Venecia

Advanced modification of VINCENTA

Brief description

Computer Code for Simulation of Thermohydraulics in Cryogenic Systems of Superconducting Magnets

ALPHYSICA

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Brief description

Karlsruhe
2009

Introduction

General description

Design of complex cryogenic systems, in particular, for large superconducting magnets and cryopumps cooled by forced flow, requires accurate modelling of thermohydraulic transients in order to predict helium flow parameters in cooling channels and temperature distribution in different components. The code **VENECIA** is the next generation of the code VINCENTA developed for simulation of transient thermohydraulic processes in superconducting magnet systems cooled by forced flow of single and two-phase helium 4 (He I). VINCENTA has been extensively used for the last 11 years in R&D activities on a number of tokamaks (ITER, KSTAR, JT-60SA) and proved itself as a reliable tool for modelling various cryogenic systems [4-10].

As compared to VINCENTA, the new code enables comprehensive prediction of thermohydraulic behaviour of modern cryogenic systems for both LTS and HTS applications. The code utilizes an extended database of coolants that includes helium 4, helium 2 and nitrogen. The database has a universal format suitable for description of any coolants and may be easily supplemented with a new coolant, even non-cryogenic, such as water. Different coolants can be used in a single calculation model simultaneously.

A complex computational model is built as a combination 1D nonlinear thermohydraulic models for coolant flows and 1D or 2D models for heat diffusion in solid material linked together. Complex models are able to simulate transient behavior of cryogenic systems and superconducting magnet systems simultaneously, with allowance for the realistic magnet geometry, cryogenic accessories, nonlinear thermal properties of coolant and materials. VENECIA is capable of simulation of both “short” transients (stability and quench of conductors, different emergency conditions) and "long" transients (operation modes, cool down, warm up etc.).

Application

The code is applicable for thermohydraulic studies for a wide range of devices including

- thermonuclear facilities,
- accelerators and transport systems,
- MRI-magnets,
- superconducting motors, generators and storage rings,
- experimental and diagnostic devices for scientific research,
- generators,
- superconducting cables and joints.

Validation

The code has been validated using the complex thermohydraulic model of the ITER Central Solenoid Model Coil (CSMC) coupled with external cryogenic circuit [4]. **VENECIA** results have been compared with existing VINCENTA simulations and huge experimental database collected during CSMC tests under pulsed high power heat loads

Excellent match between numerical and physical results in terms of temperature-pressure-flow at more than 50 principal points of the CSMC cooling circuit has proved that **VENECIA** is suitable for thermohydraulic analysis of complex magnet systems.

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Several global **VENECIA** models were developed for the ITER studies on transient thermohydraulic behaviour of the Toroidal Filed (TF) magnet system, Poloidal Field (PF) magnet system, Central Solenoid (CS) magnet system and Correction Coils magnet system with interface elements of their cryogenic system. The models were thoroughly treated for different plasma scenarios and operational modes.

ITER. Toroidal Field Coils

The Toroidal Filed Coil (TFC) model together with the its cooling circuit allows detailed thermohydraulic simulations of the TFC winding pack and structure under different operational conditions including mitigation of pulsed heat load, plasma disruption and fast energy discharge.
Model features:

- individual modelling of 14 cable in conduit conductors (CICC) in a 1-D approximation for the TF winding pack using a two-channel approach;
- individual modelling of external pipes, cryolines, manifolds and heat exchangers in a 1-D approximation;
- the total number of different 1-D objects exceeds 300;
- detailed description of different transient heat loads over 1-D objects;
- quasi-3D simulation of the TFC structures via 2D modelling of 32 cross-sections of the TF case with radial plates and insulation (the total number of mesh nodes exceeds 1,000,000);
- detail description of different transient heat loads over 2D cross-sections;
- modelling of pressure-mass flow rate characteristics of control valves and pumps;
- modelling of a liquid helium bath.

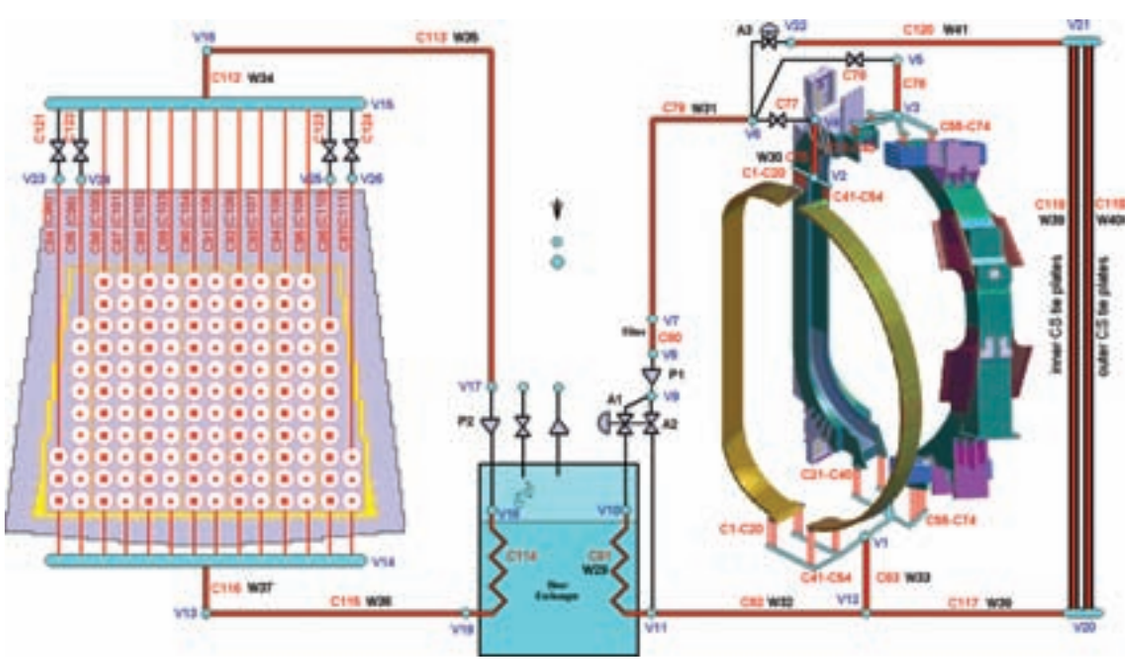

Figure 1. TF coil hydraulic scheme used in VENECIA simulation of normal operation.

Introduction

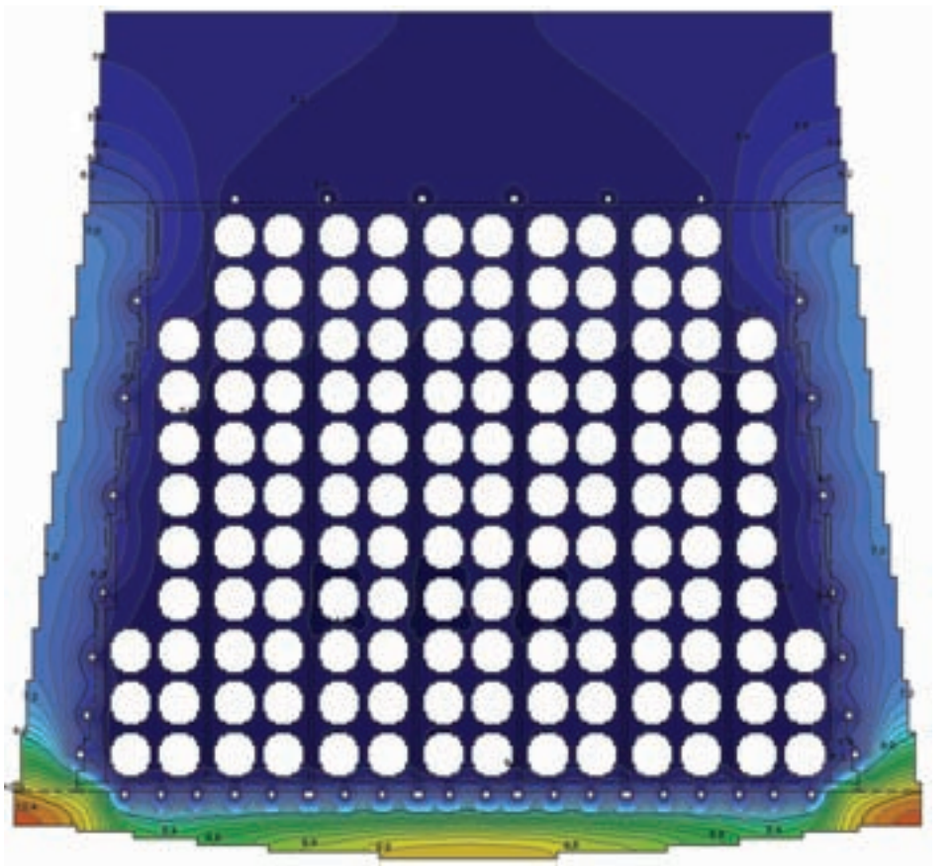

Figure 2. Temperature map for TF model cross-section 9 at 530s of reference plasma ulsing (repetitive mode).

ITER. Central Solenoid and Poloidal Field Coils

VENECIA models for the CS and Poloidal Field Coils (PFC) allow detailed simulations of the CS and PF winding packs thermohydraulic behaviour together with its cooling circuit under different operational conditions.

CS model provides:

- individual modelling in two-channel approach of 240 CICC's in a 1-D approximation for 6 CS winding sections;
- individual modelling of external pipes, cryolines, manifolds and heat exchangers in a 1-D approximation;
- the total number of different 1-D objects exceeds 1000;
- detailed individual description of different transient heat loads over 1-D objects;
- quasi-3D simulation of the CS winding sections via 2D modelling of 6 cross-sections of the CS conduits with insulation (the total number of mesh nodes exceeds 3,500,000);
- modelling of pressure-mass flow rate characteristics of pumps;
- modelling of a liquid helium bath.

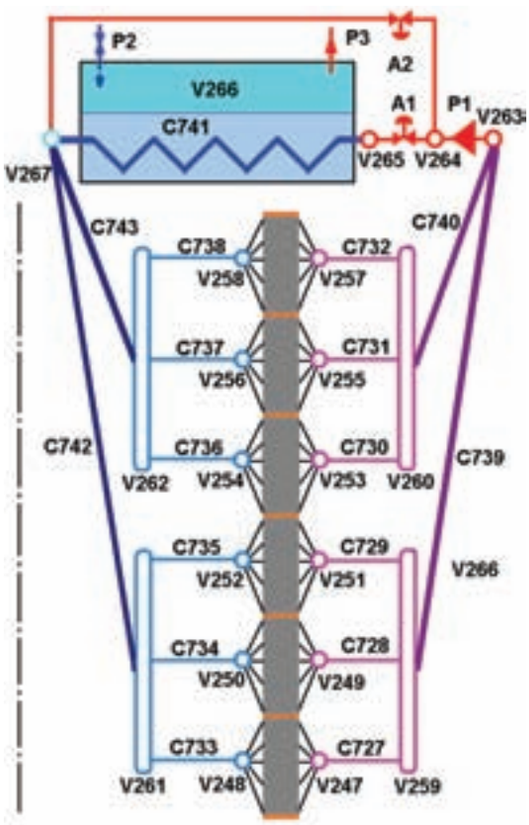

Figure 3. Cooling scheme of the CS coil VENECIA model.

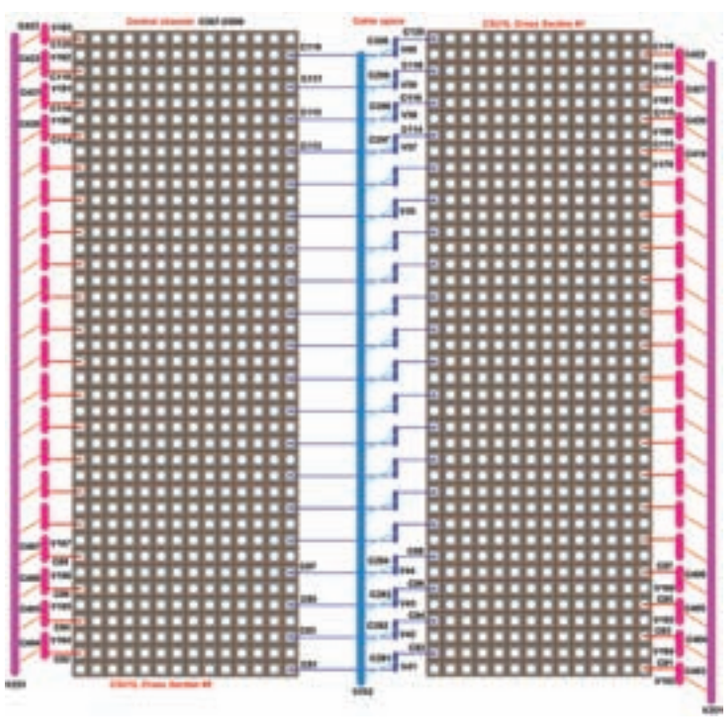

Figure 4. Cooling layouts and cross sections positions for the CS1L coil pancakes.

Introduction

The PF magnet system model features:

- individual modelling in two-channel approach of all CICC's in a 1-D approximation for 6 PF coils;
- each PF's pancake is modelled as wounded by CICC using two-in-hand;
- individual modelling of external pipes, cryolines, manifolds and heat exchangers in a 1-D approximation;
- the total number of different 1-D objects exceeds 800;
- detailed individual description of different transient heat loads over 1-D objects;
- quasi-3D individual modelling each of six PF coils via 2D modelling of their corresponding cross-sections of the PF conduits with insulation (the total number of mesh nodes for 72 cross-sections exceeds 3,100,000);
- modelling of pressure-mass flow rate characteristics of control valves and pumps;
- modelling of a liquid helium bath.

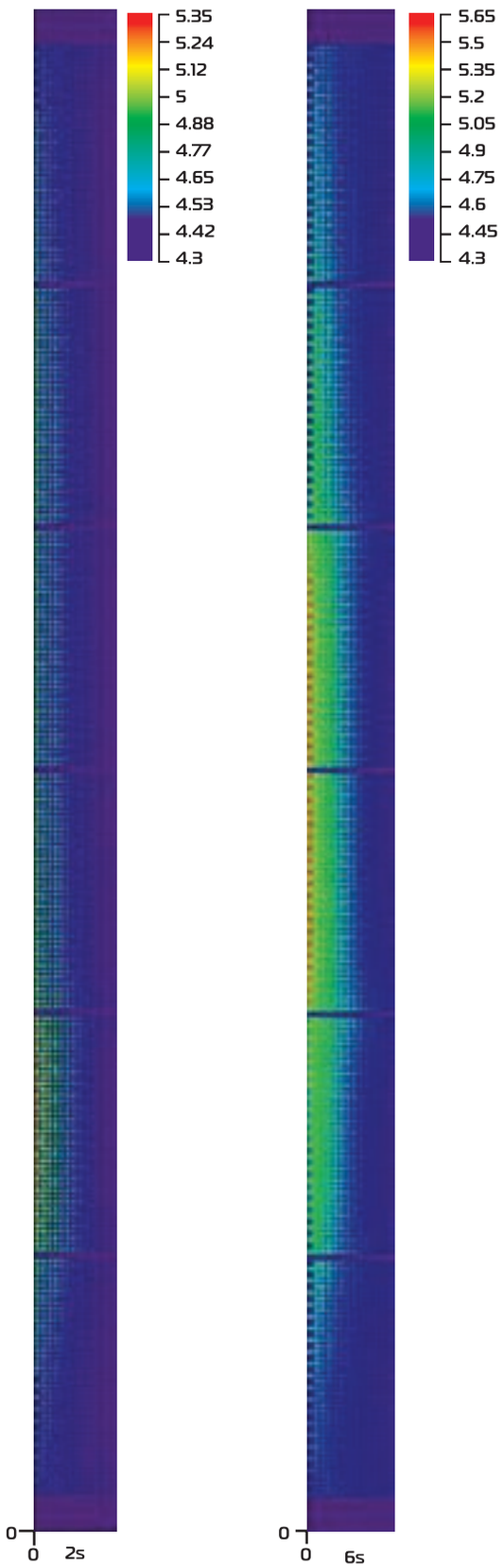

Figure 5. Temperature maps for the CS coil cross section #1 at different time points of simulation.

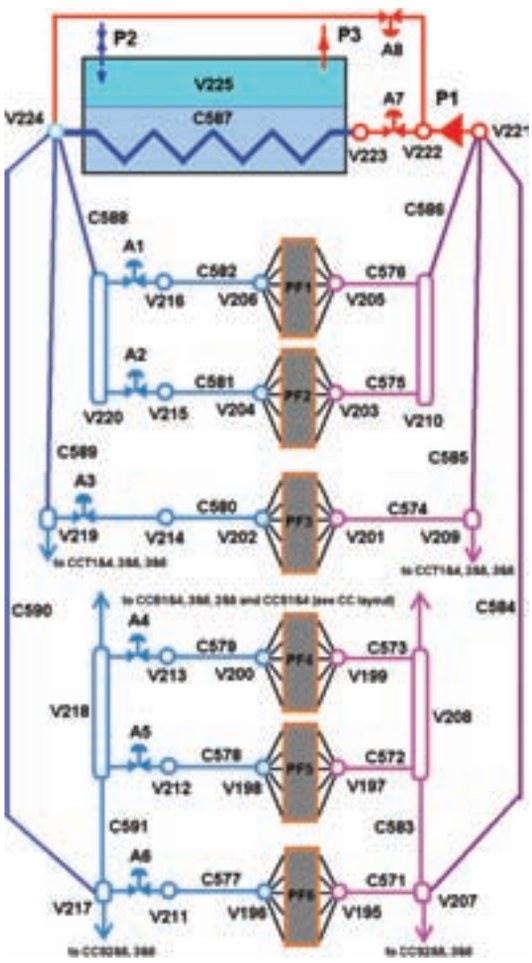

Figure 6. Cooling scheme of the PF magnet system VENECIA model.

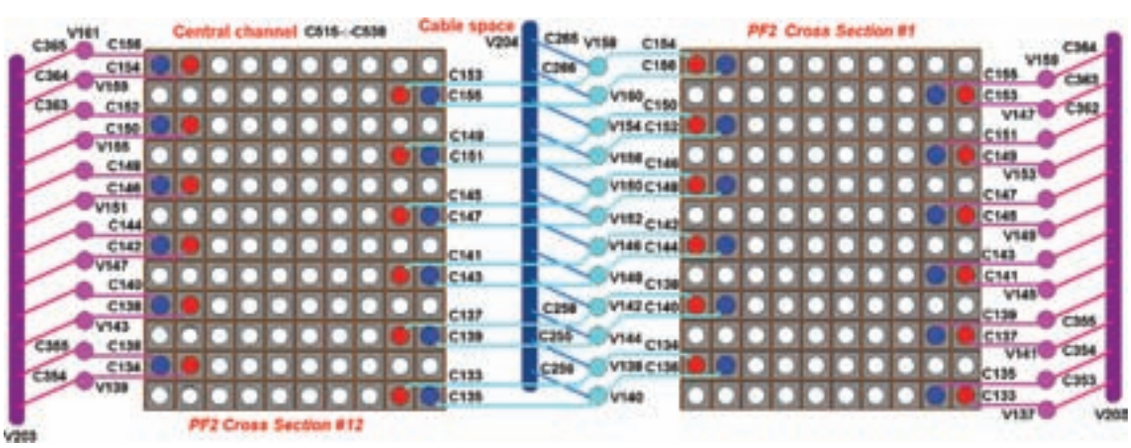

Figure 7. Cooling layout and 2D cross sections for the PF2 coil pancakes. About 23,500 mesh nodes for each of 12 sections (totally 282,000 nodes).

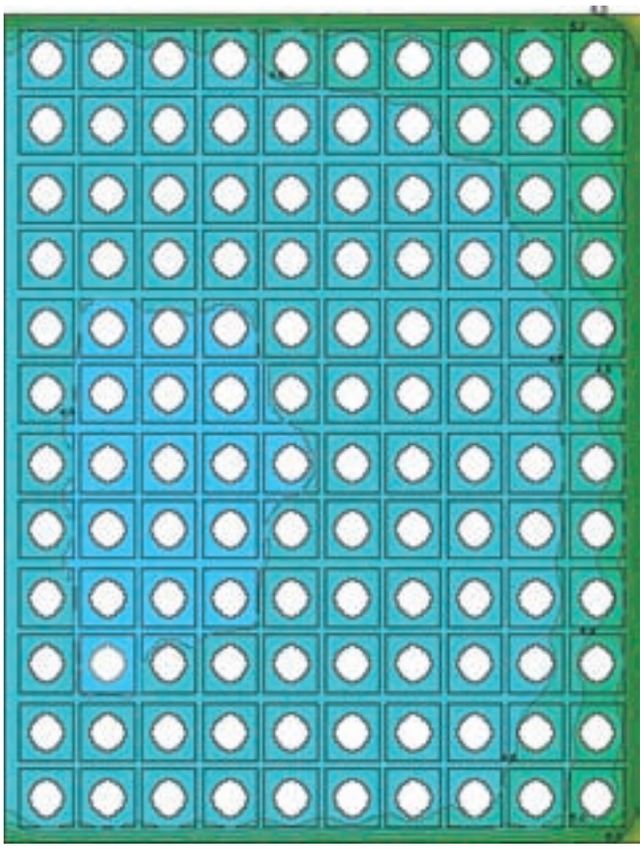

Figure 8. Temperature map for PF2 coil VENECIA model at 1.35s of 4th plasma pulse. Section #6.

AutoCAD meshing.

The models take into account the interturn and interpancake heat transfer (in a limited number of coil cross-sections) and heat load distributions. This permits a qualitative analysis of the cryogenic system necessary to operate these different coils in normal operating conditions (plasma burn, plasma disruption) as well as during fast transients (safety discharge).

VENECIA modelling is supplemented with special 2D meshing techniques. One such technique implements AutoCAD tools in order to generate basic 2D finite-element meshes. These meshes are then treated by **VENECIA** so as to make them consistent with **VENECIA** models. The main steps are:

1. A set of reference points is taken on an AutoCAD drawing.
2. When AutoCAD is running, a dedicated package is started which is consistent with AutoCad and generates a number of additional command for building and modifying a 2D FE mesh.
3. The resultant 2D mesh is in a standard AutoCAD format and can be treated with AutoCad tools.
4. The 2D mesh is then post-processed by **VENECIA** in order to generate a 3D output mesh.
5. The 3D mesh has a DXF format and is suitable for further AutoCAD treatment including generation of a realistic 3D image.

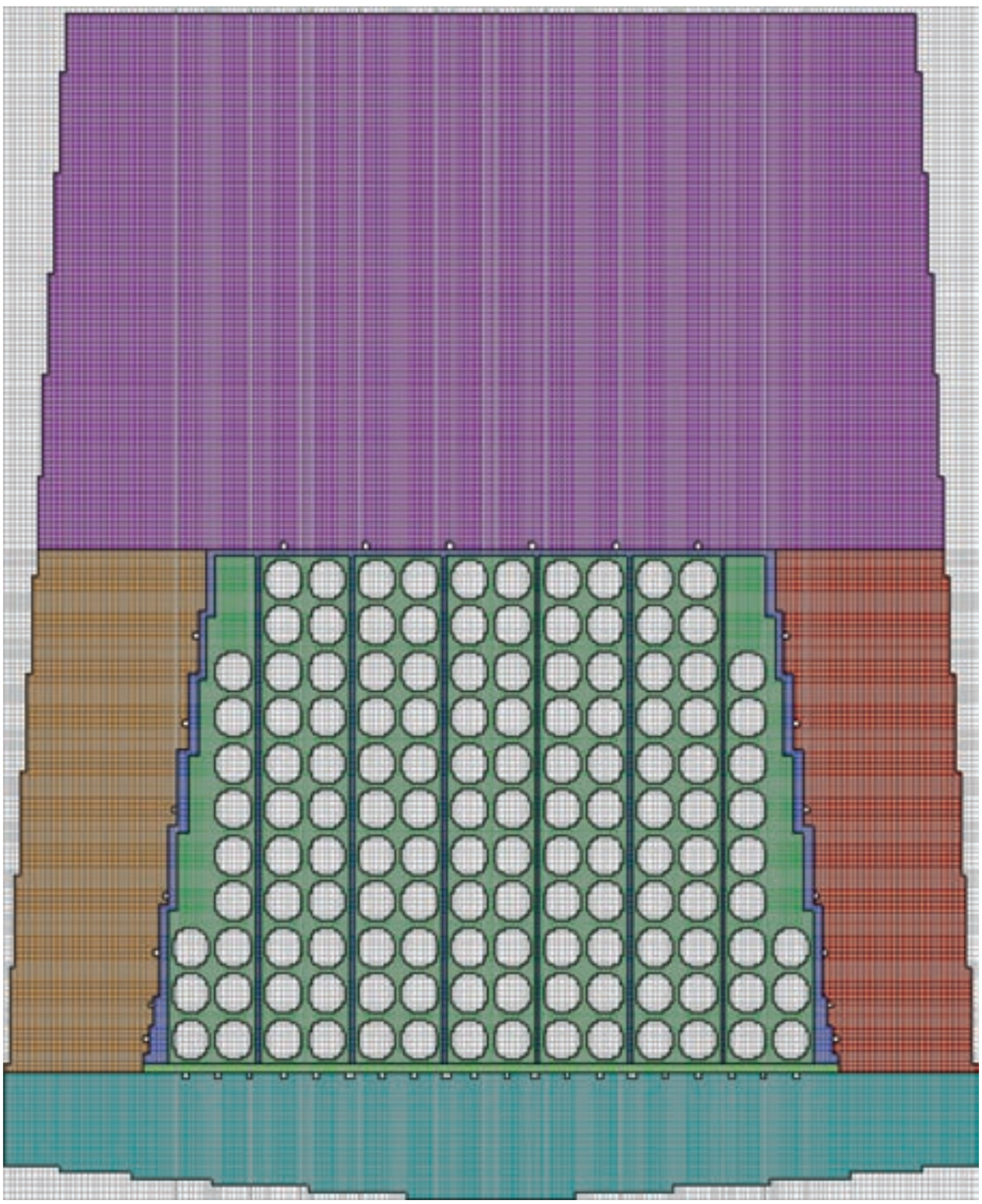

Figure 9. Cross-section No16 for the TF coil model based on AutoCAD meshing.

Structure

Structure of the code and modelling strategy.

VENECIA is aimed to complex thermalhydraulic simulation of superconducting and cryogenic systems, including cryogenic plant elements and armature such as pumps, valves and heat exchangers. A set of basic mathematical models is used to simulate typical components of magnet and cryogenic systems. Each component is described by an individual set of algebraic, differential equations and equations in partial derivatives. The equations are solved using the intrinsic numerical technique. VENECIA implements the following basic models:

- helium flow
- conductor
- collector
- valve
- solid
- etc.

Helium flows are modeled using a 1-D approximation. Solid materials are described with 2D models. The number of basic models of each type used in simulations depends only on task specifics and adopted assumptions and approach. A global calculation model of a real magnet with its cooling system is constructed from these basic models by linking them to each other. The general structure of VENECIA models is shown in 9.

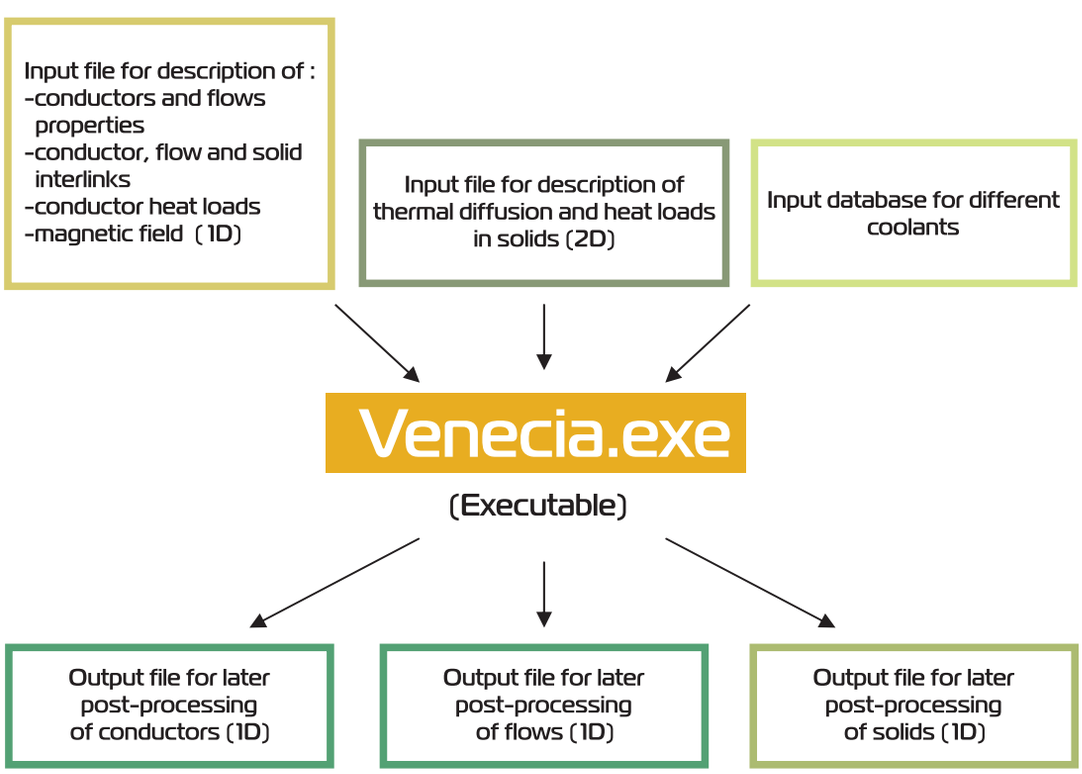

Figure 10. General structure of a VENECIA calculation model.

Each basic model (helium flow, valve, etc…) has a fixed argument list which provides an adequate description of the component to cover typical operation conditions. To simulate the loading conditions each model is linked with a standardized data set defining the loading modes and magnitudes. These data are implemented in VENECIA via the NAMELIST module, which is a unificated core of the code. NAMELIST should be modified solely if new basic models are added to VENECIA.

These program elements do not provide a general formalism for all possible designs and operating modes. However, due to simple module structure of the code, **VENECIA** simulation capabilities are easily extendable to a specific demand. Practical experience of **VENECIA** users evidences that **VENECIA** allows implementation of global models for complex superconducting magnet systems. An adequate modeling of thermohydraulic behavior of superconducting systems involves detailed description of variations and distributions for a variety of loads. These data from different sources collected are typically supplied in different formats, which necessitate additional efforts to standardize the database for the simulations. Although suffering from obvious drawbacks, this approach offers very flexible data treatment and formatting.

VENECIA model describes the network of different components (or “lego” assembly) which could be coupled between themselves through the different kind of links and associated through boundary conditions with 2-D cross-sections in which the thermal diffusion problem considered, thus obtaining a quasi-3D code.

The code provides a linkage of 1-D and 2D models within a single algorithm using a semi-implicit method to integrate and solve the equations. The model discretization varies over a wide range, depending on the nature of problem and accuracy required.

Interface.

As the bulk of Venecia and Vincenta simulations has been performed by the code authors, development of a user-friendly version was not an immediate task. Now a more comfortable interface is under development.

On demand, an user interface oriented for a specific task/project or consistent with popular commercial programs such as Excel, AutoCAD etc can be created.

Mathematical models

Helium flow modelling.

The core of the program consists in the description of the helium flow in channels, possibly coupled (exchange of mass and energy), also possibly coupled with walls (or conductors) which can also be coupled to each other. The helium flow model *channel* simulates transient parameters of a compressible helium flow inside a channel. *Channel* is described by a set of 1-D equations of continuity, momentum and energy conservation laws completed with the transverse mass, momentum and energy transfer terms to take into account the thermal-hydraulic coupling with different flows and solid materials. Generally, the helium flow in a channel can simultaneously have a thermal contact with some various solid materials and helium in other channels. Besides, different helium flows inside channels can be hydraulically coupled between themselves in the longitudinal direction (due to the transverse holes) as, for example, in the Cable-In-Conduit Conductor (CICC) with a central channel. The final set of equations describing a transient process for helium flow in the *i* channel in terms of interaction with flows in *k* channels and *m* conductors has a form:

$$\frac{\partial \rho_i}{\partial t} + \frac{\partial \rho_i V_i}{\partial x} = \frac{\sum_k \Gamma_{ki}^{\rho}}{A_i} \tag{1}$$

$$\frac{\partial \rho_i V_i}{\partial t} + \frac{\partial}{\partial x}\left(P_i + \rho_i V_i^2\right) = \frac{-2 f_i \rho_i V_i |V_i|}{D_{h_i}} + \rho_i F_i(x) + \frac{\sum_k \Gamma_{ki}^{\rho V}}{A_i} \tag{2}$$

$$\frac{\partial}{\partial t}\rho_i\left(H_i + \frac{V_i^2}{2} - \frac{P_i}{\rho_i}\right) + \frac{\partial}{\partial x}\rho_i V_i\left(H_i + \frac{V_i^2}{2}\right) = \frac{\sum_m Q_{mi}^{conv} + \sum_k \Gamma_{ki}^{\rho H}}{A_i} + \rho_i V_i F_i(x) \tag{3}$$

where ρ, P, H, V – helium density, pressure, enthalpy and velocity accordingly; f – friction factor; A – helium cross-sectional area; D_h – hydraulic diameter; Q_{mi}^{conv} – convective heat transfer from conductor *m* to helium *i* per unit of length; $\Gamma_{ki}^{\rho} = -\Gamma_{ik}^{\rho}$, $\Gamma_{ki}^{\rho V} = -\Gamma_{ik}^{\rho V}$, $\Gamma_{ki}^{\rho H} = -\Gamma_{ik}^{\rho H}$ – mass, momentum and enthalpy flux from *k* to *i* channel (and vice versa), $\rho_i F_i(x)$ – volumetric force applied to helium in *i* channel.

To determine a transverse mass flux it is assumed that the pressure difference between coupled flows is small enough. In such approach the local transverse mass and enthalpy flux from *k* to *i* flow can be obtained in the following simple form:

$$\Gamma_{ki}^{\rho} = S_{ki} \cdot \begin{cases} \sqrt{2(P_k - P_i)\rho_k}, & P_k > P_i \\ -\sqrt{2(P_i - P_k)\rho_i}, & P_k < P_i \end{cases},$$

$$\Gamma_{ki}^{\rho H} = \Gamma_{ki}^{\rho} \cdot \begin{cases} H_k + V_k^2/2, & \Gamma_{ki}^{\rho} > 0 \\ H_i + V_i^2/2, & \Gamma_{ki}^{\rho} < 0 \end{cases}.$$

where S_{ki} is a coefficient with the dimensionality of cross-section area per unit of length between *k* and *i* flows. As the transverse mass flux from *k* flow is suggested to be normal to *i* flow, the momentum transport term is negligible (i.e. $\Gamma_{ki}^{\rho V} = -\Gamma_{ik}^{\rho V} = 0$).

Such description of the transfer processes between flows is applicable to modelling mass and energy exchange if an assumption of a small pressure drop between flows is valid (transverse cross area is large enough). The advantage of this model is a possibility to

analyze the influence of transverse coupling on thermal and hydraulic parameters of coupled flows and to estimate the transverse mass and energy transport term.

The following boundary conditions are used to close the system (1)-(3). The helium pressures at the ends of the *channel* are supposed to be identical to pressures in joined *collectors*. When helium enters the *channel*, the helium enthalpy at an appropriate end of the *channel* is assumed to be equal to the enthalpy in the joined collector. At the closed end of the tube the helium velocity assumed to be zero.

Conductor modelling.

A transient temperature distribution in conductor components is described by a 1-D equation of heat balance with the transverse conductive and convective heat exchange and Joule heating terms. A temperature distribution across the conductor section is assumed to be uniform. Uniform temperature distribution is a “natural” assumption for a 1-D approach and treated as an average temperature for the given cross-section. In the general case, *conductor* could have simultaneously a contact with different helium flows as well as with other *conductors*. So the equation for a binary conductor *m* including the heat exchange with conductors *n* and helium flows *i* has a form:

$$\left(A_m^1 C_m^1 + A_m^2 C_m^2\right)\frac{\partial T_m}{\partial t} = -\cos^2\theta\frac{\partial}{\partial x}\left(\left(A_m^1 k_m^1 + A_m^2 k_m^2\right)\frac{\partial T_m}{\partial x}\right) + Q_m^{Joule} + \sum_i Q_{im}^{conv} + \sum_n Q_{nm}^{cond} + \sum_k Q_{km}^{wall} \quad (4)$$

$$Q_m^{Joule} = \frac{I_{op}^2}{\left(\sigma_m^1 A_m^1 + \sigma_m^2 A_m^2\right)\cos^2\theta} g(T_m),$$

$$g(T_m) = \begin{cases} 0, T_m < T_{cs} \\ 1 - \dfrac{I_c(T_m)}{I_{op}}, T_{cs} < T_m < T_c \\ 1, T_m > T_c \end{cases} \quad (5)$$

$$Q_{im}^{conv} = h_{im} \cdot \gamma_{im} \cdot (T_i - T_m) \quad (6)$$

$$Q_{nm}^{cond} = h_{nm} \cdot \gamma_{nm} \cdot (T_n - T_m) \quad (7a)$$

$$Q_{km}^{wall} = \gamma_{km} \cdot k_k^{wall} \frac{\partial}{\partial r}\left(T^{wall}(x, r)\right) \quad (7b)$$

where T, C, k, A^1+A^2 – conductor temperature, heat capacity, thermal conductivity and cross-section area of components accordingly; h, γ –coefficient and perimeter of heat exchange; Q_{nm}^{cond} –conductive heat transfer from the conductors *n* and *m* per unit of length; Q_{im}^{conv} - convective heat transfer from helium in the channel *i* to the conductor *m* per unit of length; Q_m^{Joule} - Joule heating of the conductor *m* per unit of length; Q_{km}^{wall}, k^{wall}, T^{wall} - heat flux to the wall *k*, thermal conductivity and temperature of the wall *k*, correspondingly; I_{op} - conductor current; σ - conductor electrical conductance; I_c, T_c, T_{cs} - critical current, critical temperature and current sharing temperature, accordingly.

Mathematical models

In these equations the material cross-section A_m is treated as the cross-section in a plane normal to the conductor axis ("twisted" cross-section). The same assumption is applied to the material heat exchange perimeter γ_m. It is taken that the "twisted" material cross-section and the perimeter (for twisted superconducting strands) used in the above equations are defined as $A_{tw} = A_{non\ tw}/cos\theta$ and $\gamma_{tw} = \gamma_{non\ tw}/cos\theta$, where $\theta>0$ is an average twist angle. This generalized angle takes into account the average twist of cabling stages. For non-twisted materials $\cos\theta =1$.

The following boundary conditions are used to close equation (4). The temperatures at the ends of the conductor are defined through temperature of connected joints by boundary condition of third kind:

$$\kappa_m \frac{\partial T_m}{\partial x} + h_i \cdot \left(T_m - T_j^{jo\,\mathrm{int}}\right) = 0 .$$

Collector modelling.

The mathematical model *collector* is intended for 0-D simulation of helium behaviour in a collector and used as a node element for connecting different *channels* and *valves* in series-parallel to one another. The laws of mass and energy conservation define the helium behaviour inside the collector. For the collector *i* the following equations are used:

$$\Omega_i \frac{d\rho_i}{dt} = \sum_k G_{ki}^{\rho} + \sum_n G_{ni}^{\rho} \qquad (8)$$

$$\Omega_i \frac{d}{dt}\left(\rho_i H_i - P_i\right) = \sum_k G_{ki}^{\rho H} + \sum_n G_{ni}^{\rho H} + \sum_m Q_{mi}^{conv} \qquad (9)$$

where Ω – collector volume; ρ, P, H – helium density, pressure and enthalpy correspondingly; $G_{ki}^{\rho}, G_{ni}^{\rho}$ - mass flow from the channel *k* and the valve *n* to the collector *i*; $G_{ki}^{\rho H}, G_{ni}^{\rho H}$ - enthalpy flow from the channel *k* and the valve *n* to the collector *i*; Q_{im}^{conv} - convective heat exchange between helium in the collector *i* and the joint *m*.
The mass flow terms in (8) are assumed to be positive if the flow is coming into the collector considered and vice versa. The energy term in (9) is defined as

$$G_{ki}^{\rho H} = G_{ki}^{\rho} \times \begin{cases} H_k + V_k^2/2, & G_{ki}^{\rho} > 0 \\ H_i & G_{ki}^{\rho} < 0 \end{cases} ,$$

where H_k, V_k are enthalpy and velocity of helium outbound at the end of the channel *k* connected to the collector *i*. The same equation takes place for an energy flow from a valve.

Valve modelling

The model *valve* is intended for calculation of a He mass flow through cryogenic elements, such as valves, holes, gaps, etc. It is assumed that mass flow through the *valve* is forced by pressure difference in pare collectors to which it is connected.

To associate the mass flow through the valve with the thermodynamic properties of helium in both collectors we use a simplest classical conception. The flow through the valve is modelled as isentropic expansion ($\delta H - \delta P/\rho = 0$) of the compressible fluid from the inlet pressure (before the valve) to the outlet pressure. Depending on a pressure drop between the inlet/outlet the outlet valve pressure is equal to the outside pressure (sub-critical flow out) or critical pressure (critical flow out, the outlet velocity is equal to the local sonic speed). In both cases, the full enthalpy ($h+u^2/2$) of the flow under the isentropic expansion is conservative, that allows calculation of all thermodynamic characteristics of the outlet flow. Two basic parameters are assigned for the valve: the minimum cross-section area A of the valve (which depends on the valve lift) and correction factor μ to take into account a non-isentropic expansion.

For a sub-critical flow the pressure at the valve outlet is equal to the pressure in the outlet collector. In the case of the critical flow the outlet pressure is equal to the critical one. So, for calculation of helium properties in the valve outlet k the following system of equations is used:

$$H_k + \tfrac{1}{2}U_k^2 = H_\Omega^{in}, S_k = S_\Omega^{in} \tag{10}$$

$$P_k = \begin{cases} P_\Omega^{out}, U_k < C_k \\ P_k^{crit}, U_k = C_k \end{cases} \tag{11}$$

$$G_k = \mu_k A_k \rho_k U_k \tag{12}$$

where H_k, U_k, P_k, ρ_k is the enthalpy, velocity, pressure and density of helium at the valve outlet; H_Ω^{in}, S_Ω^{in} is the enthalpy and entropy of helium in the inlet collector; P_Ω^{out} is the pressure in the outlet collector and P_k^{crit} is the critical pressure in the valve outlet. For a real non-isentropic flow the correction factor $\mu_k < 1$ is used.

The set of additional parameters allows control of the valve lift depending on the pressure variations in adjoining collectors applicable for modelling the multi-purpose valves.

Modelling of solids.

To simulate transient heat diffusion in the winding composite a 2D model is used in the Cartesian or axial-symmetrical approach. A differential equation for temperature over the given cross-section S of the winding k is:

$$C_k(T)\frac{\partial T_k}{\partial t} = q_{V\,k}(x,r,t) + \\ + \frac{\partial}{\partial x}\left(\kappa_k(T)\frac{\partial T_k}{\partial x}\right) + \frac{1}{r^n}\frac{\partial}{\partial r}\left(\kappa_k(T)\cdot r^n \frac{\partial T_k}{\partial r}\right) \quad , for\, S \times S_t \tag{13}$$

$$T_k(x,r,0) = \psi(x,r), \quad t = 0,$$

n=0 – Cartesian coordinates; n=1 – cylindrical coordinates.

The boundary condition of the third kind is formulated for the *section k* having heat exchange with helium flow *i*

$$\kappa_k \frac{\partial T_k}{\partial n} + h_i \cdot \left(T_k - T_i^{He}\right) = 0$$

where h_i is the heat transfer coefficient and T_i^{He} is the corresponding temperature of helium inside the *channel i*. At the outer surface of the winding the appropriate boundary condition is formulated.

Pump modelling.

The pumping process is modelled as adiabatic compression of fluid from inlet pressure P_{in} to outlet pressure P_{out}. The enthalpy change from H_{in} to H_{out} assumed to be isentropic during compression. The coefficient η=70% is used to take into account non-isentropic expansion for the H_{out} calculation.

In the general case, the mass flow rate through the pump is a function of the pressure head dictated by the given characteristic of the pump. The mass flow rate varies in accordance with SHe enthalpy and pressure in adjacent collectors before and after the pump.

Some simulations were performed for a centrifugal pump using approximation formulae derived from experimental results. A typical operational curve $\dot{m}$ =f(*P*) of the centrifugal pump is approximated by the formula

$$\left(\frac{m_{op}}{m_{\max}(rpm)}\right)^{1.4} + \left(\frac{\Delta P_{op}}{\Delta P_{\max}(rpm)}\right)^{1.9} = 1,$$

where: m_{op} , ΔP_{op} - operational mass flow rate and pressure head, accordingly; m_{max}, ΔP_{max} - maximal mass flow rate and pressure head for the given rotational speed,: $m_{max}(rpm) = m_{max0}*(rpm/rpm0)$ and $\Delta P_{max}(rpm)=\Delta P_{max0}*(rpm/rpm0)^2$.

A set of another VENECIA models is used to close the described models by linking them to each other. These models describe a variety of insulation elements, perforation etc. New models could be easy added, if necessary.

Coolant properties.

Coolant properties are calculated from the unified coolants database. The base consists of a set of tables prepared for each coolant from a known source [2]. Enthalpy *H* and pressure *P* are accepted as independent variables for these tables and form a common 2D mesh for all thermodynamic and thermo-physical properties of the coolant. Special subroutines provide an appropriate approximation accuracy of 0.2% for coolant properties in arbitrary (P,H)-point. A two-phase coolant region is simulated as a homogenous mixture. An equation of state for such mixture has a form

$$1/\rho_{\text{homo}}(P,H) = 1/\rho'(P) + \left[1/\rho''(P) - 1/\rho'(P)\right] \cdot \left[H - H'(P)\right] / \left[H''(P) - H'(P)\right], \quad (14)$$

where ρ', ρ'', are the liquid and vapor coolant densities on the boundary line of coolant TS-diagram; *H'*, *H''* are the liquid and vapor enthalpies as a function of pressure *P*.

Numerical solution

For computations, the analysis equations (1)-(3), (8), (9) were re-written in the non-conservative form using pressure P, enthalpy H and velocity V as flow variables. The Gruneisen parameter ϕ and isentropic speed of sound c were introduced in the equations [1]. Using the basic thermodynamic identity

$$d\rho = \left(\frac{\partial \rho}{\partial P}\right)_H dP + \left(\frac{\partial \rho}{\partial H}\right)_P dH = \frac{1+\phi}{c^2} dP - \frac{\phi \rho}{c^2} dH ,$$

the equations (1)-(3) are transformed to the form

$$\frac{\partial P_i}{\partial t} = -V_i \frac{\partial P_i}{\partial x} - \rho_i c_i^2 \frac{\partial V_i}{\partial x} + \frac{c_i^2 \sum_k \Gamma_{ki}^{\rho}}{A_i} + \\ + \frac{\phi_i}{A_i}\left[\sum_m Q_{mi}^{conv} + \sum_k \Gamma_{ki}^{\rho H} + \left(\frac{V_i^2}{2} - H_i\right)\sum_k \Gamma_{ki}^{\rho} + \frac{2 f_i \rho_i V_i^2 |V_i|}{D_{h_i}} A_i\right] , \quad (15)$$

$$\frac{\partial H_i}{\partial t} = -V_i \frac{\partial H_i}{\partial x} - c_i^2 \frac{\partial V_i}{\partial x} + \frac{c_i^2 \sum_k \Gamma_{ki}^{\rho}}{\rho_i A_i} + \\ + \frac{1+\phi_i}{\rho_i A_i}\left[\sum_m Q_{mi}^{conv} + \sum_k \Gamma_{ki}^{\rho H} + \left(\frac{V_i^2}{2} - H_i\right)\sum_k \Gamma_{ki}^{\rho} + \frac{2 f_i \rho_i V_i^2 |V_i|}{D_{h_i}} A_i\right] , \quad (16)$$

$$\frac{\partial V_i}{\partial t} = -V_i \frac{\partial V_i}{\partial x} - \frac{1}{\rho_i}\frac{\partial P_i}{\partial x} - \frac{2 f_i V_i |V_i|}{D_{h_i}} + F_i(x) - \frac{V_i \sum_k \Gamma_{ki}^{\rho}}{\rho_i A_i} , \quad (17)$$

$$t \in [0, \infty), \quad x_{(i)} \in [0, L_i] ,$$

where

$$c^2 = \frac{1}{\left(\frac{\partial \rho}{\partial P}\right)_H + \frac{1}{\rho}\left(\frac{\partial \rho}{\partial H}\right)_P} , \quad (18)$$

$$\phi = -\frac{c^2}{\rho}\left(\frac{\partial \rho}{\partial H}\right)_P . \quad (19)$$

Equations (8) and (9) are re-written as

$$\frac{dP_i}{dt} = \frac{\phi_i\left[\sum_m Q_{im} + \sum_k G_{ki}^{\rho H} - H_i \sum_k G_{ki}^{\rho}\right] + c_i^2 \sum_k G_{ki}^{\rho}}{\Omega_i} , \quad (19)$$

Numerical solution

$$\frac{dH_i}{dt} = \frac{(1+\phi_i)\left[\sum_m Q_{im} + \sum_k G_{ki}^{\rho H} - H_i \sum_k G_{ki}^{\rho}\right] + c_i^2 \sum_k G_{ki}^{\rho}}{\rho_i \Omega_i} \qquad (20)$$

So, the time derivatives for different helium parameters are separated and assigned in explicit form.

All equations related to *channels* and *conductors* are represented via finite differences with respect to the space variable *x* using the following approximation for the first and second order derivatives in a mesh node "*i*"

$$\frac{\delta Y_i}{\delta x} = \frac{8 \cdot (Y_{i+1} - Y_{i-1}) - (Y_{i+2} - Y_{i-2})}{12 \cdot h} + o(h^5) , \qquad (21)$$

$$\frac{\delta^2 Y_i}{\delta x^2} = \frac{16 \cdot (Y_{i+1} - Y_{i-1}) - 30 \cdot Y_i - (Y_{i+2} - Y_{i-2})}{12 \cdot h^2} + o(h^4) , \qquad (22)$$

where *h* is a step of uniform spatial discretization. A special attention is paid to approximation of derivatives in the boundary nodes. In **VENECIA,** this approximation is significantly improved and allows provide stable calculation for very fast process at the boundaries (explosion of pipe etc.). As a result of such discretization procedure, the initial system of three partial differential equations for the *P-H-V channel* parameters is transformed into 3*N* ordinary differential equations for the parameters in the mesh nodes with respect to time.

The number of steps (nodes) on the space variable *x* is arbitrary and individual for each *channel*. For the *channels* coupled by heat and mass transfer in the longitudinal direction the number of nodes should be identical.

Integration of the complete system of ordinary differential equations $\frac{d}{dt}\mathbf{Y} = \mathbf{f}(t,\mathbf{Y})$, concerning *P*, *H*, *V* and *T* variables for all nodes of all *channels* and *conductors* (including all equations for *collectors*), is performed by the RK4 method

$$\mathbf{Y}^{t+\tau} = \mathbf{Y}^t + \tau\cdot(\mathbf{k}_1+2\mathbf{k}_2+2\mathbf{k}_3+\mathbf{k}_4)/6 ,$$

$$\mathbf{k}_1 = \mathbf{f}(t, \mathbf{Y}^t) ,$$

$$\mathbf{k}_2 = \mathbf{f}(t+\tau/2, \mathbf{Y}^t+\tau\mathbf{k}_1/2) , \qquad (23)$$

$$\mathbf{k}_3 = \mathbf{f}(t+\tau/2, \mathbf{Y}^t+\tau\mathbf{k}_2/2) ,$$

$$\mathbf{k}_4 = \mathbf{f}(t+\tau, \mathbf{Y}^t+\tau\mathbf{k}_3) ,$$

where τ is the time step for integration.

The numerical method for solving equation (14) is based on a semi-explicit spliting-up method for parabolic partial differential equations [3].

Summary

1. VENECIA enables numerical simulation of transient behavior of superconducting magnet systems as whole making allowance for:

- real geometry of magnet structure
- real nonlinear properties of materials
- real coolant properties
- real cryogenic accessories.

2. Efficient and adequate simulation is possible for both

- “short” transients (stability and quench of conductors etc.)
- "long" transients (operating modes, cool down, warm up etc.) to be modeled both for the entire cryoplant and components.

The code makes it possible to consider a realistic arrangement of the cryoplant accessories (valves, pumps etc.). 1D and 2D models are combined within a single algorithm. The model detalization is variable over a wide range, depending on the nature of problem and accuracy required.

A time pitch is dictated by the nature of transient processes and approximation conditions. It may be as much as tens of seconds.

Simulations of the ITER of TF,CS and PF magnets demonstrated that the run time for complex thermohydraulic models usually does not exceeds a day and night at an up-to-date PC.

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Venecia

Advanced modification of VINCENTA

Brief description

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