A Comparison between 1- and 2-Fluid Simulations of the QUELL Conductor

R.Zanino, L.Bottura and C.Marinucci

Abstract— **In QUELL (QUench Experiment on Long Length) a Cable-In-Conduit-Conductor with central cooling hole has been tested under fusion reactor relevant conditions. A first comparison is presented here between the results of a recently developed 2-fluid code - Mithrandir - and those of the reference 1-fluid code - Gandalf - for the case of the QUELL conductor. Mithrandir allows for different thermodynamic properties of the helium in the hole and that in the bundle, thereby providing a more accurate description of the physics involved when a central cooling hole is present.**

I. Introduction

In recent years particular attention has been devoted to Cable-in-Conduit Conductors (CICC's) with separate central cooling passage[1],[2], which offer the advantage of a low hydraulic impedance for the flow of helium. In normal operation this allows to limit the pressure drop for large cooling lengths, typically of the order of 1 km for a fusion magnet, or, conversely, increase the mass flow under the same pressure drop, thus reducing the He residence time in the coil. During a quench the low hydraulic impedance is also advantageous, providing a preferential He expulsion path and reducing the maximum pressure increase [3]. (The obvious drawback of such a geometry is the lower cable space current density.) We will call this geometry a "CICC with cooling hole", and the cable area, where the He flows in the interstitial spaces among the strands, will be referred to as the "bundle".

In spite of the large R&D programme in place for the technological development of such conductors for fusion [1] or SMES [2] applications, theoretical and modeling questions are still open on the performance and the physics details of such conductors. With this problem in mind, a 2-fluid model - Mithrandir [4] - was recently developed from the reference 1-fluid model - Gandalf [5] (see Section III), extending the latter in order to take into proper account the different thermodynamic state of the He in the cable bundle and in the cooling hole.

Mithrandir and Gandalf were already compared previously [6] with the experimental results obtained on dummy cables at CEA Grenoble, which however aimed only at the study of slow cooling processes. In that comparison some significant effects due to the 2-fluid approximation were noticed.

The main purpose of the present work is to compare the two models with reference to the QUELL experiment [7] (see next Section), identifying regimes in which their predictions differ and establishing the need for a 2-fluid description.

Manuscript received August 26, 1996.

R.Zanino is with Dipartimento di Energetica, Politecnico, Torino, Italy. E-mail: zanino@alphaz.polito.it .

L.Bottura is with CERN, Geneva, Switzerland.

C.Marinucci is with CRPP-Fusion Technology, Switzerland.

II. The QUELL experiment

Goals of the QUench Experiment on Long Length (QUELL) [7], a joint effort of the European Union, Japan, Russian Federation and the United States, are: (a) simulation and measurement, in the SULTAN facility, of quench propagation in typical ITER relevant geometry and scaled performance; (b) development, test and qualification of new quench sensors; (c) validation of the numerical codes. The measurements have now been completed and the interpretation of the experiment is in progress.

Data on the QUELL conductor can be found in [7]. Here we only mention that the wall at the interface between cable bundle and hole is a spiraling tape with thickness δ_w = 0.5mm, nominally wound in such a way as to periodically leave 1mm without wall every 7mm along the conductor (i.e., nominal degree of wall perforation ~14%).

III. Simulation codes

A brief overview is given here of the two FORTRAN77 codes that have been used for the present simulations:

- Mithrandir [4] - a 2-fluid code;
- Gandalf [5] - the reference 1-fluid code.

Gandalf solves a system of 1-D (along the conductor) time-dependent balances: heat conduction in the jacket and (separately) in the conductor, (cross section) averaged continuity and energy balances for the He, momentum balance in the hole and (separately) in the cable bundle, where the fluid can flow at different speeds. The transient is typically driven by heat sources in the jacket and/or in the conductor. Finite elements are used for the spatial discretization on an adaptive grid following the quench front, together with an implicit time marching procedure with automatic adaptation of the time step Δt.

Mithrandir includes all of Gandalf's features, the major extension with respect to its parent being in the possibility of having different temperatures and pressures of the He in the hole and of the He in the cable bundle. The two regions are coupled by exchanges of mass, momentum and energy; in particular, the He in the hole is assumed to exchange energy only with the He in the bundle, both by convection due to transversal pressure differences between hole and bundle, and by conduction; the latter can go both through the hole wall, or be due to the turbulence at the interface between the two fluids [8] where no wall is present. For each of the two fluids, then, a separate couple of mass and energy balances is included in the system of equations to be

1051-8223/97$10.00

TABLE I

LOCATION OF PRESSURE AND TEMPERATURE SENSORS.

p sensor	x (m)	T sensor	x (m)
P01	0.12	TA1	0.14
P02	40.96	TA2	40.94
P03	41.76	TA3	42.91
P04	43.28	TA4	43.26
P05	65.78	TA5	44.82
P06	90.84	TA6	49.31
–	–	TA7	53.80
–	–	TA8	58.29
–	–	TA9	90.82

solved. As to the input parameters, the major additional parameter is the percentual degree of perforation, $\mathcal{P}$, of the wall delimiting the hole.

As a result of the homogenization in Gandalf, the He heat capacity in the bundle and in the hole is considered as completely available for heat exchange with the strands. This leads to an overestimate of the stability margin as compared to the model implemented in Mithrandir.

One rather subtle but important difference between the two codes was not previously discussed: when $\mathcal{P}$ is sufficiently large (above 10% or so) the maximum relative difference between the He pressures in the bundle and in the hole can become very small (below 10^{-7}, say), so that double precision is required in the routine of Mithrandir which steps the system forward in time. Notice however that *both* Gandalf and Mithrandir have, for typical physical and numerical parameters as used here, estimated condition numbers O(10^4-10^5); this means that the single precision (IEEE 32 bit standard) gives results with at most about two significant digits in the worst case.

IV. Comparison between codes and experiment

For the present comparison we have chosen two QUELL runs:

- The first one is the propagation of a heat slug without quench (no current and no magnetic field in the conductor); the transient results from a very short ($\sim$ 40ms) pulse ($\sim$ 180J) from the inductive heater (located between 42.96m and 43.08m from the entrance), going mostly into the jacket.
- The second one is a typical normal quench (nonvanishing time-dependent current and external + self-field); the transient results from a 1.5s pulse (100 W/m, see below) from the long resistive heater (located between 40.93m and 43.23m from the entrance), assumed again to go mostly into the jacket.

The comparison will be based on the time evolution of: total resistive voltage drop ΔV in the conductor; He pressures in the cable bundle at the location of the P0x sensors (see Table I); jacket temperatures at the location of the TAx sensors (see Table I).

Since the QUELL conductor is about 91m long, we use the signals of P01 and P06 as boundary conditions (possibly time-dependent, e.g., in case B below); whenever, at any of the terminals, the mass flow enters the conductor, a further boundary condition is needed: since the detectors at TA1 and TA9 were affected by a strong radiative heat we use in that case fixed in time values taken from TA2 and/or TA8, before the quench (if any) reaches them.

In the following, all input parameters which are common to both Gandalf and Mithrandir have been given the same value in both codes; in particular, the jacket was assumed to have 25% of its perimeter directly in contact with the strands. Unless otherwise noticed, the nominal value $\mathcal{P}$=14% was assumed in Mithrandir.

Possibly the most critical parameter peculiar of Mithrandir is the heat transfer coefficient h_{HB} at the interface between hole and bundle, *where no wall is present.* We have experimented several recipes for h_{HB}, including assuming it proportional to the heat transfer coefficient obtained with vanishing wall thickness from the standard formula, or else assuming it proportional to the heat transfer coefficient h_{Long} given in [8]. Unless otherwise noticed, the results in the following refer to the choice $h_{HB}=10\times h_{Long}$, which leads to the best agreement both with the heat slug and with the quench data; this agreement would also seem to indicate that the direct heat exchange between the two fluids is more efficient than predicted by theory.

A. Heat slug propagation (experimental run e_02_05_008)

In this case the inlet and outlet boundary pressures are taken as constant in time and equal to 0.565MPa and 0.520MPa respectively. The inlet temperature is also constant and equal to 5.05K. A mesh with 2000 elements is used, fixed in time and refined between 42.5m and 43.5m; Δt varies between 10^{-5}s at the beginning and 10^{-1}s at the end of the transient, which starts at the beginning of the heat pulse and lasts 80s.

The recorded pressure variations are small as expected and noisy, therefore we compare with the jacket temperature signals (because of the slow time scale here, the O(1s) time lag of the temperature sensors is not as important as in the case of a quench, see below).

The experimental and computed traces of the thermometers downstream of the heater are shown in Fig.1. The shock-like heat pulse generates a warm slug that is convected downstream, but the slug in the hole (flow speed $\sim$ 0.8m/s) anticipates that in the bundle (flow speed $\sim$ 0.2m/s). This has at least two consequences: a) the heat must still go through the hole-bundle heat resistance before heating the jacket at a given location downstream of the heater; this resistance is not taken into account in Gandalf, so that the jacket sees a warmer He and reaches a higher peak temperature (although at the correct time); b) since in Gandalf heat is convected at an average flow speed between those of hole and bundle He, whereas in Mithrandir heat is convected separately in the two channels at the respective speed, the temperature profiles show a much larger dispersion [9] in Mithrandir than in Gandalf. One sees that both qualitatively and quantitatively a much better agreement with the experimental results is provided by Mithrandir than by Gandalf.

B. Normal quench (experimental run e_04_10_001)

In this case the inlet and outlet boundary pressures are taken from the sensors as given in Fig.2. The inlet temperature is fixed at 6.9K. The current decreases linearly from 8kA to about 7.77kA over the first 6s, then goes to about zero between 6s and 8s. The external field is 11T.

An adaptive mesh with initially 2000 elements is used; Δt varies between 10^{-5}s at the beginning and 2×10^{-3}s at the end of the transient, which starts at the beginning of the heat pulse and lasts 8s ($\sim$ current decay time).

Because of the finite time constant of the resistive heater the actual value of the heating power Q into the jacket is not known exactly. Here we choose Q=100W/m, which allows one to approximately capture with Mithrandir the onset time of the quench (see also below).

Since part of the conductor becomes normal in this case, we consider first of all the evolution of a global quantity - ΔV - as shown in Fig.3, together with the related normal zone length, shown in Fig.4.

ΔV is reasonably reproduced by both codes. In particular, except for the delay in the Gandalf prediction for the onset time of the quench (see below), both codes agree with each other (ΔV is essentially dominated by the energy balance of the initial normal zone, which is rather independent of the details in the model). However, when one considers the evolution of the normal zone length (Fig.4) a more striking, also qualitative difference appears between the predictions of the two codes, and Mithrandir gives a better agreement with the experimental results. Because of the assumed perfect heat exchange between bundle and hole, Gandalf also predicts a later onset of the quench with respect to Mithrandir, for the same input power Q=100W/m; if the power is increased to Q=125W/m (Fig.4, dash-dotted curve extending to 4s only) then Gandalf captures the correct onset time, but the subsequent evolution is not in good agreement with the experiment.

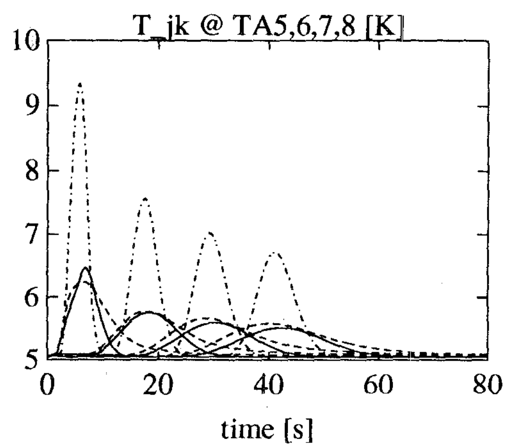

Fig. 1. Jacket temperatures at the sensors TA5,6,7,8: experimental (dashed), Mithrandir (solid), Gandalf (dash-dotted).

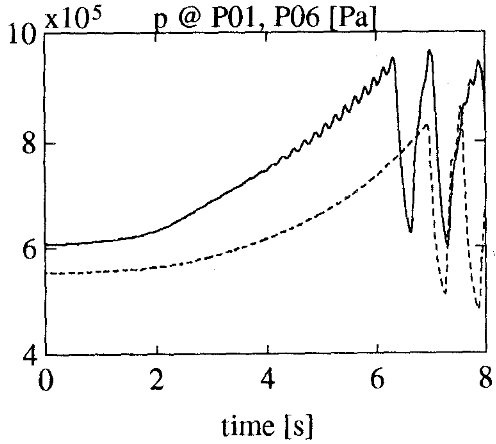

Fig. 2. Inlet (solid) and outlet (dashed) He pressures.

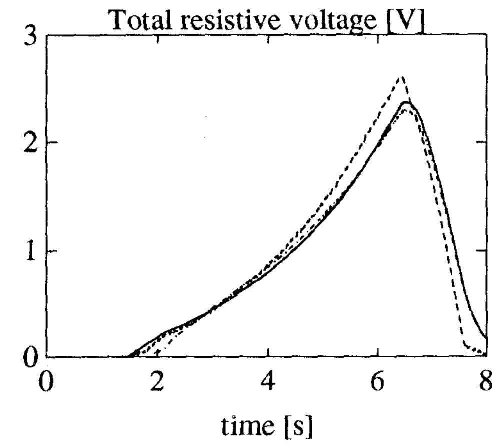

Fig. 3. Total resistive voltage drop during quench: experimental (dashed), Mithrandir (solid), Gandalf (dash-dotted).

The time scale of the transient we are considering is comparable with the time lag of the temperature sensors, therefore the temperature signals cannot be used directly. However, the pressure undergoes now significant variations, and we compare with the signals from the local pressure sensors P03 (Fig.5), located in the heater region, and P05 (Fig.6), located further downstream, which is not reached by the quench (P02 and P04 give responses almost identical to P03 and are not shown).

The He pressure increases slightly at the beginning because of the external heating, then rises more steeply as soon as the information of the onset of the quench has reached the sensor; after some time the pressure profile becomes sensitive to the boundary conditions and the pressure slope changes again; when the current in the conductor finally decays so does the Joule heating, and the pressure starts decreasing.

Already using a perforation $\mathcal{P}$=0.1%, the maximum pressure reached during the transient is reduced by about 30% with respect to the case of no perforation (not shown).

The agreement between Mithrandir and the experiment is remarkably good, considering that, e.g., the friction fac-

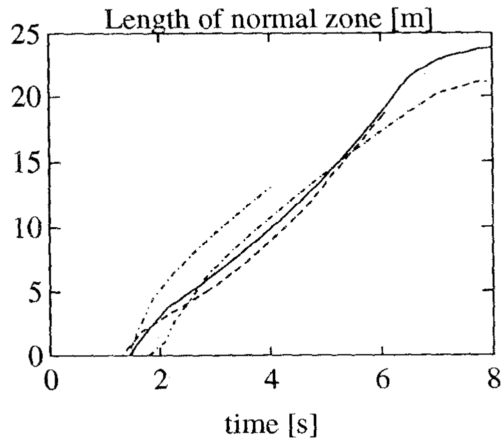

Fig. 4. Normal zone length during quench: experimental (dashed), Mithrandir (solid), Gandalf (dash-dotted). The curve extending to 4s was computed with external input power Q=125W/m.

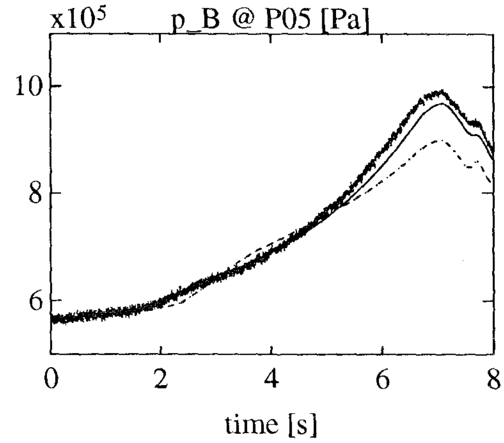

Fig. 6. He pressure at the P05 sensor: experimental (dashed), Mithrandir (solid), Gandalf (dash-dotted).

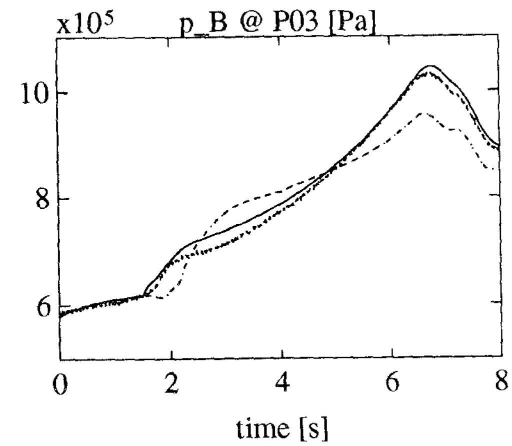

Fig. 5. He pressure at the P03 sensor: experimental (dashed), Mithrandir (solid), Gandalf (dash-dotted).

tor alone used in these calculations has an estimated uncertainty O(10-15%). Gandalf, apart from the already noticed later onset of the quench, predicts a transient which, although in rough agreement with the experiment, is somewhat qualitatively dissimilar from it. Notice finally that the quantitative disagreement between Gandalf and Mithrandir is smaller now than in the heat slug case; this is because the flow speeds are now much larger (by about a factor of five), leading to much larger heat transfer coefficients, and thus improved thermal coupling between bundle and hole.

V. Conclusions and Perspective

We have shown that although the homogenized model of the CICC with cooling hole is known to be practical for quench calculations, and indeed gives reliable answers to important questions such as the maximum temperature, pressure and voltage in a coil, its drastic simplification of the physics of He flow and heat exchange can lead to significant errors and wrong trends.

Both in the case of the heat slug and of the normal quench considered here it has been seen that Mithrandir gives a better agreement than Gandalf with the experimental results, i.e., the 2-fluid model seems to represent a true improvement vs. the 1-fluid.

On this basis, we believe that the appropriate modeling of extreme time scales, either very slow (normal operation) or very fast (stability), must be done taking properly into account the differences in thermodynamic properties arising in the cross section of the conductor.

In perspective we are extending the present analysis to other QUELL runs, including thermohydraulic quenchbacks, and studying in detail the parametric effects of different degrees of perforation of the wall delimiting the central cooling hole. A study of stability is also being undertaken: here even more significant differences than for a quench should arise between 1- and 2-fluid models.

Acknowledgments

We thank S.DePalo (Politecnico) for help in modifying and running the codes, and S.P.Smith (MIT) for the experimental data on heat slug propagation.

References

[1] M.Huguet, et al., Proceedings of the 1995 Symp. on Fus. Energy, 138.
[2] C.Luongo, *J. Fus. Energy*, vol. 14, pp.103-112, 1995.
[3] L.Dresner, *Cryogenics*, vol.33, pp. 958-961, 1993.
[4] R.Zanino, S.DePalo and L.Bottura, *J. Fus. Energy*, vol.14, pp.25-40, 1995.
[5] L.Bottura, *J. Comp. Phys.*, vol. 125, pp. 26-41, 1996.
[6] S.DePalo, L.Bottura and R.Zanino, *J. Fus. Energy*, vol. 14, pp.49-58, 1995.
[7] A.Anghel, *J. Fus. Energy*, vol. 14, pp.129-139, 1995.
[8] A.Long, Master's thesis, MIT, 1995.
[9] A.Martinez and B.Turck, CEA Report P/EM/93.18, 1993.