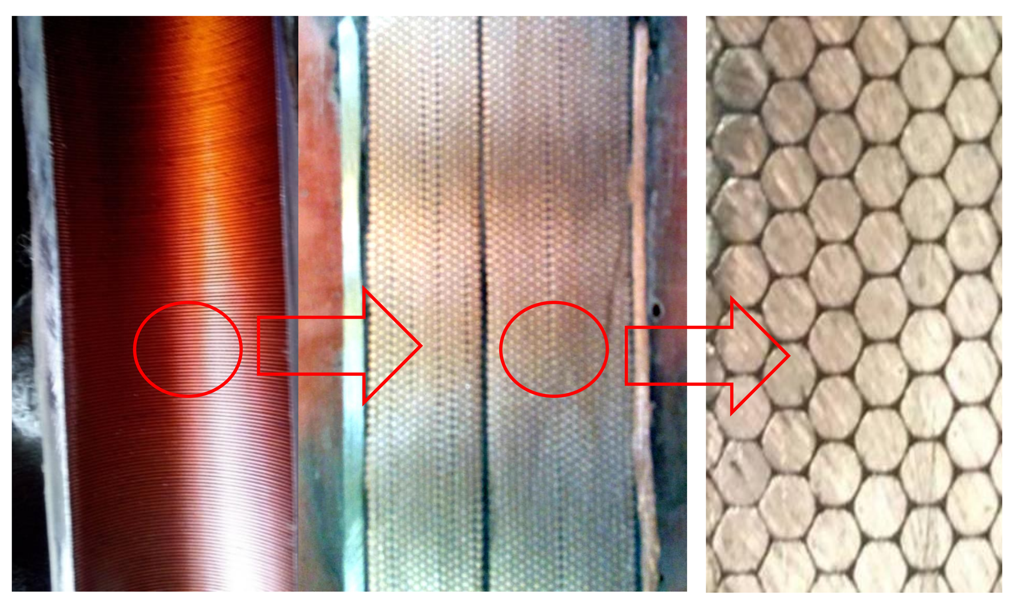


Limit depth of impregnation under different temperatures

3D Dynamic Simulation Study



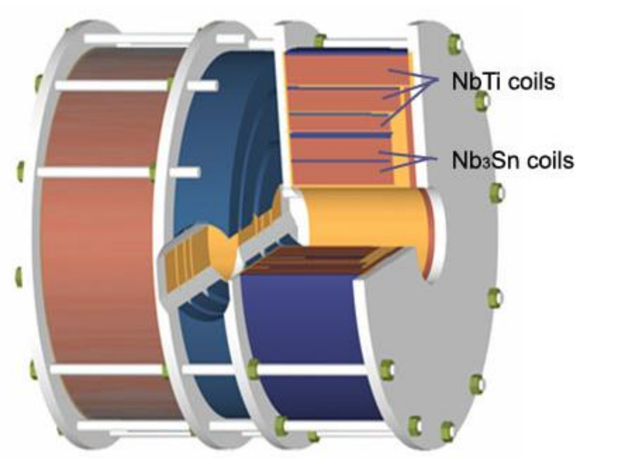
The simulated results indicate that the impregnation process can be generally divided into three stages, namely, circular impregnation, axial impregnation, and ending.



Surface and cross section morphologies of the impregnated Nb_3Sn coil

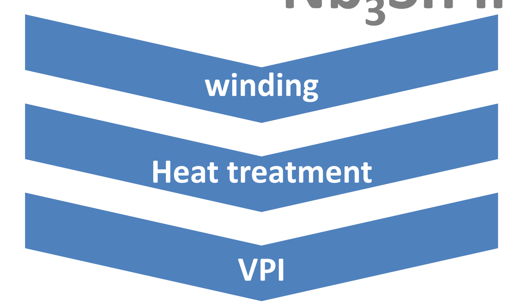
Practical VPI Coil Application

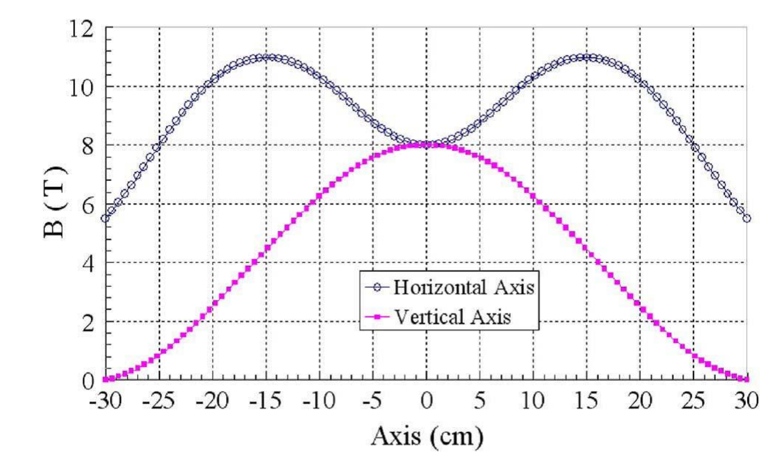
Magnet parameters



Parameter	1/2#	3/4#	5/6#	7//8#	9/10#
Conductor	Nb_3Sn	Nb_3Sn	NbTi	NbTi	NbTi
Wire size, mm	Φ0.82	Φ0.82	1.0×1.46	0.8×1.37	0.78×1.38
I.D., mm	144	218	290	346	432
O.D., mm	202	276	332	407	503
Height, mm	180	180	180	200	220

Nb_3Sn insert coil fabrication





- Nb_3Sn coi self-field test showed that the four coils were charged 150 A and no quench were happened. The central magnetic fields reached 3.36 T for the 3# or 4 # coil and 5.13 T for the 1# or 2 # coil.
- The whole split magnet test showed that the central magnetic field of the magnet reached 8.07 T without quench. Meanwhile, the maximum field in the Nb_3Sn and the NbTi coils are 11.7 and 6.2 T, respectively.

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