Introduction, Context and Issues

Numerical Flow Model: Gandalf, Flower and Vincenta

Example 1: Application to the ITER Toroidal Field Model Coil (TFMC)

Example 2 & 3: Model on ITER TF fast discharge and operation

Example 4: Model of JT60-SA TF Conductor with temperature margin

Conclusion

Nicollet S., Duchateau J.L., Lacroix, B.

Association EURATOM-CEA, CEA/ DSM/ DRFC, CEA-Cadarache, F-13108 Saint Paul lez Durance, France
Introduction and Context : Tokamak, Magnets & Thermohydraulics

Toroidal field

Poloidal field created by \( I_p \)

Total field

- Fusion domain: Very high magnetic fields to confine the Plasma (induce, shape and control)
- Design and Operation of superconducting magnets with high current conductors and high voltages during protection phases, when the magnet must be rapidly deenergised.
- Aim of thermohydraulics studies: determine in function of heat loads the temperature margin of the conductors and coils.
Introduction and Context: ITER Magnets

International Thermonuclear Experimental Reactor Project
- Toroidal Field (TF) coils (9 T on conductor) → confine the plasma
- Central Solenoid (CS) and 6 Poloidal Field (PF) equilibrium coils → induce, shape & control the 15 MA plasma current (1800 s typical plasma scenario, 400s burn).
Problematics: ITER Magnet’s Conductor

ITER Cable-In-Conduit Conductor (CICC) characterised by:
- a steel jacket
- an external electrical insulation
- forced flow cryogenic cooling with supercritical helium at few bars and a temperature ~4.5 K

The CICC comprises two regions in parallel:
- bundle region where the superconducting strands are located
- central hole delimited by central spiral.
Problematics: ITER Superconductors

ITER: choice of superconducting coils like in Tore Supra (Cadarache) to keep the electricity consumption at low level.

PF coils in NbTi CICC (45kA) 

TF & CS coils in Nb₃Sn
An overheating of the bundle region can decrease the temperature margin.
Numerical Flow Model : Numerical Codes & Equations

To evaluate conductor margins and possible quench, thermal and hydraulic analysis are performed with two type of codes:
- 1-D CRYOSOFT codes Gandalf & Flower (L. Bottura, CERN), model one CICC coupled with cryogenic loop
- quasi-3D VINCENTA code developed by Efremov Institute (N. Shatil, St Petersburg) → model of a system of coils coupled with cryogenic circuit.

Are taken into account: described heat loads, conductor parameters, current, magnetic field and external cooling circuit, a series of parameters such as friction factor in CICC channels, heat exchange coefficient, mass flow distribution, etc...

**Euler Equations** with mass, momentum & energy bilance (fluid with negligible viscosity but significant friction factor and wetted perimeter)

→ Equivalent system in velocity, pressure and temperature

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \cdot v)}{\partial x} &= 0 \\
\frac{\partial (\rho \cdot v)}{\partial t} + \frac{\partial (\rho \cdot v^2)}{\partial x} + \frac{\partial p}{\partial x} &= -\rho \cdot F \\
\frac{\partial (\rho \cdot e)}{\partial t} + \frac{\partial ((\rho \cdot e + p) \cdot v)}{\partial x} &= \frac{Q}{A}
\end{align*}
\]

\[
\begin{align*}
\frac{\partial v}{\partial t} + v \cdot \frac{\partial v}{\partial x} + \frac{1}{\rho} \cdot \frac{\partial p}{\partial x} &= -F \\
\frac{\partial p}{\partial t} + \rho \cdot c^2 \cdot \frac{\partial v}{\partial x} + v \cdot \frac{\partial p}{\partial x} &= \Phi \cdot (\frac{Q}{A} + \rho \cdot v \cdot F) \\
\frac{\partial T}{\partial t} + \Phi \cdot T \cdot \frac{\partial v}{\partial x} + v \cdot \frac{\partial T}{\partial x} &= \frac{Q}{A} + \rho \cdot v \cdot F
\end{align*}
\]
Numerical Flow Model: GANDALF & FLOWER

GANDALF CODE: 1-D code with finite elements in space and finite differences in time
...for study and simulation of superconducting CICC Conductor

Studied Systems and Parameters:
Helium in bundle and in central hole region: Temperature, Pressure, Velocity in each channel.
Initial and boundary conditions: with pressure drop imposed along the CICC
Numerical Flow Model : GANDALF & FLOWER

FLOWER CODE : model of external cryogenic circuit (possibility coupled with gandalf)

Volumes identified by couple (Pressure, Temperature)
Connexions (conduits, valves, compressor, heat exchanger)

mass, momentum and energy balance (incompressible fluid)
pump and compressor have a perfect thermodynamic behaviour, with efficiency coefficient

The model of TFMC external hydraulic circuit
In preparation of the ITER project, two model coils at reduced scale have been produced with Nb3Sn CICC and tested:
- the Central Solenoid Model Coil (CSMC, scale 1/2) in JAERI (Japan)
- the European Toroidal Field Model Coil (TFMC, scale 1/5 except cable & joints) with 10 parallel pancakes in FZK-Germany in 2001 and 2002.
Numerical flow model and thermohydraulic analyses \(\rightarrow\) steady state and transient operation to determine the performances of the coils [REF1].
TFMC steady state operation \[
\Delta P_f = (f_{EU} \cdot m^2 \cdot U \cdot L) / (8 \cdot \rho \cdot A^3)
\]

**Bundle channel friction factor (previous experiments on TFMC):**
\[
4 \cdot f_{US} = f_{EU} = (1 / \text{void})^{0.742} \cdot (0.0231 + 19.5 / \text{Re}^{0.7953})
\]

**Central spiral friction factor depends on spiral characteristics. 2 type of TFMC spirals:** Showa and Cortaillod → correlations presented in the ITER Design Criteria.
\[
f_{EU,SHO} = 0.3024 \cdot \text{Re}^{-0.0707} \quad f_{EU,COR} = 0.7391 \cdot \text{Re}^{-0.1083}
\]

**Use of the Reynolds-Colburn analogy between fluid friction and heat transfer**
\[
St \cdot Pr^{2/3} = f_{EU} / 8 \quad h_{\text{conv}} = (f_{EU} \cdot \lambda \cdot \text{Re}^{1/3}) / (8 \cdot Dh) \quad St = Nu / \text{Re} \cdot Pr
\]
\[
h_{\text{perfor}} = h_{\text{open, perfor}} + h_{\text{close}} \cdot (1 - \text{perfor}) \quad Nu = h_{\text{conv}} \cdot Dh / \lambda
\]
TFMC fast discharge at 25 kA and 3.55s time constant

Radial diffusion Model coupled with two codes Gandalf and Flower

The system is modelled by 3 concentric zones: the CICC, the cable insulation and the stainless steel pancakes.

Symetric (geometrical) 1D data are considered where the axial heat conduction is negligible and the equation of radial heat diffusion is:

\[
\rho c_p(T) \left( \frac{\partial T(r,t)}{\partial t} \right) = \left( \frac{\partial \lambda(r)}{\partial r} + \frac{\lambda(r)}{r} \right) \frac{\partial T}{\partial r} + \lambda(r) \frac{\partial^2 T}{\partial r^2} + P_{pv}(r,t)
\]

The deposited energy (eddy currents) = 23.9 kJ per pancake:

\[
E_p = \int_0^{\tau_d} P_{vo} e^{2t/\tau_d} dt = \frac{P_{vo} \cdot \tau_d}{2} V_p
\]

We suppose:
- no heat flux outside the pancake
- the limit conditions on the inside face of pancakes are coupled with Gandalf code

S. Nicollet et al., Heat transfer from plates to conductors: from TFMC analysis to ITER model, Cryogenics 43 (2003)
TFMC safety discharge (4/4)

TFMC fast discharge @ 25 kA and 3.55s

Thermal Conductivity

Temperature at outlet of DP1.2 CICC (83m)

- K Stainless Steel
- K Epoxy Resin
- K Fiberglass
- K TFMC

Cable & Cut Sheet
Insulation
Stainless Steel
Cable jacket & Insulation

CICC side Insulation
Plates side Insulation
Insulation side Plates
Case side Plates

Temperature (K)

Time (s)

DP1.2 outlet Temperature (K)

T outlet Exp.
T outlet with K fiberglass
T outlet with K Epoxy
T outlet with K TFMC

Time (s)

Temperature (K)
For safety discharge of the ITER TF system, the same hydraulic circuit is taken into account except with conductor length (375 m instead of 83 m) and energy deposited in the plates (9500 kJ instead of 23.9).

Hydraulic circuit after quench: the pump is disconnected and helium flow through relief valves with pressure drop greater than 1.6 MPa.

Model of only one pancake (instead of Vincenta calculation of the whole coil)

Supposition:
- 216 pancakes receive the same energy
- discharge volume and massflow 216 times smaller
- conduits with length and DP identical
- hydraulic diameter divided by $216^{2/5} = 8.6$

$$\Delta P_f = f_{EU} \cdot \frac{8}{\pi^2} \cdot \rho \cdot \frac{m^2}{D_h^5}$$
ITER TF safety discharge (2/3)

ITER TF Application: safety discharge @ 68 kA with 11s time constant

insulation : epoxy resin

Power peak = 72 kW and quench 0.5MJ after 10s
PHe = 7.5 MPa after 25 s and THe = 40K after 150s

---

Association Euratom-CEA

ITER TF safety discharge (2/3)
ITER TF Application: safety discharge @ 68 kA and 11 s time constant
TFMC Insulation = fiberglass /6

Power peak = 28 kW and “smooth quench” at 35 s
PHe = 4.5 MPa after 55 s and THe = 32K after 150s
→ !! Important influence of insulation thermal conductivity during safety discharge

![Graphs showing pressure, temperature, and power over time and spatial distribution.](image-url)
Numerical Flow Model: VINCENTA

mTF winding = 2 kg/s
mTF case = 2.5 kg/s
The bath is constant = 4.3 K

quasi-3D VINCENTA code developed: 1-D Thermohydraulic coupled with 2D Radial Conduction.
Numerical Flow Model: VINCENTA
ITER operation Scenario 2
ITER operation Scenario 2

including: AC losses, resistive, eddy currents, nuclear and thermal radiation/conduction

excluding: circulating pump heat loads and cryodistribution thermal losses

The main heat loads are due to the nuclear heating on the Structures and the TF coils

Plasma period = 30 min (1800 s); Dwell time < 10 min (590 s)
Power of 6 cycles for normal plasma operation (of each 1800s) \(\rightarrow\) periodic temperature is obtained after the 3rd cycle.

The heat load from the winding is transmitted to the cryoplant through the helium bath. A part of heat load from TF structure is stored within the structure in such a way that the power transmitted to the cryoplant is smoothed to cope with the capability of the cryoplant to handle the very dynamic heat loads.
ITER TF operation with VINCENTA (2/4)

Average TF Coil power / pulse of 1800s and burn of 400s

<table>
<thead>
<tr>
<th>Description</th>
<th>Load (W)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nuclear Heating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winding pack</td>
<td>1368</td>
<td>8,4</td>
</tr>
<tr>
<td>Cases</td>
<td>1677</td>
<td>10,3</td>
</tr>
<tr>
<td>AC losses</td>
<td>957</td>
<td>5,9</td>
</tr>
<tr>
<td>joints</td>
<td>1003</td>
<td>6,2</td>
</tr>
<tr>
<td>Eddy current losses in cases</td>
<td>1438</td>
<td>8,8</td>
</tr>
<tr>
<td>Thermal radiation and conduction in Cases</td>
<td>5325</td>
<td>32,8</td>
</tr>
<tr>
<td>Thermal radiation on cryolines and feeders</td>
<td>0,0</td>
<td></td>
</tr>
<tr>
<td>Winding pack</td>
<td>950</td>
<td>5,8</td>
</tr>
<tr>
<td>Cases</td>
<td>250</td>
<td>1,5</td>
</tr>
<tr>
<td>Pump power</td>
<td>0,0</td>
<td></td>
</tr>
<tr>
<td>Winding pack loop</td>
<td>2840</td>
<td>17,5</td>
</tr>
<tr>
<td>Case loop</td>
<td>216</td>
<td>1,3</td>
</tr>
<tr>
<td>CS tie plates</td>
<td>227</td>
<td>1,4</td>
</tr>
<tr>
<td><strong>Total TF Coils</strong></td>
<td><strong>16251</strong></td>
<td></td>
</tr>
<tr>
<td>From PF and CS coils</td>
<td>10785</td>
<td></td>
</tr>
<tr>
<td><strong>Total COILS</strong></td>
<td><strong>27036</strong></td>
<td></td>
</tr>
</tbody>
</table>

Total load on TF represents 60% of the loads on magnet system

- mTF winding = 2 kg/s
- mTF case = 2.5 kg/s
- The bath = 4.3 K

quasi-3D VINCENTA Model = 1-D Thermohydraulic coupled with 2D Radial Conduction.
ITER TF operation with VINCENTA (3/4)

Temperature along the conductors at End Of Burn & 2-D cross section temperature map
Section # 5 at End Of Burn
Maximal conductor temperature and Minimum temperature margin governed by the nuclear heating obtained at EOB
ITER TF operation with VINCENTA (4/4)

Electrical field along conductors at EOB for Normal Operation of reference plasma scenario (15 MA, 500 MW, 400s) \( \rightarrow \) AC losses on conductor

**SUMMERS LAW as a function of conductor B and T**

\[
B_{c2} (T) = B_{c20} \left( 1 - \left( \frac{T}{T_c} \right)^2 \right) \left( 1 - 0.31 \left( \frac{T}{T_c} \right)^2 \left( 1 - 1.77 \ln \left( \frac{T}{T_c0} \right) \right) \right)
\]

\[B_{c20} = B_{c20m} \left( 1 - \alpha |\varepsilon| \right)^{1.7}\]

is the critical field for zero temperature,

\[T_{c0} = T_{c0m} \left( 1 - \alpha |\varepsilon| \right)^{1/3}\]

is the critical temperature for zero field.

\[B_{c20m} = 28 T\]

\[T_{c0m} = 18 K\]

\[C_0 = 1.16 \times 10^{10}\]

\[n = 7\]

\[E_0 = 10 \mu V / m\]

\[C = C_0 \left( 1 - \alpha |\varepsilon| \right)^{1.7} \]

\[J_c (T, B) = C B^{-1/2} \left( 1 - \frac{B}{B_c2 (T)} \right)^{2} \left( 1 - \left( \frac{T}{T_c0} \right)^2 \right)^{2}\]

\[E = \frac{E_0}{A} \int_{A} \left( \frac{J}{J_c (T, B, \varepsilon)} \right)^n dA = \frac{E_0}{J (T, B_{eff}, \varepsilon)}\]

The electric field is maximum (\( =0.63 \mu V / m\)) at this point with maximum strain (\( \varepsilon = -0.00761 \))
Example 4

JT60 TF with Gandalf: Operation Margin (1/2)

AC losses: $\tau = 150\text{ms}$ (or 750), $\text{deff} = 5\mu\text{m}$ (or 25), $\text{SnonCu} = 74.5 \times 10^{-6}$, $\text{Cu/nonCu} = 1.6$
$Bc20 = 14.93\text{T}$, $Tc0 = 8.7\text{K}$, $C0 = 12.2 \times 10^{10}$, $\alpha = 0.9$, $\beta = 1.2$, $\gamma = 1.94$, $n = 1.7$, segregation = 2/3

He inlet

Distance from He inlet to point M ~ 3.3 m
$m\text{He} = 5\text{ g/s}$ (limit acceptable DP)
$T\text{inlet} = 4.4\text{ K}$, $P\text{inlet} = 6\text{ bar}$

Nuclear Heat

B calculated by TRAPS code

JT60 TF with Gandalf: Operation Margin (1/2)

CEA-Cadarache
DSM/DRFC

S. Nicollet
Numerical Flow Model for Controlled Fusion
16-20 April 2007
25
Temperature Margin (clock wise) $\rightarrow$ Min = 1.08 K at $x = 14.39$ m and time = 115s (EOB, End Of Burn) $\rightarrow$ still greater than 1K
WHAT HAS BEEN PERFORMED

→ Flow model of thermohydraulics in Cable In Conduit Conductor: simple tools developed for steady state (heat transfer)
→ Available hydraulics code for 1-D simulation of CICC: Gandalf code
→ Possibility to model the thermal 2-D radial diffusion process: Vincenta code
→ Both code permit also the simulation of external cryogenic circuit (coupled bath for Vincenta and Flower circuit for Gandalf)

→ Application to the Toroidal Field Model Coil (TFMC) Project and determination of influence of some parameters (friction factor, heat transfer coefficient between two channels, ground insulation thermal conductivity)
→ Studies and Model of hydraulic behaviour of ITER Toroidal Field coils, EFDA Task THCOIL
→ Studies and Model of JT60-SA Toroidal Field coils, with determination of Temperature Margin and impact on the design and choice of conductor
CONCLUSION & PERSPECTIVES

...TO BE DONE

- Development of one 1-D Flow model of thermohydraulics in Cable In Conduit Conductor for TRANSIENTS (massflow imposed), with collaboration of Ecole Centrale Marseille (ECM)
- Development of Gandalf, Flower and Thea Codes, with L. Bottura (CERN)
- Collaboration with Efremov Institute for development of Vincenta Code.

- Application of these tools to experiments on new ITER TF Sample (with advanced strands) tested in Sultan facility (CRPP, Switzerland)
- Application & benchmark to thermohydraulics of the Poloidal Field Coil Insert (PFCI) to be tested in JAERI (Japan), end of 2007
- Studies and Model of JT60-SA Toroidal Field (NbTi) Magnets with Vincenta code and determination of temperature margin with Gandalf code
- Studies and Model of ITER Poloidal Field Coil (NbTi) during normal operation scenario with updated nuclear heat.

- Tools developed for design of the CICC could be used to evaluate the temperature margin during operation process and cold tests to be performed.