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# VENECIA: New Code for Simulation of Thermohydraulics in Complex Superconducting Systems

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An advanced computer code VENECIA is introduced intended for simulation of thermohydraulic transients. The code uses an extended database for a range of compressible coolants and capable of prediction of behaviour of both superconducting and warm magnet systems. Basic features of the VENECIA thermo-diffusion and thermohydraulic modelling are described. A computational model for the ITER toroidal field coil is presented.

**Key words and phrases:** computer code, superconducting system, thermo-hydraulic transients, coolants, cooling channel, heat load, cable-in-conduit conductor.

## 1. Introduction

In 1998 the computer code VINCENTA [1] was introduced for full scale thermohydraulic simulations of transients in ITER [2] superconducting magnets and their cryogenic systems. The code was intensively used for detailed modelling of the ITER coils as well as multiparameter analysis and design/operation optimisation. Originally, the code was strictly ITER-oriented, however, constantly growing computational complexity and demand for new applications initiated its radical modification. The advanced code named VENECIA is based on the database approach and has an extended range of use and new functionalities. VENECIA enables detailed modelling of thermo-hydraulic transients for both superconducting and warm magnet systems, in a whole and in their components, using realistic geometry and operational conditions. An efficient algorithm makes it possible to analyse behaviour of a range of compressible coolants ($He^4$, N, water) under a variety of conditions. Different coolants can be used in a single calculation model simultaneously.

## 2. VENECIA: structure and modelling strategy

VENECIA is aimed to complex thermo-hydraulic simulation of superconducting and cryogenic systems, including cryogenic plant elements and armature such as pumps, valves and heat exchangers. The code uses a multi-level modular approach to modelling. Basic mathematical sub-models for typical elements of magnet and cryogenic systems (coolant flow, conductor, collector, valve, pump etc) are linked in a complex global model taking into account their hydraulic and thermal coupling. Each sub-model is described by an individual set of algebraic, differential equations and equations in partial derivatives. The equations are solved using an intrinsic numerical technique. Coolant flows are modeled using a 1D approximation. Solid materials are described with 1D and 2D models.

The code is based on a database concept. The inputs for computation are arranged as unified databases for typical coolants and solids that can be easily updated or extended. Due to a modular structure of the code, VENECIA simulation capabilities are easily extendable to a specific demand. Such modelling allows due regard for

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properties of different materials, non-linear effects or geometry specifics. Also, the code uses space and time variations for various heat loads.

As compared to VINCENTA, VENECIA is a more flexible and efficient code applicable 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.

# 3. Principal mathematical models

### Coolant

The core of the code is a description of coolant flows, possibly coupled via mass and energy exchange to each other and solid components. The basic set of non-conservative equations of continuity, momentum and energy is completed with the transverse mass, momentum and energy transfer terms to take into account the thermal and hydraulic coupling. In 1D approximation, transient behaviour of a coolant flow $i$ interacting with $k$ flows and $m$ solids is described in a form:

$$\begin{aligned}\frac{\partial P_i}{\partial t} &= -V_i\,\frac{\partial P_i}{\partial x} - \rho_i\,c_i^2\,\frac{\partial V_i}{\partial x} + \frac{c_i^2 \sum\limits_k \Gamma^{\rho}_{ki}}{A_i} + \\ &+ \frac{\phi_i}{A_i}\left[\sum_m Q^{\text{conv}}_{mi} + \sum_k \Gamma^{\rho H}_{ki} + \left(\frac{V_i^2}{2} - H_i\right)\sum_k \Gamma^{\rho}_{ki} + \frac{2 f_i\,\rho_i\,V_i^2\,|V_i|}{D_{h_i}}\,A_i - \right. \\ &\left. - \rho_i\,V_i\,F_i(x)\,A_i - A_i\,\frac{\partial q_{\text{He}_{\text{II}}\,i}}{\partial x}\right], \qquad (1)\end{aligned}$$

$$\begin{aligned}\frac{\partial H_i}{\partial t} &= -V_i\,\frac{\partial H_i}{\partial x} - c_i^2\,\frac{\partial V_i}{\partial x} + \frac{c_i^2 \sum\limits_k \Gamma^{\rho}_{ki}}{\rho_i\,A_i} + \\ &+ \frac{1+\phi_i}{\rho_i\,A_i}\left[\sum_m Q^{\text{conv}}_{mi} + \sum_k \Gamma^{\rho H}_{ki} + \left(\frac{V_i^2}{2} - H_i\right)\sum_k \Gamma^{\rho}_{ki} + \frac{2 f_i\,\rho_i\,V_i^2\,|V_i|}{D_{h_i}}\,A_i - \right. \\ &\left. - \rho_i\,V_i\,F_i(x)\,A_i - A_i\,\frac{\partial q_{\text{He}_{\text{II}}\,i}}{\partial x}\right],\end{aligned}$$

$$\frac{\partial V_i}{\partial t} = -V_i\,\frac{\partial V_i}{\partial x} - \frac{1}{\rho_i}\,\frac{\partial P_i}{\partial x} - \frac{2 f_i\,V_i\,|V_i|}{D_{h_i}} + F_i(x) - \frac{V_i \sum\limits_k \Gamma^{\rho}_{ki}}{\rho_i\,A_i}\,,$$

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

Here $\rho$, $P$, $H$, $V$ are the coolant density, pressure, enthalpy and velocity accordingly; $f$ is the friction factor; $A$ is the coolant flow cross-sectional area; $D_h$ is the hydraulic diameter; $Q^{\text{conv}}_{mi}$ is the convective heat transfer from 1D solid $m$ to flow $i$ per unit of length; $\Gamma^{\rho}_{ki} = \Gamma^{\rho}_{ik}$, $\Gamma^{\rho V}_{ki} = \Gamma^{\rho V}_{ik}$, $\Gamma^{\rho H}_{ki} = \Gamma^{\rho H}_{ik}$ are the mass, momentum and enthalpy flux, $\rho_i F_i(x)$ is the volumetric force applied to flow $i$; $c$ is the isentropic sound velocity, $\phi$ is Grüneisen parameter, $q_{\text{He}_{\text{II}}\,i} = -\left(\frac{1}{f(T_i)}\,\frac{\partial T_i}{\partial x}\right)^{1/3}$ is the heat flux in turbulent $\text{He}_{\text{II}}$ flow, $f(T)^{-1}$ is the $\text{He}_{\text{II}}$ thermal conductivity function for turbulent flow.

Coolant properties are calculated from the unified coolants database using enthalpy $H$ and pressure $P$ as independent thermo-hydraulic parameters. Such description is applicable for both the two-phase and single phase coolants.

**Solids**

To simulate transient heat diffusion in a solid a 2D approximation is used with regard for thermal coupling with the coolant. The description is given in the Cartesian or axial-symmetrical coordinates. A differential equation for temperature over a given 2D region $S$ is:

$$\begin{aligned} C(T,x,r)\,\frac{\partial T}{\partial t} = {} & q_V(x,r,t) + \\ & + \frac{\partial}{\partial x}\left(\kappa(T,x,r)\,\frac{\partial T}{\partial x}\right) + \frac{1}{r^n}\,\frac{\partial}{\partial r}\left(\kappa(T,x,r)\cdot r^n\,\frac{\partial T}{\partial x}\right), \qquad \text{for } S \times S_t\,, \end{aligned}$$

$$T(x,r,0) = \psi(x,r)\,, \qquad t = 0\,,$$

$$n = 0 \text{ — Cartesian coordinates;} \qquad n = 1 \text{ — cylindrical coordinates.}$$

The boundary condition of the third kind is formulated taking into account heat exchange with coolant flow

$$\kappa\,\frac{\partial T}{\partial n} + h_i \cdot \left(T - T_i^{\mathrm{He}}\right) = 0\,,$$

where $h_i$ is the heat transfer coefficient, $T_i^{\mathrm{He}}$ is the corresponding temperature of coolant flow $i$. At the outer surface of the solid the appropriate boundary condition is formulated.

**Numerical Solution**

All equations related to coolant and 1D solids are represented via finite differences with respect to the space variable x using the approximation of forth order for the first and second order derivatives.

Integration of the complete system of ordinary differential equations over a time is performed by the RK4 method.

Solving of 2D equations is based on a semi-explicit spliting-up method for parabolic partial differential equations.

# 4. Global calculation model

As an example, a calculation model is described which was applied for thermo-hydraulic computations of the toroidal field (TF) magnet system in the ITER machine [3]. A full scale thermo-hydraulic VENECIA model of a TF coil includes elements of CS structure cooling circuit and cryoplant interface. The TF coil hydraulic layout is shown in Fig. 1. The mesh and geometry of a modeled TF cross-section are given in Fig. 2.

The model allows detailed thermo-hydraulic simulations of the TFC winding pack and structure under different operational conditions including mitigation of pulsed heat load, plasma disruption and fast energy discharge.

The model implies:

- individual modelling of 14 cable-in-conduit conductors (CICC) in a 1D approximation for the TF winding pack using a two-channel approach;
- individual modelling of external pipes, cryolines, manifolds and heat exchangers in a 1D approximation;
- the total number of different 1D objects exceeds 300;
- detailed description of different transient heat loads over 1D 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;

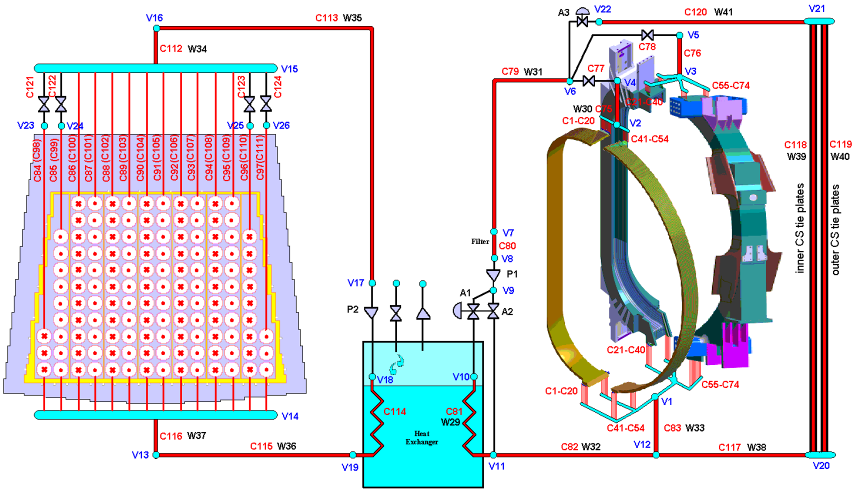

Figure 1. **TF coil hydraulic scheme used in VENECIA simulation of normal operation**

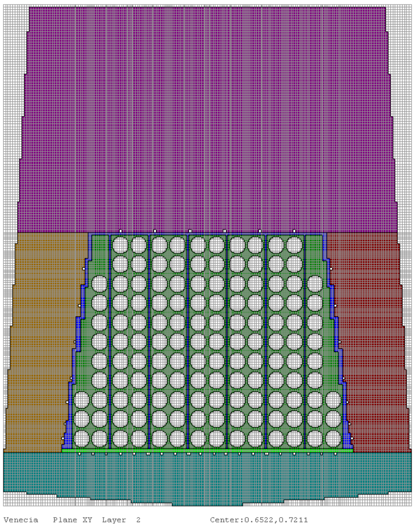

Figure 2. **Cross-section 16**

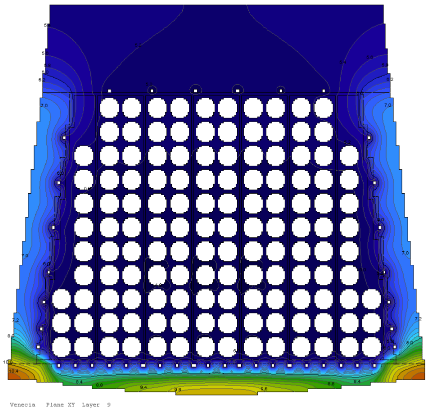

Figure 3. **Temperature map for TF model cross-section 9 at 530s of reference scenario (repetitive mode)**

– modelling of pressure-mass flow rate characteristics of control valves and pumps;
– modelling of a liquid helium bath.

Some illustrative results are given in Figs. 3–5.

# 5. Conclusions

An original modelling concept has been implemented in the computer code VENECIA to enable simulation of thermo-hydraulic behaviour of magnet systems. The simulations provide comprehensive predictions for operation of coils taking into account a combination of thermal, hydraulic, electromagnetic phenomena and their coupling. A multi-level modular structure makes the VENECIA adaptable to a range of specific tasks. Initially ITER-oriented, the code has evolved for a more universal application in the field of R&D for complex magnet systems.

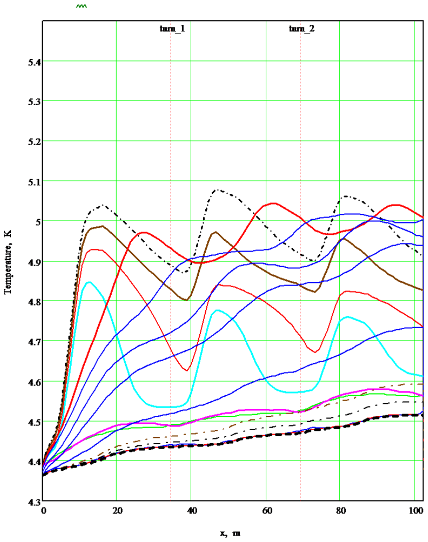

Figure 4. **Variation of temperature along 1st pancake for various moments of reference scenario**

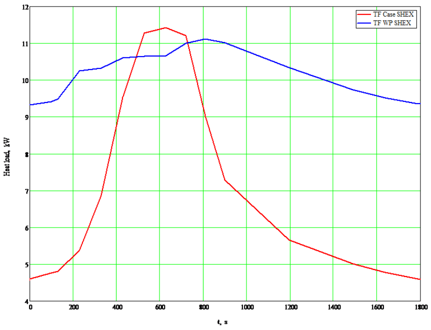

Figure 5. **Heat loads absorbed by heat exchangers)**

## References

1. Validation of VINCENTA Modelling on the Experiment with the Model Coil of the ITER Central Solenoid / V. Amoskov, A. Belov, V. Belyakov et al. // Plasma Devices and Operation. — 2006. — Vol. 14, No 1. — Pp. 47–61.
2. International Thermonuclear Experimental Reactor (ITER). — `http://www.iter.org/default.aspx`.
3. *Bessette D., Zapretilina E., Shatil N.* Simulation of the ITER toroidal field coil operation with the VINCENTA code // IEEE Trans. on App. Superconductivity. — 2006. — Vol. 16, No 2. — Pp. 795–798.

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# VENECIA: новый пакет программ для моделирования нестационарных термогидравлических процессов в сложных сверхпроводящих магнитных системах

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Современный пакет программ VENECIA предназначен для численного моделирования термогидравлических переходных процессов. VENECIA использует расширенную базу данных термодинамических и теплофизических свойств ряда хладагентов и способна моделировать поведение как суперпроводящих, так и обычных магнитных систем. Описываются основные особенности VENECIA при моделировании задач термодиффузии и термогидравлики. Представлена вычислительная VENECIA-модель для катушки тороидального поля ITER.

**Ключевые слова:** пакет программ, сверхпроводящая магнитная система, термогидравлические переходные процессы, хладагенты, охлаждение, тепловая нагрузка, проводник кабель-в-кожухе.