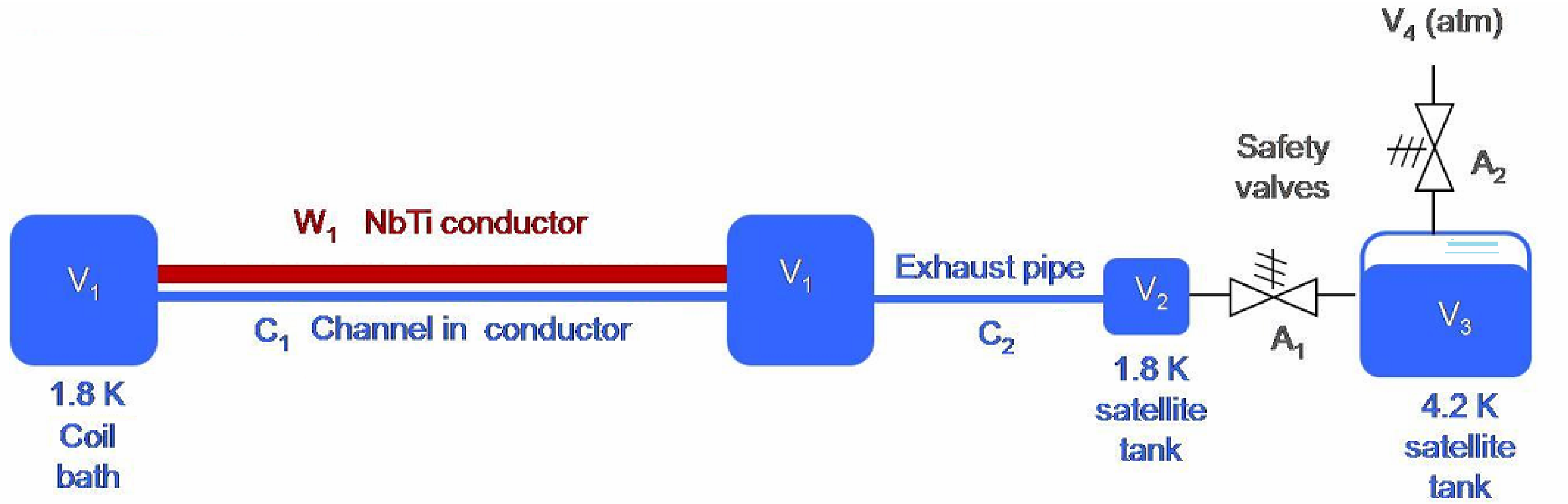
DEMO EXAMPLE №1

Superconductor quench and safety helium exhaust in condition of He II state



Hydraulic schematic for demo sample 1

Table

Basic parameters of different elements of the thermal hydraulic circuit

37 identical channels C1	
Channel length, m	260
Wettedd perimeter, mm	18.85
Helium area, mm^2	28.27
Friction factor	$4f=0.11(68/Re+S/D_h)^{0.25}$

Initial pressure, MPa	0.11
Initial temperature, K	1.8
37 identical channels C1	
Conductor cross section area, mm^2	204
NbTi crosssection area, mm^2	20.22
Magnetic field, T	9.4
Critical properties	$B_{c2}(T) = 14.5\left(1-(T/9.2)^{1.7}\right)$ $j_c(T,B) = 2580.\times 10^6\,\frac{31.4}{B}\left(\frac{B}{B_{c2}(T)}\right)^{0.63}\left(1-\frac{B}{B_{c2}(T)}\right)^{1.0}\left(1-\left(\frac{T}{9.2}\right)^{1.7}\right)^{2.3}$
n-factor	20
Thermal coupling between channel C1 and conductor W1	
Heat transfer coefficient, W/m^2K	500
Heat exchange perimetr, mm	18.85
Exhaust pipe C2	
Channel length, m	6
Hydraulic diameter, m	0.11
Helium area, m^2	0.0348
Wall cross section area, m^2	300.10^{-6}

Coil bath volume V1, satellite tank V2, LHe bath V3	
V1, m^3	0.8
V2, m^3	0.046
V3, m^3	0.5
Valve parameters	
A1, mm^2	1180
A2, mm^2	10000

Task description

A NbTi conductor **W1** with the length of 260 m has a cooling channel **C1** with superfluid He at the initial temperature of 1.8 K and pressure of 1.1 bar. The conductor is hydraulically connected at each end to a bath **V1** 0.8 m^3 in volume with superfluid He at the same temperature and pressure. There are no other hydraulic coupling between the conductor and helium. The initial helium velocity is zero.

The bath **V1** is hydraulically connected to a satellite **V2** via an exhaust pipe **C2**. The satellite **V2** is 0.046 m^3 in volume and contains the helium at the same temperature and pressure as in the bath **V1**. **V2** is hydraulically connected through a safety valve **A1** to a 4.2 K tank **V3**. **V3** is 56% filled with saturated liquid helium at a pressure of 1 bar and has a safety valve **A2** at its top to exhaust gaseous vapour. Both valves are initially closed and will open when the helium pressure reaches 2 bar.

The initial operating current I_0 of conductor **W1** is 7100 A.

A 50 W/m heat pulse is applied at the beginning of conductor over 3 m during 0.1s. This heat pulse initiates a quench and normal zone propagation. The hot helium is expelled from the channel **C1** into the bath **V1**. The helium pressure rises that leads to opening safety valve **A1**.

Simultaneously with the quench, the current discharge is started with a law:

$$L\frac{dI}{dt} = -I\left(R_D + R_{coil}\left(t\right)\right),$$

where L=3 H is the coil inductivity; R_D=0.07 Ohm is dump resistor resistivity; R_{coil}(t) is instant resistivity of coil during quench.

Task features

Modelling of this case is a formidable task due to a complex of physical phenomena involved. Typical quench simulations do not imply such combination of processes. Note that superfluid helium properties are an important but not the most challenging aspect of the case. In the context of mathematical formulations, the main numerical difficulty is strong non-linearity of the thermodynamic equations in vicinity of the normal zone boundary, where substantial variations of helium properties are observed, primarily at HeII-to-HeI and saturated liquid-to-saturated vapour local transitions. Drastic time variations of boundary conditions also have unfavourable effect on solution.

As compared to VINCENTA, VENECIA implements an improved solver capable of much more efficient and stable calculations. Special numerical procedures are used to provide good numerical stability and convergence to a smooth solution. The code gives more consistent and comprehensive description fluid behaviour.

Stable and continuous computations are enabled for transition zones, particularly, when passing from the two-phase liquid–gas zone to the pure gas.

Below are some results to illustrate the code performance. The reference results were obtained on a mesh with a step of 0.1 m. Test runs revealed that approximation with better convergence is achieved when the mesh is substantially refined. This led, however, to an increase of runtime.

Analytical description of helium thermodynamics

In order to simulate behaviour of superfluid helium, VENECIA implements the following modification of basic equation for energy conservation:

$$\frac{\partial}{\partial t}\rho_i\left(H_i+\frac{V_i^2}{2}-\frac{P_i}{\rho_i}\right)+\frac{\partial}{\partial x}\rho_i V_i\left(H_i+\frac{V_i^2}{2}\right)+\frac{\partial}{\partial x}q_{HeII}=\frac{\sum\limits_m Q_{mi}^{conv}+\sum\limits_k \Gamma_{ki}^{\rho H}}{A_i}$$

where $q_{HeII_i}=-\left(\frac{1}{f(T_i)}\frac{\partial T_i}{\partial x}\right)^{\frac{1}{3}}$ - heat flux in turbulent HeII flow,

$f(T)^{-1}$ - HeII thermal conductivity function for turbulent flow.

Meshing and assumptions

- Space step for the mesh along both channels C1 and C2 is taken as 0.1 m
- Two-phase liquid-gas region is simulated as a homogeneous mixture.
- Safety valve A2 in tank V3 operates with the saturated He vapour in condition of two-phase helium bath and with the single phase He, when vapour quality in the bath is zero.

Results obtained on reference mesh (step 0.1 m)

Below some basic results are presented to demonstrate principal features and benefits of VENECIA simulation.

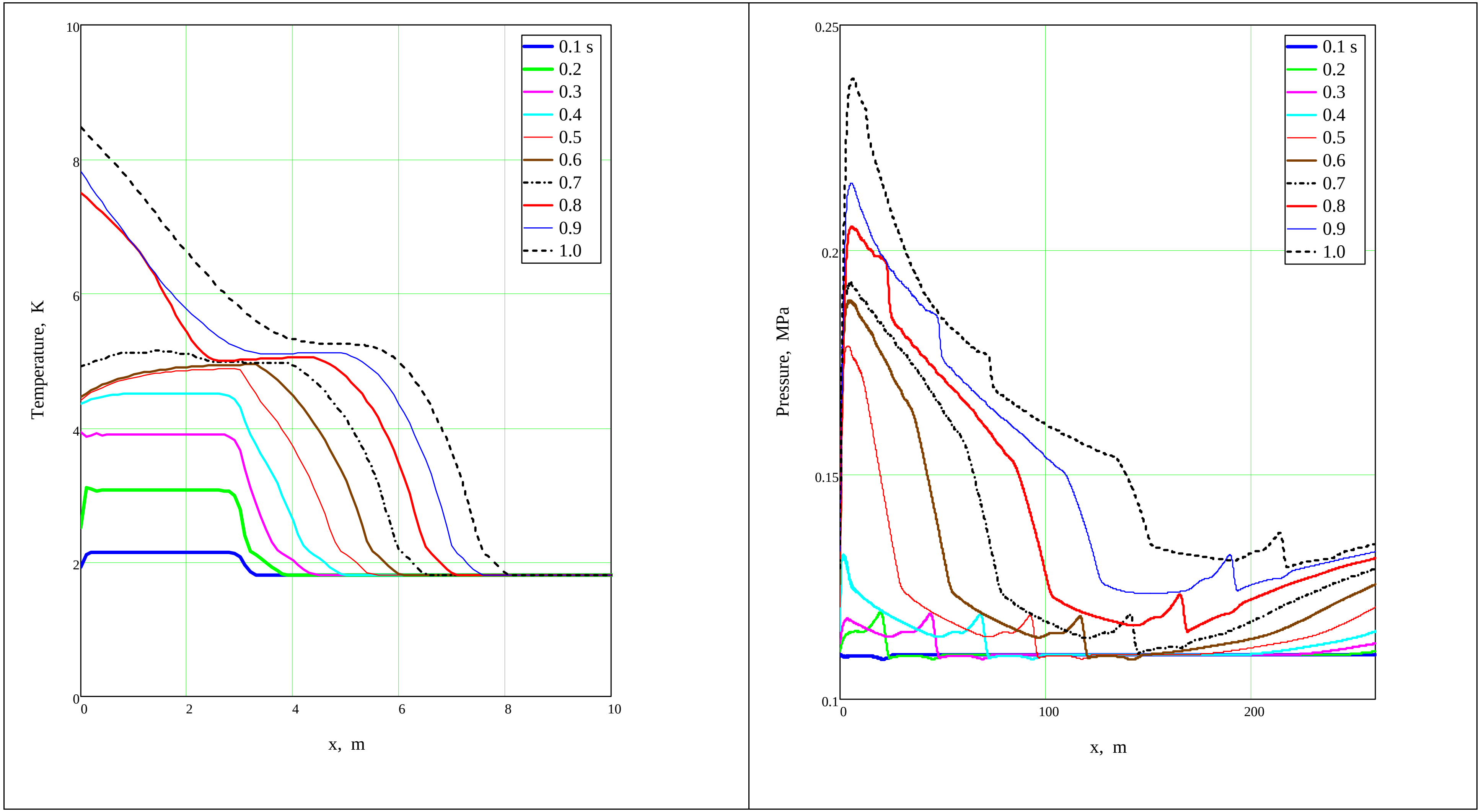


Figure 1. Helium temperature / pressure variations in conductor channel C1 during 0..1 s.

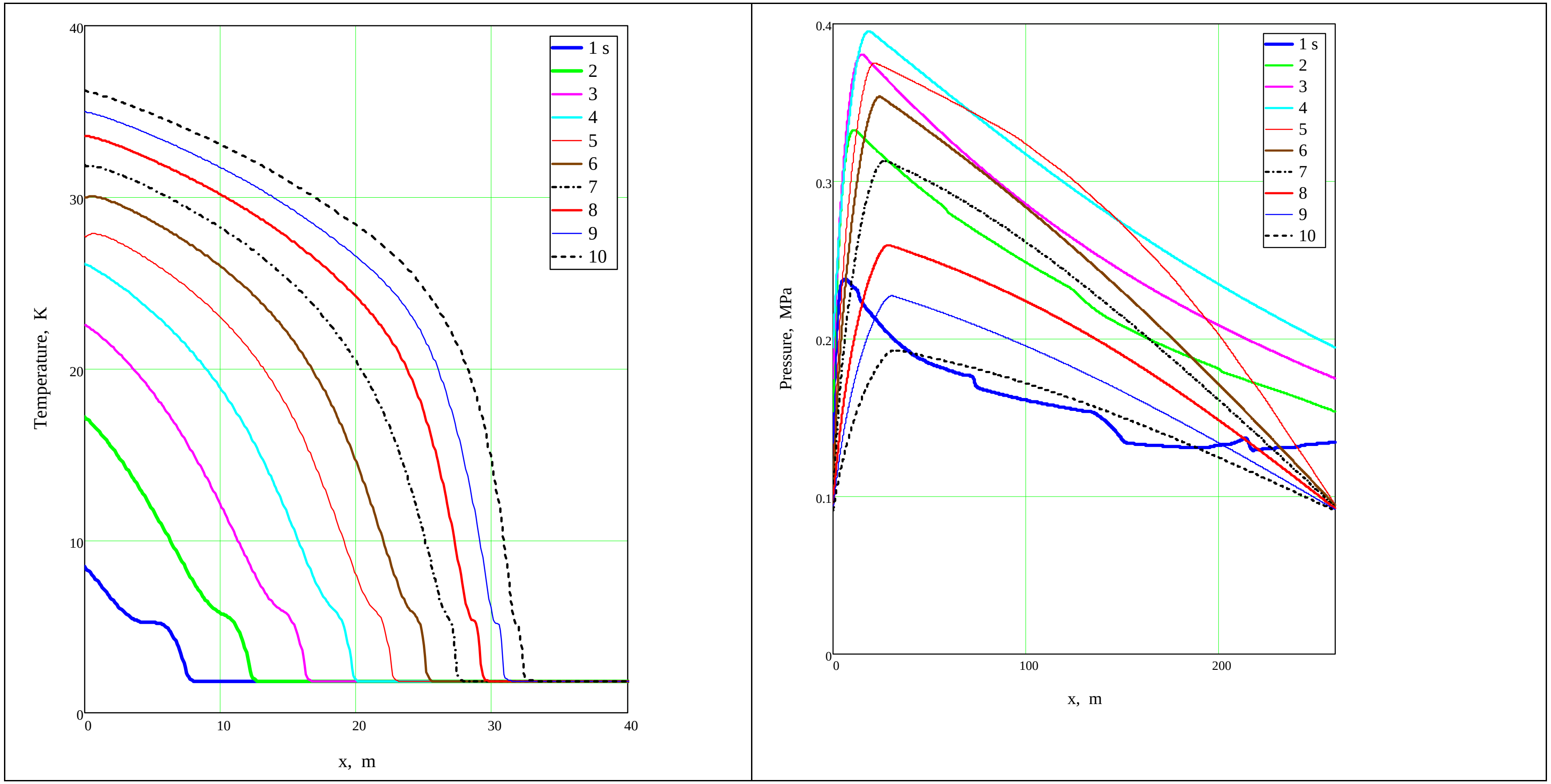


Figure 2. Helium temperature / pressure variations in channel C1 during 1..10 s.

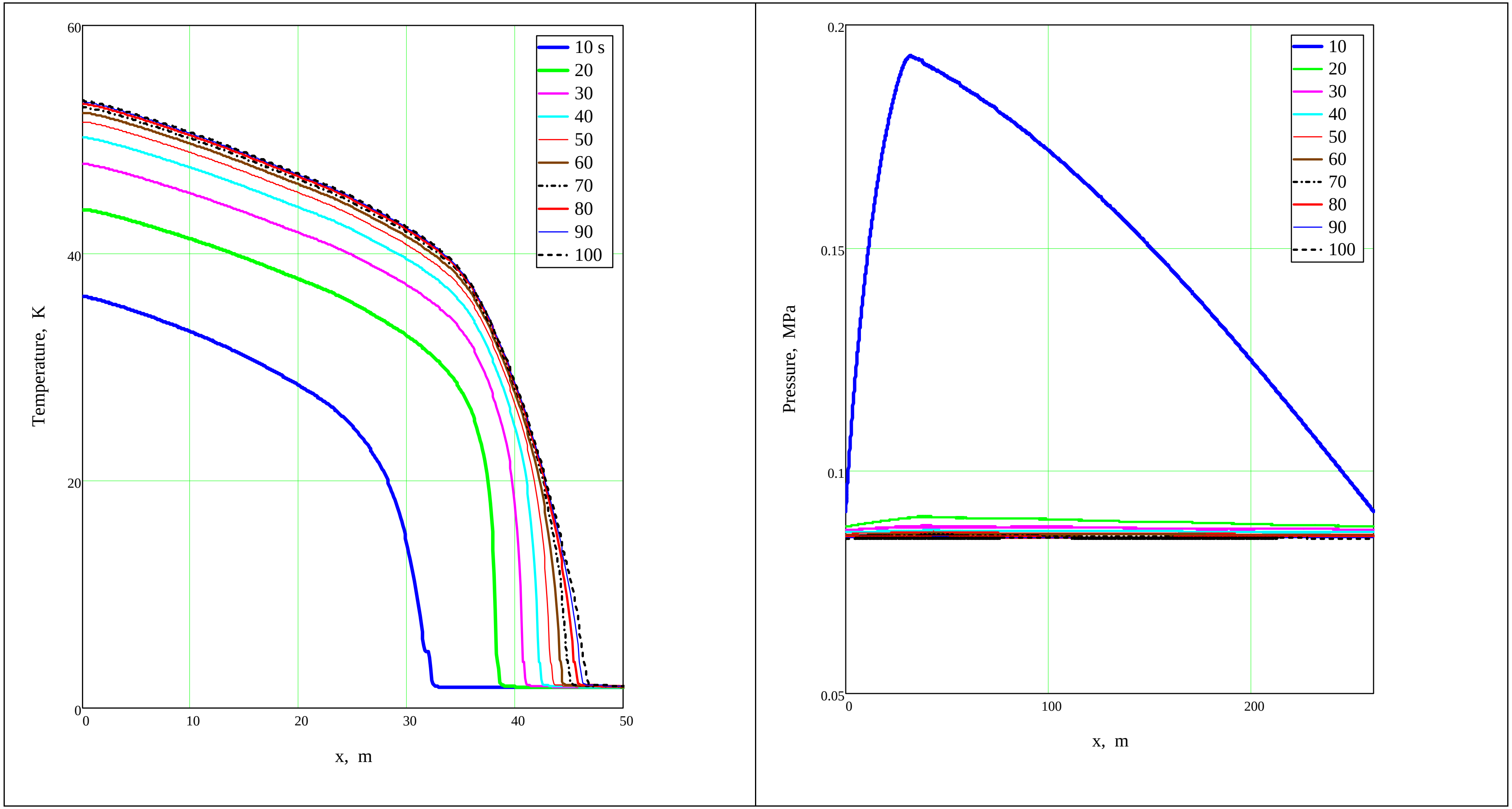


Figure 3. Helium temperature / pressure variations in channel C1 during 10..100 s.

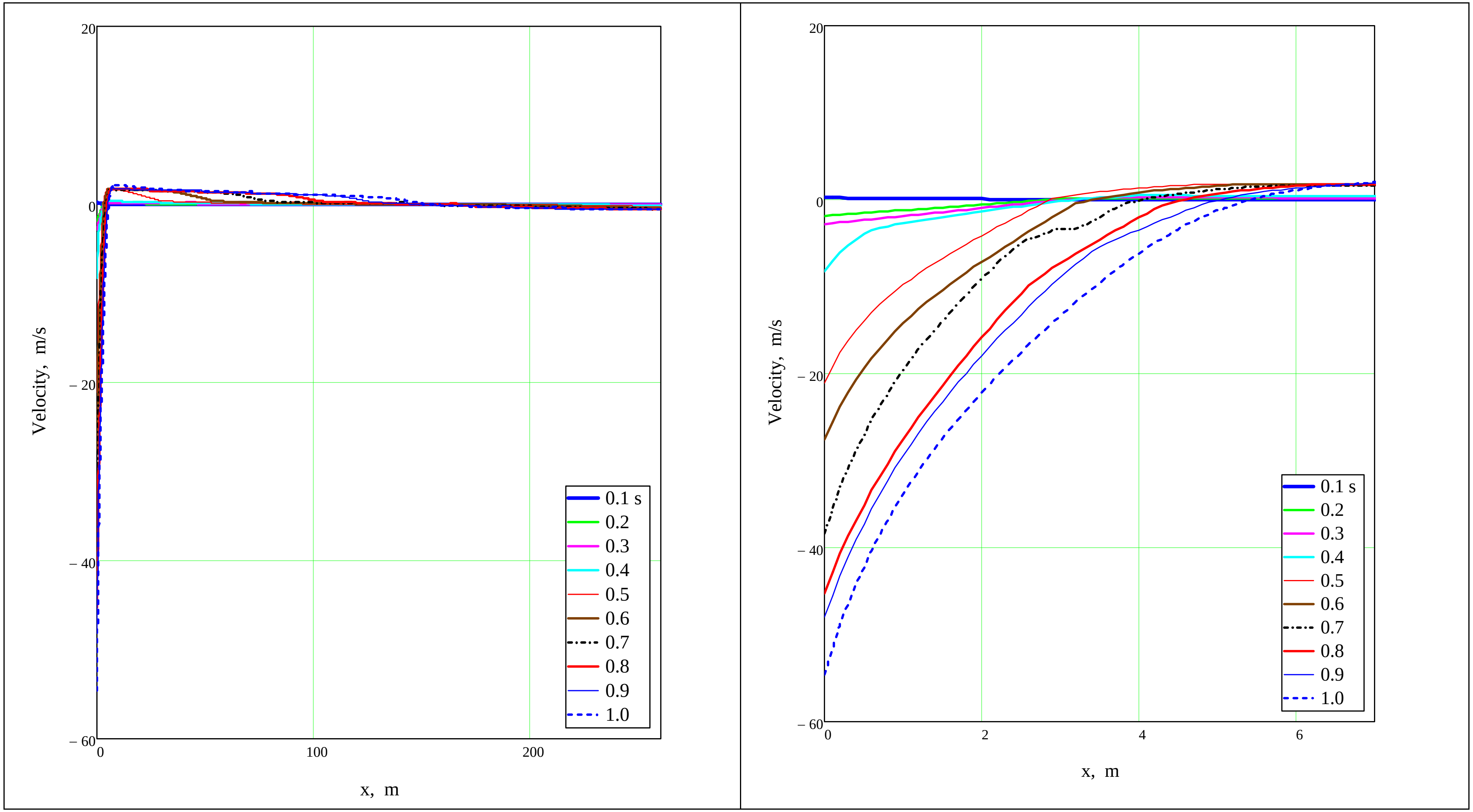


Figure 4. Helium velocity variations in channel C1 during 0.1..10 s.

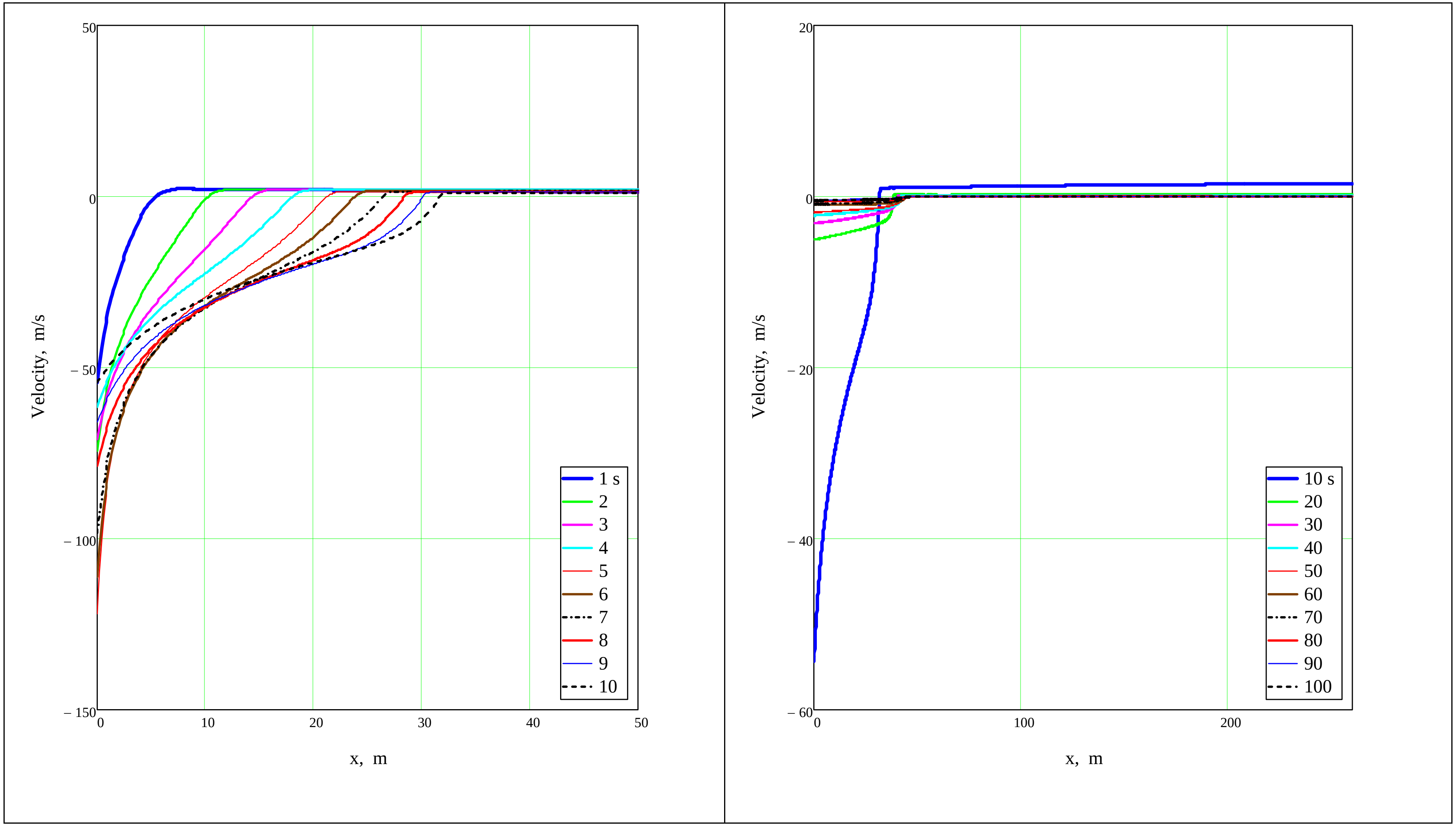


Figure 5. Helium velocity variations in channel C1 during 1..100 s.

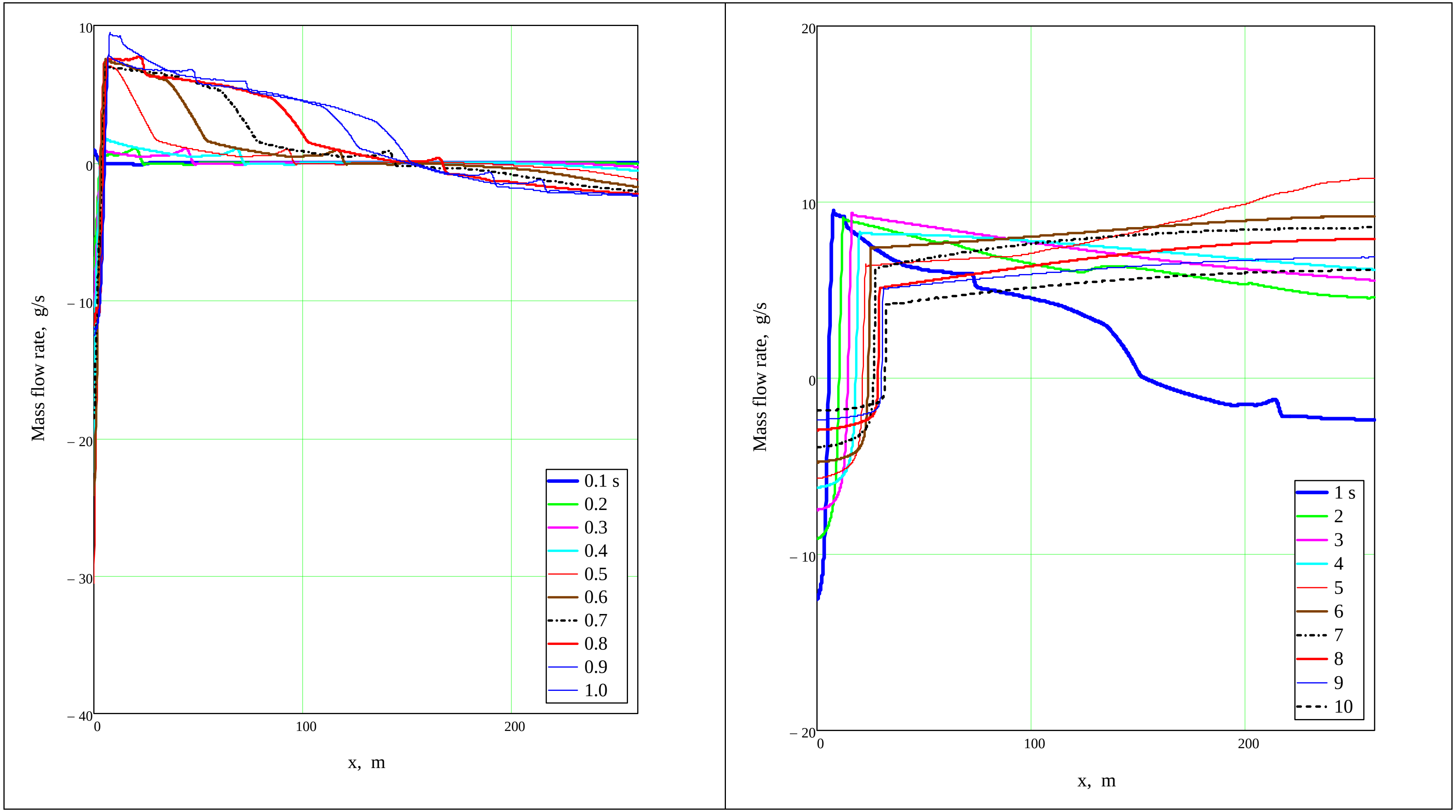


Figure 6. Helium mass flow rate variations in channel C1 during 0.1..10 s.

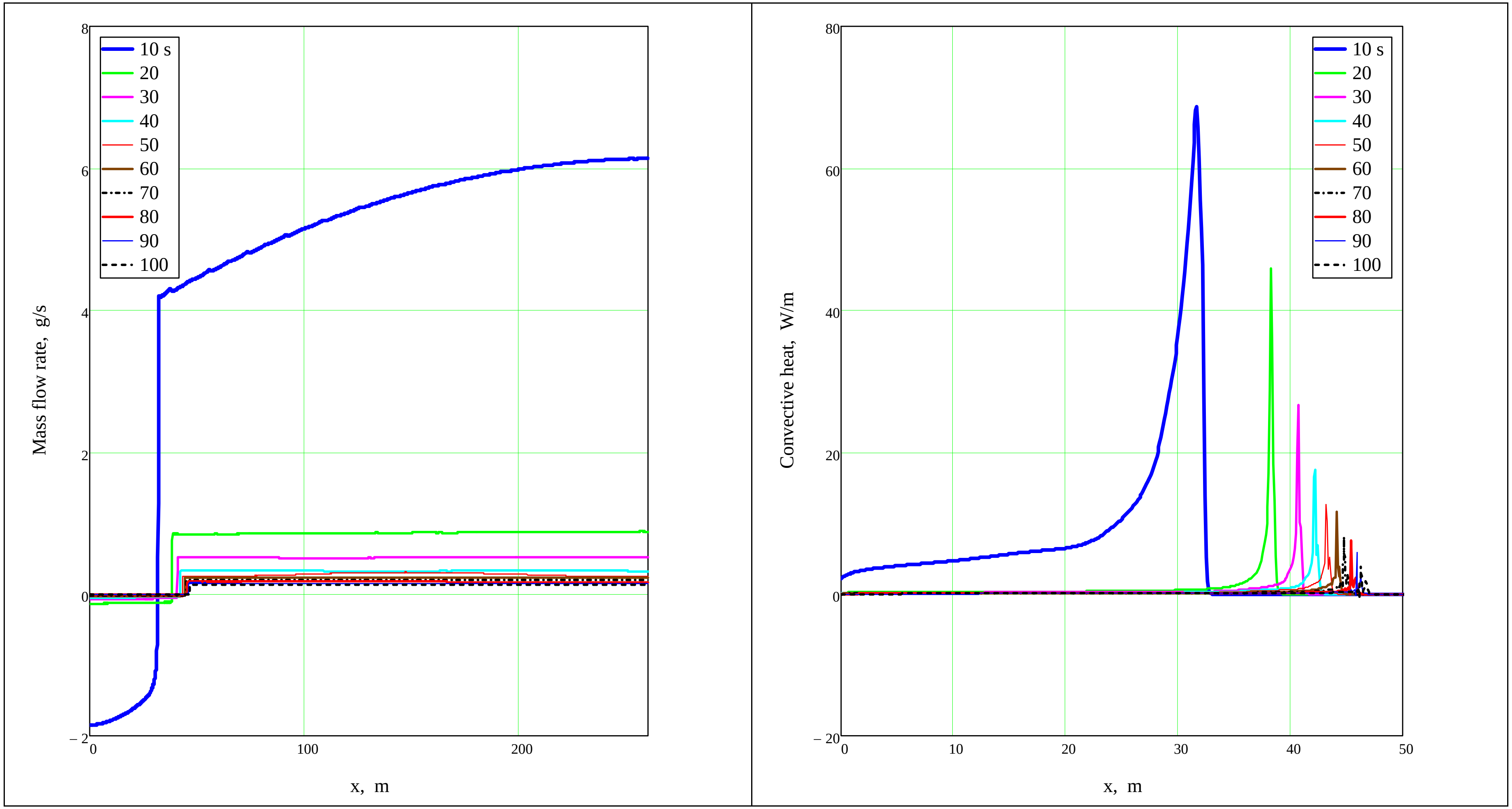


Figure 7. Helium mass flow rate (a) and convective heat flux variations in channel C1 during 10..100 s.

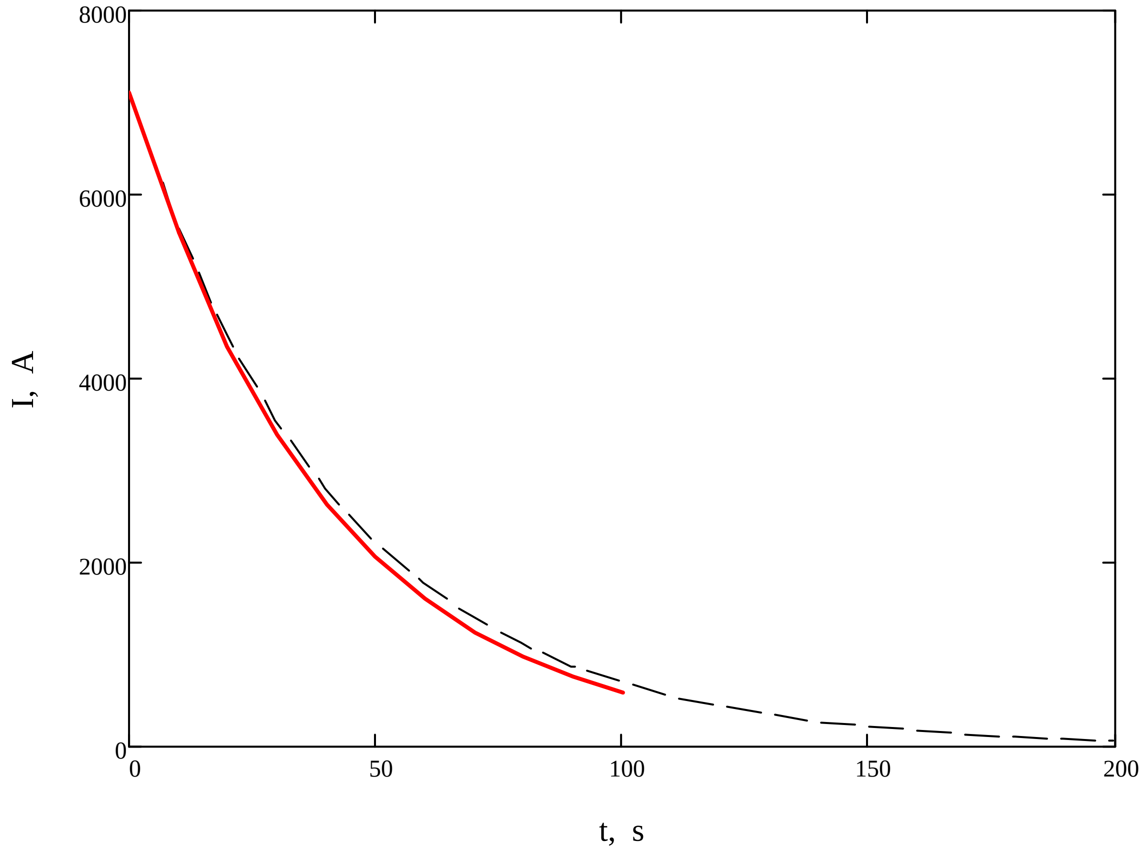


Figure 8. Current decay during the coil energy discharge in the dump resistor and the conductor normal zone (red) line. Dash line shows $I_0 exp(-tL/R_D)$

Evolution of parameters in the coil bath V1, the satellite V2 and the LHe bath V3

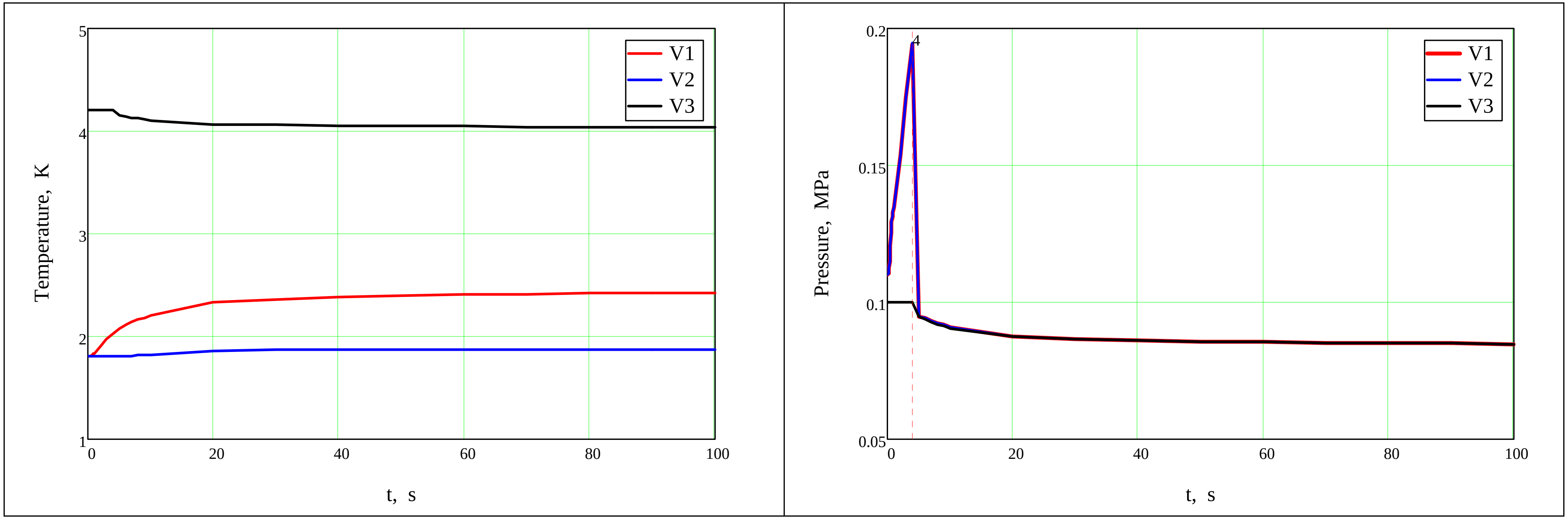


Figure 9. Evolution of helium temperature and pressure in the coil bath V1, satellite tank V2 and LHe bath V3

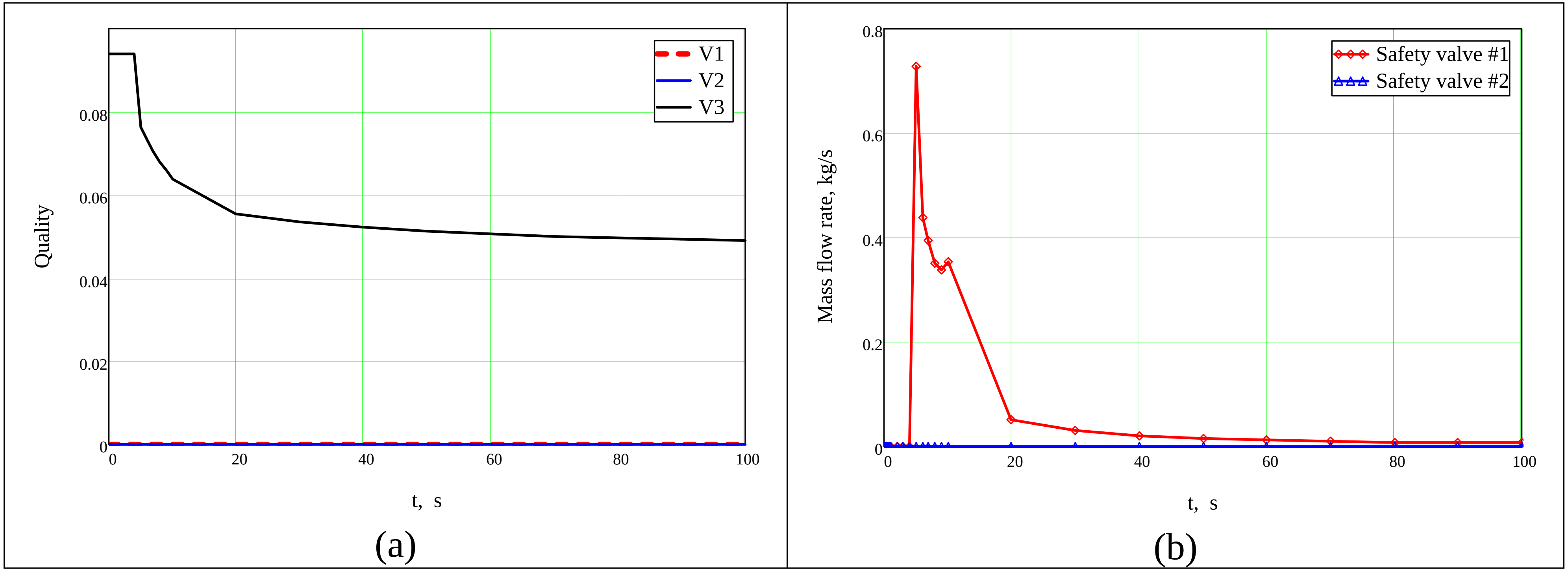


Figure 9. Evolution of helium vapour quality in the coil bath V1, satellite tank V2 and LHe bath V3 (a) and mass flow rate of safety valves A1 and A2 (b).

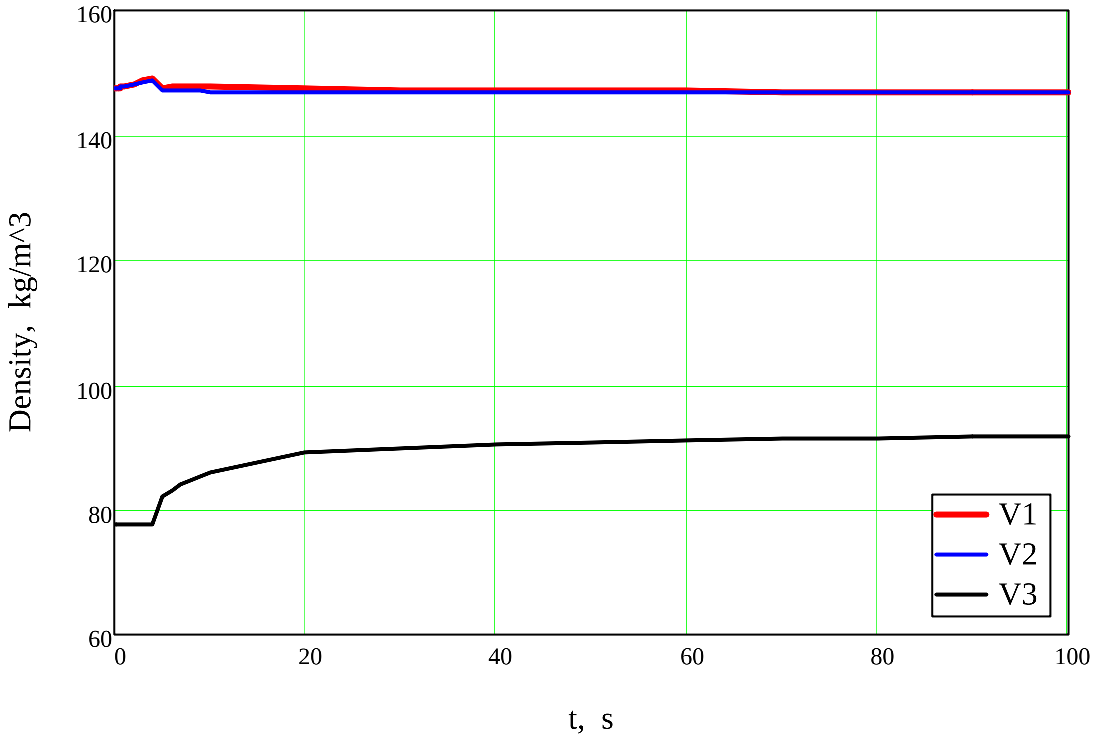


Figure 10. Evolution of helium density in the coil bath V1, satellite tank V2 and LHe bath V3.

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