The hydraulic solver *Flower* and its validation against the QUELL experiment in SULTAN

Claudio Marinucci
CRPP • Fusion Technology, CH-5232 Villigen PSI, Switzerland

Luca Bottura
CERN, Div. LHC-MTA, CH-1211 Geneva 23, Switzerland

***Abstract*--Knowledge of the hydraulic boundary conditions is a prerequisite for accurate estimates of the quench characteristics of superconducting magnets. A set of routines (Flower) has been designed and interfaced to the code Gandalf to provide a simplified model of the hydraulic connections to a cryogenic plant of a coil using cable-in-conduit conductors with central cooling channel. The validation against experimental data provided by the Quench Experiment on Long Length (QUELL) in the CRPP facility SULTAN have shown that Flower is able to simulate the hydraulic boundary conditions within engineering limits of accuracy.**

I. INTRODUCTION

Force-flow cooling with supercritical helium is foreseen for the superconducting magnets of a number of large projects, including ITER. Accurate estimates of the quench characteristics of these coils require a detailed knowledge of the hydraulic boundary conditions (HBC). Usually simplified HBC have to be assumed (e.g., given pressure at inlet and outlet) because the correct conditions are not known. To avoid this limitation, a set of routines (Flower) has been designed, and interfaced to the 1-D simulator Gandalf [1], to provide a simplified model of the hydraulic connections of coil to a cryogenic plant. To gain confidence, Flower has then been validated against experimental data provided by the Quench Experiment on Long Length (QUELL) in the CRPP facility SULTAN.

II. MODEL

The model implemented in Flower approximates a set of pipes, valves, volumes, manifolds, pumps, compressors and heat exchangers as typical of a cryogenic system attached to a superconducting coil cooled by a forced-flow of single phase, supercritical helium I. The assembly of components in the cryogenic system will be generally referred to as *hydraulic network*. The basis of this model is given in [2]. An arbitrary network is composed of:

- volume nodes (called *reservoirs* in [2]) with perfect mixing of helium and zero flow, and
- junctions (called *connections* in [2]) where the flow can be steady state or transient.

The junctions interconnect volume nodes, that can, in principle, have negligible volume. The junction definitions are based on the four following types:

- 1-D transient flow pipes, describing full compressible flow and propagation delay and waves,
- 1-D steady state flow pipe, with space-averaged flow properties and instantaneous propagation of waves and profiles,
- valves, with concentrated head loss and isenthalpic flow, and
- pumps, with concentrated head and isentropic flow.

All components, except the transient, compressible flow pipe, were already presented in [2]. Therefore here we describe in detail only the changes with respect to the model discussed there.

A. Volumes

A volume node is a point where two or more junctions are interconnected. Such a node can have a negligible volume in case that it represents merely a connecting point, or it can have a non-negligible volume if it represents a physical buffer, such as a storage tank. This is a first improvement with respect of the model discussed in [2], as there all volume nodes needed a non-negligible volume to advance the time integration. The main equations for a volume are the conservation of mass and energy. In [2] they have been solved in integral form. The major drawback is that mass and energy fluxes in the junctions connecting volumes are driven by pressure gradients. Pressure, however, did not appear explicitly in the equations. Therefore the evaluation of the fluxes and their influence on the pressure in the volume nodes required an iterative procedure that could fail to converge. For this reason, we follow here a different approach. We write the mass and energy conservation in the following form involving the volume node pressure p and temperature T:

$$V\frac{\partial p}{\partial t} + \sum \dot{m}_i\left[c^2 + \phi\left(h_i + \frac{v_i^2}{2} - h\right)\right] = \phi\dot{q} \qquad (1)$$

$$V\rho C_v\frac{\partial T}{\partial t} + \sum \dot{m}_i\left[\phi C_v T + h_i + \frac{v_i^2}{2} - h\right] = \dot{q} \qquad (2)$$

where V is the volume associated with the node and we introduced the helium density ρ, enthalpy h, the Gruneisen parameter ϕ, the isentropic sound speed c and the specific heat at constant volume C_v. The sum of the massflows $\dot{m}_i$ and of the

Manuscript received Sept. 14, 1998
This work was performed within the frame of the European Fusion Technology Program, with partial financial support through contract NET/96-425 (CM).

E-mail: claudio.marinucci@psi.ch, fax: +41-56-310-3729

stagnation enthalpy flux $\dot{m}\left(h_i + \frac{v_i^2}{2}\right)$ is intended over all the in- and outflows of the volume. Finally, $\dot{q}$ is the heating power in the volume from external sources. These equations contain explicitly mass and energy fluxes from the junctions. Both depend on the type of junction, and need to be determined in the network assembly process.

B. Junctions

The new component added is the compressible flow pipe element with cross section A, hydraulic diameter D_h, wetted perimeter p_w, friction factor f, heat transfer coefficient η with the pipe wall at temperature T_0, and heating linear power density deposited $\dot{q}'$. For this element we write the descriptive equations in the following convenient (v, p, T) form (see Ref. [1] for more details on the derivation):

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + 2\frac{f}{D_h}v|v| = 0 \tag{3}$$

$$A\frac{\partial p}{\partial t} + A\rho c^2\frac{\partial v}{\partial x} + Av\frac{\partial p}{\partial x} - 2A\phi\frac{f}{D_h}\rho v^2|v| + \phi p_w \eta T = \phi p_w \eta T_0 + \phi\dot{q}' \tag{4}$$

$$\rho C_v A\frac{\partial T}{\partial t} + \rho C_v A\phi T\frac{\partial v}{\partial x} + \rho C_v A v\frac{\partial T}{\partial x} - 2A\frac{f}{D_h}\rho v^2|v| + p_w\eta T = p_w \eta T_0 + A\dot{q}' \tag{5}$$

Equations (3)-(5) are a complete and exact description of compressible flow in the pipe. Wave propagation and mass convection can be properly modeled with such a component. Boundary conditions are needed at the end of the pipe. The boundary conditions used are of prescribed pressure and temperature in the case of inflow, prescribed pressure in the case of outflow. Equations (3)-(5) are solved by a finite element method in space and finite difference in time [1]. The compressible, transient flow pipe is a costly component in term of CPU and memory, but augments considerably the model capabilities. The other types of junctions have been modified to improve the stability and efficiency of the model. In particular, the equations given in [2] were rewritten using pressure and temperature as state variables. In fact, it can be shown [3] that the governing equations for a steady state flow pipe, a valve, a heat exchanger, a pump or a compressor can be obtained as a special case of (3)-(5). For the ideal, isentropic compressor the following characteristic was taken:

$$\begin{aligned} \dot{m} &= \dot{m}_0\left[1 - \left(\frac{\Delta p}{\Delta p_0}\right)^2\right] \text{ for } \Delta p > 0 \\ &= \dot{m}_0 \text{ for } \Delta p \le 0 \end{aligned} \tag{6}$$

where $\dot{m}_0$ and Δp_0 are constants corresponding to the maximum massflow and pressure head delivered by the compressor.

C. Network assembly

All components listed in the previous sections produce matrix equations for pressure and temperature in the volume nodes and velocity, pressure and temperature in the in- and outlet of the junctions. The network assembly is achieved:

- assigning the same degree-of-freedom to the pressure and temperature of steady state junctions and connected volumes;
- imposing boundary conditions on pressure and inlet temperature of the compressible flow pipes, taking as boundary values those from the connected volumes, and
- coupling the in- and outflows of compressible flow pipes to the mass and energy fluxes in the connected volume nodes.

By virtue of this procedure, negligible volume nodes are overridden by the volume contributions from the connected junctions. This is not true for the compressible flow pipes, for which coupling of boundary conditions and fluxes does not imply lumping of volumes. The resulting system is solved implicitly, by matrix inversion at each time step. This improves largely the robustness of the scheme.

The coupling of Flower and Gandalf is explicit, that is no iterative procedure insures consistency of the boundary conditions and the flow in the hydraulic network. This is practical and sufficient for most situations. Pathological situations can arise for (a) very small manifold at inlet and outlet of the flow path analyzed (typically below 1cm^3), (b) large time steps in the Gandalf main solver (above 10ms), or (c) very large heating powers along the conductor and resulting induced flow. The symptoms are instability of the flow (oscillations in time) that can be cured forcing a smaller maximum time step of Gandalf until stable results are obtained.

III. VALIDATION

A. The QUELL experiment

The QUELL experiment in the CRPP facility SULTAN has provided a broad and detailed quench propagation database which has been used for the validation of numerical codes for the simulation of thermal hydraulic transients. The detailed validation of the code Gandalf was done by using as HBC the experimental helium pressure at inlet and outlet of the QUELL sample, i.e. the SULTAN cryogenic system was not simulated [4]. Here we report on the simulation of the same experiment using the hydraulic solver Flower (version 2.0) interfaced to Gandalf (version 1.8).

The approach is to approximate the complex cryogenic system of the SULTAN facility with the simplest possible model which retains the essential characteristics of the system without unnecessary complications. The resulting model includes (see Fig. 1): two manifolds, at inlet (V-1) and outlet (V-2) of the QUELL sample (J-1), a compressor (J-2), two relief valves for protection against high pressures during a quench (J-3 and J-4), and a reservoir at room temperature and 1.2 bar (V-3). The compressor is connected to the manifolds with two pipes, each 5m long and with D_h=6mm. Each pipe connecting the manifolds V1 and V2 to the buffer is 3.5m long with D_h=25mm. Experimental initial conditions of the inlet and outlet manifolds, i.e. temperature of the sample and helium pressure, have been used. The relief valves are programmed to open when the He pressure exceeds 10.5bar.

.

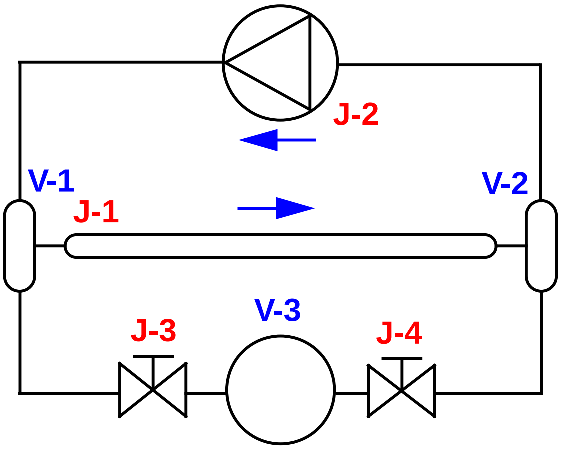

Fig. 1. Model of the SULTAN cryogenic system used for the validation of Flower against the QUELL experiment. The arrows indicate the direction of the steady state helium flow. J-1 is the QUELL sample.

B. Reference case

A total of 8 quench propagation runs have been investigated in a broad spectrum of operating conditions; they have been selected among over 60 QUELL experimental runs for their physical relevance and data consistency. The reference case (run #02) is presented here in detail, whereas details of all runs are given in [5]. The most relevant quench characteristic for hydraulic comparison is the helium pressure; the time history of this variable during the quench evolution is shown at the 6 locations of the QUELL pressure taps in Fig. 2. At each location three curves are shown: the simulated pressure using Flower (p_{SF}), the simulated pressure using the experimental HBC (p_{SE}) and the filtered and sampled experimental pressure (p_E).

At the inlet and outlet of the cooling channel (in reality in Fig. 2 the data are shown at the locations of the sensors, i.e. x=0.12m and x=90.84m, where the nodal coordinate x is the distance from the inlet of the cooling channel) the agreement between p_{SF} and p_E is good for 9/10 of the duration of the 8s quench run. The relative difference is <10% and more pronounced at the outlet than at the inlet. In the final part of the quench evolution ($t > 7.4$s) p_E at the inlet exceeds the threshold of the relief valve (10.5bar) and the discrepancy between simulation and experiment begins to quickly deteriorate. The opening and closing time constant of the relief valve, finite in reality, has been assumed to be zero in Flower for simplicity and this explains why the large experimental oscillation is not reproduced by the simulation. At x=0.12m and x=90.84m p_E and p_{SE} are coincident by definition.

For the validation of Flower only the results at the hydraulic boundaries are relevant. The quench evolution of the sample, however, depends on the behavior of all quench characteristics

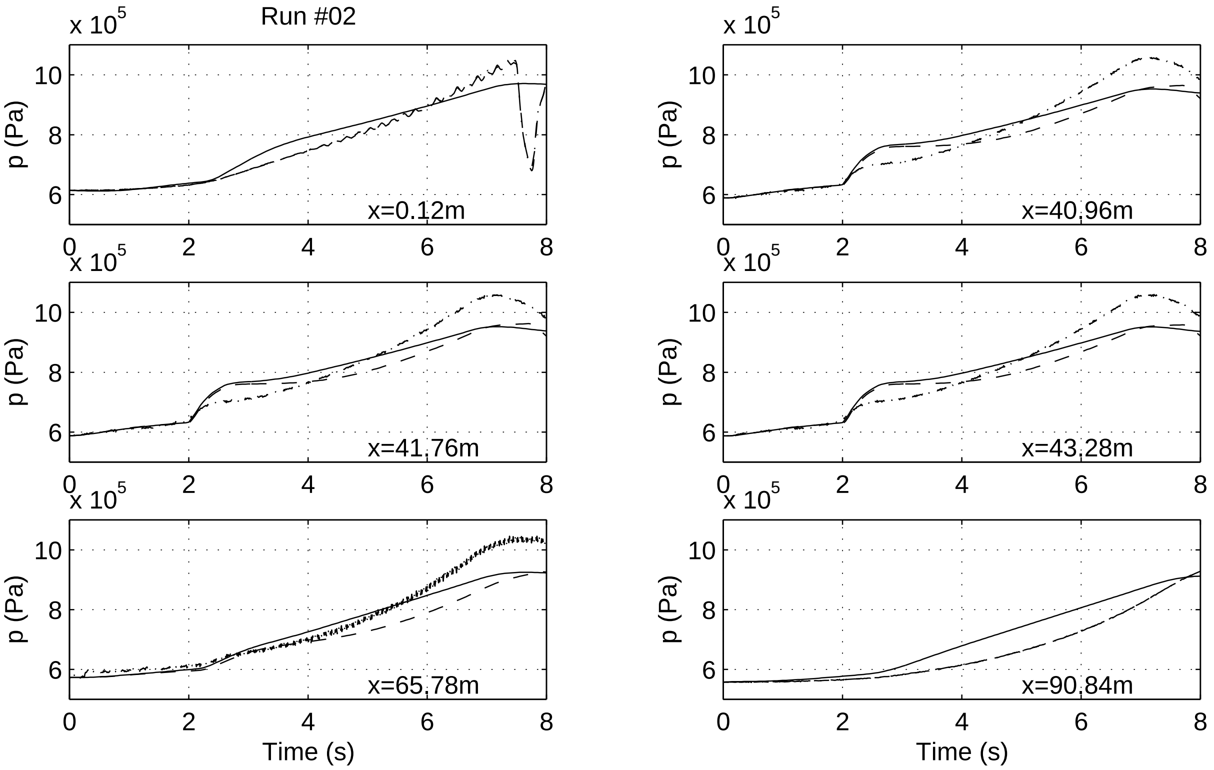

Fig. 2. Reference case. Helium pressure time history at 6 tap locations along the QUELL sample length. At each location three curves are shown: the simulated pressure using Flower (solid lines), the simulated pressure using the experimental HBC (dashed lines) and the filtered and sampled experimental pressure (dash-dotted lines).

along the complete conductor length and even when fed by the best possible (i.e. experimental) HBC the code Gandalf is not capable of reproducing without error the experimental quench results, including the helium pressure, as discussed in detail in [3].

C. Global validation

One indicator of the capability of Flower to feed Gandalf with accurate HBC during the QUELL quench propagation runs is the comparison of simulated and experimental helium pressure at the inlet and outlet of the sample, i.e., the relative error $dp/p[\%]=(p_{SF}-p_E)/p_E$. The time history of dp/p for all 8 investigated runs is shown in Fig. 3.

There are few general remarks which apply to all the cases. In quasi steady state mode of operation of the cryogenic system, i.e. before the quench has started, the agreement of simulation and experiment is very good (few%). During the quench, but before the conditions for opening of the relief valves are met, the agreement deteriorates but remains within engineering limits (<20%). When one or both relief valve opens the error can increase considerably (>30%), as discussed for the reference run. These limitations are relevant only when assessing the quench characteristics of a magnet system under faulty conditions of the quench detection system and when relief valves are used for protection of the cryogenic system.

IV. CONCLUSIONS

A set of routines (Flower) has been designed and interfaced to the code Gandalf to provide a simplified model of the hydraulic connections to a cryogenic plant of a coil wound with supercritical helium force-flow cooled cables.

The validation against experimental data provided by the Quench Experiment on Long Length (QUELL) in the CRPP facility SULTAN have shown that Flower is able to simulate the hydraulic boundary conditions within engineering limits of accuracy, with few marginal limitations.

The main advantage of the addition of the hydraulic network simulator is that a self consistent simulation can be achieved without any free parameters, extending remarkably the predictive capability of the model.

ACKNOWLEDGMENT

The authors are grateful to Alexander Anghel of CRPP for valuable discussions.

REFERENCES

[1] L. Bottura, “A Numerical Model for the Simulation of Quench in the ITER Magnets,” *J. Comp. Phys.* **125**, pp. 26-41, 1996.
[2] L. Bottura, “Quench Propagation Through Manifolds in Forced Flow Cooled Coils,” *IEEE Trans. Appl. Supercond.* **3**, 1, pp. 606-609, 1993.
[3] L. Bottura and C. Rosso, “Hydraulic Network Simulator Model,” Internal CryoSoft Note, CRYO/97/004, 1997.
[4] C. Marinucci, L. Bottura, G. Vecsey and R. Zanino, “The QUELL experiment as a validation tool for the numerical code Gandalf,” to appear in *Cryogenics* **38**, pp. 467-477, 1998.
[5] C. Marinucci, “Validation of the hydraulic solver Flower against the QUELL experiment in SULTAN”, Internal Report CRPP/FT/CM/98-RE-02, 1998.

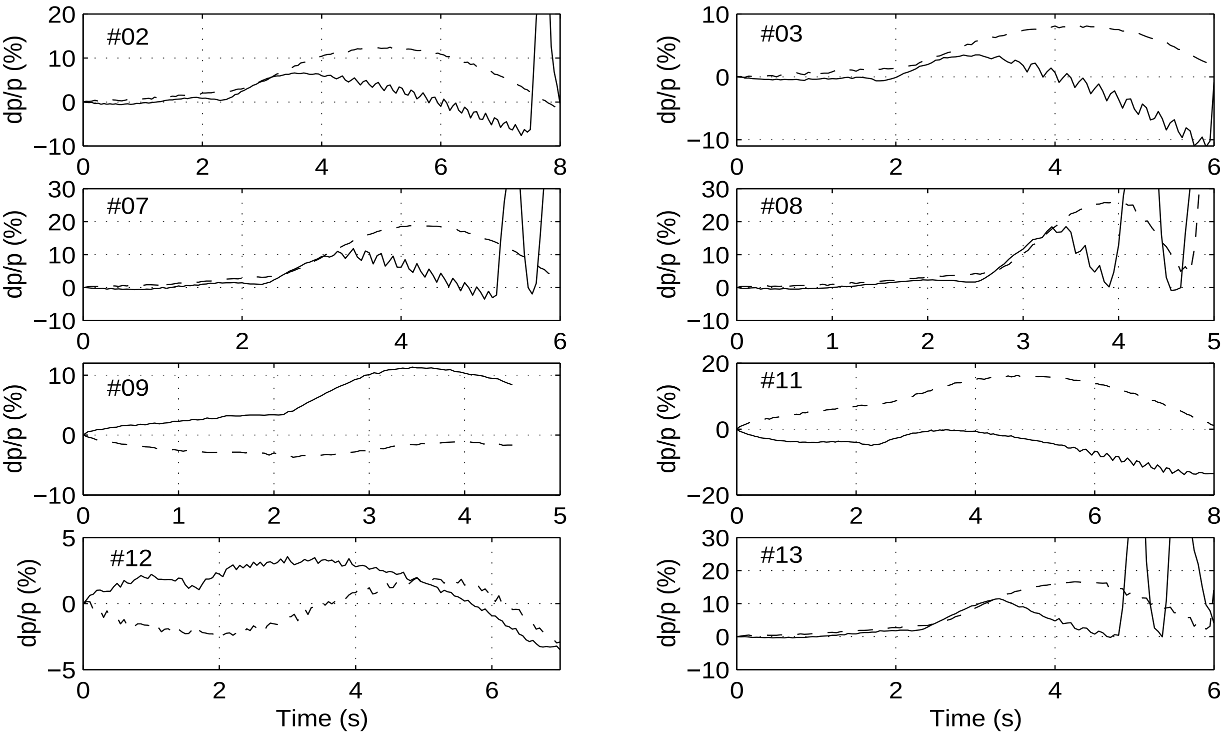

Fig. 3. Relative error (Flower vs. experiment) of helium pressure time history at inlet (solid lines) and outlet (dashed lines) of the QUELL sample. The error is shown for all 8 investigated runs.