KSME International Journal, Vol. 14, No. 9, pp. 985~996, 2000

Numerical Model for Thermal Hydraulic Analysis in Cable-in-Conduit-Conductors

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The issue of quench is related to safety operation of large-scale superconducting magnet system fabricated by cable-in-conduit conductor. A numerical method is presented to simulate the thermal hydraulic quench characteristics in the superconducting Tokamak magnet system. One-dimensional fluid dynamic equations for supercritical helium and the equation of heat conduction for the conduit are used to describe the thermal hydraulic characteristics in the cable-in-conduit conductor. The high heat transfer approximation between supercritical helium and superconducting strands is taken into account due to strong heating induced flow of supercritical helium. The fully implicit time integration of upwind scheme for finite volume method is utilized to discretize the equations on the staggered mesh. The scheme of a new adaptive mesh is proposed for the moving boundary problem and the time term is discretized by the-implicit scheme. It remarkably reduces the CPU time by local linearization of coefficient and the compressible storage of the large sparse matrix of discretized equations. The discretized equations are solved by the IMSL. The numerical implement is discussed in detail. The validation of this method is demonstrated by comparison of the numerical results with those of the SARUMAN and the QUENCHER and experimental measurements.

Key Words : Cable-in Conduit-Conductors, Staggered Mesh, Thermal Hydraulic Behavior, Finite Volume Method of Upwind Scheme, Fusion Superconducting Magnet

Nomenclature

ρ : Density of supercritical helium
T_{he} : Temperature of supercritical helium
α : Bulk compressibility coefficient of supercritical helium
β : Expansion coefficient of supercritical helium
C_v : Specific heat of helium at the constant volume
γC_{st} : Heat capacity of strands
k_{jk} : Thermal conductivity of conduit
p_{jk} : Wetted perimeter of conduit
A_{jk} : Cross sectional area of conduit
h_{jk} : Heat transfer coefficient between helium and conduit
f : Friction factor
q_{jst} : Joule heat power in strands
q_{dst} : Disturbance power in strands
Lo : Disturbance center coordinate
t_d : Disturbance duration time
Tc : Critical temperature of superconductor
ηC_u : Copper resistivity
C_p : Specific heat of helium at constant pressure
h_t : Transient heat transfer coefficient
h_s : Steady state heat transfer coefficient
Re : Reynolds number
u : Velocity of supercritical helium
t : Coordinate of time
x : Coordinate of space

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T_{jk} : Conduit temperature
γC_{jk} : Heat capacity of conduit
k_{st} : Thermal conductivity of strands
d_h : Thermal hydraulic diameter
A_c : Total cross sectional area of strands
A_{he} : Total cross sectional area of helium
f_{Cu} : Copper/non-copper ratio
q_{jjk} : Joule heat power in conduit
q_{djk} : Disturbance power in the conduit
L_d : Disturbance length
T_{sh} : Current sharing temperature
τ : Strength factor of mesh
J_{opt} : Full current density in strands
P : Pressure of helium
k_{he} : Thermal conductivity of helium
h_k : Kaptiza conductance
Pr : Prandtl number
x_q : Normal zone front coordinate

1. Introduction

Superconducting magnets have many applications in the industry and large-scale experimental devices. Some useful applications are the medical devices such as MRI superconducting magnets, accelerator superconducting magnets, superconducting magnet energy storage system, Tokamak superconducting magnet, etc. The Korean Superconducting Tokamak Advanced Research (KSTAR) project is a full superconducting Tokamak device with the central magnetic field of 3. 5 T at the major plasma radius of 1.8 m (Schultz, 1997). The Tokamak adopts the cable-in-conduit conductor (CICC) as the basic elements for the TF and PF superconducting magnets (Schultz, 1998). A CICC, which is formed by cabling of superconducting strands and pure copper strands sealed in stainless steel or Incoloy conduit, is characterized by large stability margin, high breakdown voltage, good mechanical strength and smaller total mass of liquid helium necessary for cooling and lower AC losses. It has been widely employed in fabricating large-scale superconducting magnets. For safety operation of the superconducting magnets, the protection during quench of the system is one of the important issues. Therefore, predicting the quench characteristics, especially, the maximum supercritical helium pressure in the conduit, hotspot temperature of the superconducting strands is essential to issues for the designers.

If a CICC is subjected to a thermal disturbance and the conductor temperature exceeds its current sharing temperature, the parts of operating current pass through the stabilizer matrix and the Joule heat is generated. The superconductor is either recovered to the superconducting state or increased its temperature over critical temperature to the normal state depending on heat deposition and removal by convection and conduction. Because the thermophysical properties of supercritical helium are changed with respect to the temperature and pressure, the flow of supercritical helium in conduit can be driven by external and Joule heats, even the stagnant helium. The velocity of heating induced flow of supercritical helium attains very high with order of 10 m/s or more (Dresner, 1991; Lue, 1994). Such velocity of high heating induced flow can significantly improve the heat transfer characteristics between the superconducting strands and supercritical helium. On the other hand, the supercritical helium to produce the thermal expansion absorbs the high heat flux. Then, the pressure and temperature of supercritical helium in the conduit are rapidly increased. The normal zone of superconducting strands spreads with a very high propagation speed, therefore, it may produce the damage of the whole magnet system.

The problem of quench in the large-scale superconducting magnets fabricated by the CICC has been widely studied in the past few years. For various applications, some numerical codes have been developed. The numerical solution of the one-dimensional equations was announced (Bottura, 1995). The basic numerical approaches are the finite element method with artificial viscous damping term (Bottura, 1996; Zanino et al., 1995), collocation methods, time-explicit finite element methods (Bottura and Zienkiewicz, 1991) and implicit finite difference (Koizumi et al., 1996) and finite volume algorithm with artificial viscosity (Wang et al., 1999). The numerical and analytical solutions have found that the normal zone front of a superconductor is characterized by the moving boundary and contact discontinuity for the temperature and density of supercritical helium (Shaji and Freidberg, 1996). It leads to very difficult to obtain accurate numerical simulation. Especially, the CICC is used in the high current and high background field. To simulate this phenomena accurately, the fine mesh should be used in the region where the strong heat coupling occurs between the superconducting strands and supercritical helium. The converged solution can be obtained with the fine mesh in space and small time step-size, only.

The proposed method does not require the artificial viscosity. The model assumes that the temperatures of supercritical helium and superconducting strands are the same, due to the very high heat transfer phenomena between supercritical helium and superconducting strands (Luougo, 1988). The governing equations are one-dimensional fluid dynamic equations for supercritical helium and the equation of heat conduction for the conduit. A finite volume method of upwind scheme on the staggered mesh discretizes the partial derivative of space for the equations. The time integration is employed by the θ-implicit scheme. The coefficients of equation are locally linearized and the coefficient matrix of the discretized equations is characterized by the typical large sparse matrix structure. The subroutines in the IMSL are used to solve the linear sparse system. The new scheme of adaptive mesh is presented to generate the grid movements and the numerical implementation is introduced in this paper. The validation of the method is performed by other commercial software and experimental measurements.

2. Basic equations for Quench Simulation

The CICC shown in Fig. 1 contains the superconducting strands, pure copper strands, supercritical helium and conduit. While the length of the conductor for the Tokamak magnets is the dimension of 10^2-10^3 m, typically, the transverse scale of the CICC is the order of 10^{-2} m. Thus,

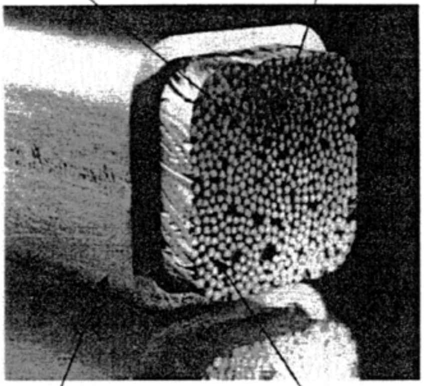

Fig. 1 Cross-sectional View of Cable-in-Conduit Conductor

one-dimensional model is reasonable to assume for the thermal hydraulic analysis. The heat conduction of supercritical helium is neglected since the heat diffusion is much lower than that of convection. Due to the large wetted perimeter of superconducting strands in contact with helium and high heat transfer coefficient between helium and superconducting strands during quench of CICC, the high heat transfer forces the temperature difference between helium and superconducting strands very small. Thus, the temperature difference can be ignored and the temperatures for superconducting strands and helium are the same. However, the temperature difference between helium and the conduit should be considered because of a small wetted perimeter of conduit. The temperature distribution of the conduit is predicted by the heat conduction equation. The current redistribution among superconducting strands is neglected in this model. The coupled equations for supercritical helium, superconducting strands and conduit are expressed as:

$$M\frac{\partial \Psi}{\partial t}+A\frac{\partial \Psi}{\partial x}+B\Psi=\frac{\partial}{\partial x}\left[K\frac{\partial \Psi}{\partial x}\right]+G \qquad (1)$$

where the unknown augment matrix of and coefficients matrix of the equations are defined as :

$$\Psi=\begin{bmatrix}\rho \\ u \\ T_{he} \\ T_{jk}\end{bmatrix},\ M=\begin{bmatrix}1 & 0 & 0 & 0 \\ 0 & \rho & 0 & 0 \\ 0 & 0 & \rho C_t & 0 \\ 0 & 0 & 0 & \gamma C_{jk}\end{bmatrix},$$

$$A=\begin{bmatrix} u & \rho & 0 & 0 \\ \frac{1}{\rho\alpha} & pu & \frac{\beta}{\alpha} & 0 \\ 0 & \left(\frac{A_{he}}{A_c}\right)\frac{\beta}{\alpha}T_{he} & \rho u C_v\left(\frac{A_{he}}{A_c}\right) & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$K=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & k_{st} & 0 \\ 0 & 0 & 0 & k_{jk} \end{bmatrix},$$

$$B=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & f\rho\frac{|u|}{2d_h} & 0 & 0 \\ 0 & -f\rho\frac{|u|u}{2d_h}\left(\frac{A_{he}}{A_c}\right) & \frac{p_{jk}h_{jk}}{A_c} & -\frac{p_{jk}h_{jk}}{A_c} \\ 0 & 0 & -\frac{p_{jk}h_{jk}}{A_{jk}} & \frac{p_{jk}h_{jk}}{A_{jk}} \end{bmatrix},$$

$$G=\begin{bmatrix} 0 \\ 0 \\ q_{dst}+q_{jst} \\ q_{djk}+q_{jjk} \end{bmatrix}$$

$$\rho C_t=\frac{A_{he}}{A_c}\rho C_v+\gamma C_{st}$$

The equation includes the convection and diffusion terms. The coefficient matrix, K, is related to the thermal diffusion term of superconducting strands and conduit. It depends on the thermal conductivity of stabilizer matrix and conduit. The coefficient matrix, A, is connected to the convection terms of supercritical helium. The source term, G, includes the external heat disturbance and Joule heating generation. Apparently, the central difference has instability for the high Reynolds number (Re) (Anderson et al., 1984). The disturbance power q_d is with the Gaussian distribution and the disturbance center is located at the L_0 and duration time td.

$$q_d=\frac{q}{t_d}e^{\left(-\pi\left(\frac{x-L_0}{L_d}\right)^2\right)} \tag{2}$$

The total input energy of the disturbance is equivalent to that of a rectangular pulse with amplitude q.

The Joule heating power depends on the current sharing temperature (T_{sh}) and critical temperature (T_C) of superconducting strands. If the critical current is linearly varied with temperature, the power of Joule heat is (Wilson, 1983)

$$q_{jst}=\begin{cases} 0 & (T_{he}<T_{sh}) \\ \frac{1+f_{cu}}{f_{cu}}\eta_{cu}J_{opt}^2\frac{T_{he}-T_{sh}}{T_c-T_{sh}} & (T_{sh}\le T_{he}\le T_c) \\ \frac{1+f_{cu}}{f_{cu}}\eta_{cu}J_{opt}^2 & (T_{he}>T_c) \end{cases} \tag{3}$$

where the Cu/SC ratio and full-current density of superconducting strands are f_{cu} and J_{opt}, respectively. There exists an implicitly moving boundary in the equation (3), i. e.

$$T_{he}(x,\ t)=T_{sh}(x,\ t) \tag{4}$$

3. Numerical Solution and Adaptive Mesh Scheme

The numerical algorithm for the coupled equations and the scheme of adaptive mesh are presented in this part. The numerical solution of the governing equation by the central difference is unstable. It is necessary to add the artificial diffusion term to stabilize the oscillation of solution. To avoid the adding artificial viscosity term which influences the accuracy of solution, the finite volume method of upwind scheme, which can stabilize the numerical solution of hyperbolic convection dominated the flow problem, is applied to discretize the space terms on a staggered mesh. The basic configuration of the staggered mesh is illustrated in Fig. 2. The control volumes for the velocity of supercritical helium are staggered relative to the control volumes of density and temperature of supercritical helium. The centers of the control volumes for velocity are always the boundaries of the control volumes for the density and temperature even when the control volume varies. The centers of the control volumes for the velocity located at the inlet and outlet ends of CICC are the half volume with the elements. The first and final control volumes of density and temperature are located at the inlet and outlet boundaries with full elements.

According to the finite volume methods of upwind scheme, the equations for the continuity, momentum and energy conservation of supercritical helium and conduit are specified as below :

$$\frac{\partial\rho}{\partial t}+u_e\frac{\rho_e-\rho_w}{SEW}+\rho\frac{u_{(i+1)}-u_{(i)}}{SEW}=0 \tag{5}$$

$$\rho\frac{\partial u}{\partial}+\rho u\frac{u_e-u_w}{SEWU}+\frac{1}{\rho a}\frac{T_{he(i)}-T_{he(i-1)}}{SEWU}$$
$$+\frac{\beta}{\alpha}\frac{\rho_{(i)}-\rho_{(i-1)}}{SEWU}+f\rho\frac{|u|}{2d_h}u=0 \qquad (6)$$

$$\rho C_t\frac{\partial T}{\partial t}+\left(\frac{A_h}{A_c}\right)\rho C_v u_e\frac{T_{he(e)}-T_{he(w)}}{SEW}$$
$$+\left(\frac{A_h}{A_c}\right)\frac{\beta}{\alpha}T\frac{u_{(i+1)}-u_{(i)}}{SEW}$$
$$-\left(\frac{A_h}{A_c}\right)f\rho\frac{|u_e|u_e^2}{2d_h}$$
$$=\left(k_{st(e)}\frac{T_{he(i+1)}-T_{he(i)}}{DXEP}\right.$$
$$\left.-k_{st(w)}\frac{T_{he(i)}-T_{he(i+1)}}{DXPW}\right)\frac{1}{SEW}+q_j$$
$$+q_d-\frac{p_{jk}h_{jk}}{A_c}(T_{he(i)}-T_{jk(i)}) \qquad (7)$$

$$\gamma C_{jk}\frac{\partial T_{jk}}{\partial t}=\left(k_{jk(e)}\frac{T_{jk(i+1)}-T_{jk(i)}}{DXEP}\right.$$
$$\left.-k_{jk(w)}\frac{T_{jk(i)}-T_{jk(i-1)}}{DXPW}\right)\frac{1}{SEW}+q_{ijk}$$
$$+q_{jkd}+\frac{P_{jk}h_{jk}(T_{he(i)}-T_{jk(i)})}{A_{jk}} \qquad (8)$$

where the subscripts e and w stand for the numbers of east and west boundaries of the control volume. The values of the boundaries are calculated by linear interpolation (Tao, 1987). The subscript i indicates the number of the nodes. SEWU, SEW, DXEP and DXPW are shown in Fig. 2.

The time term of the variable is approximated by using $(n+\theta)$ where θ is varied in the range of (0-1). For $\theta=1/2$, the time integral has second-order accuracy (Reddy, 1993).

$$\left.\frac{\partial\Psi}{\partial t}\right|^{n+\theta}=(1-\theta)\left.\frac{\partial\Psi}{\partial t}\right|^{n}+\theta\left.\frac{\partial\Psi}{\partial t}\right|^{n+1}$$
$$=\frac{\Psi^{n+1}-\Psi^{n}}{\Delta t} \qquad (9)$$

After discretization of space and time terms, a nonlinear problem with full implicit time for $0<\theta\leq 1$ can be obtained. Typically, the system of nonlinear equation can be solved on the basis of iterative methods such as the Global Convergence method. However, the fine mesh should be taken to obtain the converged numerical solution in the long length of CICC conductor which is used in the superconducting Tokamak magnets. Therefore, a lot of control volumes must be employed and the iterative methods needed much more CPU time. In order to overcome the problem, the coefficients of the discretized equations at the $(n+1)$ th time are calculated by n th time parameters. Then, the system of nonlinear equation is treated as a linear equation. Before the assembly of the matrix structure for the linear system, it must note the order of the discretized equation, such as continuity, momentum, energy and conduit. This is the reason why the main diagonal term over the other elements in the matrix structure should be dominated to get a stable solution. The coefficient matrix of discretized equations has a large-scale sparse structure. A compressible storage scheme for the sparse problem is applied to solve the equation, and the solvers, the subroutines of the DLFTXG and DLFSXG in

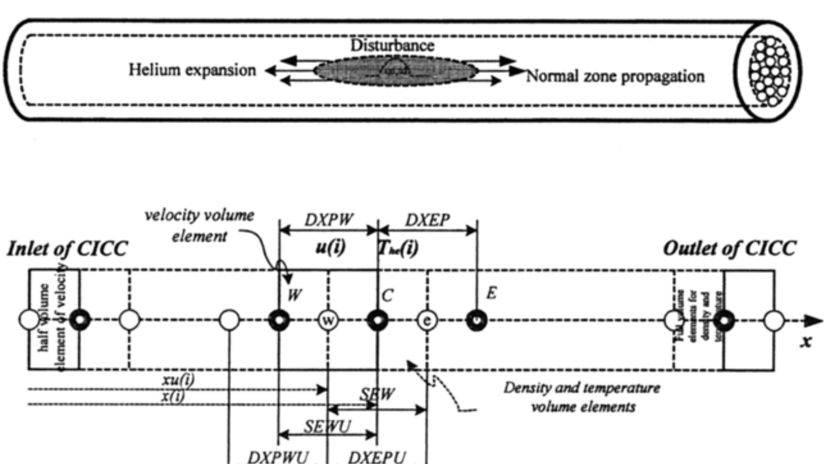

Fig. 2 Staggered mesh scheme in the calculation domain

IMSL are suitable to this problem.

When the superconducting strands in the CICC quench, the strong heat coupling between supercritical helium and superconducting strands may induce discontinuity of the temperature and density at the normal zone front. In order to capture the short normal zone, the fine mesh at the front region of normal zone is essential. The typical mesh size should be at the region of 1-5 mm, depending on the material characteristics. Unfortunately, the length of CICC for the superconducting magnet is very long, typical length is over 10^2-10^3 m, therefore, a uniform mesh is impossible to simulate the problem. A scheme of adaptive mesh is presented by using the normal zone front coordinate as an indicator. The new mesh is generated with the finest mesh at the normal zone front and is independent of the old mesh. The scheme uses an algebraic transformation of the equal interval coordinate (ξ) to the non-equal interval coordinate (x). The basic transformation is given as :

$$x = x_q\left(1+\frac{\sinh[\tau(\xi-\delta)]}{\sinh(\tau\delta)}\right),$$
$$\delta = \frac{1}{2\tau}\ln\left(\frac{1+(e^{\tau}-1)x_q}{1+(e^{-\tau}-1)x_q}\right) \quad (10)$$

In the transformation, x_q is the normal zone front coordinate, τ is the stretching parameter which varies from zero to large values and generates the maximum refinement near x_q . The smoothly varying mesh size is controlled by setting the maximum mesh size, $\Delta x_{\max}$, and minimum mesh size, $\Delta x_{\max}$. Figure 3 plots a typical mesh distribution along the CICC.

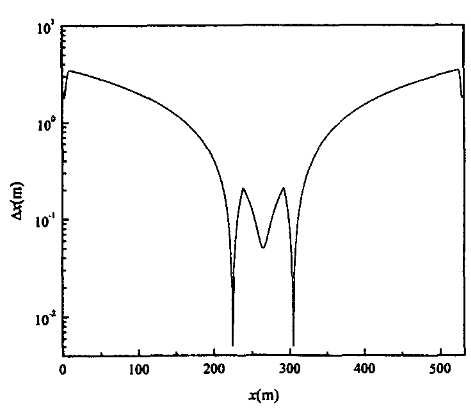

Fig. 3 Distribution of typical mesh size for CICC with the length of 530 m

4. Boundary and Initial Conditions, Transportation Coefficients

The initial and boundary conditions are needed to solve the discretized equations. In reality, superconducting magnets of the Tokamak system are generally connected with the constant pressure reservoirs at inlet and outlet. If P_{in}, P_{out} and T_{in} indicate the inlet and outlet pressures and temperature of the supercritical helium, constant pressure boundary conditions are given as follow :

$$p(\rho,\ T_{he}) = P_{in} \text{ and } P(\rho,\ T_{he}) = P_{out} \quad (11)$$

The boundary condition for the velocity of supercritical helium is determined on the basis of $\partial u / \partial x = 0$. The boundary condition of the temperature depends on the direction of velocity. When the supercritical helium flows into the CICC, i. e. the velocity of supercritical helium is positive, the $T_{he} = T_{in}$ is set. Otherwise the adiabatic boundary conditions are imposed for the temperature for supercritical helium flowing out the CICC. The boundary condition of the density depends on the boundary conditions of temperature and pressure.

In normal operation condition of the CICC, the steady-state heat flux is removed by supercritical helium and the superconductor operates in superconducting state. If a disturbance pulse is applied to the conductor, the transient heat transfer will occur. Therefore, the initial condition is based on the steady state operating condition for superconducting magnets. It can be defined by the solution of steady state supercritical helium equations for the specified pressure drop and inlet temperature.

The heat transfer coefficient, h, between supercritical helium and conduit includes three components, i. e. the transient heat transfer coefficient, h_t, Kapitza conductance and steady state heat transfer coefficient, h_s. The h_s is estimated by the Giarratano correction. The Reynolds number is very small in the initial time of quench in the CICC. With development of quench, the heating induced flow increases the Reynolds number to a very high value, and the transition between the laminar and turbulence flow is not obvious. Therefore, it is necessary to give a lower limit of the heat transfer. The steady state component of the heat transfer coefficient for supercritical helium is (Koizumi et al., 1996; Wong, 1989).

$$h_s=\max\left[0.0259\frac{k_{he}}{d_h}Re^{0.8}Pr^{0.4}\left(\frac{T_{he}}{T_{jk}}\right)^{0.716} \frac{8.235k_{he}}{d_h}\right] \tag{12}$$

The transient heat transfer coefficient, h_t , is responsible for heat coupling between supercritical helium and the conduit at the initial time of the Joule heat and disturbance. If a heat pulse starts at $t=0$, the h_t and h_k are:

$$h_t=\sqrt{\frac{k_{he}\rho C_p}{\pi t}} \text{ and } h_k=200(T_{he}^2+T_{jk}^2)(T_{he}+T_{jk}) \tag{13}$$

The total heat transfer coefficient h between the conduit and supercritical helium must include the transient and steady state characteristics. In the initial stage of disturbance, the heat transfer coefficient is expressed as

$$h=\frac{h_t h_k}{h_t+h_k} \tag{14}$$

The Eq. (14) is equivalent to the series of the transient boundary layer diffusion and Kapitza conductance. The heat transfer coefficient will be kept until the boundary layer is fully developed, and the temperature profile established. After this time, the heat transfer coefficient is determined by

$$h=\frac{h_s h_k}{h_s+h_k} \tag{15}$$

A smooth transition should be obtained from Eqs.(14) and (15). It is replaced in the simulation by taking the larger of the two expressions (Wang et al., 2000; Buturra et al., 1999), i. e.

$$h=\max\left(\frac{h_s h_k}{h_s+h_k}, \frac{h_t h_k}{h_t+h_k}\right) \tag{16}$$

Due to the large heating induced flow velocity, there exists a boundary of turbulence flow for supercritical helium in the CICC. The correlation of friction factors for the laminar and turbulence flow is based on the Reynolds number.

5. Thermal-Physical Characteristics for the Supercritical Helium, superconducting Material and Conduit

The parameters of the supercritical helium used in this code include α, β, C_v, C_p and p etc. . All of the parameters are the functions as the independent arguments of density and temperature. The thermophysical characteristics of supercritical helium are calculated from the program $NIST_{12}$ HE(Arp and McCarty) and the data are built as a library. In the code, the parameters are calculated by interpolation value of a two-dimensional cubic spline. The thermal conductivity, specific heat, resistivity of the superconducting material, stabilizer and conduit depending on the temperature and field are considered.

6. Verification and Validation of the Code

Based on the above discussions of numerical methods, the code, QSAIT, has been developed for the thermal hydraulic analysis. The simulation of quench in CICC is a very complex nonlinear problem, therefore, it is difficult to verify the validation of the code. Verification of the numerical code QSAIT is performed by comparison with the experimental measurements and the numerical results of SARUMAN and QUENCHER(Shaji, 1994). The SARUMAN was developed by the Cryosoft, and this code was a finite element tool which solved the fluid equations using an explicit time stepping method(Buttora). The QUENCHER was developed by MIT, and this code used the collocation methods to solve the ordinary differential equations utilizing the subsonic flow approximation. The results of two codes have been demonstrated by the QUELL experiment (Shajii et al., 1998; Balsamo et al., 1993).

The conductor used in this calculation has 530 m in length. The main parameters are listed in Table 1. The initial operating current of the CICC is 43 kA under the uniform background field of 13 T. The helium in the conduit is with

Table 1 Parameters of Cable-in-Conduit-Conductor

Conductor length	530 m	Copper cross section area	390 mm^2
Supercritical helium area	450 mm^2	Superconductor Nb3Sn area	260 mm^2
Conduit cross sectional area	260 mm^2	Conduit wetted perimeter	1.3 mm
Thermal hydraulic diameter	1.6 mm	Initial operating current	43 kA
Detection time	2 s	Dump time	20 s
Inlet pressure	5 atm	Outlet pressure	5 atm
Inlet temperature	5 K	Copper RRR	100

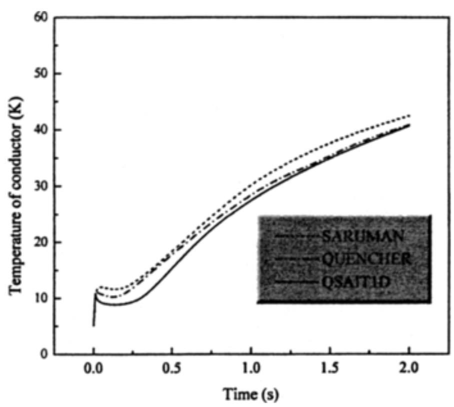

Fig. 4 Comparison with QSAIT, SARUMAN and QUENCHER's results for maximum temperatures of superconducting strands

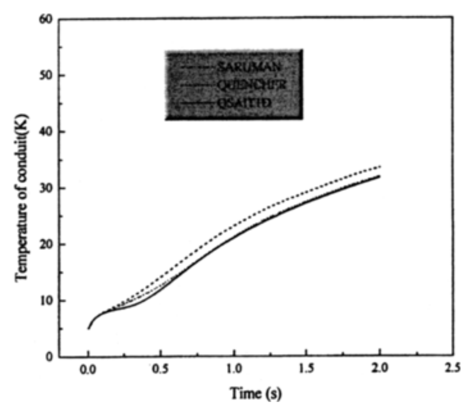

Fig. 5 Comparison for maximum temperature of conduit by QSAIT, SARUMAN and QUENCHER

initial operating temperature of 5 K, pressure of 5 atm. The initial helium mass flow rate is zero, i. e. stagnant helium in the conduit. After the disturbance is imposed at the center of the conductor, the operating current is kept 2 s and then decayed with time constant 20 s. The disturbance length and duration time are 2 m and 10 ms, respectively.

The quench simulation for 2 s is studied by the codes SARUMAN, QUENCHER and QSAIT. In SARUMAN, the total of 800 elements with 600 elements located at the center region of 30 m length is employed. The size of mesh in quench region of the CICC is 5 cm. QUENCHER uses adaptive mesh with the mesh size between 3 to 5 cm within the boundary layer. In QSAIT, the size of the minimum mesh, $\Delta x_{min}=5$ mm, is assumed. The operating time step-size is set as $\Delta t = 0.125$ ms and the integral time control parameter is equal to 0.5 so as to obtain second-order time accuracy. Figures 4 and 5 show the hotspot temperature of superconducting strands and conduit with respect to the time functions, respectively. The differences of simulation results are indeed small. Especially, the differences between QSAIT and QUENCHER are much smaller than those of between QSAIT and SARUMAN. The slight differences between the QSAIT and SARUMAN are at initial time, after that, the differences has been reduced. In SARUMAN, the temperatures between the superconducting strands and supercritical helium are separated. Therefore, the initial disturbance is directly deposited to the superconducting strands. On the other hand, the QSAIT and QUENCHER assume the same temperature between the superconducting strands and supercritical helium. Therefore, the initial disturbance is deposited to both the superconducting strands and supercritical helium. The heat capacity of single superconducting strands is smaller than that of the total heat capacity of superconducting strands and supercritical helium. Thus, there is slightly different amplitude of disturbance in two numerical models to initiate the quench of CICC. With the disturbance absorbed by supercritical helium, the heating induced flow can significantly increase the heat transfer between the superconducting strands and supercritical helium. The temperature difference between the superconducting strands and supercritical helium is dribbled away. The approximate model of high thermal transfer is much more complying with the practical process during CICC quench.

Figures 6 and 7 illustrate the profiles of the pressure of supercritical helium and normal zone length versus time, respectively. From the simulation results, the differences are varied small with the development of the CICC quench. It is noticed that the calculated pressure and normal zone length of SURMAN are slightly over those of the QUENCHER and QSAIT. This is because the SUARMAN takes a large mesh size in the normal zone front. It shows that the maximum pressure and normal zone length are sensitive to the mesh size at the front of normal zone. The CPU time used by the code SARUMAN during 2 s quench simulation is about 10 h on a cray-2 Supercomputer. The same results obtained by QSAIT are about 1 h on an Alpha PC computer. It is slightly longer that that of the QUENCHER about 50 min of CPU time on a VAX Station 4000/90. On the Alpha PC computer, the quench of 35 s is simulated. The profiles of the normal zone length with respect to time are shown in Fig. 8, for the disturbance lengths of Ld= 3 and 5 m and disturbance duration of 10 ms. Typical CPU time is about 13 h.

Figures 9 and 10 plot the space profiles of temperature and density of supercritical helium for disturbance length of 3 m and duration of 10 ms, respectively. The mesh redistribution is vital to achieve both the high calculation efficiency and the accurate solution. In the Figures, we have shown the actual space mesh redistribution with the time. The profiles of temperature and density have demonstrated that the adaptive mesh scheme

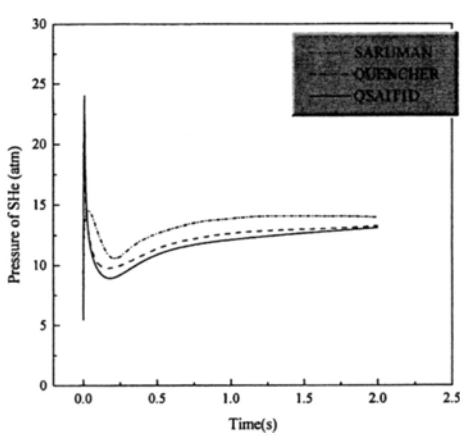

Fig. 6 Comparison for the maximum pressure of supercritical helium by QSAIT, SARUMAN and QEUNCHER

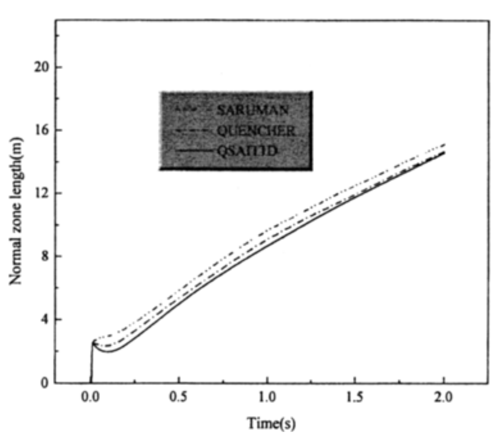

Fig. 7 Comparison for the profiles of normal zone length by QSAIT, SARUMAN and QUENCHER

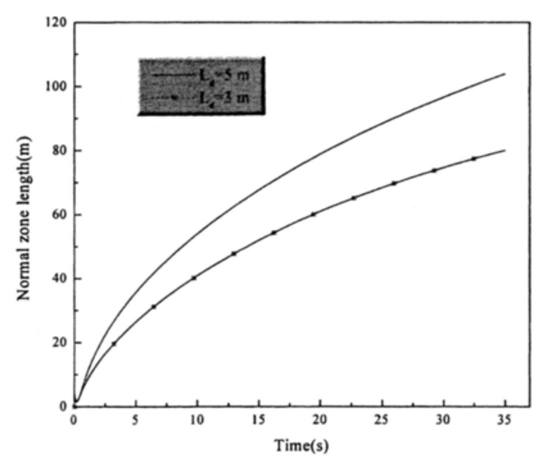

Fig. 8 Normal zone length with respect to time function of 35 second simulation at disturbance lengths of 3 and 5 m by QSAIT

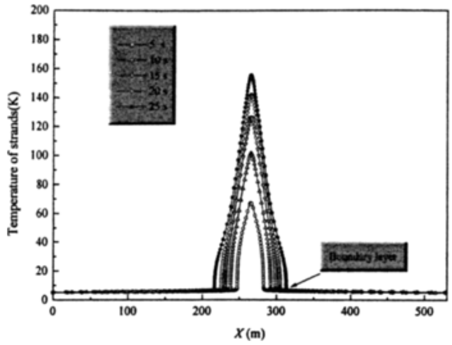

Fig. 9 Temperature distribution of superconducting strands along the full length of CICC, for disturbance length of 3 m

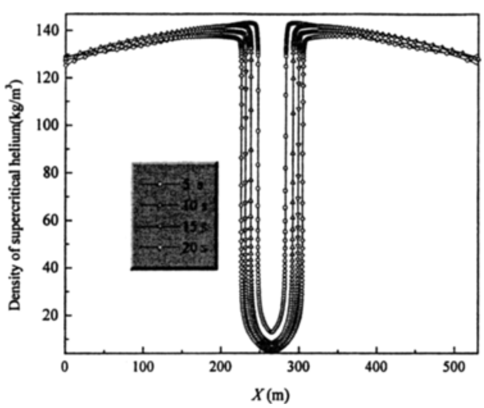

Fig. 10 Density profiles of supercritical helium along the full length of CICC, for disturbance length of 3 m

Table 2 Parameters of triplex NbTi Cable-in-conduit conductor

Diameter of strands	0.8 mm
Number of filament	7890
Copper/non-copper	1.3
Inner diameter of conduit	2.175 mm
Outer diameter of conduit	3.175 mm
Void fraction	48 %
Conductor length	2 m

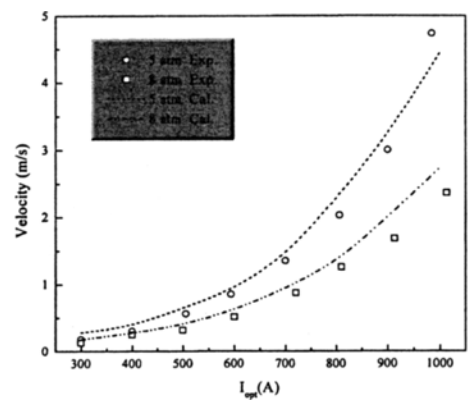

Fig. 11 Comparison of computational and experimental normal zone propagation velocity for a triplex NbTi cable-in-conduit conductor with length of 2 m and where initial mass flow rate of supercritical helium is zero

can efficiently capture the discontinuity of temperature and density in the normal zone front. The heat coupling boundary layer can be observed in the figures.

Finally, we compare the simulation results with those of the experimental measurements. The experiment was reported in the reference (Jiang et al., 1998) in detail. The experimental data about the normal zone propagation velocity versus operating current were obtained by testing a triplex NbTi superconducting CICC with length of 2 m. The CICC is located at the 6 T uniform background field. The initial helium mass flow rate is zero and operating temperature is 4.2 K. The parameters of the CICC are listed in Table-2. The results of simulation compared to the experimental measurement are illustrated in Fig. 11, for the pressure of 5 and 8 atm, respectively. Generally, the agreement between the measurement and calculation is excellent.

7. Conclusions

A numerical method has been developed based on the finite volume method of upwind scheme. The model uses the high heat transfer approximation between the superconducting strands and supercritical helium. The code, QSAIT, has following characteristics:

(1) The methods and model developed can be used to analyze the quench characteristics of cable-in-conduit conductor. Thus, the code can be used to design the large-scale superconducting magnets which are fabricated by CICC, such as

Tokamak, superconducting magnet energy storage system etc.

(2) Using the staggered mesh scheme and upwind, the finite volume method can circumvent the artificial viscosity. The simulation results of QSAIT have shown the agreement with the experimental measurements as well as the general numerical models.

(3) The stable solutions can be obtained at larger time step-size, i. e. the limiting time step -size can be eliminated by the θ-implicit scheme. Compared to the existing computer program, an improvement of about one to two orders of magnitude in the CPU time has been achieved by the linearization coefficients of the discretized equations and by the solution of the linear system with compressibly stored the large sparse coefficient matrix.

(4) The adaptive scheme installed in the code reduces the number of control volumes so as to obtain a converged solution. It is efficient to capture the strong heat coupling boundary layer in the CICC.

Acknowledgements

This work is supported by KSTAR project through Korean Ministry of Science and Technology.

References

Anderson, Dale A., Tannehill, J. C. and Pletcher, R. H., 1984," *Computational Fluid Mechanics and Heat Transfer*, Hemispere Publishing Corporation.

Arp, V. D. and McCarty, R. D., Thermophysical Properties of Helium-4 from 0. 8 to 1500 K with Pressure to 200 MPa, NIST Technical Note 1334.

Balsamo, E. P., Bottura, L., Cicchelli, O., Gislon, P., Ricco, M. and Spadoni, M., 1993, "Experimental Analysis and Computer Simulation on Stability Margin and Quench Behavior in a NbTi Forced Cooled Winding Pack," *IEEE Transaction on Magnetics* Vol30, pp. 2142 ~2146.

Bottura, L., 1995, "*Numerical Aspects in the Simulation of Thermohydraulic Transients in CICC's,*" *J. of Fusion Energy*, Vol. 14, pp. 13 ~24.

Bottura, L., 1996, "A Numerical Model for the Simulation of Quench in the ITER Magnets," *J. of Computational Physics*, Vol. 125, pp. 26~41.

Bottura, L. and Zienkiewicz, O. C., 1991, "Quench Analysis of Large Superconducting Magnets," *Cryogenics*, Vol. 32, pp. 719~728.

Boturra, L., Marinucci, C., Luongo, C., Shimada, M., Mitchell, N., Takigami, H., Heller, R., Prestemon, S., Nocollet, S., Duchateau, J. L., Xiao, B. and Latypov, D., 1999, Heat Transfer Corrections, Cryosoft Report, CRYO/99/010.

Buttora, L., EUR-FU XII/185/93

Dresner, L., 1991 Superconductor Stability 90: A Review, *Cryogenics*, Vol. 31, pp. 489~498.

Jiang, H., Oh, S., Ha, D., Ha, H., Bae, J., Kim, S., Ryu, R. and Wang, Q., 1998, "Stability of Triplet NbTi Cable-in-Conduit Conductor," *Proceeding of Korea Electrical Engineering Conference, PEO45*.

Koizumi, N., Takahashi, Y. and Tsuji, H., 1996, "Numerical Model Using an Implicit Finite Difference Algorithm for the Stability Simulation of a Cable-in-Conduit Conductor," *Cryogenics*, Vol. 36, pp. 649~659.

Lue, J. W., 1994, "Review of Stability Experiments on Cable-in-Conduit Conductors," *Cryogenics*, Vol. 34, pp. 779~786.

Luougo, C. A., Loyd, R. J., Chen, F. K. and Peck, S. D., 1988, "Thermal Hydraulic Simulation of Helium Expulsion from a Cable-in-Conduit Conductor," *IEEE Transactions on Magnetics*, Vol. 25, pp. 1589~1595.

Reddy, J. N., 1993, *Finite Element Method*, McGraw Hill, Inc.

Schultz, J. H., 1997, KSTAR Superconducting Magnets System, *KSTAR design point definition workshop, Princeton Plasma Physics Laboratory, USA , pp. 205~243.*

Schultz, J. H., 1998, KSTAR Design Description Document, KSTAR Magnets System review, Samsung Advanced Institute of Technology, Korea , pp. 3~105.

Shaji, A., 1994, PFC/RR-94-5, Plasma Fusion

Center Report.

Shaji, A. and Freiderg, J. P., 1994, "Quench in Superconducting Magnets. I. Model and Numerical Implementation," *J. Applied Physics*, Vol. 76, pp. 3149-3158.

Shaji, A. and Freidberg, J. P., 1996, "Theory of Hybrid Contact Discontinuities," *Physical Review Letter*, Vol. 76, pp. 2710~2713.

Shaji, A., Smith, S. P., Pourahimi, S. and Freidberg, J. P., 1998, "Analysis pf the QUELL Experimant and Comparsions with Numerical Simulations (QUENCHER)," *Cryogenics*, Vol. 38, pp. 479~490.

Tao, W., 1987, *Numerical Heat Transfer*, Xi'an University Publishing Company.

Wang, Q., Oh, S., Ryu, K., Yoon, C. and Kim, K., 1999, "Numerical Analysis on Stability Margin and Quench Behavior in Cable-in-Conduit NbTi Conductor," *IEEE Transactions on Applied Superconductivity*, Vol. 9, pp. 620~624.

Wang, Q., Yoon, C. and Kim, K., 2000, "Analysis on Stability Margin of Nb3Sn Cable in-Conduit Conductor, to be Appeared in *IEEE Transaction on Applied Superconductivity*.

Wilson, M., 1983, Superconducting Magnets, Clarendon Press Oxford.

Wong, Robert, 1989, Program CICC, Flow and Heat Transfer in Cable-in-Conduit Conductor, UCID-2173, Lawrence Livermore National Laboratory.

Zanino, R., De Palo, S., and Bottura, L., 1995, "A Two-Fluid Code for the Thermohydraulic Transient Analysis of CICC Superconducting Magnets," *J. of Fusion Energy*, Vol. 14, pp. 25~40.