DEMO SAMPLE 4

Cable in Conduit Conductor (CICC) quench modelling

This demo gives an example of quench simulation for a Central Solenoid (CS). CS is divided into 6 geometrically identical sections (see Fig. 1) wounded by Cable-in-Conduit Conductor (CICC). Each section consists of 20 CICC double pancakes. CS cooling is provided by supercritical helium (SHe) flow in parallel for all 240 pancakes. Helium inlet is at the innermost turn of each pancake and outlet is at outermost turn.
Quench occurs in CICC's of section CS2L.

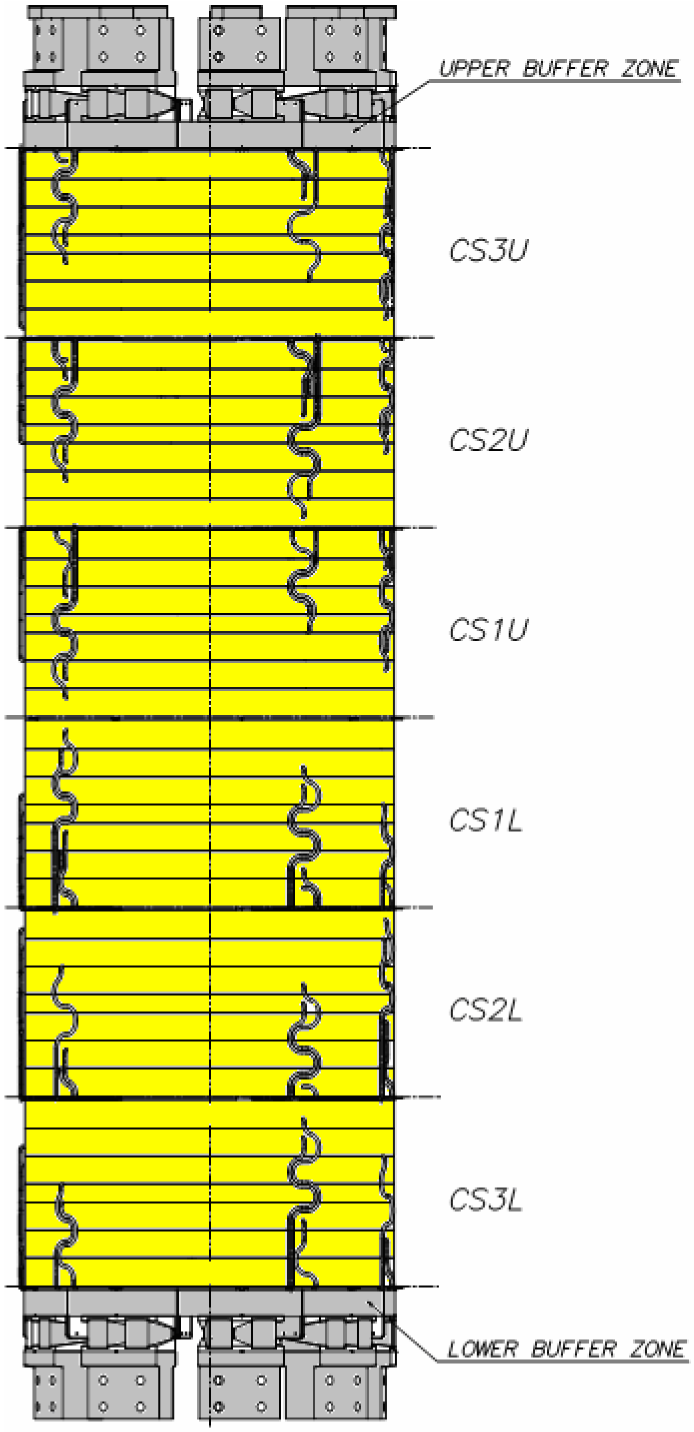


Figure 1. 6 CS sections with lower/upper buffer zones

It is assumed that CS2L quench is initiated in each innermost turns of 40 CS2L pancakes at 1790s of a regular plasma pulse, when constant and maximal currents (~40kA) excite different CS sections.

The VENECIA model of CS includes CS and an external cooling circuit.
CS is modelled as 240 CICC pancakes (C1-:-C240+C487-:-C726), 120 inlet (C241-:-C360) and 126 outlet (C361-:-C486) tubes, 6 supply (C733-:-C738) and 6 return (C727-:-C732) feeders.

The external cooling circuit is modelled as 2 SHe heat exchangers (C741, C744), circulator (P1), 2 control valves (A1, A2), 2 supply/return cryolines (C739, C740, C742, C743), 12 relief valves (A3-:-A14) with opening pressure of 2 MPa and a set of quench line tubes (C745-:-C765) with the quench tank (V289).

Control valve A1 is used to mitigate pulsed heat load from CS on the cryoplant. Control valve A2 provides protection of a SHe circulator when the pressure difference between the outlet and inlet of the circulator is close to the design limit on the pressure head.

In each pancake, CICC is individually modelled with 240 pares of SHe flows in the bundle and central channel which interact through mass- heat exchange.

The CS model includes individual descriptions for magnetic field B, strains ε, AC losses and currents I distribution in each of 240 CICC. These space/time descriptions for CS section CICC are provided through inputs as external data.

Electrical field in CICC is calculated using a tabular description of superconductor properties parameterized via B, dB/dr, ε, I and temperature T.

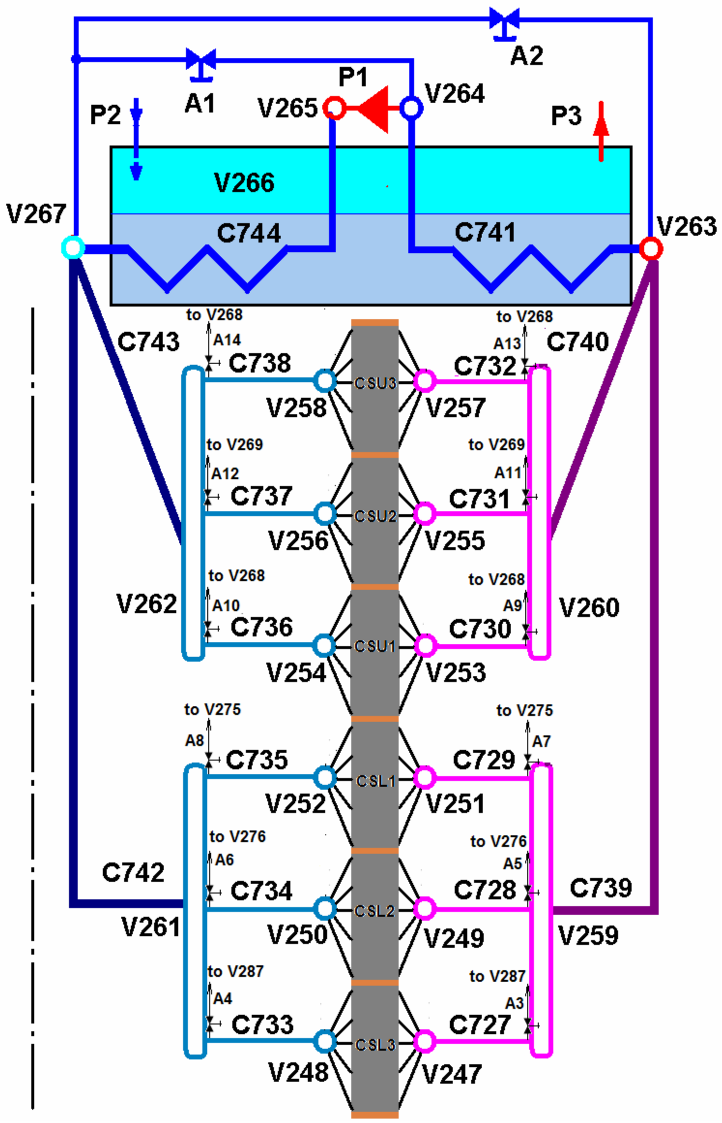


Figure 2. Hydraulic scheme of CS cooling cirquit.

An inter turn and inter pancake heat exchange in CICC is modelled by solving a 2D thermal diffusion problem over CS cross-sections normal to the cable axis. Each cross-section includes 3360 (240x14) stainless steel cable conduits, inter turn and inter pancake insulation, intersection insulation and upper/lower buffer zones. 5 cross-sections taken for the simulation are meshed with 3.5 million nodes in total.

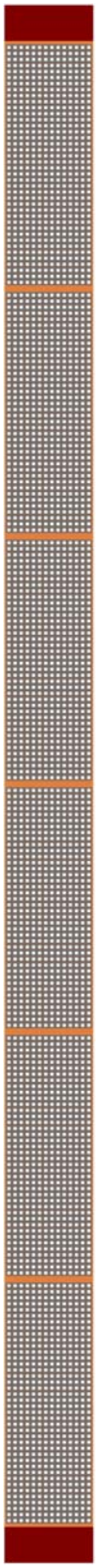


Figure 3. Meshing over a 2D CS cross-section. 700,000 nodes

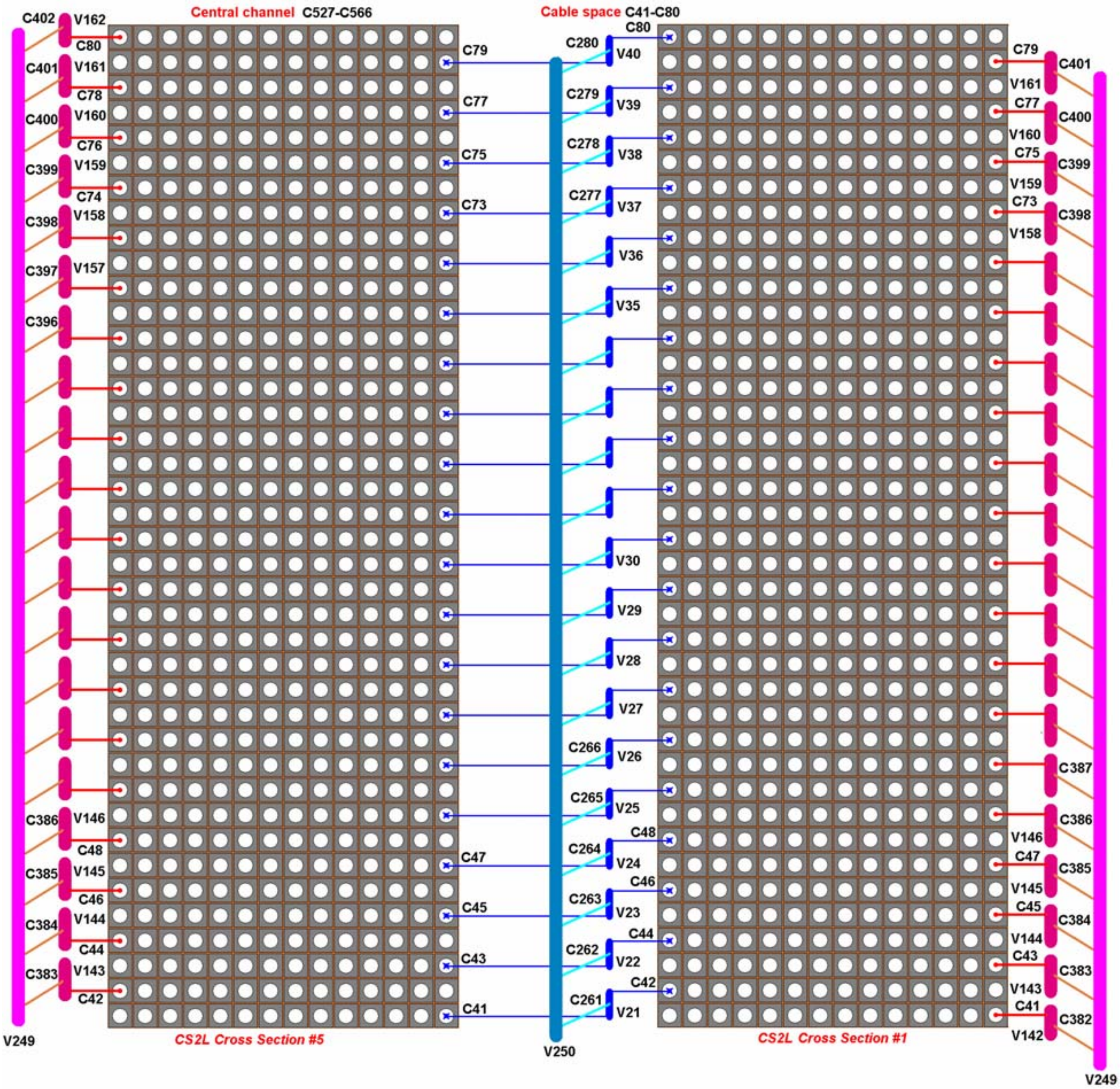


Figure 4. Extraction from CS hydraulic model: CS2L cooling circuit with position for cross sections #1 and #5

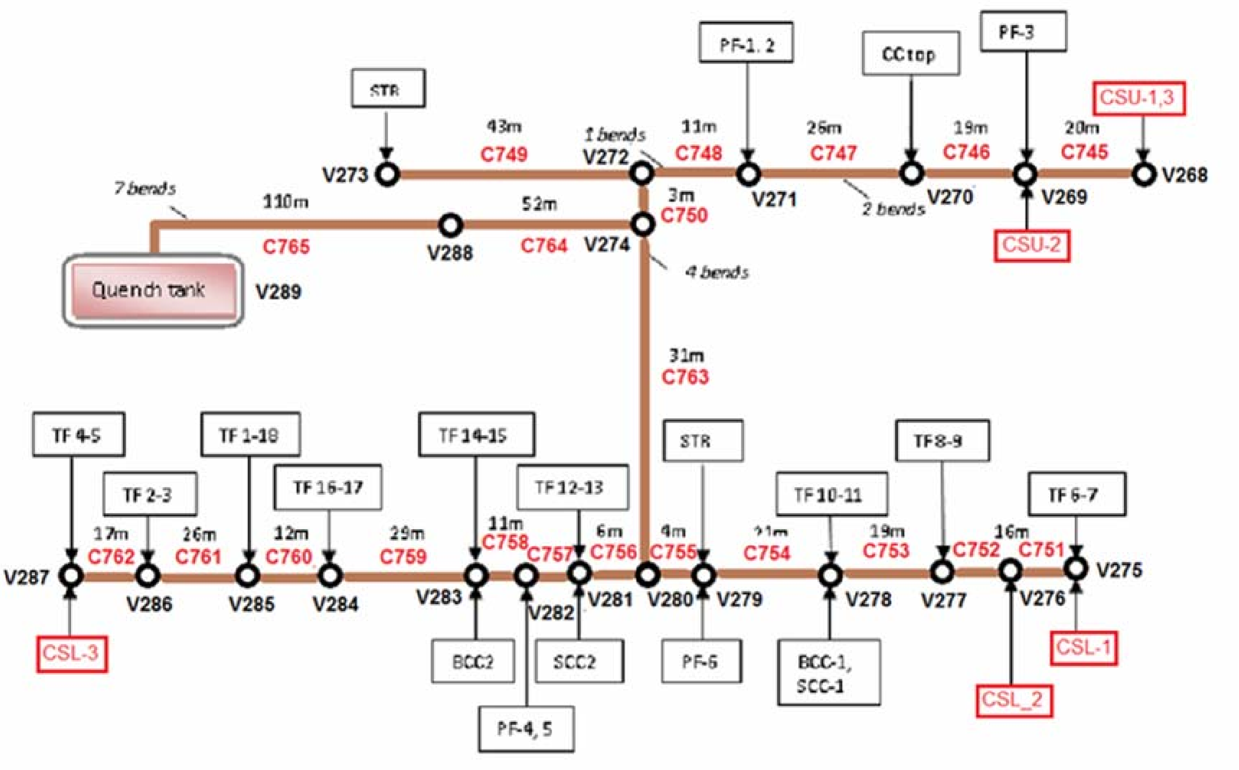


Figure 5. Hydraulic scheme of quench lines

Hydraulic parameters of CS cooling circuit and quench lines are listed in Table 1 and Table 2.

Table 1. ***Parameters of CS cooling circuit***

Channels #	Cross section area, mm^2	Hydraulic ID, mm	Length, m	Comments
C1-C240	256.2		145.7	Cable space
C487-C726	63.6	9	145.7	Central pipe
C241-C360	78.5	10	5	Supply tubes
C361-C486	78.5	10	5	Return tubes
C727-C732	2165	52	53	Return feeders
C733-C738	2165	52	53	Supply feeders
C740,C743	5632	85	39	Cryolines
C742, C739	5632	85	95	Cryolines
C741, C744	20000	40	30	SHEXs

Table 2. ***Parameters of quench lines***

Channels #	Cross section area, mm^2	Hydraulic ID, mm	Length, m	Comments
C745	31416	200	20	L3 lines
C746	31416	200	18	L3 lines
C747	31416	200	26	L3 lines
C748	31416	200	11	L3 lines
C749	31416	200	43	L3 lines
C750	70700	300	3	L3 lines
C751	31416	200	8	L3 lines
C752	31416	200	8	B2 lines
C753	31416	200	19	B2 lines
C754	31416	200	21	B2 lines
C755	31416	200	4	B2 lines
C756	31416	200	6	B2 lines
C757	31416	200	5	B2 lines
C758	31416	200	6	B2 lines
C759	31416	200	29	B2 lines
C760	31416	200	12	B2 lines
C761	31416	200	26	B2lines
C762	31416	200	17	B2 lines
C763	70700	300	31	Line between L3 & B2 levels
C764	96200	350	52	Common line to quench tank
C765	96200	350	110	Common line to quench tank

Volume V289 models a 80K quench tank of 720 m^3.

This demo example is aimed to show VENECIA capabilities in modelling complex thermal hydraulic processes associated with CICC quench in CS, in particular

- assessment of a minimum heat pulse energy for quench initiation;
- simulation of normal zone evolution resulted in temperature (T) and helium pressure (P) rise caused by Joule heat deposited during quench;
- investigation of protection strategy against overpressure in a cryogenic circuit via controlled opening of relief valves and evaluation of instant parameters of helium flows released from the CS;
- prediction of temperature & pressure rise along quench lines.

Simulation of 40 CS2L conductors quench allows revealing the conditions for helium release from CS through the relief valves and the maximum helium parameters along the quench lines.

The demo simulation is only illustrative and has certain limitations due to taken for consideration the simplified quench scenario. Simulated CS behaviour is reduced to a 10 s quench at constant currents in CS sections that corresponds to overheat conditions without quench protection and fast energy discharge. Modelling of complex phenomena occurred in a cryomagnetic system in case of quench and CICC protection against overheating requires more detailed description beyond demo purposes and is a subject of contractual investigations.

Initial conditions for modelling

The quench is initiated by a uniform heat pulse applied to 40 innermost turns of CS2L CICC's when the other 200 CICCs of CS have zero currents.

A 4000W/m heat pulse with a 0.2s duration is applied at the end of plasma pulse (1790s) when a 10s plateau of constant maximum currents in sections (~40 kA) is supported. The magnetic field in the "fired" innermost turns is close to the maximal value of 12 T.

As initial thermal-hydraulic conditions for CS quench simulation, pre-determined data are used from input files **CS3600.BS** and **HEAT2D_1.BAS** that gathered in a CS simulation at normal operation. For illustration, the plots below shows CS behaviour at normal operation for a 1800s regular plasma pulse.

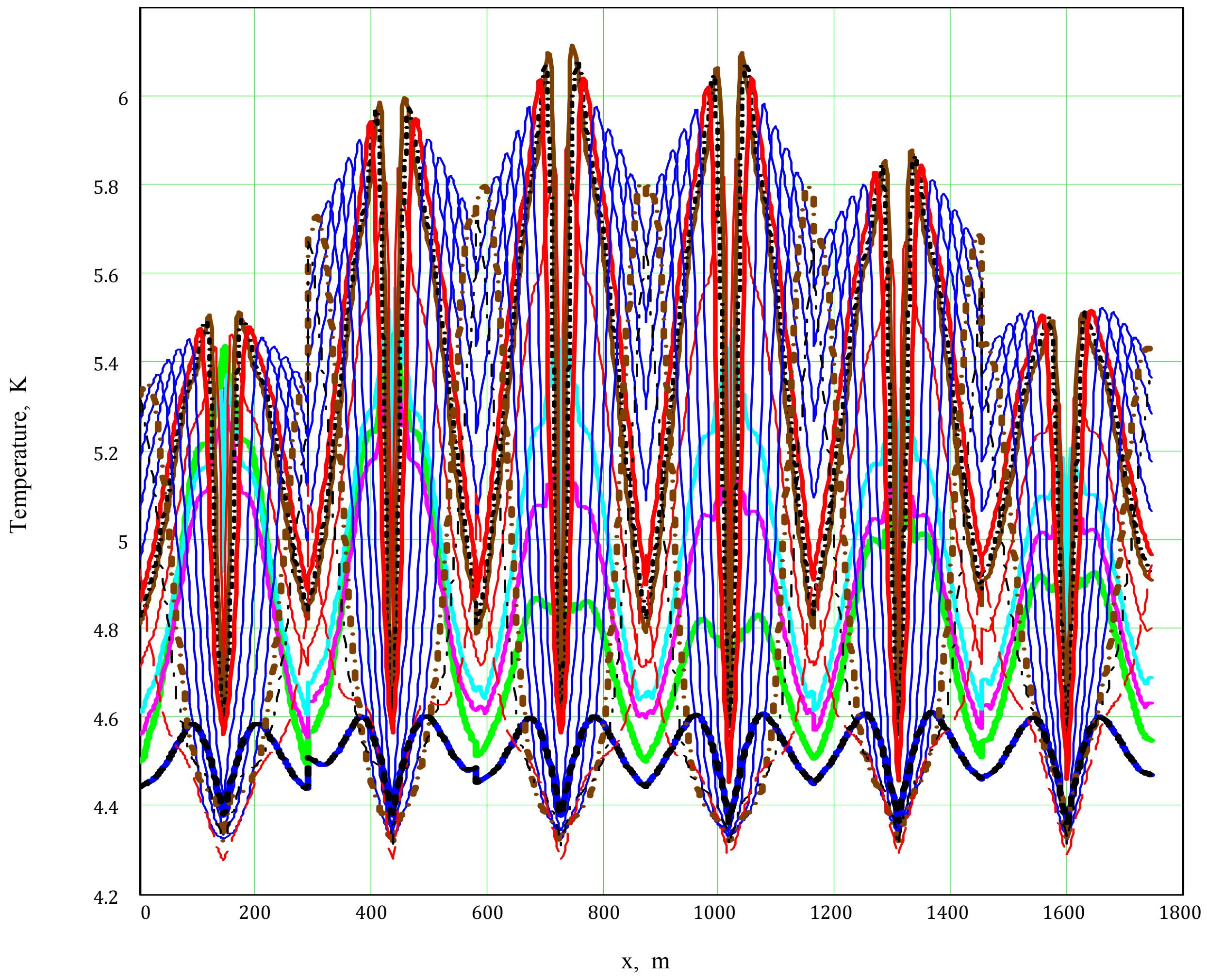


Figure 6. Variation of CICC temperature in 6 middle double pancakes of six CS sections CS3L, CS2L, CS1L, CS1U, CS2U, CS3U during a 1800 s plasma pulse. Normal operation

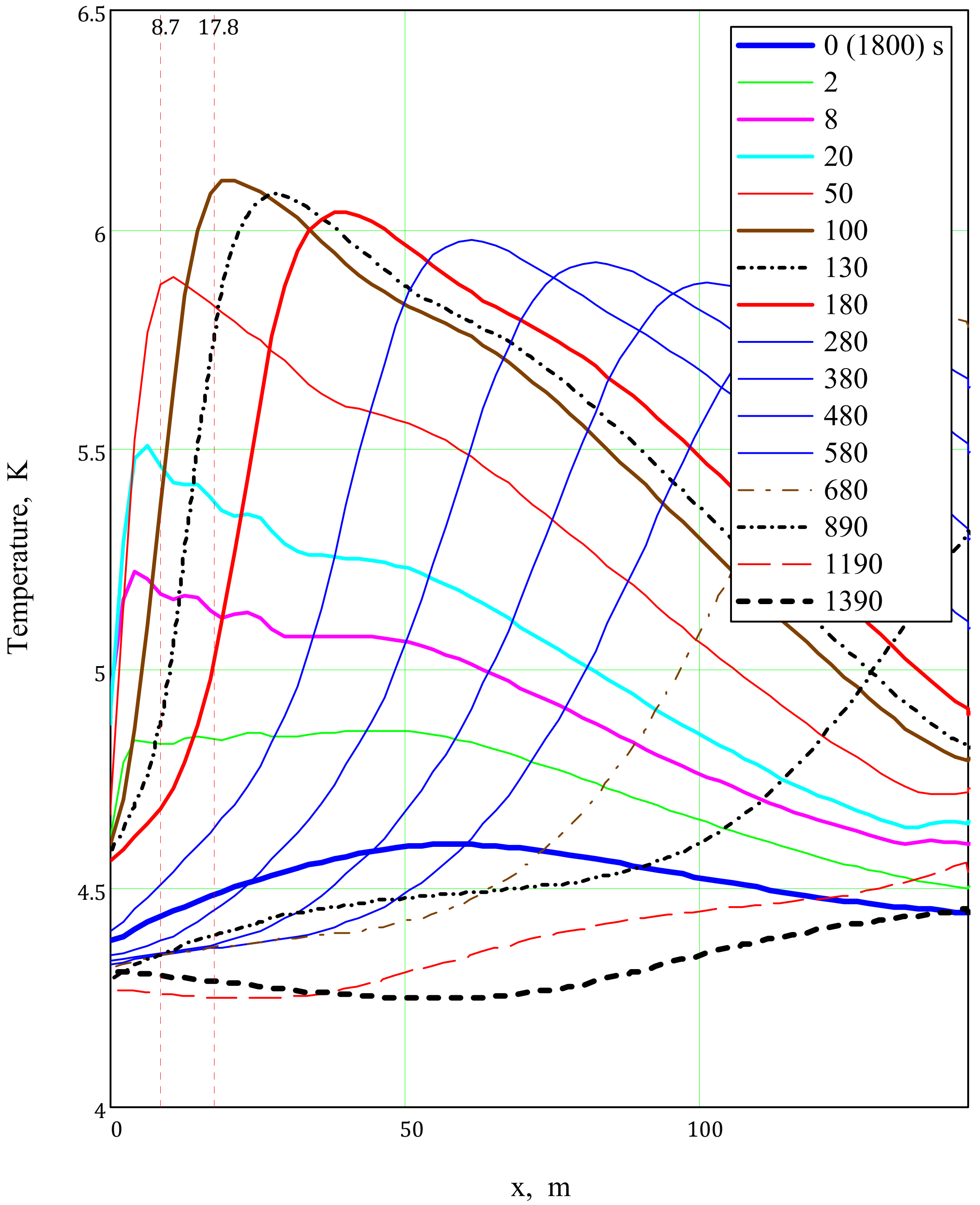
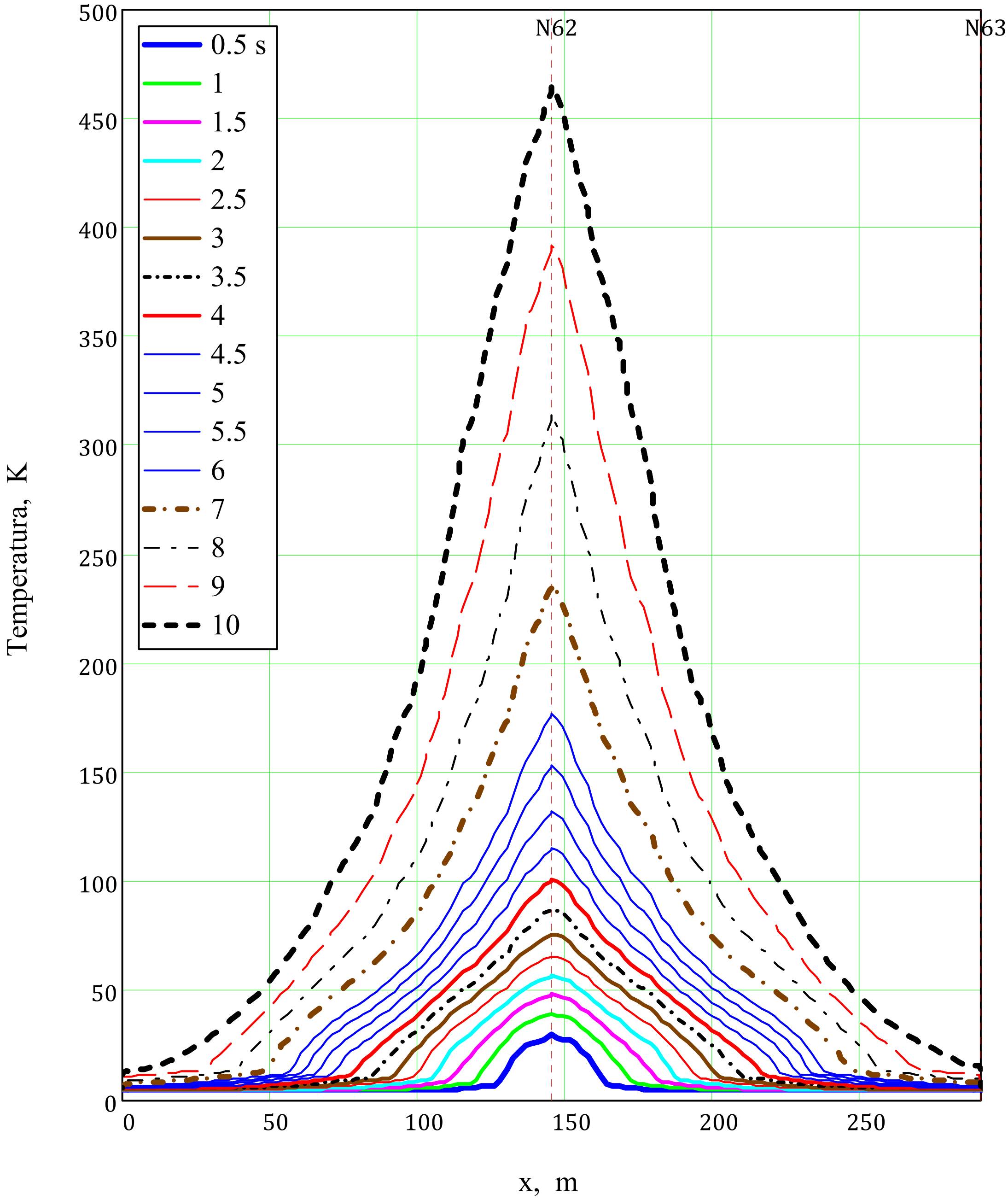


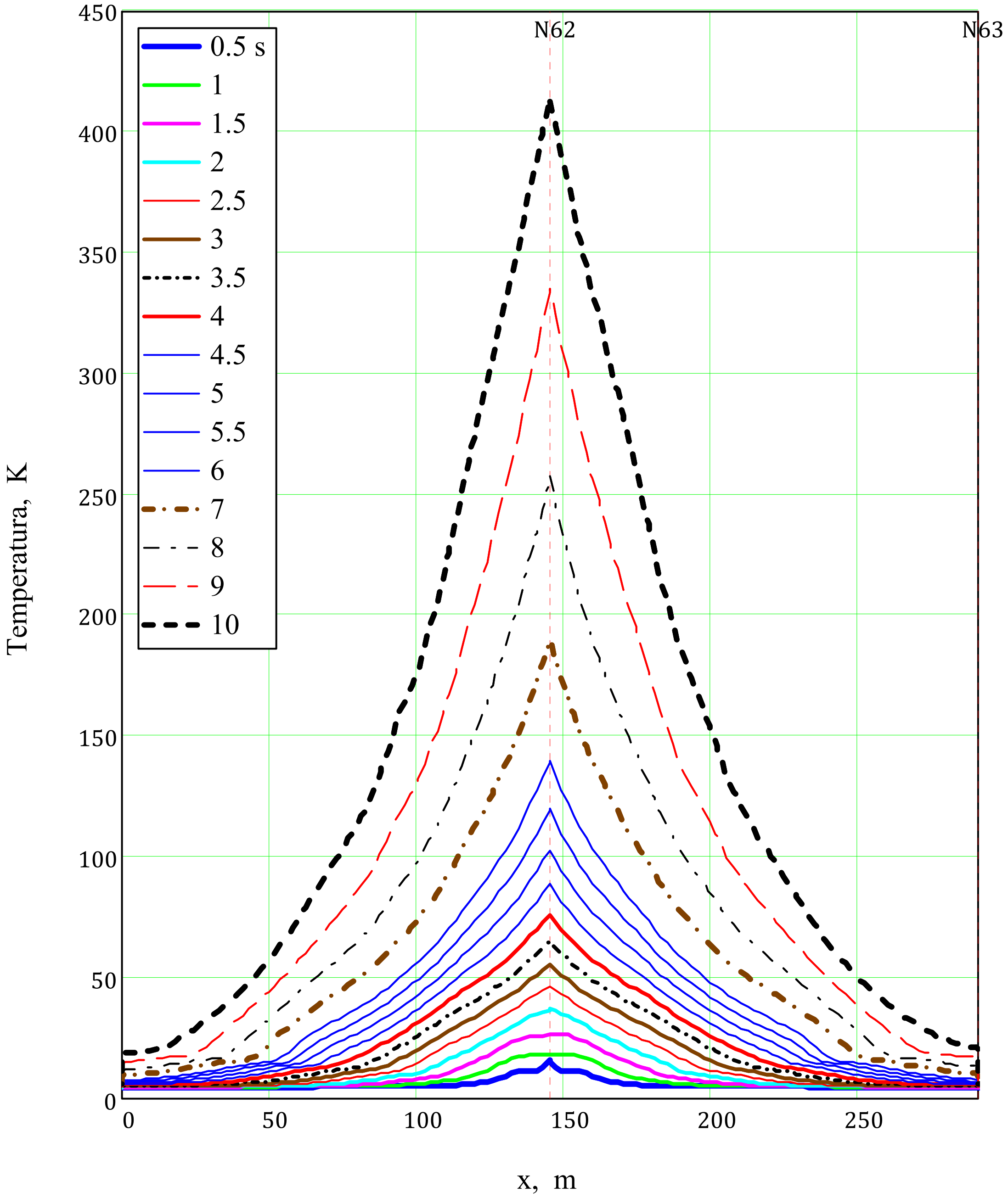
Figure 7. Temperature variation along pancake #102 (middle of CS1L). Normal operation

The full set of inputs for the demo quench simulation is available in the input files **DEMO4.IN** and **HEAT2D_1.IN**. Files **VENECIA.MAT** and **ETAB5D_1.IN** describe thermal properties of different materials in the CS assembly and electrical properties of CICC, correspondingly.

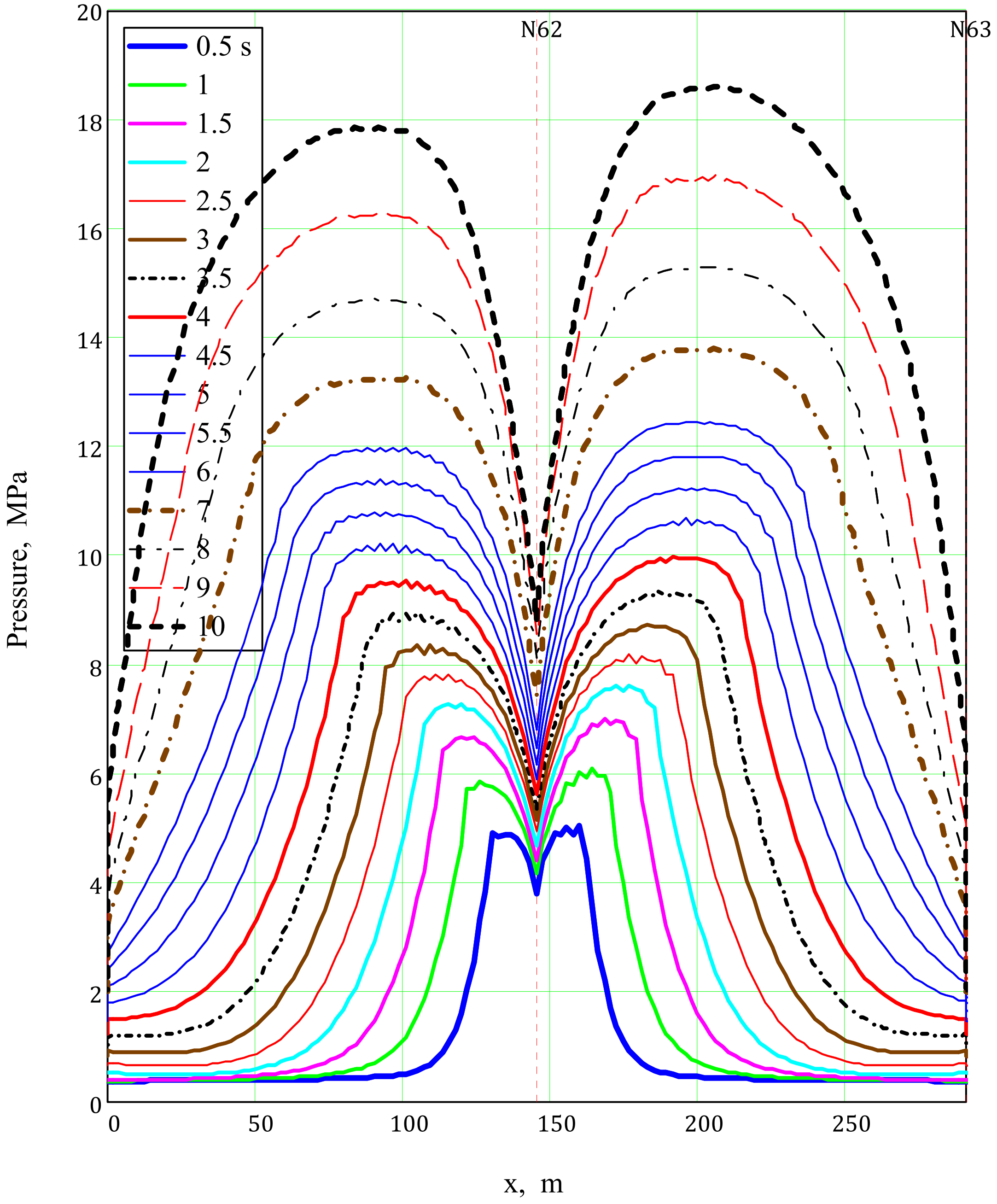
Basic simulated results for CS quench started in CS2L section



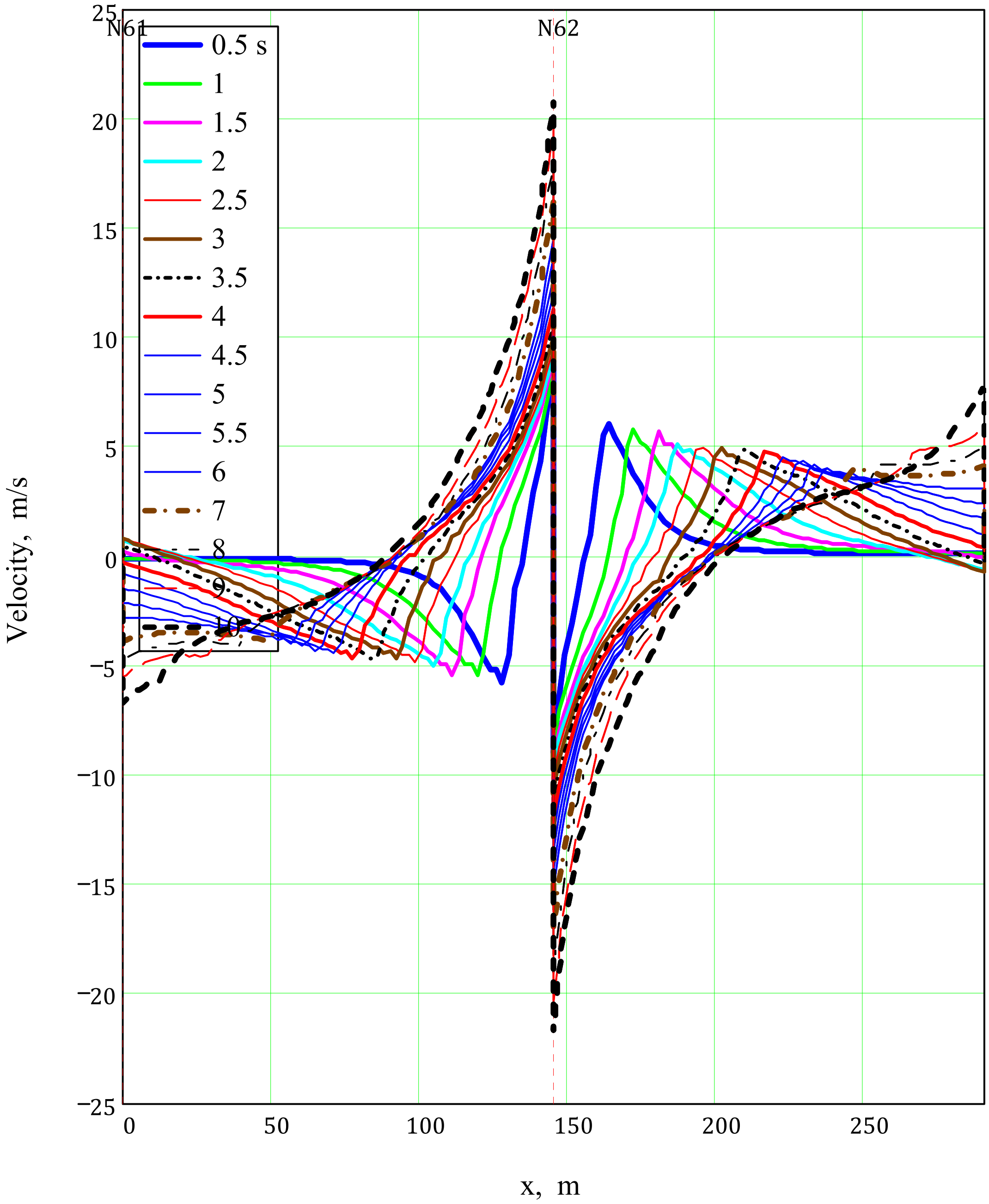
Temperature evolution of CICC bundle for adjacent pancakes #61 and #62 of quenched CS section CS2L



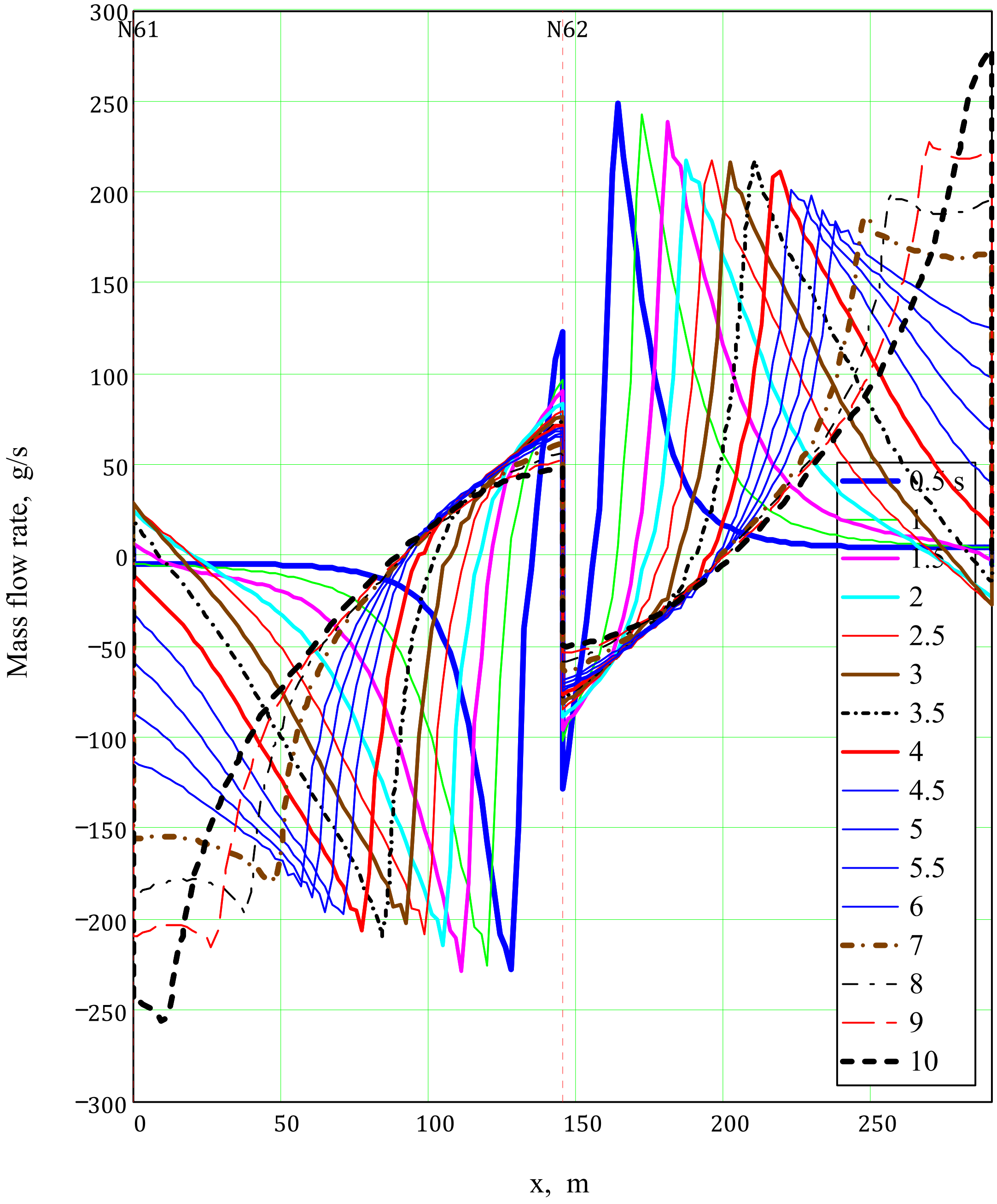
Helium temperature evolution in central channel for adjacent pancakes #61 and #62 of quenched CS section CS2L



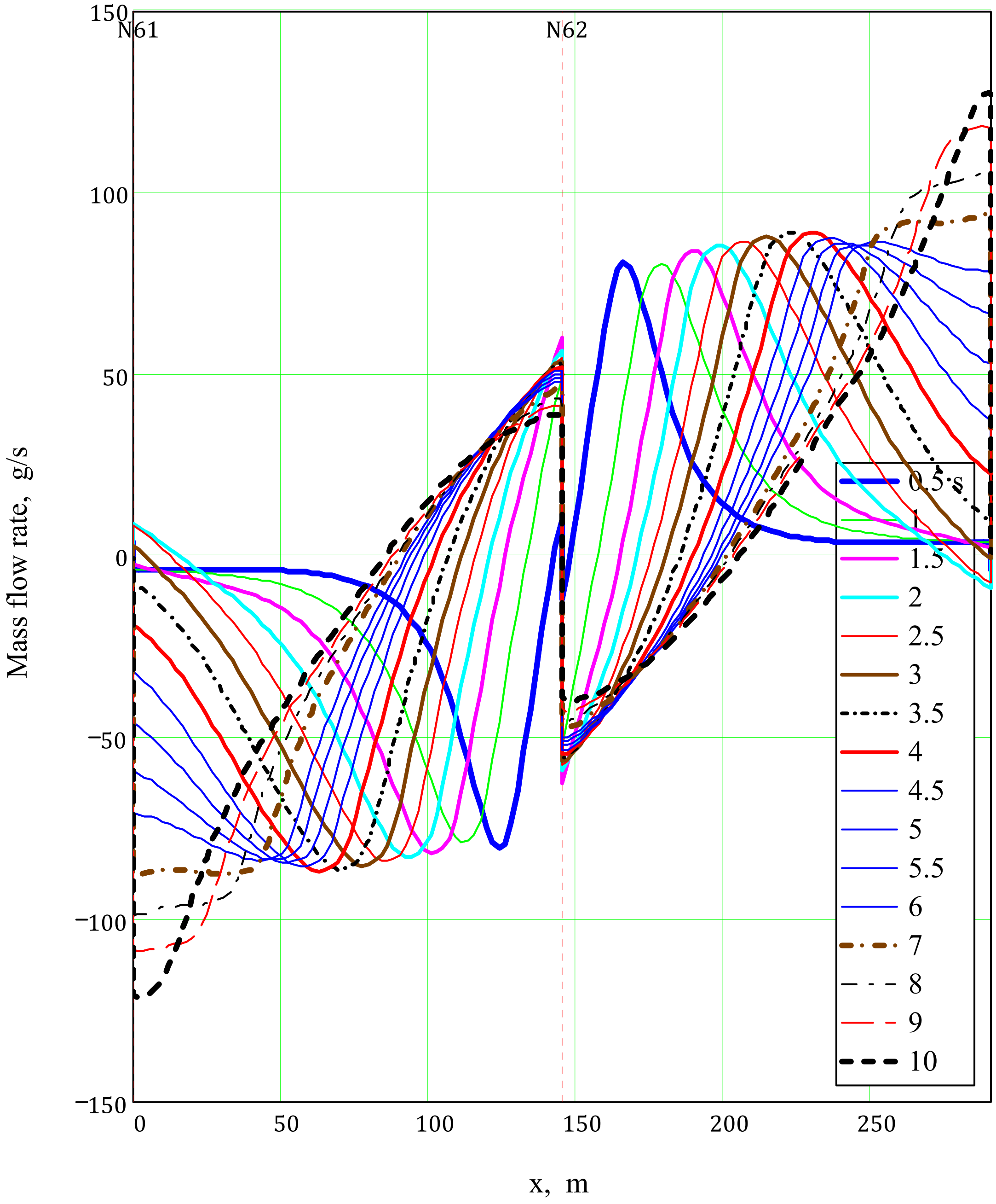
Helium pressure in cable space for adjacent pancakes #61 and #62 of quenched CS section CS2L



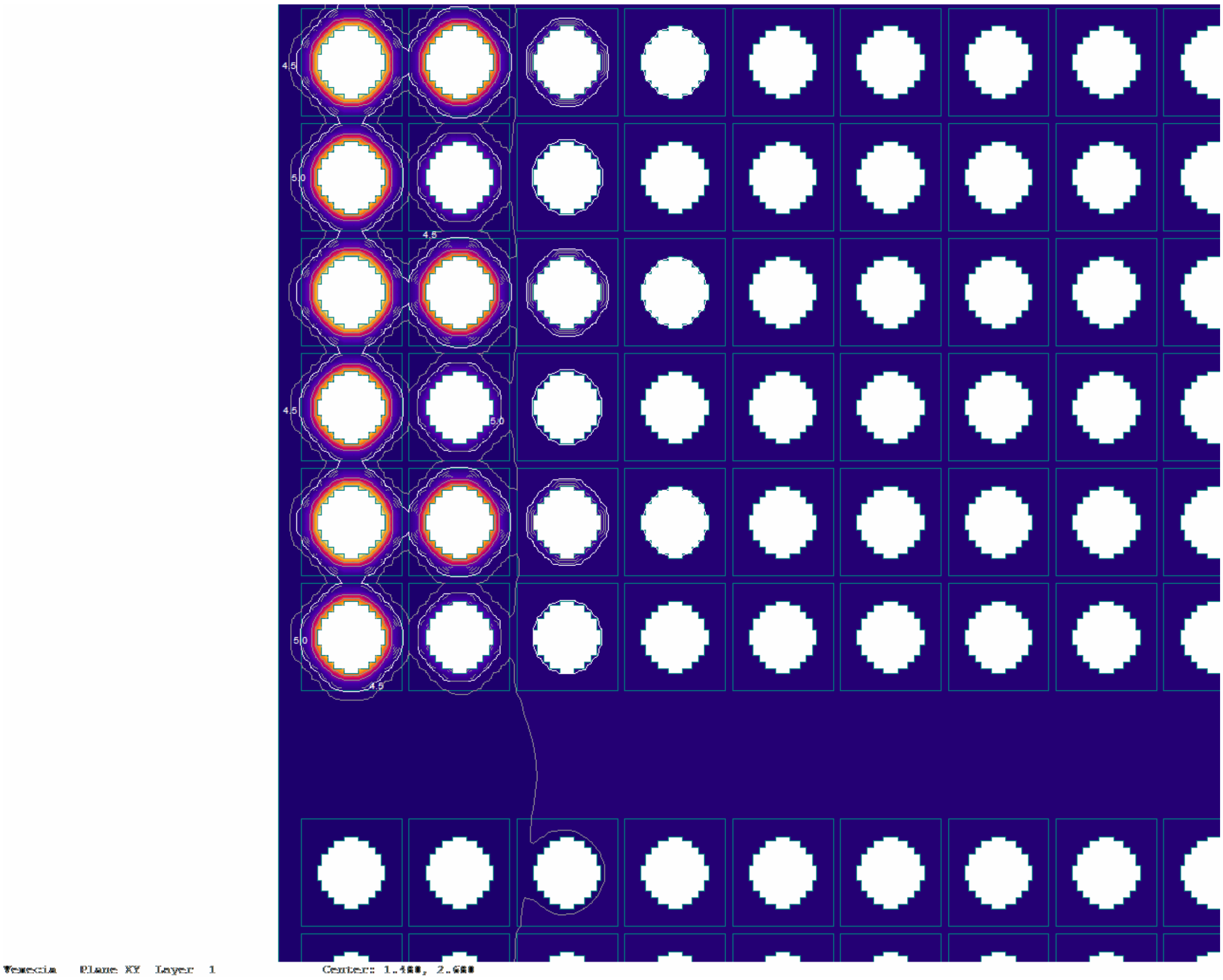
Helium velocity in cable space for adjacent pancakes #61 and #62 of quenched CS section CS2L



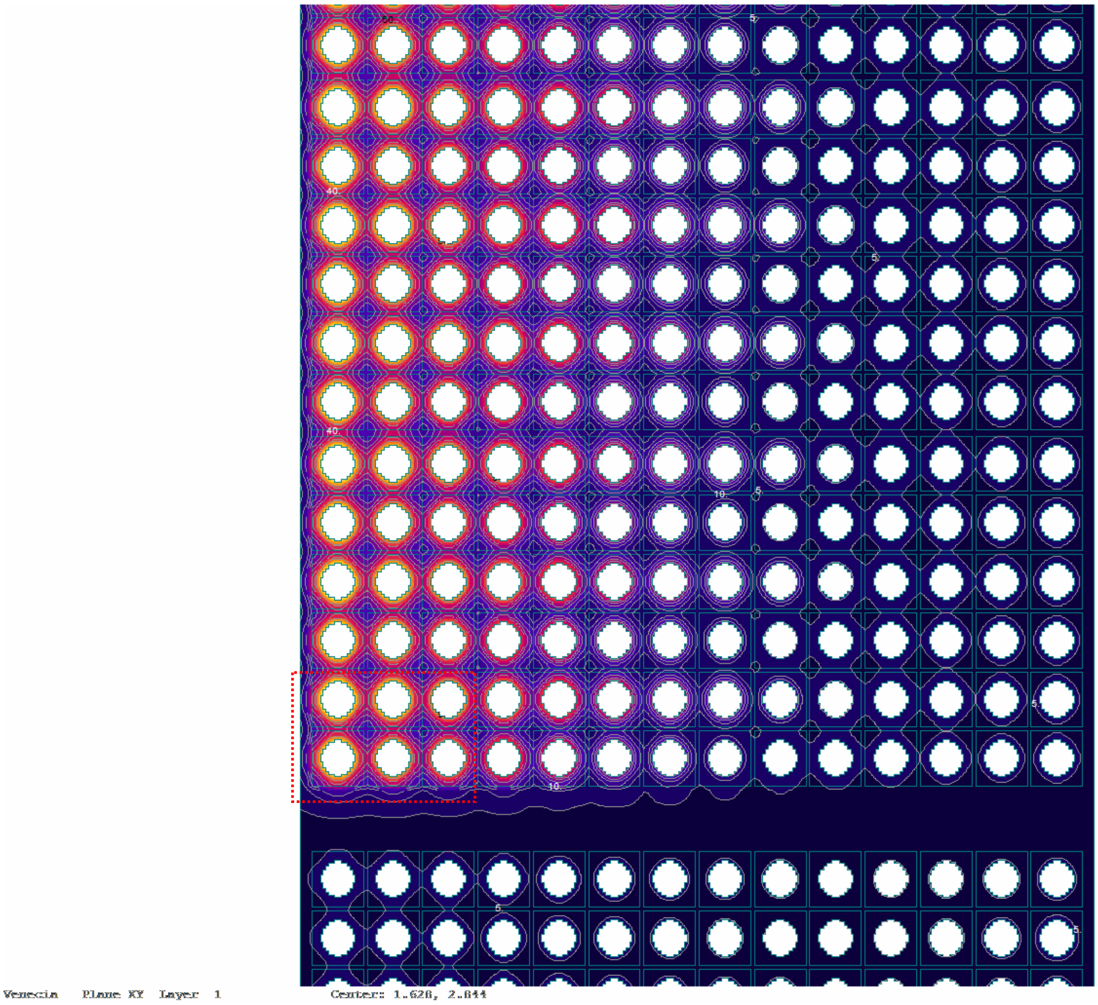
Helium mass flow rate in cable space for adjacent pancakes #61 and #62 of quenched CS section CS2L



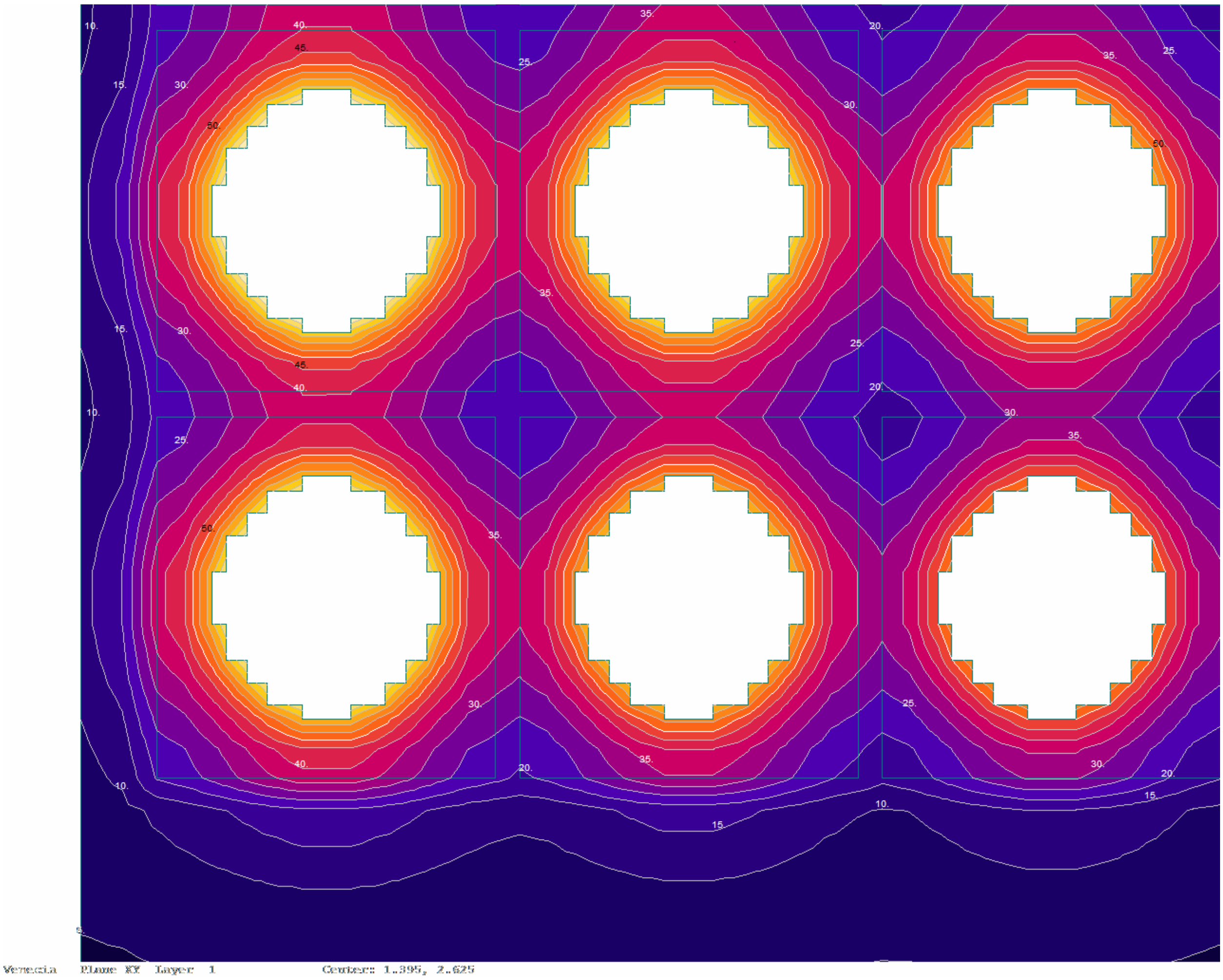
Helium mass flow rate in central channel for adjacent pancakes #61 and #62 of quenched CS section CS2L



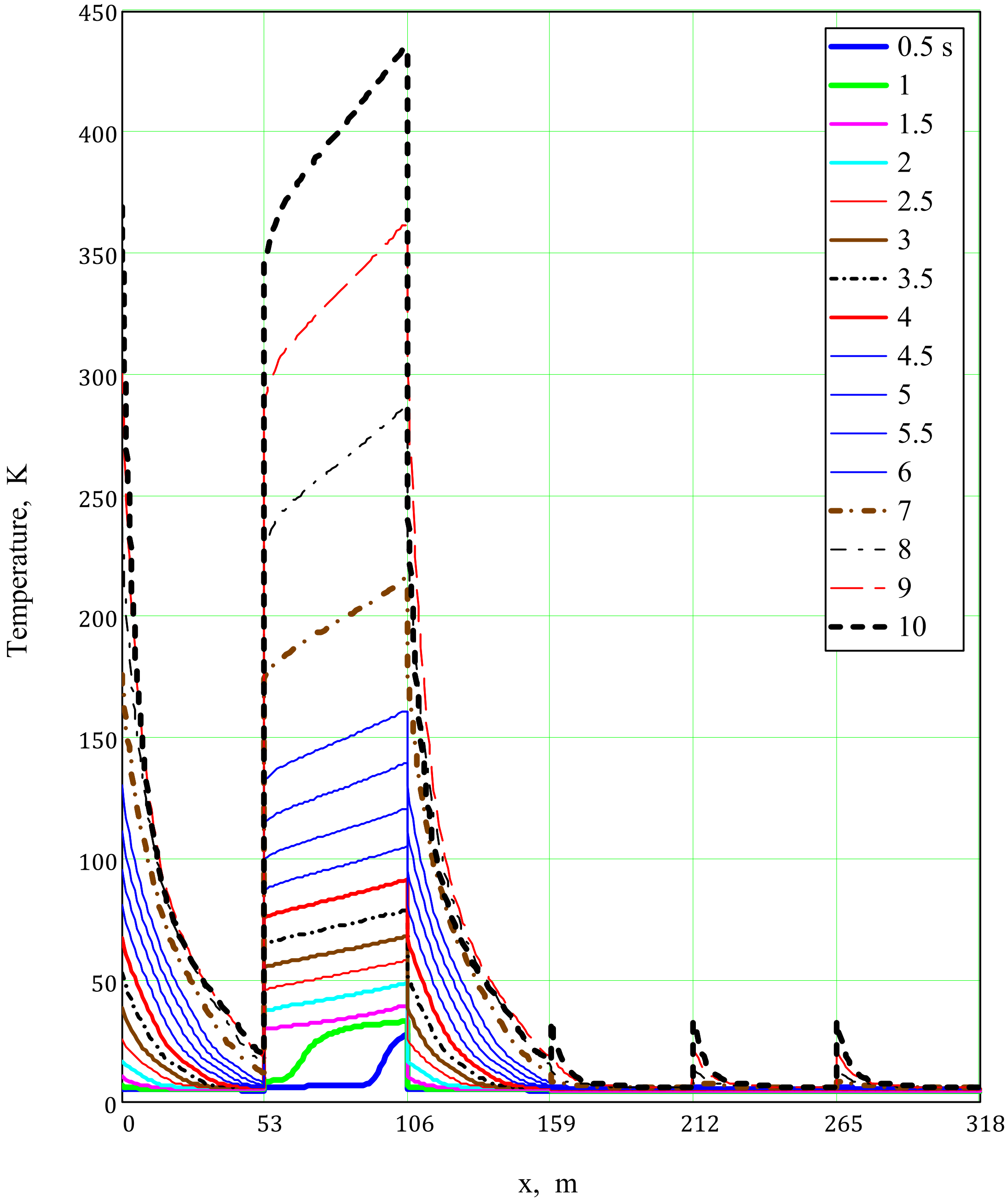
Temperature map for cross section #1 of CS model in vicinity of adjacent sections CS3L and CS2L at t=0.25s



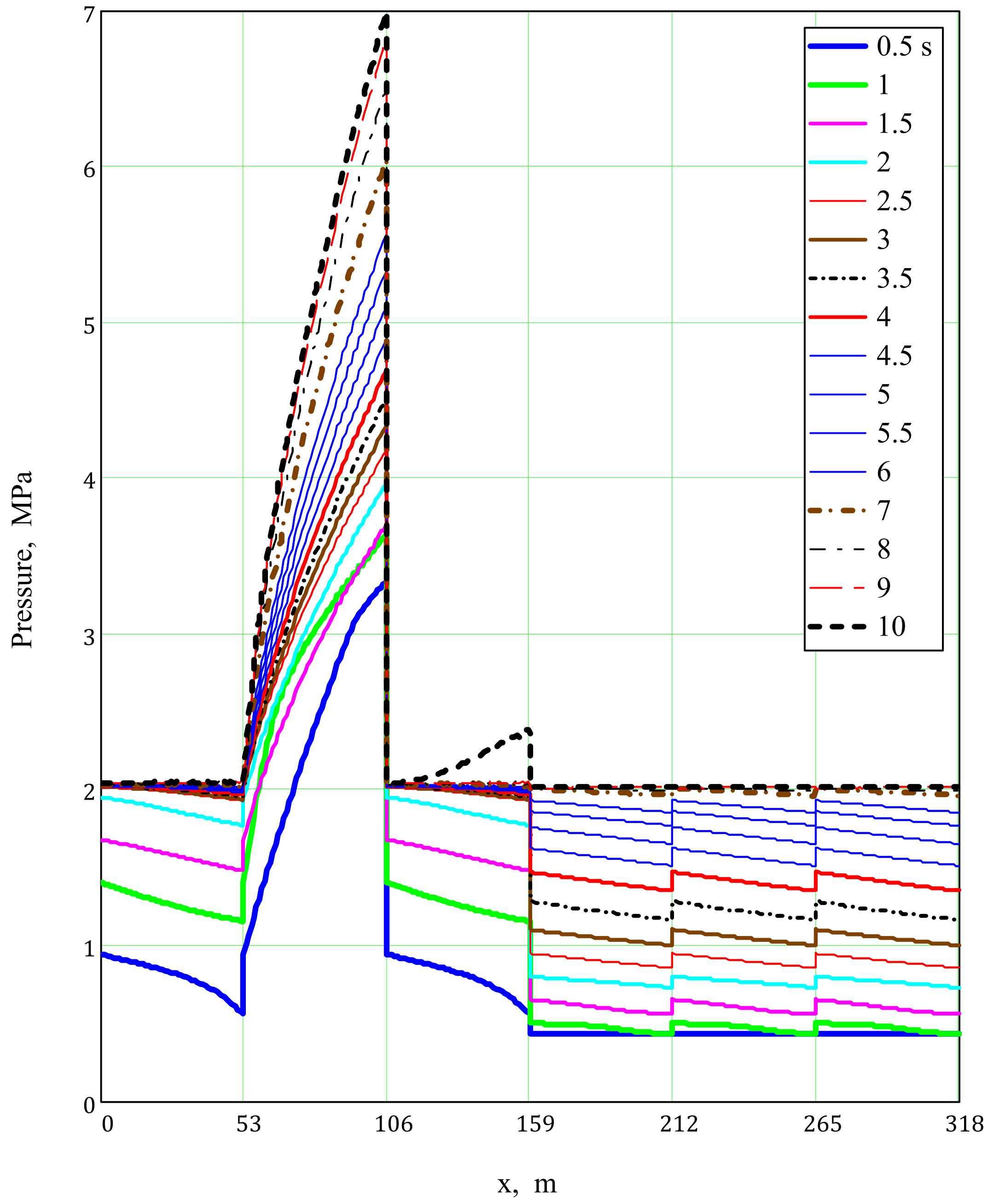
Temperature map for cross section #1 of CS model in vicinity of adjacent sections CS3L and CS2L at t=5.0s



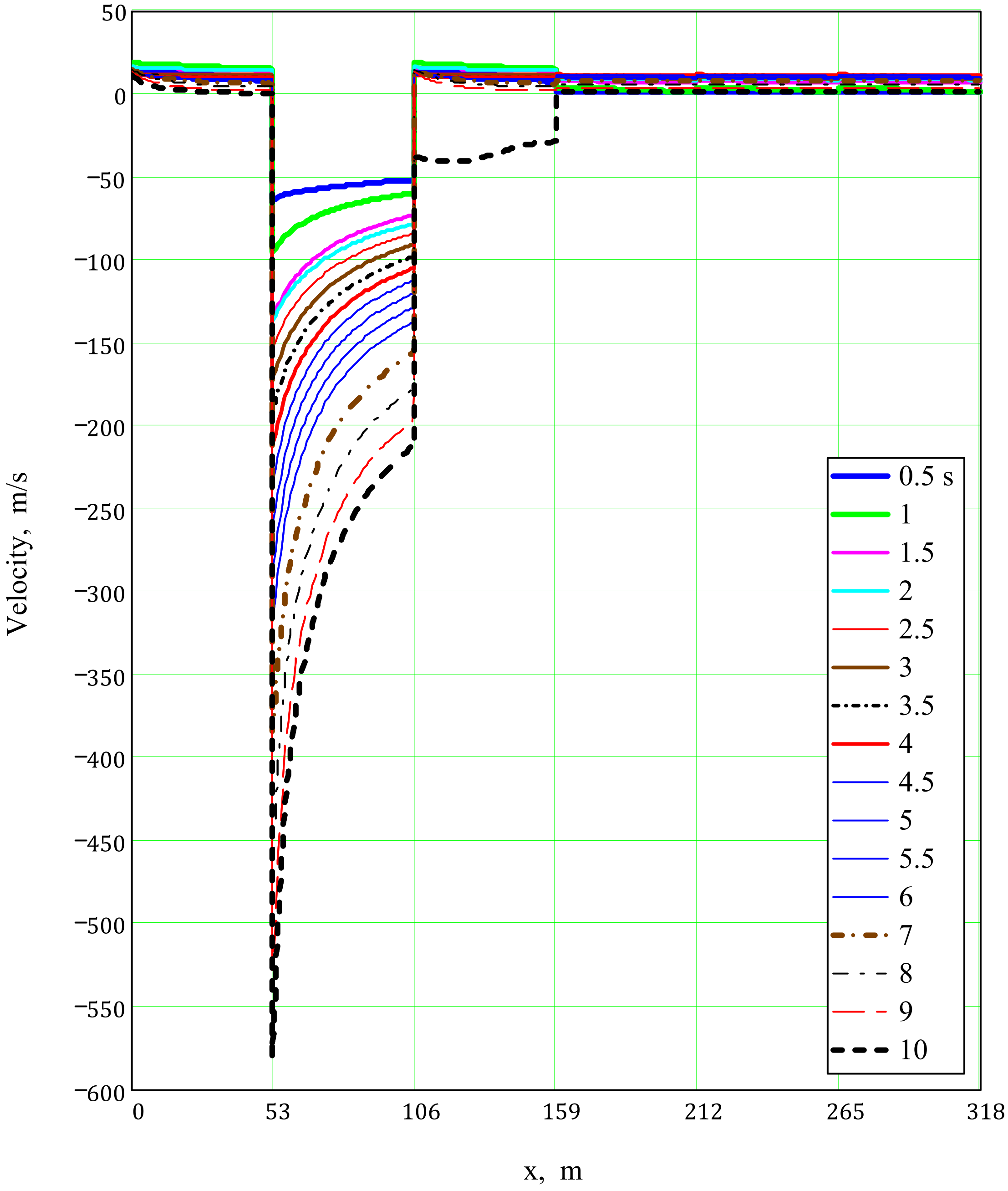
Temperature map for cross section #1 of model in vicinity of adjacent CS sections CS3L and CS2L at t=5.0s (zoom-in of marked region from previous plot)



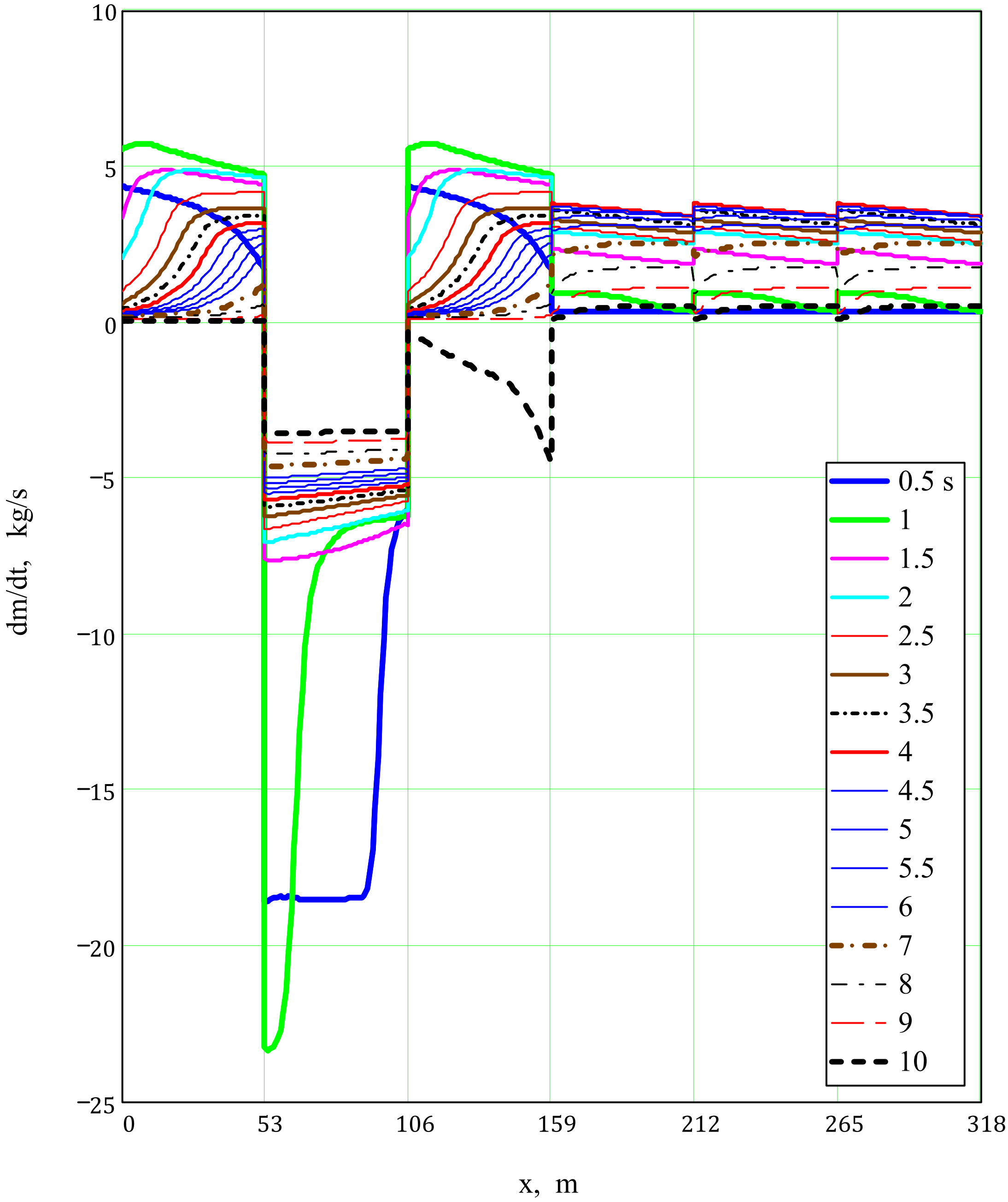
Helium temperature variation in 6 inlet feeders (C733, C734, C735, C736, C737, C738, each 53 m in length) for six CS sections: CS3L, CS2L, CS1L, CS1U, CS2U, CS3U



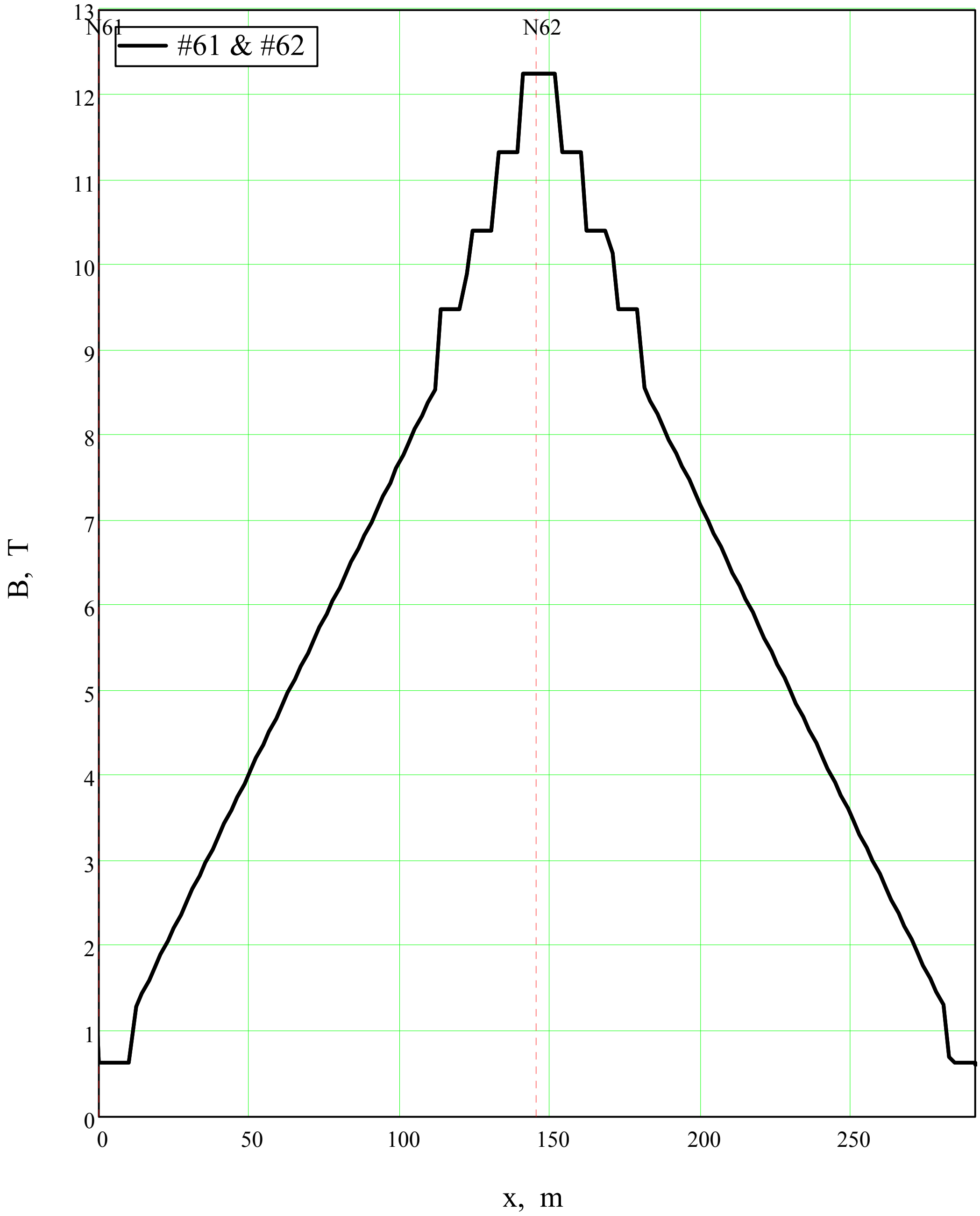
Helium pressure variation in 6 inlet feeders for six CS sections



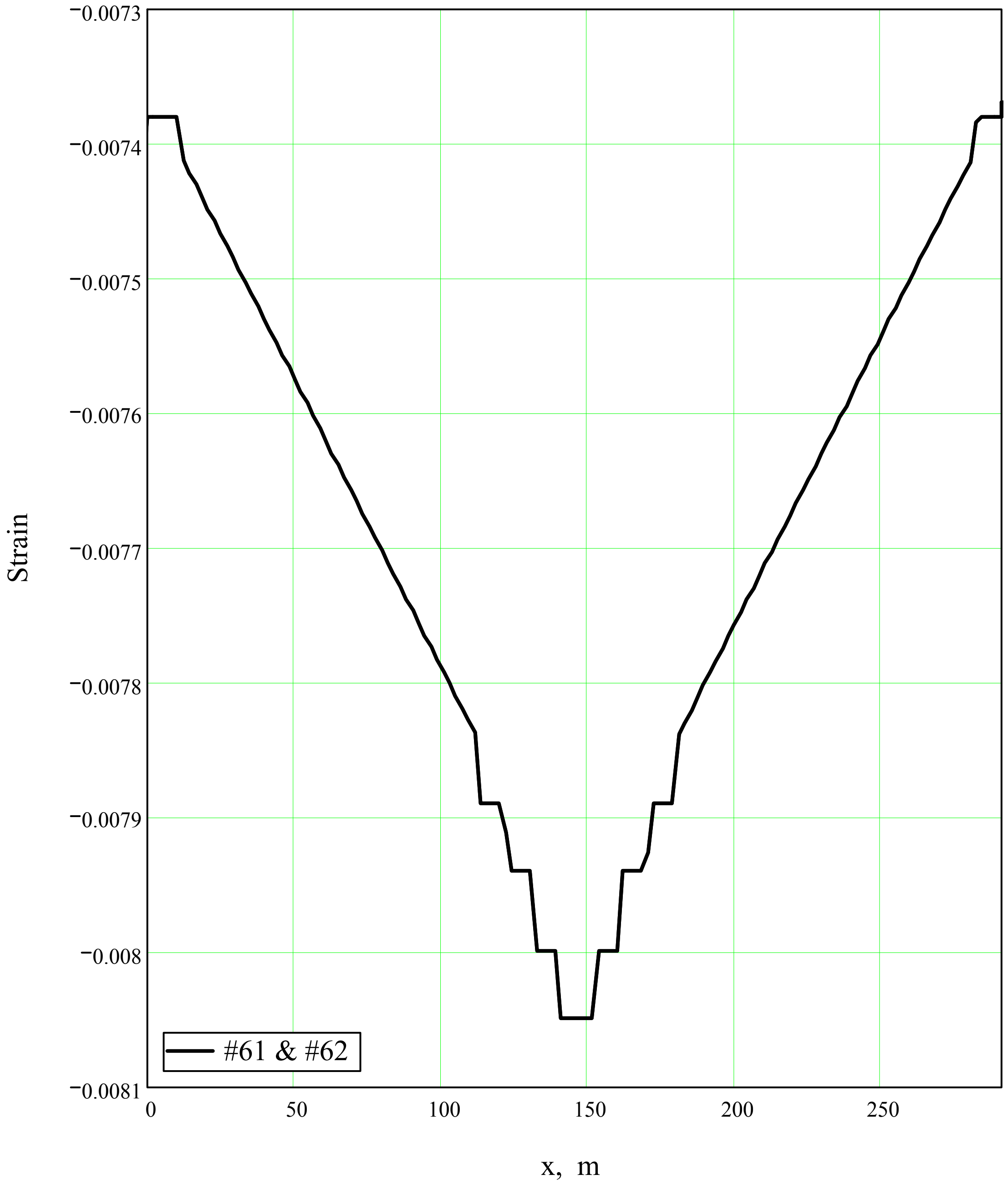
Helium velocity variation in 6 inlet feeders for six CS sections



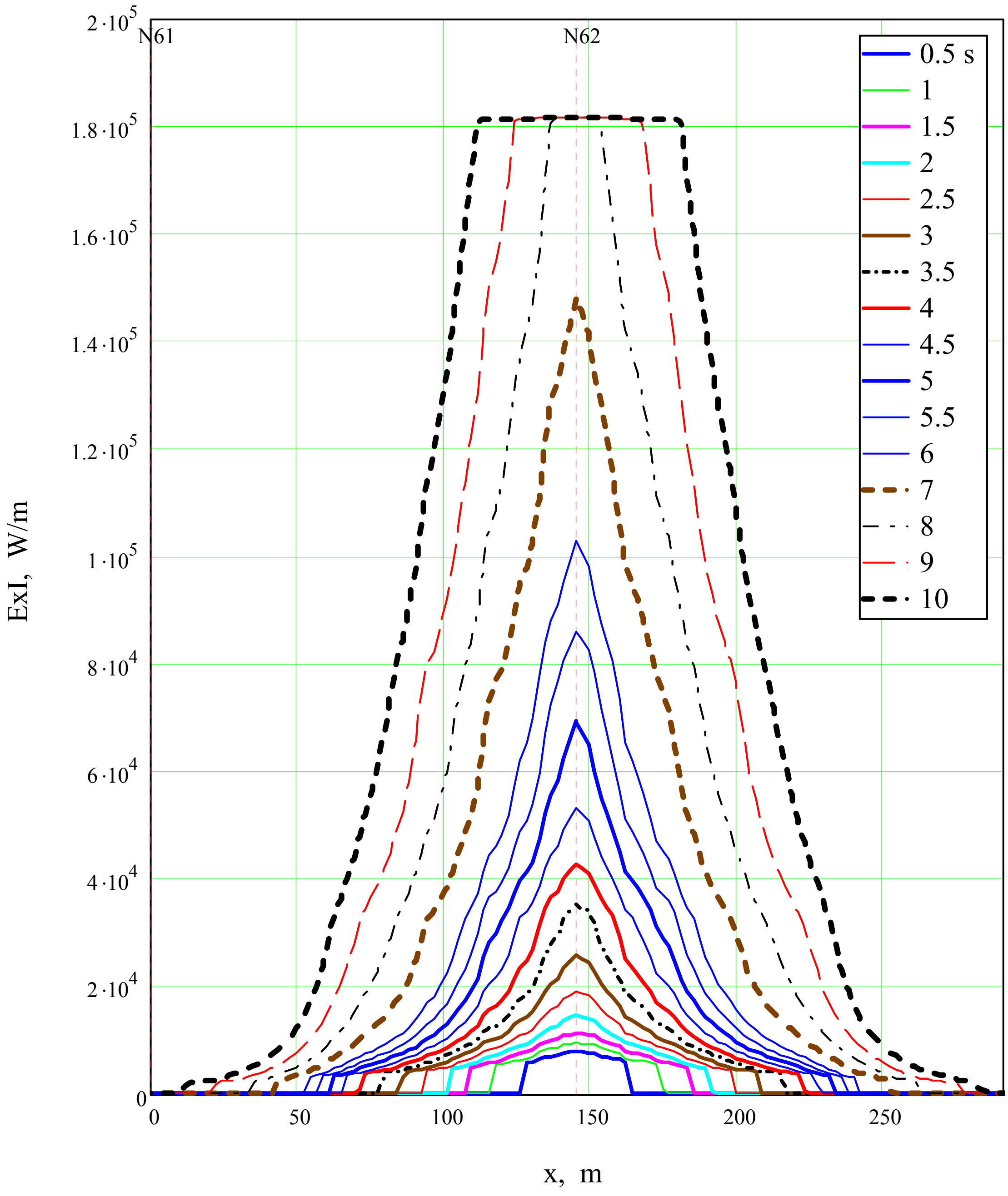
Helium mass flow rate variation in 6 inlet feeders for six CS sections



Local distribution of magnetic field B along CICC in pancakes #61 & #62

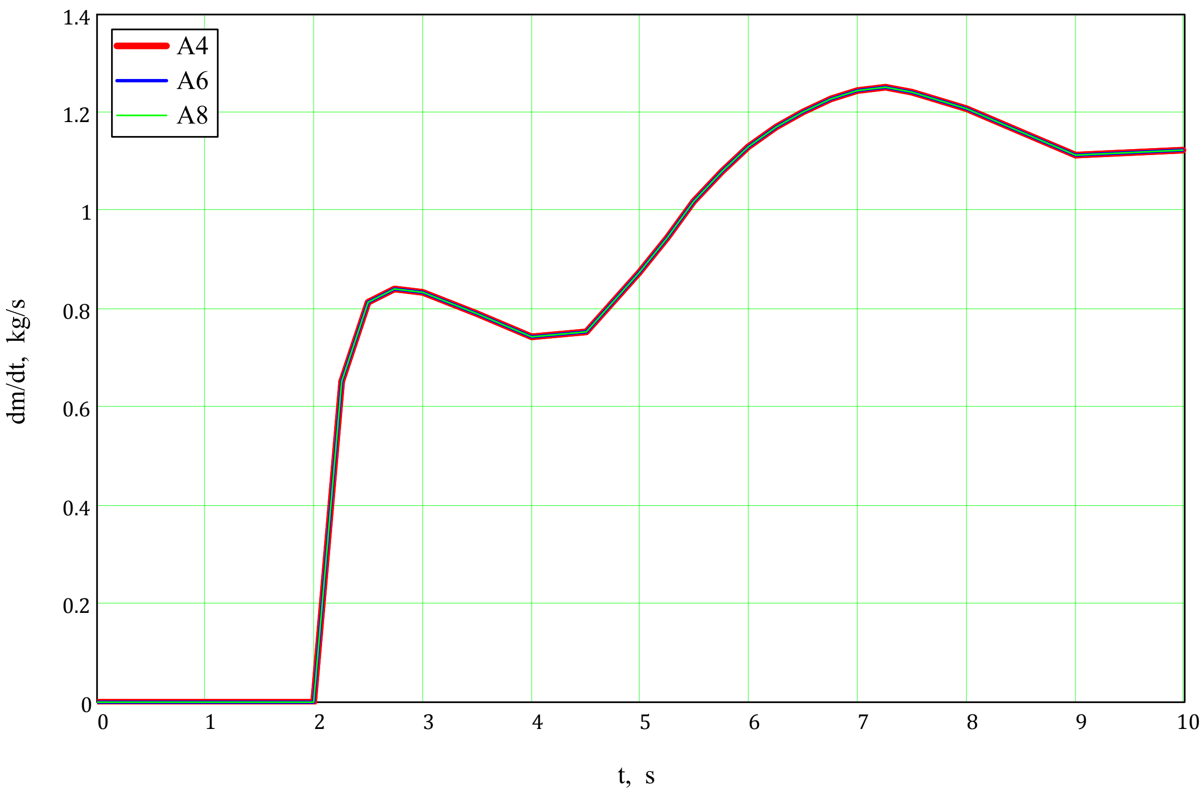


Local distribution of strain along CICC in pancakes #61 & #62

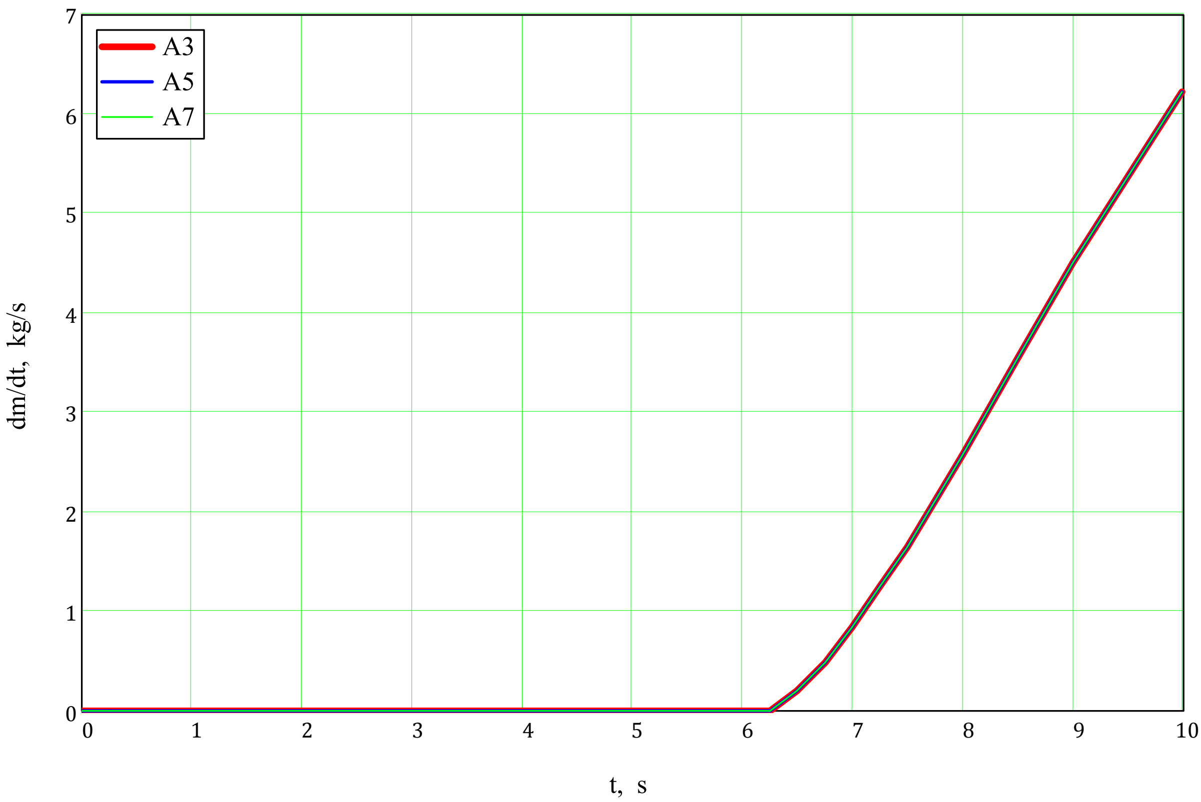


Variation of Joule heat along CICC in pancakes #61 & #62 at constant current of 40kA.

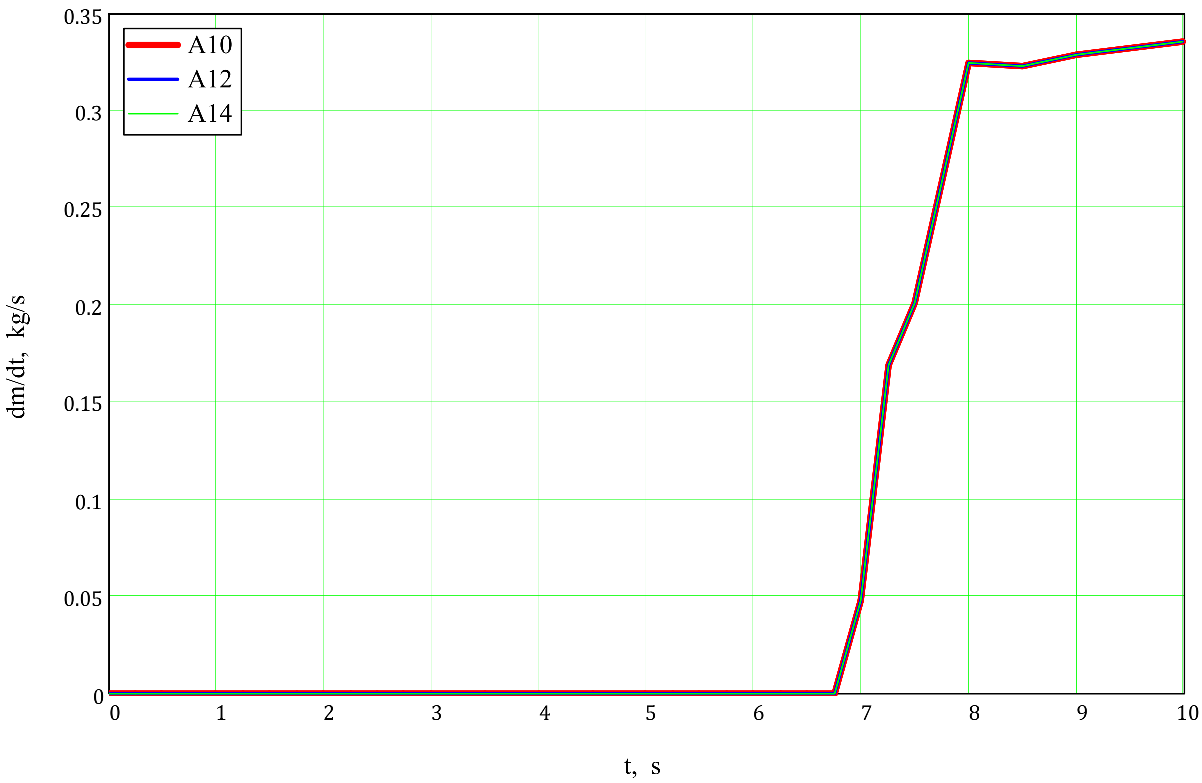
NOTE: Plateau of Joule heat at a level ~180kW/m is explained by limited input data on CICC property in file **ETAB5D_1.IN**, where the tabulated maximal temperature is given as 300K, so for *T*>300K electric field *E*(*T*, *B*, *dB*/*dr*, *ε*, *I*)= *E*(300K, *B*, *dB*/*dr*, *ε*, *I*).



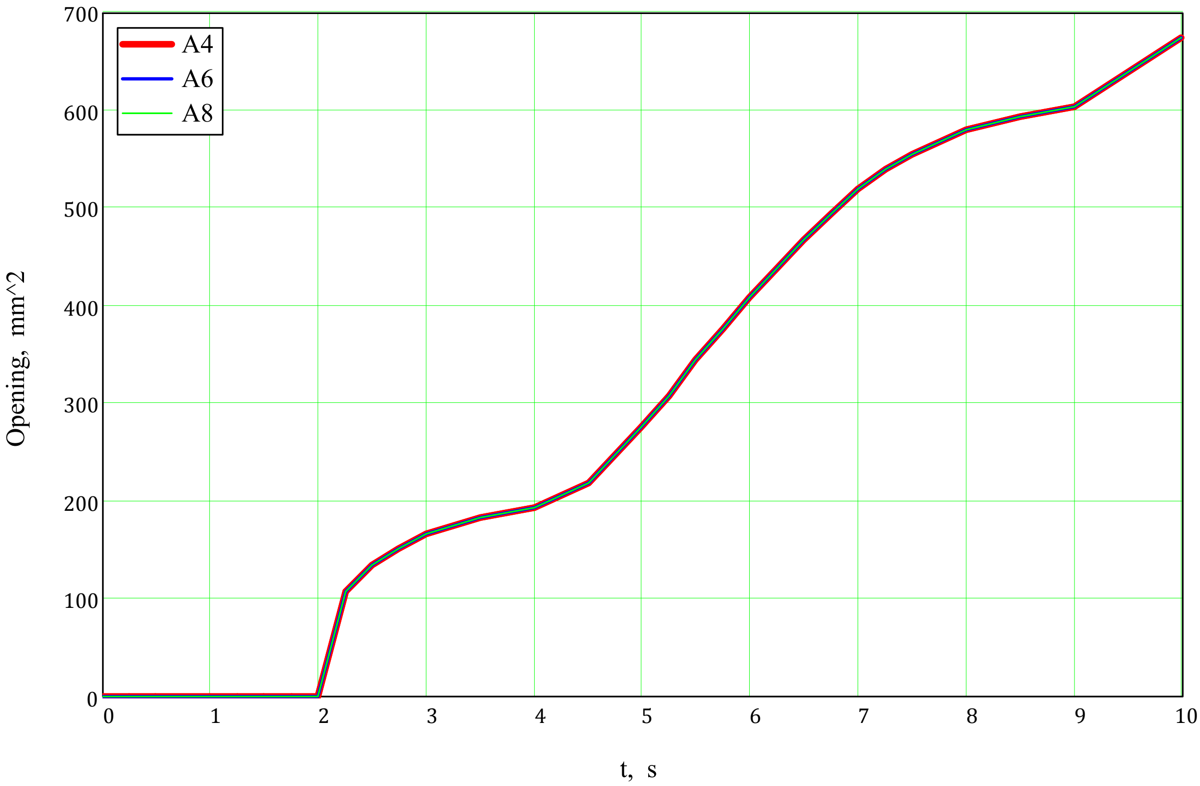
Helium mass flow rate at inlets of relief valves A4, A6, A8



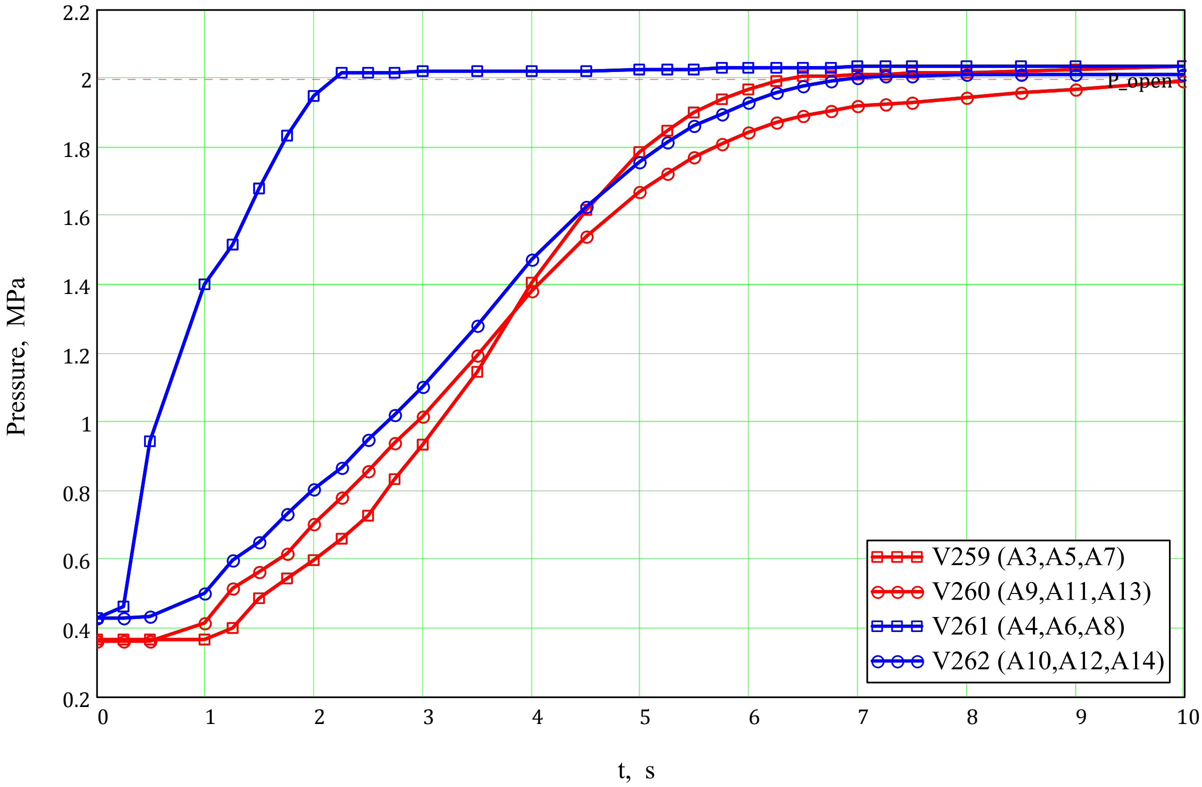
Helium mass flow rate at inlets of relief valves A3, A5, A7



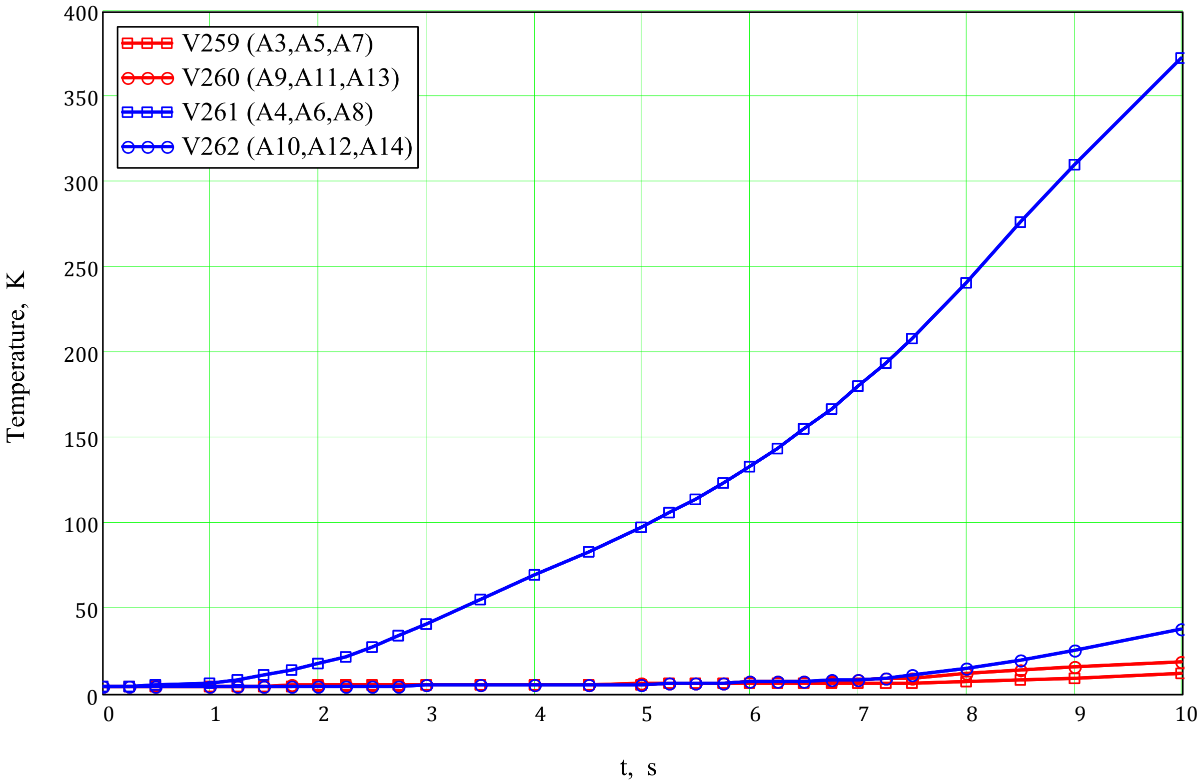
Helium mass flow rate at inlets of relief valves A10, A12, A14



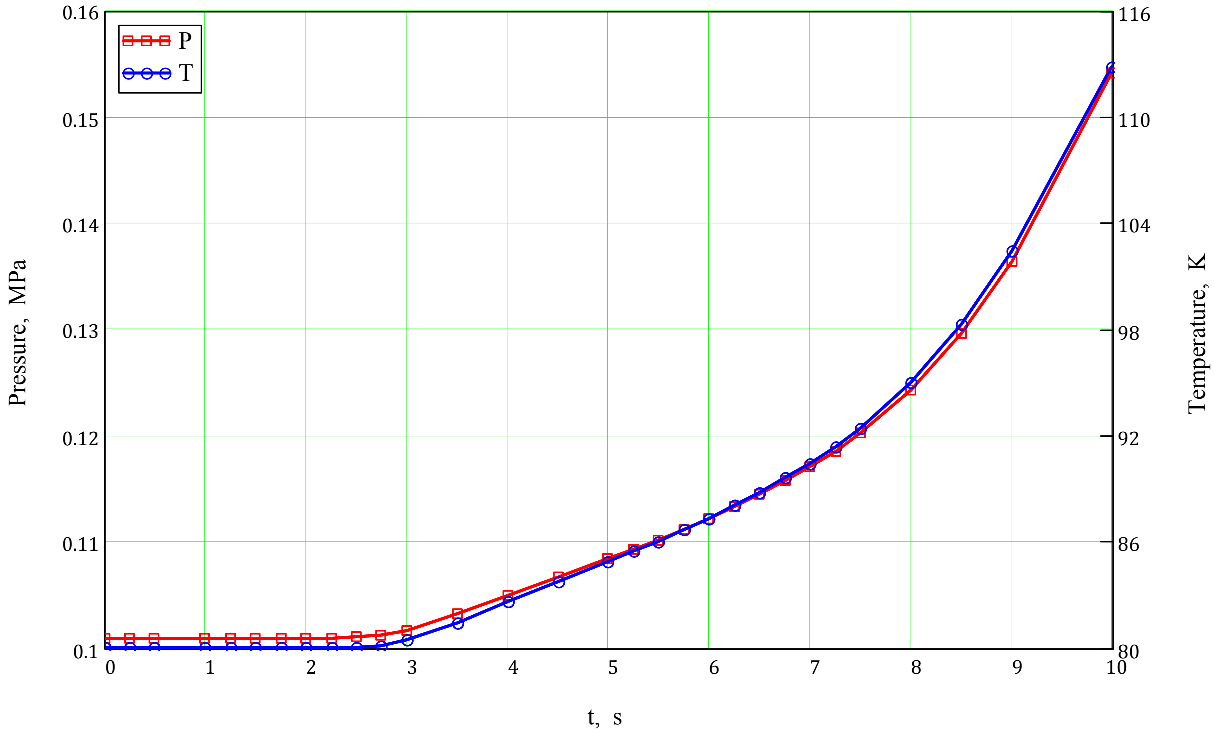
Variation of opening for relief valves A4, A6, A8



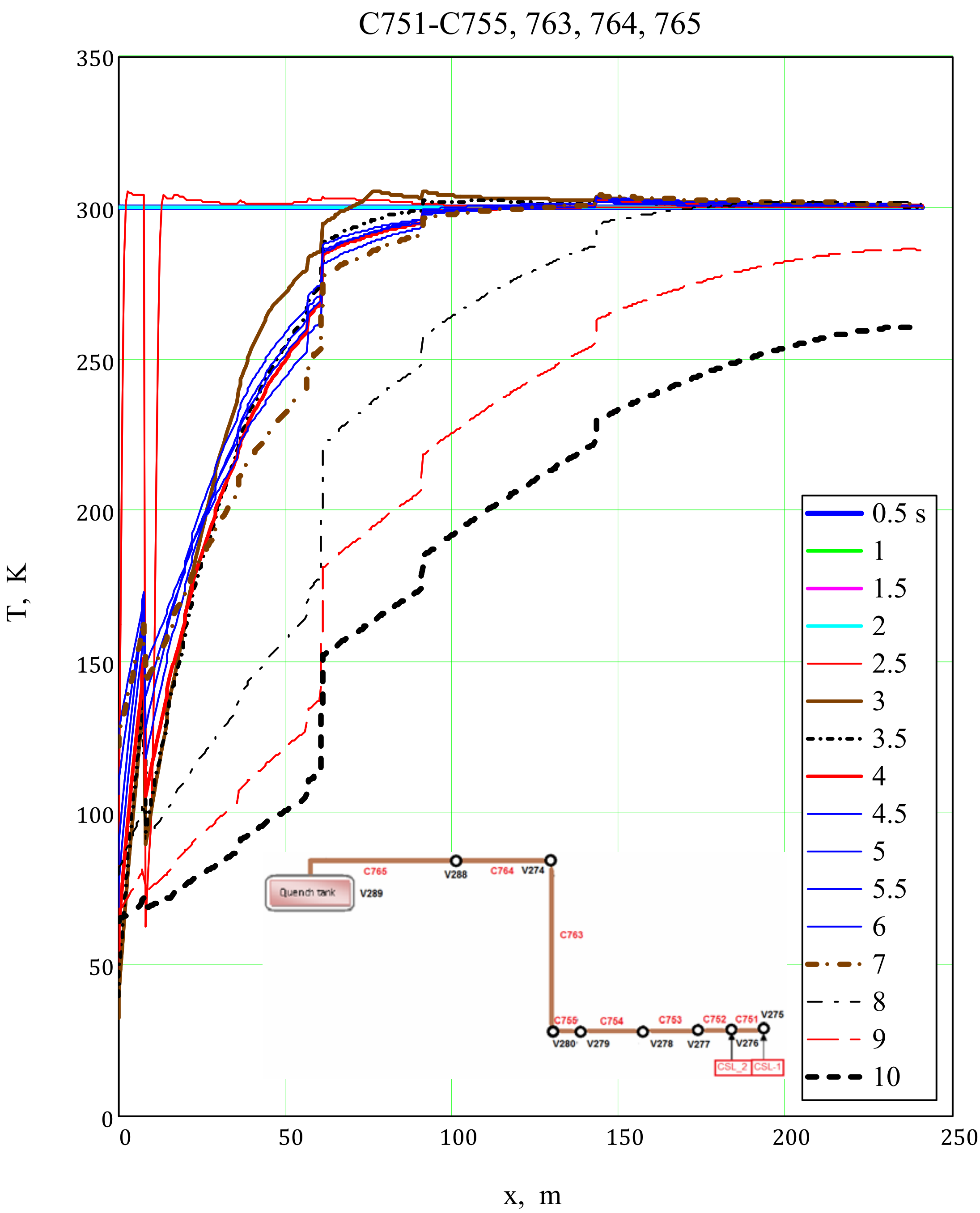
Helium pressure at inlets of the safety relief valves



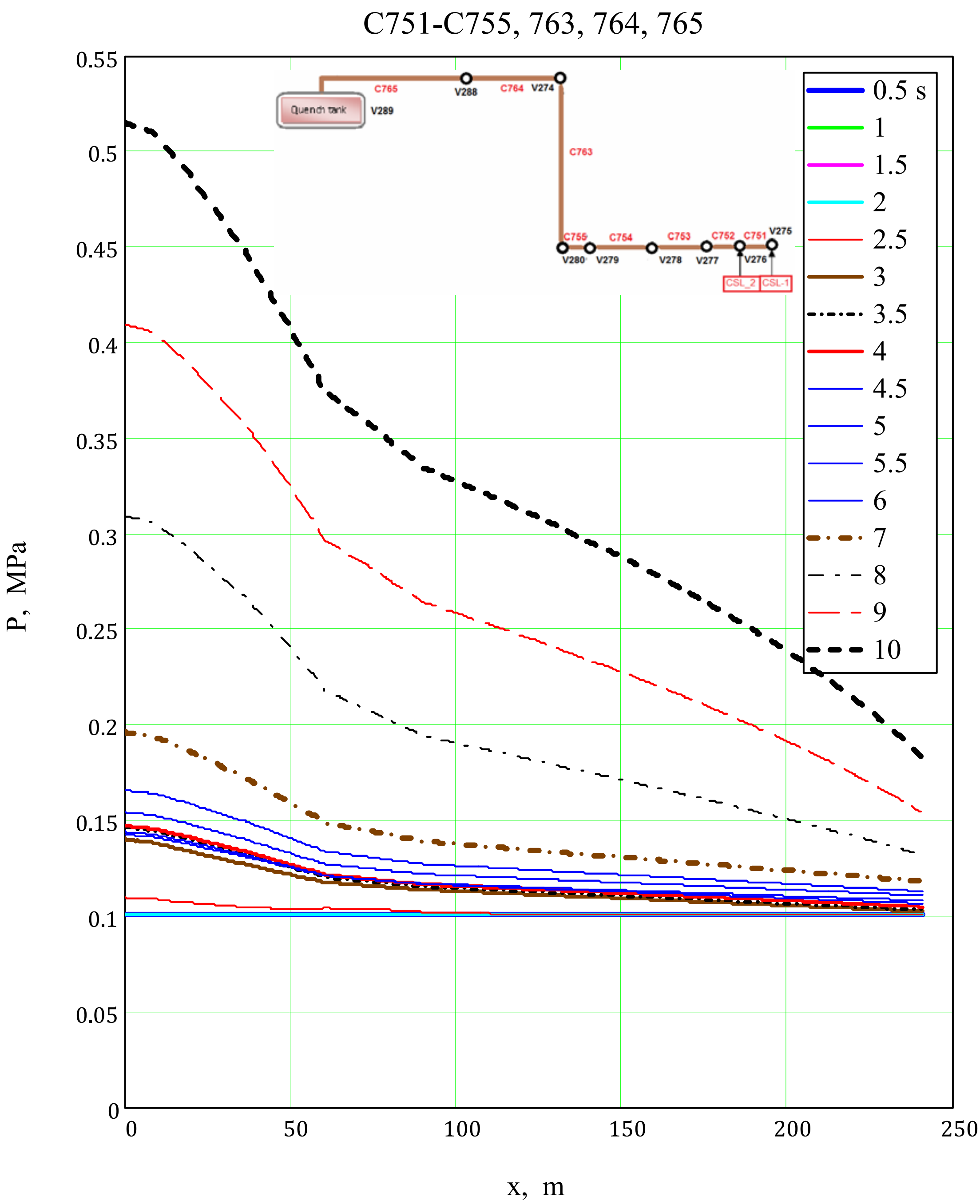
Helium temperature at inlets of the safety relief valves



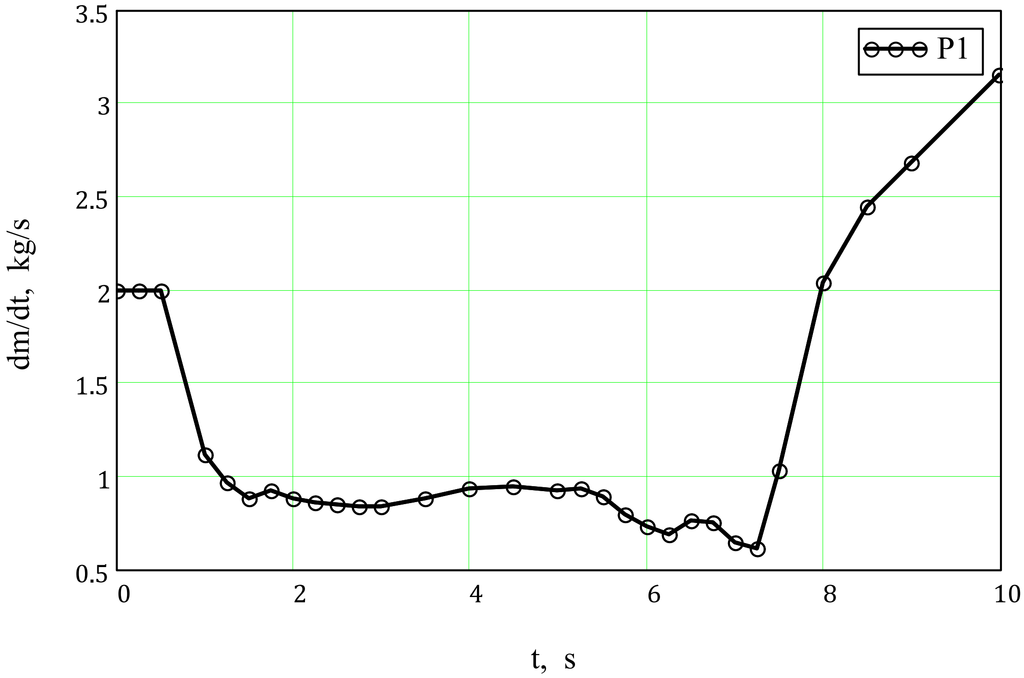
Evolution of helium pressure and temperature inside quench tank V289 due to helium release via safety valves



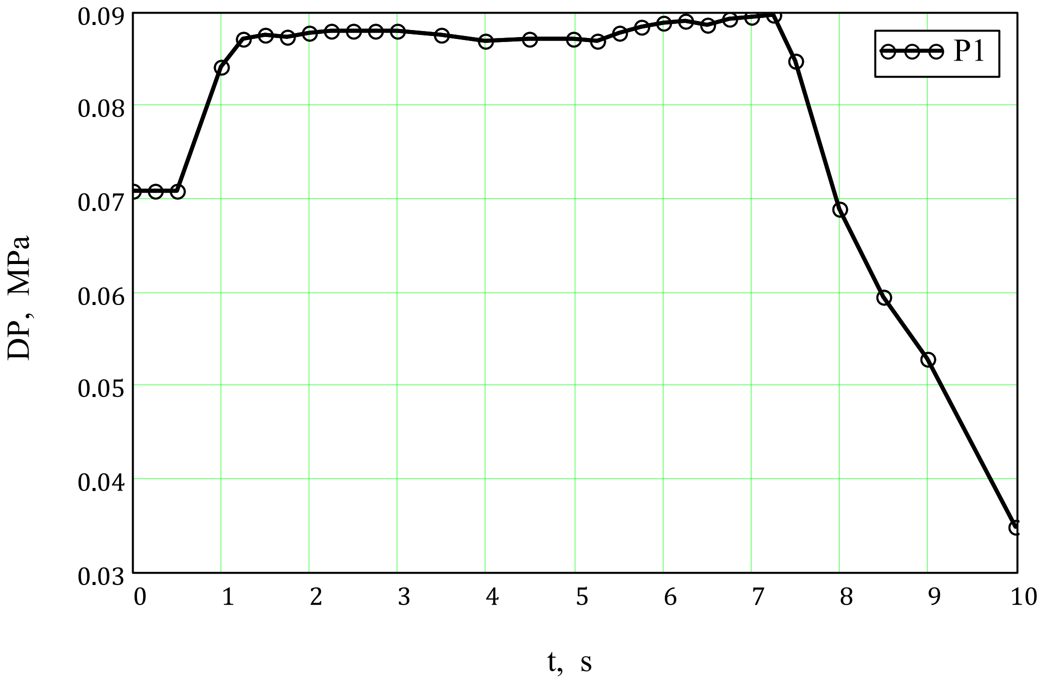
Evolution of temperature along selected portion of quench lines (see total layout of quench lines in Fig. 5)



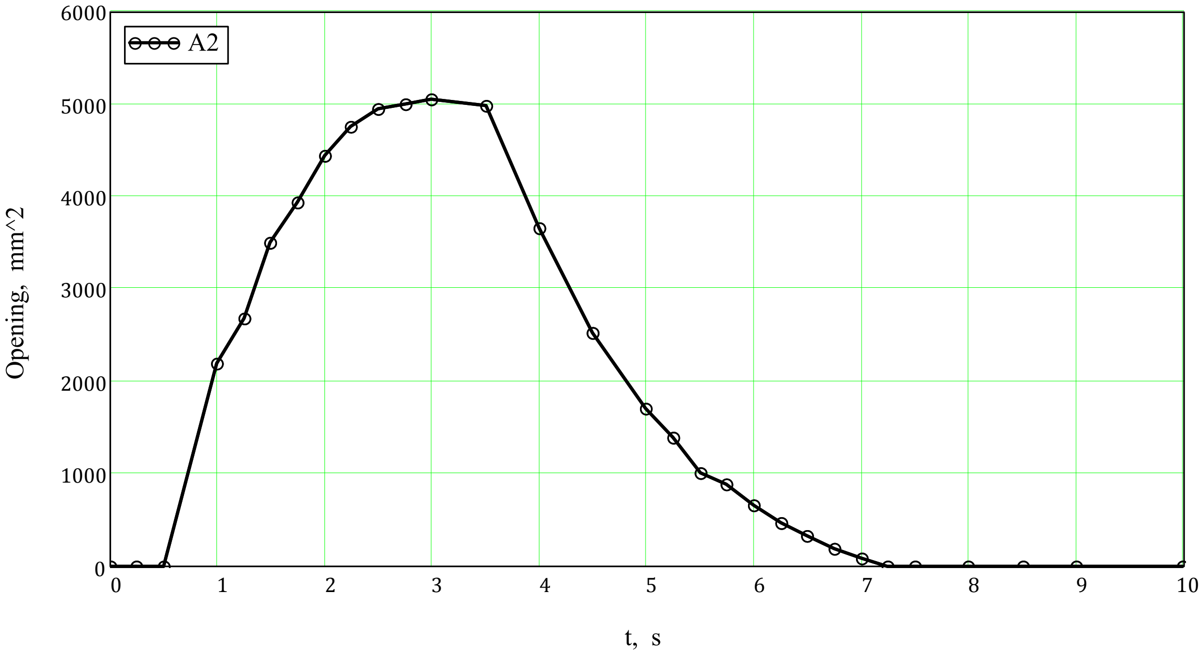
Evolution of pressure along selected portion of quench lines (see total layout of quench lines in Fig. 5)



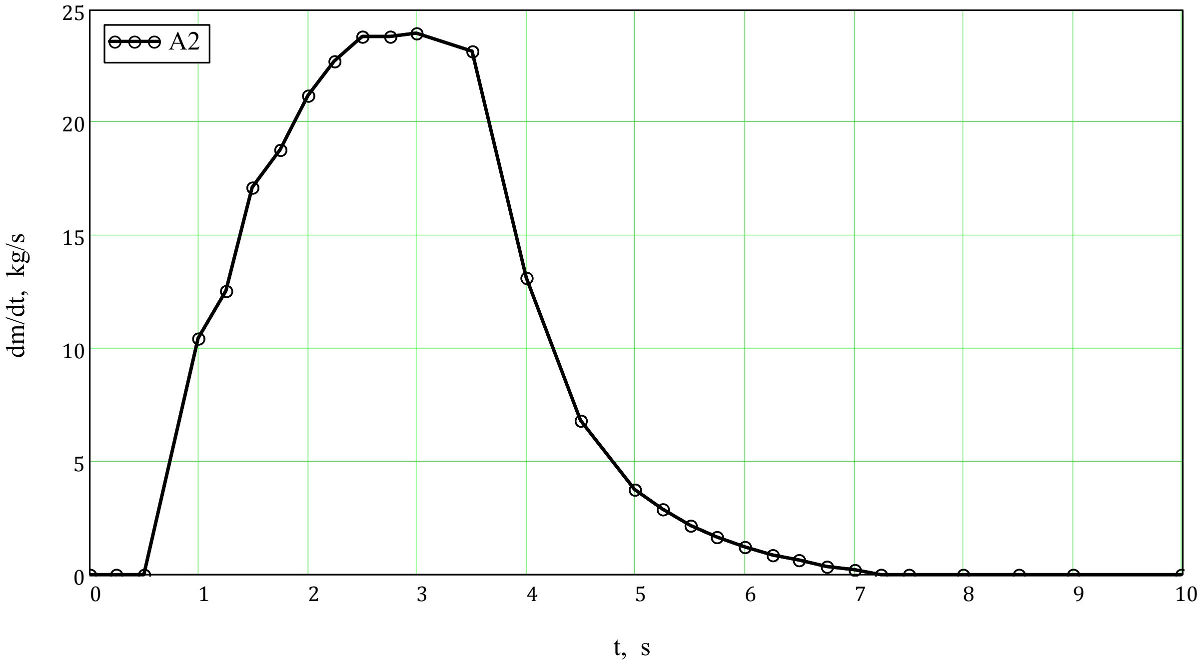
Flow rate variation of circulator P1 in accordance with its characteristic $\dot{m}$ - ΔP



Pressure head variation in circulator P1 limited by control valve A2 opening



Variation of control valve A2 opening



Variation of control valve A2 mass flow rate