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Simulation of Quench in Pancake-shaped Superconducting Magnet Using a Quasi-three-dimensional Model

Qiuliang Wang[b*], Cheon Seog Yoon[a], Keeman Kim[b]

[b] *Samsung Advanced Institute of Technology, Taejon, Korea*

[a] *Hannam University, Taejon, Korea*

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Abstact

A quench phenomenon is caused by an external disturbance in a superconducting magnet, where the magnet is operating in a cryogenic environment. The heat coupling between the layers and pancakes of the magnet can induce the normal zone propagation with fast speed. In order to analyze quench behavior in a pancake-shaped superconducting magnet, a quasi-three-dimensional model is proposed. A moving mesh finite volume method is employed in solving the heat conduction equation. The quench process of the superconducting magnet is studied under the various operating conditions and cooling conditions.

Keyword : Quench characteristics, Pancake-shaped superconducting magnet, Quasi-three-dimensional model, Moving mesh method

I .Introduction

A superconducting magnet is disturbed by local dissipation of energy due to the conductor motion, epoxy-resin crack and ac loss etc.. Such a disturbance can induce a local temperature rise. When the Temperature rise is attained to the critical temperature of the superconductor, a normal zone is formed. Quench can result in the normal zone spread to the whole superconducting magnet and the damage of the magnet and cryogenic system in serious case. Stability and quench analysis are two essential aspects of designing superconducting magnet system. The magnet system should be designed against the permanent damage caused by overheating, overstressing, and arcing that may stem from quench. Hence, the considerable amount of attention has been paid to the study of the problem [1-4].

The quench characteristics and stability margin of the superconducting magnet are related to operating conditions and characteristics of the external disturbance. Because the superconducting magnet has a three-dimensional structure, the heat coupling occurs between the layers and pancakes. If the external disturbance is enough to quench the superconducting magnet, the normal zone propagates through the layers and pancakes. The heat is conducted to radial, axial, and azimuthal directions of the magnet. Although the approximation of high normal zone propagation speed in the azimuthal direction was adapted to analyze the small-scale superconducting magnet [4,5]. Generally, it is not used for the analysis of the large bore superconducting magnets and the high temperature superconducting magnet with small hole [6]. The three-dimensional heat conduction problem should been employed to study quench phenomena.

The work presented here is to study quench characteristics in a pancake-shaped superconducting magnet system in various operating conditions and disturbances. A quasi-three-dimensional model is

*Corresponding author. Fax : +82 42 865 4099

e-mail: qlwang@venus.sait.samsung.co.kr

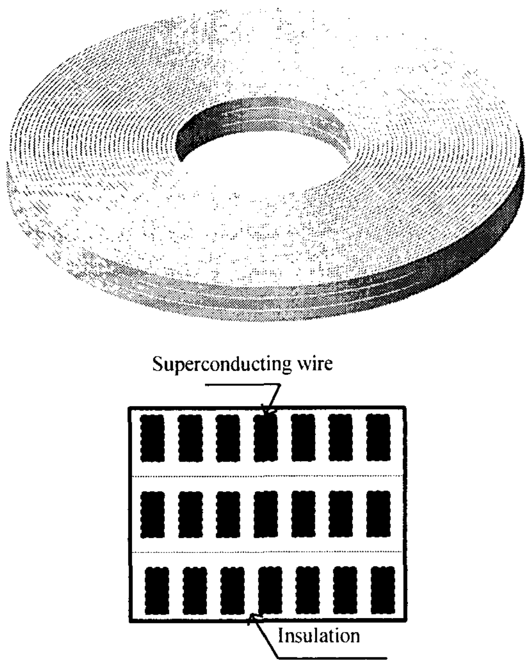


Fig. 1 Configuration of 3-pancake-shaped superconducting magnet

proposed. The heat conduction is along the superconducting wire and the heat coupling is between the layers and pancakes of the superconducting magnet. Because the superconducting magnet is fabricated by continuous superconducting wire, typically, the wire in length is over 10^2-10^3 m. A quench propagation problem is a moving boundary problem. A moving mesh finite volume method is used to solve the problem in order to obtain high accuracy of numerical simulation. This scheme is solution-adaptive method for time-dependent partial differential equations [7]. It has been demonstrated that significant improvements in accuracy and efficient can be gained by adaptive mesh points so that the mesh points are concentrated in the region of large solution variation [8].

II. Quasi-three-dimensional model and moving mesh method

A pancake-shaped superconducting magnet is studied. The superconducting magnet consists of several pancake-shaped coils where the heat coupling occurs between pancakes and layers in the coils. The superconducting magnet is immersed in the liquid helium. The temperature is assumed to be uniform in the cross-section of the superconducting wire. The thermal conductivity of the insulation film is much smaller than that of the metal in the composite, therefore, the conduction of insulation along the superconducting wire is ignored in the analysis. If a superconducting magnet is subjected to a heat disturbance and the disturbance is enough to quench the superconducting magnet, the temperature distribution is determined by following equation(1).

where t and x denote the time and space coordinates, respectively, γC is the average heat capacity of superconductor, stabilizer and insulators, Q_d is the

$$\gamma C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + s(T_c, x, t) \qquad (1)$$

external disturbance power, A is the cross-sectional area of superconducting wire, P_i and h_i are the contact perimeter and heat transfer coefficient between layers or pancakes, respectively. The Joule heat power is given by

$$s(T, T_c, x, t) = \rho J^2 H(T - T_c) \qquad (2)$$

where J=I/Am is the current density in the stabilizer, I is the prescribed current in the conductor, Am is the cross-sectional area of stabilizer, and H(T-TC) is a Heaviside-like transition function from the superconducting regions, TC is the critical temperature of superconductor.

Fig.1 shows the pack structure of arranging wire of the pancake-shaped superconducting magnet. The heat generated due to the quench flows, not only along the superconducting wires, but also in transverse direction, through the insulation. Within the pancake-shaped magnet, this tends to short-circuit the quench propagation along the conductor causing the pre-heating and birth of normal zones in the adjacent layers. Furthermore, the heat conduction will initiate the quench in the adjacent pancakes. The heat coupling term is treated as an external heat source. Therefore, the approximation of the heat transfer in the winding pack is obtained by substituting each part of wire and insulation between two conductors with an equivalent slab having the same average extension in the direction normal to heat flux. By the simplification, the heat diffusion in the winding cross-section can be regarded as a set of independent one-dimensional problems. The three-dimensional problem is reduced to one-dimensional model. The heat transfer coefficient between the pancakes or layers is calculated by the steady state temperature distribution across the superconducting wire, insulation, and other superconducting wire. The heat transfer coefficient is varied with the average temperature of the cross section of superconducting wire and insulation. The heat transfer coefficient is taken into account including the liquid helium heat transfer if the superconducting magnet contacted with helium.

When the superconducting magnet is quenched, the normal zone is propagating. The front position of normal zone, where is the boundary of Joule heat generated, is moving and the front region is very short in the lengthwise. In order to obtain the converged numerical solution, the mesh size in the front region of normal zone should be finer and other region of the solution domain might be coarser. For a long length of wire, the finite mesh number is necessary. Therefore, moving mesh finite volume method has more advantages and is applied for this problem. For the one-dimensional moving mesh equation can be given [9] :

$$\frac{\partial^2}{\partial \xi^2}\left(M \frac{dx}{dt} \right) + \frac{1}{\tau}\frac{\partial}{\partial \xi}\left(M \frac{\partial x}{\partial \xi} \right) = 0 \qquad (3)$$

where τ is the mesh smoothing parameters, ξ is the equal interval coordinate, M is the monitor function. It is well-known that for the moving finite volume method, some sort of smoothing of the mesh is often useful in order to obtain reasonable accuracy in the computed solution. Since smoothing monitor function is more straightforward to apply than smoothing mesh concentration, the technique is employed here. Specifically, the values of the smoothed monitor function M at nodes are defined by

$$M_i = \sqrt{\frac{\sum_{j=i-p}^{i+p} (M_j)^2 \left(\frac{\gamma}{1+\gamma} \right)^{|j-i|}}{\sum_{j=i-p}^{i+p} \left(\frac{\gamma}{1+\gamma} \right)^{|j-i|}}} \qquad (4)$$

where γ is a positive constant smoothing parameter and p is the non-negative integer relative to smoothing index. The monitor function of M is given by

$$M(x,t) = \sqrt{1 + \left(\alpha \frac{\partial T}{\partial x} \right)^2 + \left(\beta \frac{\partial^2 T}{\partial x^2} \right)^2} \qquad (5)$$

where α and β are used to control mesh size. Due to the moving coordinate, the equation (1) is rewritten in the Lagrangian form:

$$\gamma C \frac{\partial T}{\partial t} - \gamma C \frac{dx}{dt}\frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial t} \right) + s(T, T_c, x, t) + Q_d - \sum_i^N \frac{P_i h_i}{A}(T - Tj) \qquad (6)$$

The space of the equations (3) and (6) can be discretized by using finite volume method. The semi-discretization of the equation is the stiff ordinary differential-algebraic equation and it can be solved by DASSL [10]. In the simulation, parameters γ =2, τ = 10^{-3}, and p=4 are set.

The Nb_3Sn pancake-shaped superconducting magnet is studied. The critical current density, critical temperature and current sharing temperature of Nb_3Sn superconductor can be calculated by

$$J_c(B,T,\varepsilon) = \frac{j_{c1}(B,T,\varepsilon)}{1 + \frac{j_{c1}(B,T,\varepsilon)}{j_o(T)}} \qquad (7)$$

where B is the magnetic field and ε is the total longitudinal strain of Nb_3Sn filaments in the strands

$j_o(T) = J_{co}(1 - t^2)^2$ and

$$j_{c1}(B,T,\varepsilon) = C_o \frac{(1-t^2)^2(1-b)^2}{\sqrt{bB_{c2}}}$$

with $b = \frac{B}{B_{c2}(T,\varepsilon)}$, $t = \frac{T}{T_{co}(\varepsilon)}$,

$$T_{C0} = T_{C0M}(1 - a|\varepsilon|^{1.7})^{\frac{1}{3}}$$

$$B_{C20} = B_{C20M}(1 - a|\varepsilon|^{1.7}),$$

$$B_{C2} = B_{C20}(1-t^2)(1-\frac{1}{3}t) \text{ and } a = \begin{cases} 1250 & (\varepsilon > 0) \\ 900 & (\varepsilon < 0) \end{cases}$$

The parameters of T_{COM}, B_{C20M}, C_O and J_{co} for HP-I Nb_3Sn superconductor are 18 K, 28 T and 1.16×10^4 A-T/mm^2 and 3.3554×10^{10} A/m^2, respectively. The critical temperature T_C is calculated by setting $J_C(B, T_C, \varepsilon)=0$.

The current sharing temperature T_{CS} is calculated implicitly from the expression $J_C(B, T_{CS}, \varepsilon)=J_{OPT}$, where J_{OPT} is operating current density of superconductor for the magnet. (8)

A superconducting magnet subjected to a disturbance shows fast transient process. The heat transfer between the superconducting magnet and liquid helium depends on the temperature difference of the magnet and helium. The helium heat transfer can be expressed according to the experimental result [11,12],

$$q_h = \begin{cases} 1.2\times10^4(T-T_b) & (T-T_b \le 0.58) \\ 1.05\times10^4 - 6\times10^3(T-T_b) & (0.58 < T-T_b \le 1.5) \\ 1.2\times10^3 + 2.3\times10^2(T-T_b) & (1.5 < T-T_b) \end{cases}$$

where T_b is the ambient temperature of liquid helium.

III. Numerical results and discussion

The numerical simulation results are presented in this part. A 3-pancake-shaped magnet and 1-pancake shaped magnet are assumed to be located at the uniform background field. The background field includes the external field and self-field of magnet. Generally, the background field can be obtained by adjusting the external field to make the field to be uniform. Finally, the influence of self-field on normal zone propagation is studied by a 6-pancake-shaped magnet with the external field of 0 T.

The 3-pancake superconducting magnet wound by continuous superconducting wire and surrounded by liquid helium is located in the background field of 12.5 T and operating current of 1.1 kA. The heat disturbance with duration of 5 ms and length of 0.15 m is applied to 17th layer of the pancake-2. The main parameters of the magnet are listed in the Table-I. Fig. 2 illustrates the hot-spot temperature rise versus time for insulation thickness d_{ins} = 25, 20 and 12.5 μm with the disturbance over than their minimum quench energy. The hot spot temperature of insulation thickness of 25 μm is over than that of 12.5 μm. The heat coupling term between the layers and pancakes depends on the equivalent heat transfer coefficient. The thicker insulation results in a lower heat transfer between layers and pancakes. Therefore, during local quench of the pancake, the transfer of Joule generating heat and disturbance from the disturbance center to the lower temperature region of the superconducting magnet is more difficult. It leads to the high hot spot temperature. Fig.3 shows the profiles of the normal zone length versus time. The high hot-spot temperature makes the normal zone increased with relatively fast speed along the superconducting wire. Fig.4 illustrates the temperature distribution in the insulation thickness of 25 μm for pancakes 1, 2 and 3. The origin of coordinate is located at the outer radius of the No.1 pancake. It shows that the heat coupling between the layers and pancake is very strong. The heat diffusion between layers or pancakes can result in the adjacent layers or pancakes quench.

The influence of field and operating current on thenormal zone propagation is studied by the 1-pancake- shaped magnet with the inner radius of 30 cm and outer radius of 85 cm. The parameters of tape of Nb_3Sn are listed in Table-I. Fig. 5 plots the normal zone extension at time 10, 100 and 150 ms for the pancake-shaped magnet under the background fields of 6.5 and 12.5 T. The insulation thickness is 50 μm and the operating current is 2.1 kA. The normal zone propagation for the magnet in the field of 6.5 T is much slower than that of the magnet under the field= 100 ms, pancake-shaped magnet is reached at only partial quench for the field of 6.5 T, but the magnet in the field of 12.5 T is reached at full quench. Because of the increment of magneto-resistance effect and the decreasing critical parameters with the increasing the field, the normal zone extension at the high field is faster along transverse direction than that of lower field. Fig 6 shows the normal zone profiles for the operating currents of 1.1, 2.1 kA and background

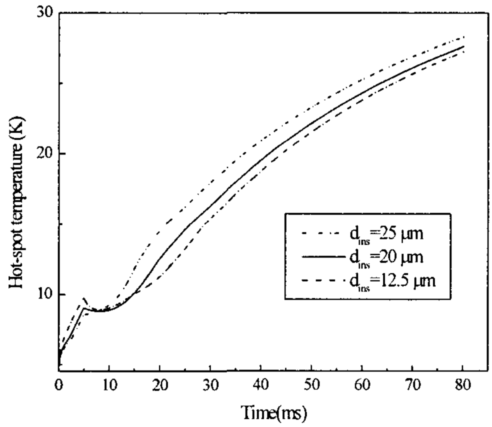


Fig.2 Hot-spot temperature rise of 3-pancake-shape superconducting magnet system versus time for insulatio thickness dins =25, 20 and 12.5 μm at background field o 12.5 T and operating current of 1.1 kA, with disturbanc duration of 5 ms and length of 0.15m.

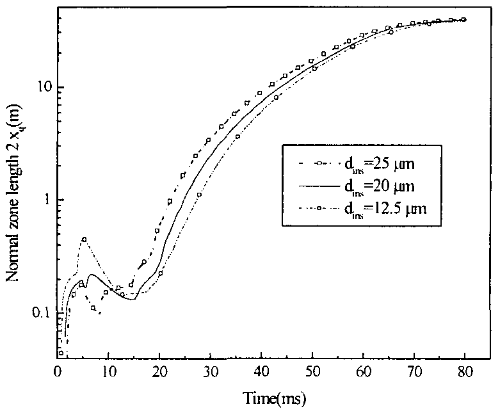


Fig.3 Profiles of normal zone length of 3-pancake-shape superconducting magnet versus time for insulatio thickness d_{ins} =25, 20 and 12.5 μm at background field o 12.5 T and operating current of 1.1 kA, with disturbanc duration of 5 ms and length of 0.15m.

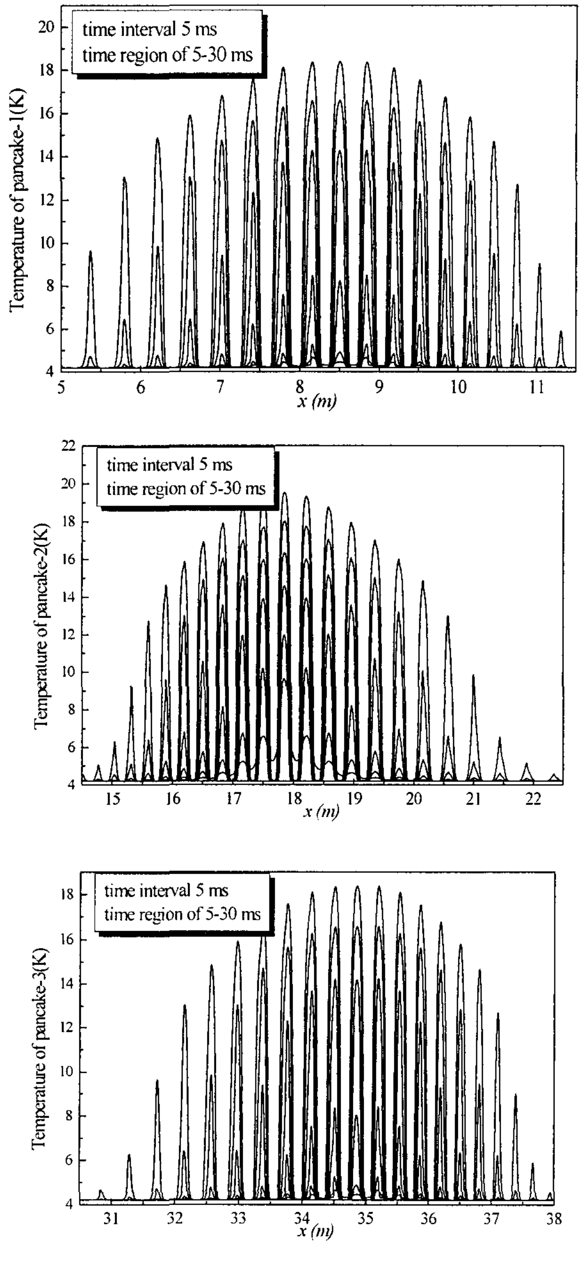
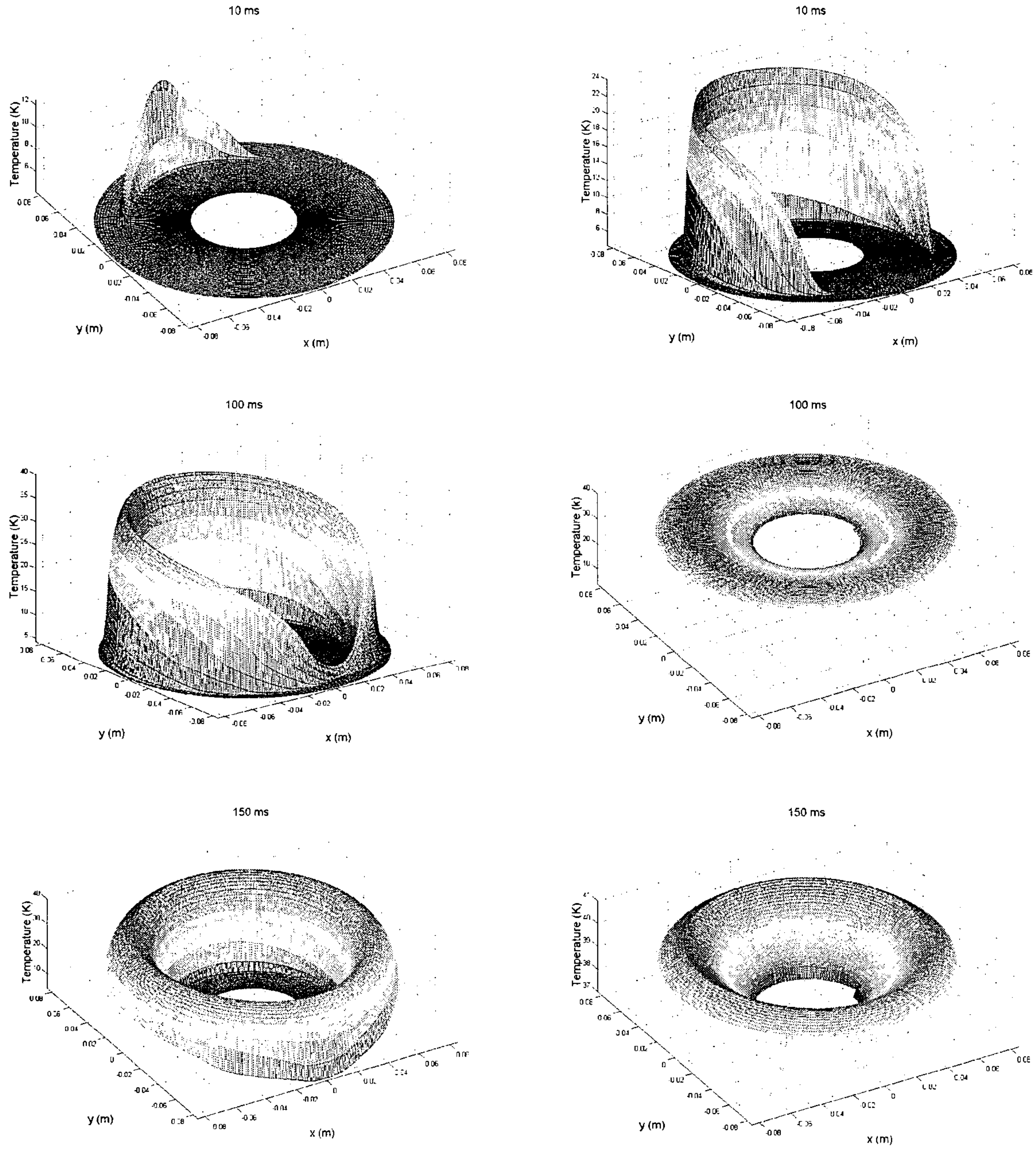


Fig. 4 Profiles of temperature of 3–pancake-shape superconducting magnet versus space coordinate fo insulation thickness d_{ins} =25μm at background field of 12. T and operating current of 1.1 kA, with disturbance duratio of 5 ms and length of 0.15m



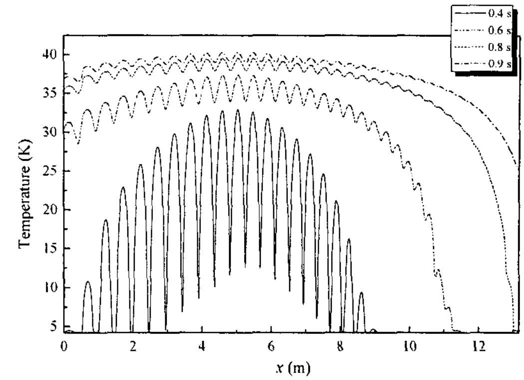
(a) (b)

Fig.5 Temperature distribution of 1-pancake-shaped magnet for (a) background field of 6.5 T and (b) background field of 12.0 T, operating current of 1.1 kA, with disturbance duration of 5 ms and length of 0.15m.

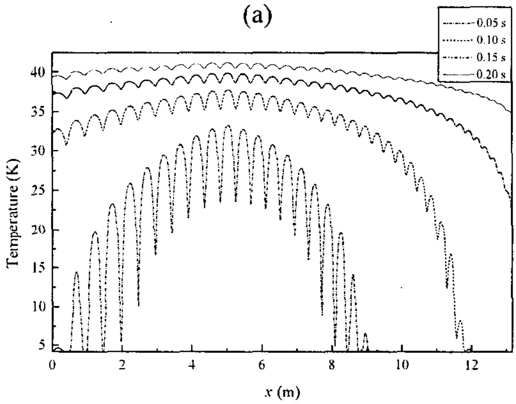
field of 8.5 T. Comparing the magnet operated at 1.1 kA and 2.1 kA, the extension of the normal zone for operated at 2.1 kA is much faster than that of 1.1 kA due to the large Joule heating generation power. Because of the temperature difference between hot spot and lower temperature region in the same layer, the temperature distribution is wave-shaped along the length of superconducting wire. Fig.7 illustrates the hot-spot temperature versus time. The higher operating current induces a higher hot-spot temperature.

The low operating current generates a relative long relaxation time for the quench process of the magnet. From the Fig.7, at first, the hot-spot temperature for operating current of 1.1 kA increases slowly and then it increases fast. When the hot-spot temperature is over than the current sharing temperature, the Joule heat is generated in the layer disturbed when the adjacent layers are still in the superconducting state. Most heat flow is conducted along the superconducting wire. With the increasing the hot-spot temperature, the transverse heat flux is increased and then the layer disturbed and its adjacent layers start into the normal state or current sharing state, the Joule heat increases with very fast speed so that the hot-spot temperature is fast increased. Then the layer disturbed and its adjacent layers start into the normal state or current sharing state, the Joule heat increases with very fast speed so that the hot-spot temperature is fast increased.

The influence of the heat transfer of liquid helium is studied. The parameters of the 1-pancake-shaped magnet are the same as above. The disturbance is located at 22^{th} layer of the pancake-shaped magnet with the disturbance length of 0.15 m and duration time of 5 ms, background field of 8.5 T and operating current of 3 kA. The heat transfer coefficients are set as h = 0, 1500, 3000 W/m^2 and the value based on the equation (8). The hot spot temperature versus time is shown in Fig.8. The lower heat transfer coefficient can generate the higher hot-spot temperature rise. The hot-spot temperature for the heat transfer calculated based on equation (8) is higher than that of h = 3000 W/m^2 after about t=10.5 ms. The transient heat transfer of liquid helium is varied with the temperature difference $\Delta T = T\text{-}T_b$. When the tem-perature difference is over that about 20 K, the heat transfer calculated based equation (8) is lower than that with h = 3000 W/m^2.



(a)



(b)

Fig. 6 Temperature distribution of 1-pancake-shaped magnet for operating current of (a) 1.1 kA and (b) 2.1 kA, background field of 8.5 T and disturbance duration of 5 ms and length of 0.15m.

The disturbance length can influence on the normal zone propagation velocity. Fig. 9 shows the simulation results for the 1-pancake-shaped magnet under the background field of 8.5 T and operating current of 3 kA. The disturbance length and duration time are 0.015, 0.15, 0.25 m and 5 ms, respectively. The longer disturbance length has a higher normal zone propagation velocity. The initial quench region of the disturbance length of 0.25 m is over than that of 0.015 m. The larger quench region results in higher transverse heat flux through layers and pancakes. The fast increasing transverse generates the adjacent layers and pancakes quench.

The influence of the self-field of magnet on the

Table I. Parameters of 3-pancake-shaped superconducting magnet system

Superconductor	Nb_3Sn
Inner diameter	30 cm
Outer diameter	85 cm
Height of magnet	1.5 cm
Magnetic field	6.5-12.5 T
Operating current	1.1-3.1 kA
Operating temperature	4.2 K
Size of tape	1.5 mm ×5 mm
Cross-sectional area of copper	5 mm^2
Cross-sectional area of superconductor	2.5 mm^2
RRR	150
ε	-0.3 %
Insulator thickness	50 μm

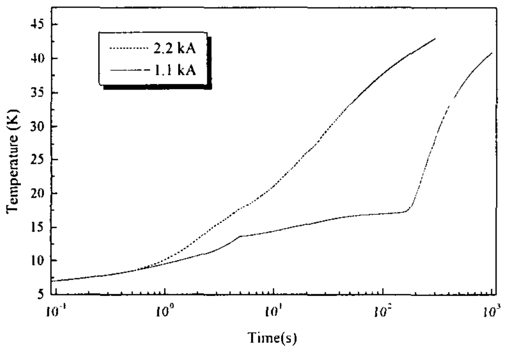


Fig. 7 Profiles of hot-spot temperature rise of 1-pancake-shaped magnet versus time for operating currents of 1.1 and 2.1 kA and background field of 8.5 T, with disturbance duration of 5 ms and length of 0.15m.

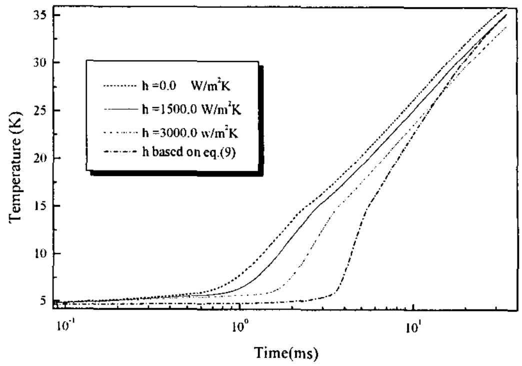


Fig. 8 Hot spot temperature rise of 1-pancake-shaped magnet versus time for the various heat transfer coefficients. The disturbance is located at the 22th layer of superconducting magnet, disturbance length of 0.15 m and duration time of 5 ms, background field of 8.5 T and operating current of 3 kA.

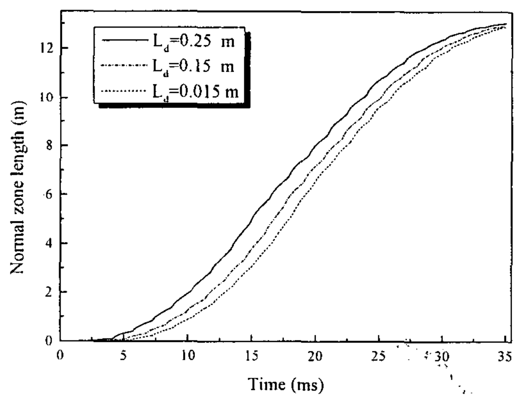


Fig. 9 Normal zone length of 1-pancake-shaped magnet versus time. The 1-pancake-shaped magnet is located at the background field of 8.5 T and operating current of 3 kA, for the duration time of 5 ms.

normal zone propagation is studied for the 6-pancake-shaped superconducting magnet with the disturbance located at 16th layer of No.4 pancake. The external field is zero. The disturbance length and duration time are 0.15 m and 5 ms, respectively and operating current of 2.8 kA. The inner radius, outer radius and height of the magnet are 30 cm, 85 cm and 3.0 cm, respectively. The parameters of tape of Nb_3Sn are shown in Table I. Fig.10 plots the self-field distribution for the superconducting magnet system. The high field region is located at the inner layer of the magnet. Fig.11 illustrates the profile of temperature disturbance for the 6-pancake-shaped superconducting magnet system for the t =10, 50, 100, 150, 200 ms. At 10 ms, No.4 is in the quench state, and the adjacent pancakes No.3 and No.5 are still in the superconducting state. At t = 50 ms, No.2, No.3, No.5 and No.6 start to quench. At t = 100 ms all the pancakes are in the normal state for the inner layers because they are located at the high field region. At t= 150 ms, all pancakes are at the normal state. From

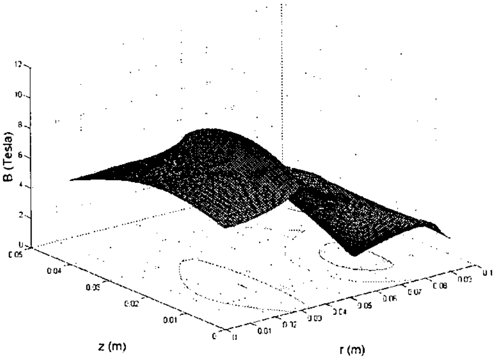
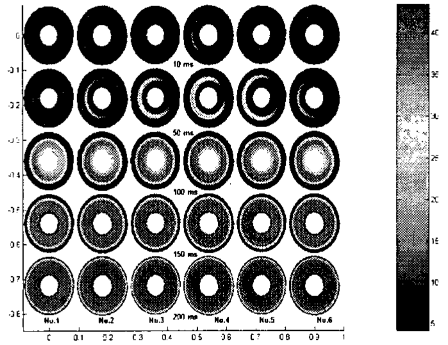


Fig. 10 Profile of self-field distribution of the 6-pancake-shaped magnet systems for operating current of 2.8A an bath temperature of 4.2 K.



(unit of temperature in bar : K)

Fig 11 Temperature distribution of 6-pancake-shape superconducting magnet during the disturbance located a 16^{th} of pancake No.4, with the disturbance length of 0.15 and duration time of 5 ms, operating current of 2.8 kA superconducting magnet located at the self-field.

the Fig. 11, the self–field results in fast quench propagation velocity along radius, and the quench of the inner layers is faster than that of the outer layer.

IV. Conclusions

The quasi-three-dimensional model can simulate quench process in pancake-shaped superconducting magnet system. The moving mesh finite volume method is suitable to solve the moving boundary problem. The simulation results of the pancake-shaped superconducting magnet show:

(1) The insulation thickness of superconducting wire can influence on the hot-spot temperature and normal zone propagation velocity.

(2) The high background magnetic field and operating current of magnet accelerate the normal zone propagation. Furthermore, the magnetic resistance effect of stabilizer in the high magnetic field induces the high hot-spot temperature rise and increases the transverse heat coupling.

(3). Comparing the constant heat transfer and the transient heat transfer of liquid helium varied from the nucleate boiling to the film boiling, the transient heat transfer can lead to the lower hot-spot temperature rise in the initial time and then high hot-spot temperature in the film boiling region.

(4) The self-field increases the normal zone propagation velocity along the inner radius directions.

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