SIMULATION OF THERMAL-HYDRAULIC TRANSIENTS IN TWO-CHANNEL CICC WITH SELF-CONSISTENT BOUNDARY CONDITIONS

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ABSTRACT

The use of boundary conditions at the conductor ends, taken from the experiment, has recently allowed an accurate thermal-hydraulic simulation of both quench [1] and heat slug [2,3] transients in the two channel cable-in-conduit conductors (CICC), using the 2-fluid MITHRANDIR code [4]. However, in order to be used as a design tool, i.e., to achieve a predictive capability, the code should be independent as much as possible of input from the experiment. Therefore it is necessary to couple MITHRANDIR to a hydraulic network simulator such as FLOWER [5], providing a self-consistent description of thermal-hydraulic transients in a cryogenic plant. We show here how the coupling is achieved and demonstrate the reliability of the coupled codes against quench and heat slug propagation runs from the QUELL experiment [6] in the SULTAN facility at Villigen PSI, Switzerland. The results show good agreement with experimental data and with simulations performed using experimental boundary conditions. Different levels of detail in the modeling of the hydraulic network are investigated for different types of thermal-hydraulic transient.

INTRODUCTION

The 2-fluid MITHRANDIR code [4] was developed specifically to simulate thermal-hydraulic transients in super-conducting cables with a two-channel topology, and was validated against quench [1] and heat slug propagation [2,3] in the QUELL experiment [6], assuming a given (experimental) pressure at the inlet and outlet of the conductor sample. Two-channel cable-in-conduit conductors have now been chosen for the Toroidal Field Model Coil (TFMC) and the Central Solenoid Model Coil (CSMC), in the frame of the International Thermonuclear Experimental Reactor (ITER) project, and the MITHRANDIR code will be used in the assessment of the test program of the TFMC. Therefore, it becomes critical that the code can be used in a *predictive* mode, as opposed to interpretative simulations. This condition can be satisfied by numerically modeling the *entire* hydraulic circuit, provided its parameters are known, in order to compute self-consistent pressure p_{in} and temperature T_{in} at the sample inlet, and outlet pressure p_{out} – a typical set of boundary conditions.

Here we shall model the super-conducting cable (i.e., the sample) using the MITHRANDIR code, and the rest of the cryogenic circuit using a specific hydraulic network solver, i.e., FLOWER [5].

FLOWER has been developed specifically to supply self-consistent boundary conditions to the 1-fluid GANDALF code. The coupling of the two modules was recently validated against quench initiation and propagation in the QUELL experiment [7].

Here we couple FLOWER to MITHRANDIR, and compare the simulations with experimental results of quench initiation and propagation, and of heat slug propagation, in QUELL.

MITHRANDIR-FLOWER COUPLING

A cryogenic system for a super-conducting coil cooled by forced-flow of supercritical helium can be simulated by FLOWER after identifying the principal components of the circuit. These components are divided into two main categories: junctions (i.e., pipes, pumps or compressors, heat exchangers, valves) and volumes (i.e., reservoirs or manifolds). They are modeled in the code by means of a restricted set of parameters, e.g., cross section, length, hydraulic diameter and friction factor, for the pipes, or volume V, temperature T and pressure p, for the reservoirs, see Bottura and Rosso [5], Marinucci and Bottura [7] and references therein for details. All the different elements must then be connected in a loop, closed by the super-conducting sample.

The coupling between MITHRANDIR and FLOWER is achieved through an explicit staggered time integration of the hydraulic network and the cable. At each time step MITHRANDIR provides inlet and outlet mass and energy flux, as input to FLOWER. The latter uses the flux values to compute pressure and temperature in all the junctions and volumes. It thus can feed back MITHRANDIR with p_{in}, T_{in}, p_{out} in a self-consistent way. No iteration is performed because MITHRANDIR uses the boundary conditions computed by FLOWER in the previous time step.

THERMAL-HYDRAULIC TRANSIENTS IN QUELL

Description of the Cryogenic Circuit

In Fig.1 a simplified sketch is shown of the cryogenic circuit of the SULTAN facility supplying helium to the QUELL sample. Pressurized helium flows from the cold-box (a two-phase component) through a valve-box that provides plant regulation, and then through the cryostat, i.e., a liquid bath heat exchanger. The supercritical helium flow from the cryostat outlet is split between sample and sample terminals plus current leads. Note that a significant fraction of the helium flow is needed in the refrigeration of the terminals and current leads (~50 % in most cases). A control valve CV and a heater are used to manage the flow and inlet temperature in the sample. The helium flows from the sample and the parallel path back to the cryostat, through two Joule-Thomson valves (JTV), and from there to the cold-box. If a strong increase of the inlet and outlet pressure takes place (e.g., in the case of quench of the sample), the fluid can vent into a reservoir through two relief valves (RV). Unless otherwise mentioned, all circuit data are obtained from Bruzzone and Marinucci [8].

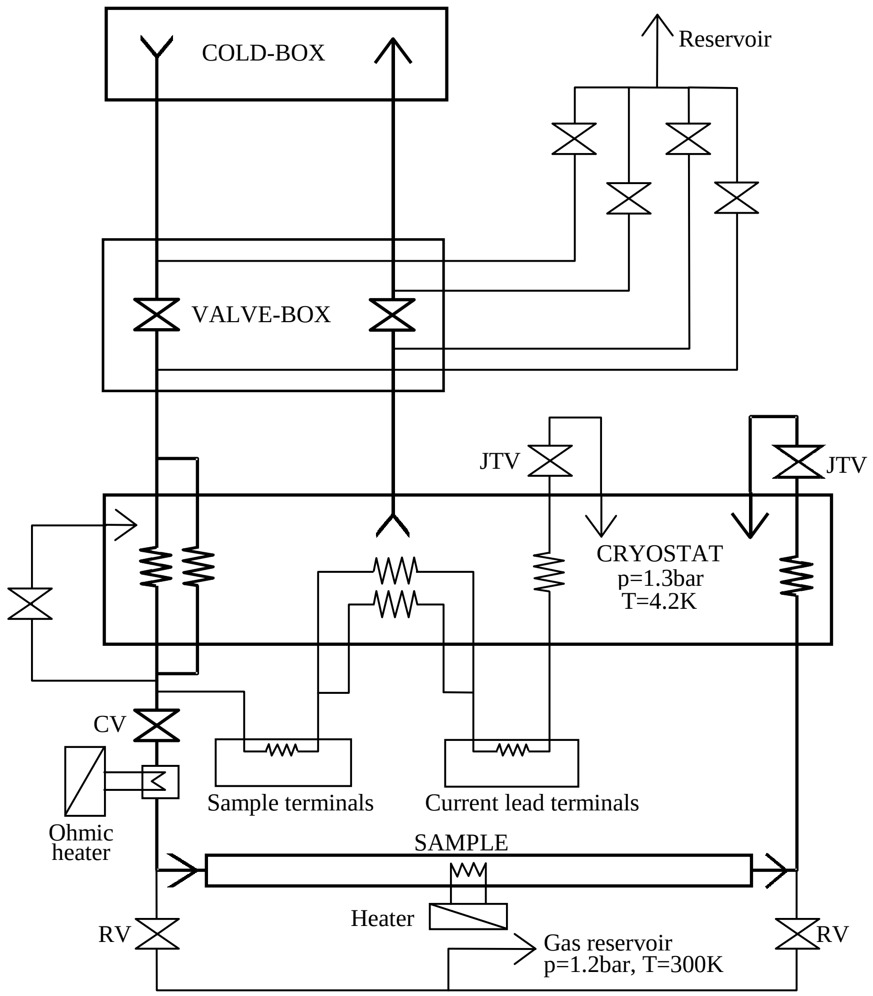

Figure 1. Simplified sketch of the cryogenic circuit of the SULTAN facility for the QUELL experiment.

Model of the Cryogenic Circuit for Quench Studies

In order to decide which components of the circuit are to be considered in quench simulations, we can observe that in quench studies p_{in} and p_{out} are expected to be driven mostly by quench evolution inside the sample (because of the strong heating induced flow), while the cryogenic circuit is less important. Furthermore, the time scale O(1-10s) of the circuit response to an external perturbation is comparable or longer than the time scale O(1s) of quench propagation. Therefore, even a relatively simple cryogenic circuit model can lead to acceptable results in quench simulations.

For this reason we use here a very simplified circuit model, shown in Fig.2a. The choice of components is the same as presented by Marinucci et al. [7], but their quantitative characterization is different. Two manifolds M_{in} and M_{out} are located at the inlet and outlet of the sample, respectively. M_{in} and M_{out} are considered here to account for the physical helium volume contained in the pipes connecting the sample to the cryostat. The two manifolds are linked by a *fictitious* compressor that gives the needed pressure head. The compressor emulates the cold-box and the pipes linking the latter with the cryostat. The cryostat is assumed to provide only a localized pressure drop, and it is "hidden" in that part of the circuit modeled as a compressor. The parallel path through the sample terminals and current lead terminals is neglected in this model by assuming that the compressor operates with ~50% of the helium volume actually flowing through the cold-box. The relief valves are assumed to open at an absolute pressure of 10.5bar.

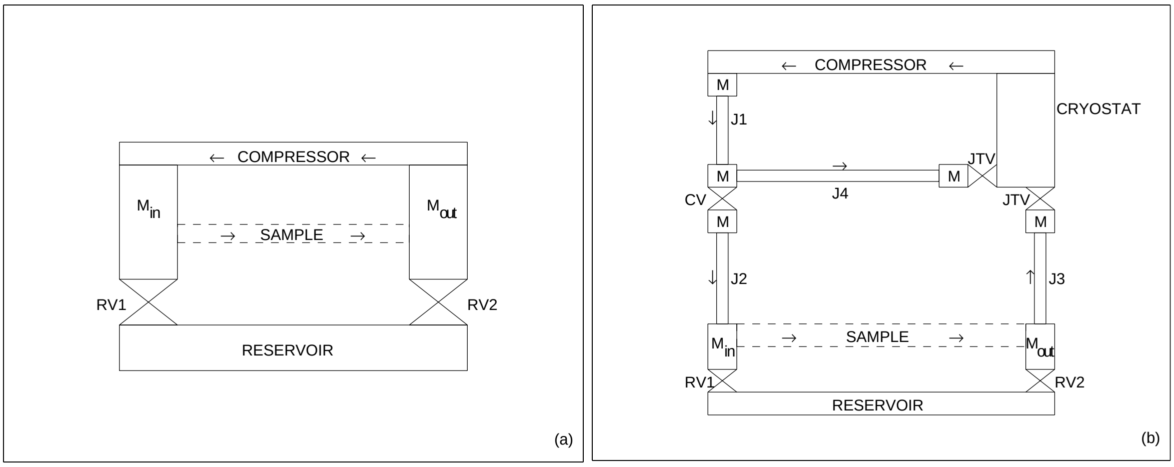

Figure 2. Two models of increasing complexity for the circuit in Fig.1. (a) The active component (compressor) acts directly on the sample. (b) Tubes (J1-J3), JTV's, "cryostat" and CV are interposed between the sample and the compressor; a simple model (J4) of the parallel path is also included. Fictitious manifolds M are included to link different junctions.

The compressor is defined by its characteristic in the (G,Δp) plane, where G is the mass flow rate and Δp is the pressure head, which is determined by two parameters. Since we have only one (G,Δp) experimental point, i.e., the operation condition at the beginning of the quench experiment, the second parameter has been chosen to give a qualitatively good global agreement with the experimental results. Notice that this is not an "ad hoc" recipe because, on the quench time scale, the helium pressure in M_{in} and M_{out}, influenced somehow by the compressor characteristic, is much more strongly influenced by the correct definition of the helium volume contained in the two manifolds.

Notice finally that in an earlier publication [7] only the part of the circuit up to the cryostat was considered, with smaller M_{in} and M_{out}, and less fluid flowing in the compressor. This results in a significant underestimation (more than a factor of 20) for the helium volume inside the circuit, compared to the present case.

Analysis of a Quench Run

We consider a "standard" quench (Run #2) [1] of QUELL.

The QUELL input for the MITHRANDIR code (both conductor geometry and material properties) is the revised one used in earlier studies [2,3]. The external heating is supplied by a resistive heater wound directly around the jacket.

The results of the simulation are presented in Fig.3. Figure 3a shows a very good agreement between the experimental and the computed total voltage drop. In Fig.3b the experimental quench front propagation, as deduced by the switching on of the voltage signal at the different voltage taps, is also very well reproduced by the simulations both with FLOWER and with experimental boundary conditions. The pressures p_{in} and p_{out} (Fig.3c and 3d, respectively) are somewhat underestimated by FLOWER (relative standard deviation σ of p_{in}, $p_{out} \approx 8\%$). Still, since the experimental pressure drop along the sample is well reproduced by the simulation (not shown), the computed quench evolution is in good agreement with the experiment. The pressure underestimation is partly due to an overestimation of the volume of helium available for the sample refrigeration. Indeed, if only a part of the cryogenic circuit is taken into account [7], p_{in} and p_{out} increase too quickly (not shown), leading to $\sigma \approx 12\%$, because the volume of helium to be pressurized in the cryogenic circuit is too small. The sensitivity of the results to the calibration of the compressor characteristic is small.

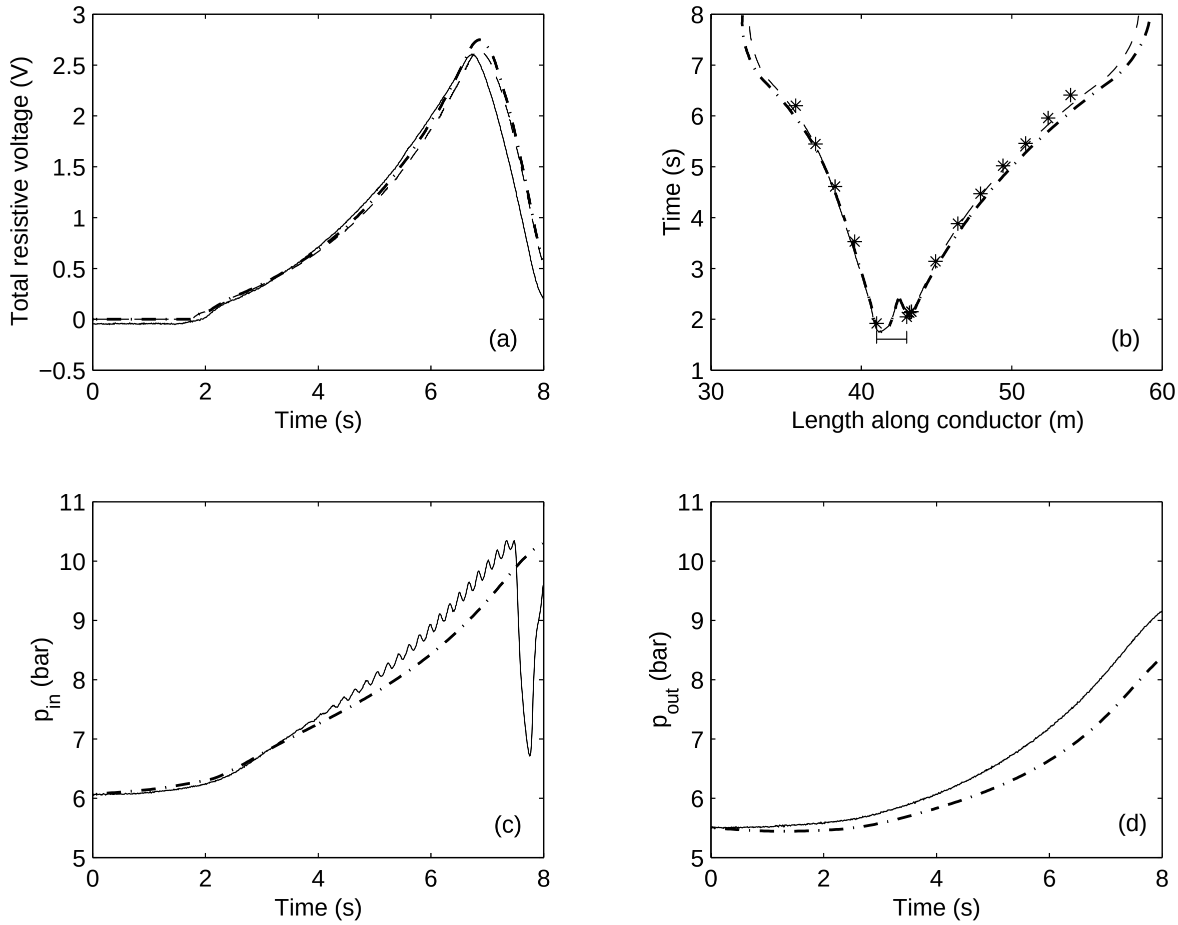

Figure 3. QUELL Quench #2 [1]: experimental data (solid,*), results computed with FLOWER boundary conditions using the circuit model in Fig.2a (dot dashed), results computed with experimental boundary conditions (dashed). (a) Total resistive voltage as a function of time. (b) Quench front propagation along the conductor as a function of time. (c,d) Pressure evolution at the sample inlet and outlet, respectively.

In the experiment the opening of the relief valve leads to a collapse of the inlet pressure This is not observed in the simulation because of the slower increase in the computed p_{in}.

Analysis of an Inductive Heat Slug Run

If we perform simulations of heat slug propagation (zero current and field) with the circuit model in Fig.2a, we obtain different degrees of accuracy in the results depending on the amount of energy deposited and on the external heating duration.

In an inductively heated case (Run #008 [2,3], linear input power Q0=63125W/m supplied on a length L_H=0.12m), a reasonable agreement is found between computed results and experimental data, see Fig.4. The computed jacket temperature evolution at different sensors along the conductor (Fig.4a) is shown to be as accurate as that with experimental boundary conditions. The characteristic of the compressor in the (G,Δp) plane has been changed with respect to the quench run, emulating the operation of CV and JTV in the real circuit, in order to provide the correct G_{in} at steady state (see Fig.4b). This explains the smaller phase shift at the temperature sensors (Fig.4a) with respect to the results obtained with experimental boundary conditions, which give an overestimation of G_{in}. The computed p_{in} and p_{out} (Fig.4c and 4d, respectively) show a qualitatively different behavior with respect to the experiment. In the simulation, the pressure tends to stabilize around a value higher than the initial one because the circuit, that can be thought here as a 0-D object, reacts to the energy supply, pressurizing. In the experiment, the cryostat possibly absorbs the energy input as latent heat of condensation/evaporation, and the pressure, after a few oscillations, tends to return to its initial value. The accuracy in the results, notwithstanding the relatively simple circuit model, is mainly due to the fact that the inductive heater acts on a short time scale (10ms). Indeed on this time scale the perturbation of the hydraulic circuit conditions is very small (i.e., the variation of p_{in} and p_{out} is < 0.5bar, see Fig.4c and 4d).

Model of the Cryogenic Circuit for Resistive Heat Slug Studies

In a resistively heated case (Run #012 [2,3], Q0=2306W/m, L_H=2.3m), the circuit model in Fig.2a gives a significant disagreement with the experiment (not shown). The external heating, which effectively acts on a much longer time scale (~10s) than the inductive one, leads here to significant changes in pressure and mass flow (see below). Furthermore, in the second phase of the transient the circuit response to the perturbation becomes the driving force of the transient evolution. A more accurate circuit model is thus needed in order to get a realistic response of the cryogenic circuit to the perturbation caused by the sample. Notice that the heat slug conditions in QUELL were rather different from those expected in the TFMC [2,3].

A more detailed circuit model is shown in Fig.2b. The cryostat is implemented as a one-phase reservoir (V=O(m^3), i.e., much larger than the real two-phase volume). Provided V is sufficiently large, the helium temperature and pressure in the reservoir will not change significantly from the initial values, behaving as in the cryostat. Differently from the previous model, the parallel path is included and pipes, CV and JTV are present here.

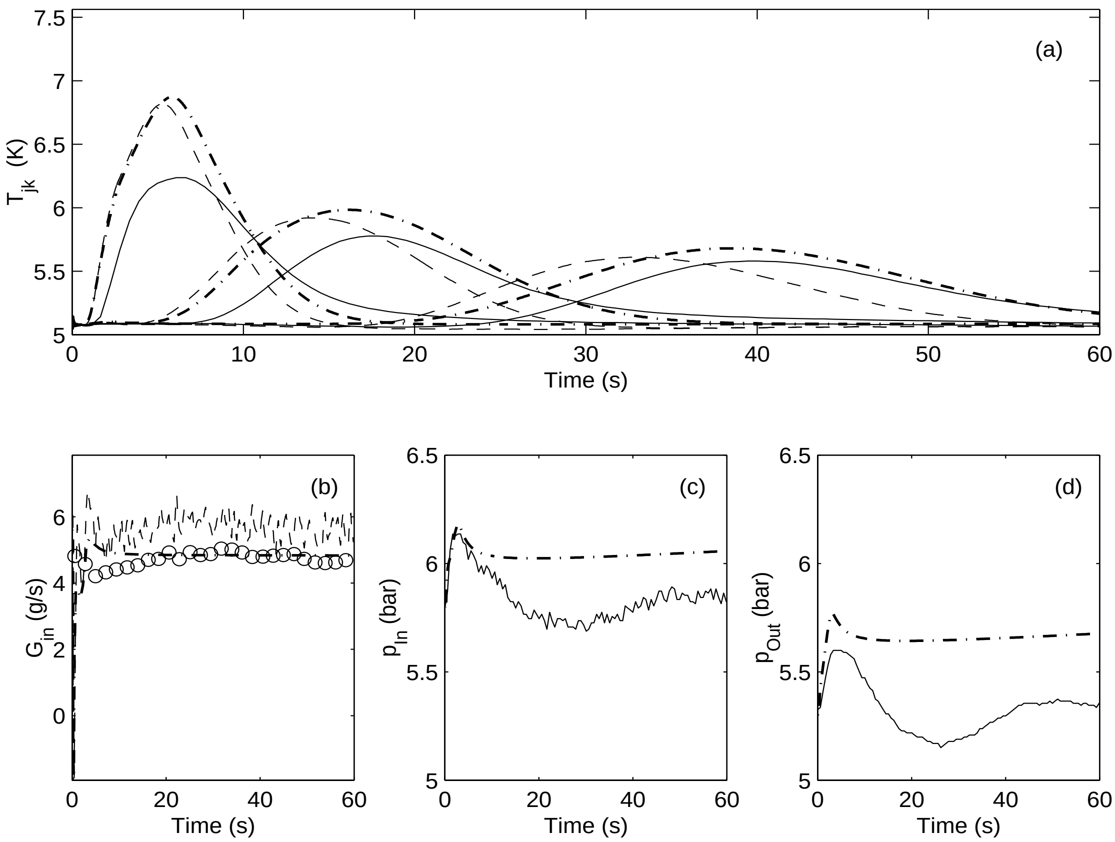

Figure 4. QUELL inductive heat slug #008 [2,3]: experimental data (solid, open circles), results computed with FLOWER boundary conditions using the circuit model in Fig.2a (dot dashed), results computed with experimental boundary conditions (dashed). (a) Jacket temperature at the sensors TA5, TA6, TA8, respectively. (b) Sample inlet mass flow rate as a function of time. (c,d) Pressure evolution at the sample inlet and outlet, respectively.

The compressor now takes into account *all* the helium flowing through the cold-box. The JTV's (implemented as valves with a high localized pressure drop coefficient) regulate the helium access to the cryostat. The CV allows, together with the calibration of the compressor characteristic, a fine regulation of G_{in}. For the parallel path J4 no heat exchange (see Fig.1) is taken into account, but the higher hydraulic resistance, due to the helium heating and to the path tortuousness, is emulated by a high friction factor. Since J4 is approximately a factor of five longer than the other tubes, and has a higher pressure drop, it is worthwhile to simulate it with compressible helium flow, because its hydraulic evolution is expected to strongly affect the sample. Pipes J1, J2 and J3 are defined by their physical parameters [8].

The compressor calibration is now expected to have an even smaller influence on the transient evolution, at least because of the presence of the parallel path J4 in the circuit model.

Analysis of a Resistive Heat Slug Run

The results obtained for Run #012 with the circuit model in Fig.2b are shown in Fig.5. The difference between the peak jacket temperature computed with FLOWER, and the experimental ones, is < 0.5K, while the phase shift is < 4s (Fig.5a). The computed G_{in} (Fig.5b) decreases faster than the experimental one in the first part of the transient. This effect can be partly attributed to some kind of delay in the response of the two-phase components (not implemented in FLOWER at present), due to condensation/evaporation of

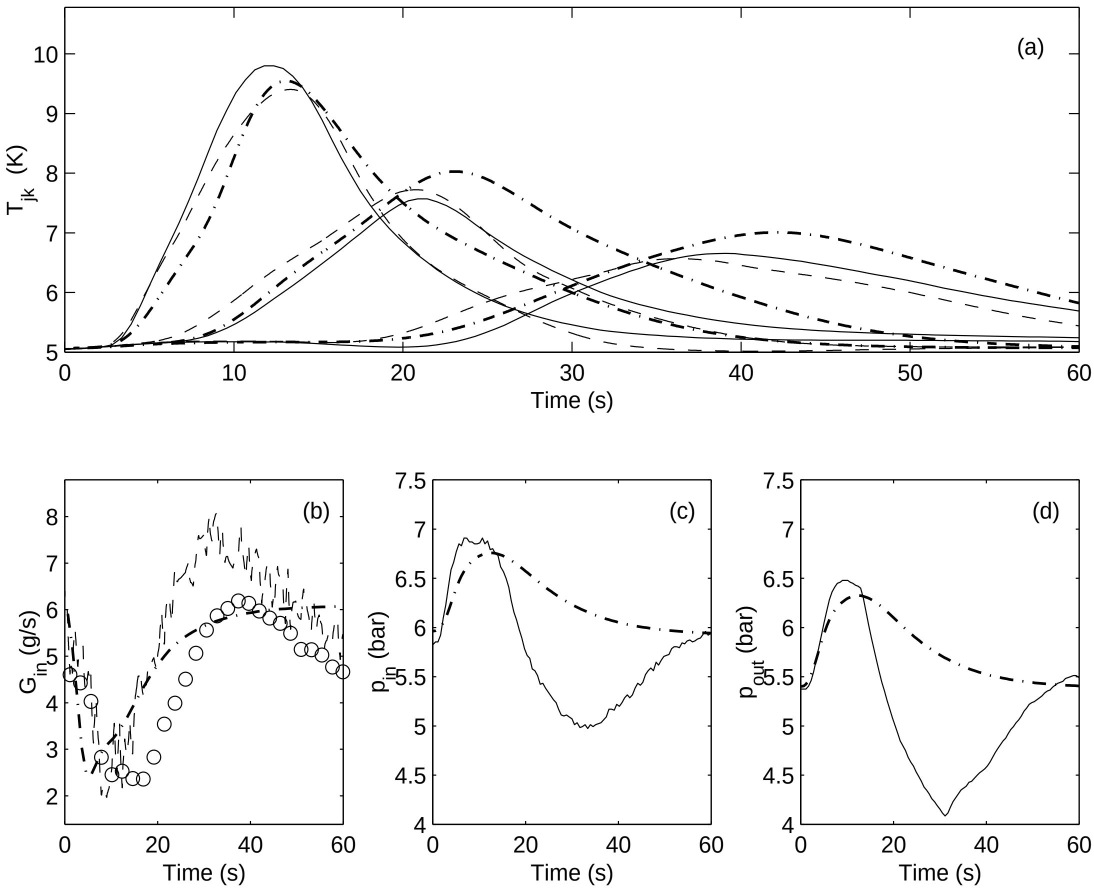

Figure 5. QUELL resistive heat slug #012 [2,3]: experimental data (solid, open circles), results computed with FLOWER boundary conditions using the circuit model in Fig.2b (dot dashed), results computed with experimental boundary conditions (dashed). (a) Jacket temperature at the sensors TA5, TA6, TA8, respectively. (b) Sample inlet mass flow rate as a function of time. (c,d) Pressure evolution at the sample inlet and outlet, respectively.

helium. After the first decrease, the computed G_{in} monotonically increases till the end of the transient, while both the experimental signal, and the evolution computed with experimental boundary conditions give a non-monotonic behavior, linked to the experimental pressure drop evolution (not shown). The boundary pressures provided in this case by FLOWER are again only qualitatively in agreement with the experimental ones (Fig.5c and 5d), which behave similarly to the inductive run. After a first increase, p_{in} and p_{out} decrease to their initial value because the supplied energy can now be absorbed by other components of the circuit (as opposed to what occurs with the circuit in Fig.2a, where p_{in} and p_{out} asymptotically increase, not shown). However, the decrease is slower than in the experiment, possibly due again to the absence of two-phase components in the model.

The circuit model in Fig.2b has also been used (not shown) for the analysis of the quench run considered in the previous section, giving comparably good results.

CONCLUSIONS

A hydraulic network solver, FLOWER, has been coupled to the two-fluid MITHRANDIR code. The cryogenic circuit of the QUELL experiment has been modeled with different levels of detail in order to simulate different kinds of transient. For fast heating transients (i.e., quench or inductive slugs), even a simple model of the circuit leads to reliable results in good agreement with the experiment, albeit for different reasons, provided a realistic estimation of the total helium volume in the circuit is given. For slow heating transients (resistive slugs), where the effective heating time scale is comparable to the circuit response time scale, a more accurate model of the circuit is needed (larger number of components, and suitable fluid equations, i.e., compressible flow) to obtain acceptable results.

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