1

Introduction to cryogenic systems with two-phase flows

1.1 Cryogenic gasification systems

Gasification systems are widely used in industry. Cryogens are transported and stored in liquid form, gasified, and delivered to the customer as a gas within given parameters. These systems typically consist of liquid storage tanks, transfer pipelines, and vaporizers in which the phase transition occurs.

An example of a gasification system is found at the Russian Baikonur launch complex. Here, liquid nitrogen at a pressure of 1–1.2 MPa and flowing at 13 kg/s is vaporized and used for a variety of purposes including purging and providing an inert atmosphere in spacecraft tanks.

Experience with gasification systems has shown that under transient conditions oscillations may develop. These oscillations are related to the properties of the cryogen, the design of the gasification system, and the nature of the disturbance. When the consuming equipment is connected or disconnected from the gasification system the product flowrate changes. The resulting disturbance propagates back to the liquid feed tank. If a large enough tank is used, the variation in the flowrate does not significantly affect the liquid parameters of the tank. In this case, the disturbance may be analyzed in terms of the subsystem consisting of the liquid and gas mains, vaporizers, and structural elements such as bellows and elbows.

Figures 1.1 and 1.2 show a commercial gasification system. The system supplies the gaseous product to the facilities of several consumers, each of which is connected by valves to the system. Liquid nitrogen from tanks (see Figure 1.3) is fed to the liquid main (0–1–2–3–4–5) and then into the evaporator (5–6). The resulting gas enters one of the consumer's facilities (8) via the gas main 6–7–8. The pressure at 0 is kept constant by a regulator. Table 1.1 lists the number, type, and hydraulic characteristics of the components within which the transient resulting from variation of the flow rate is localized (Dyachuk 1991).

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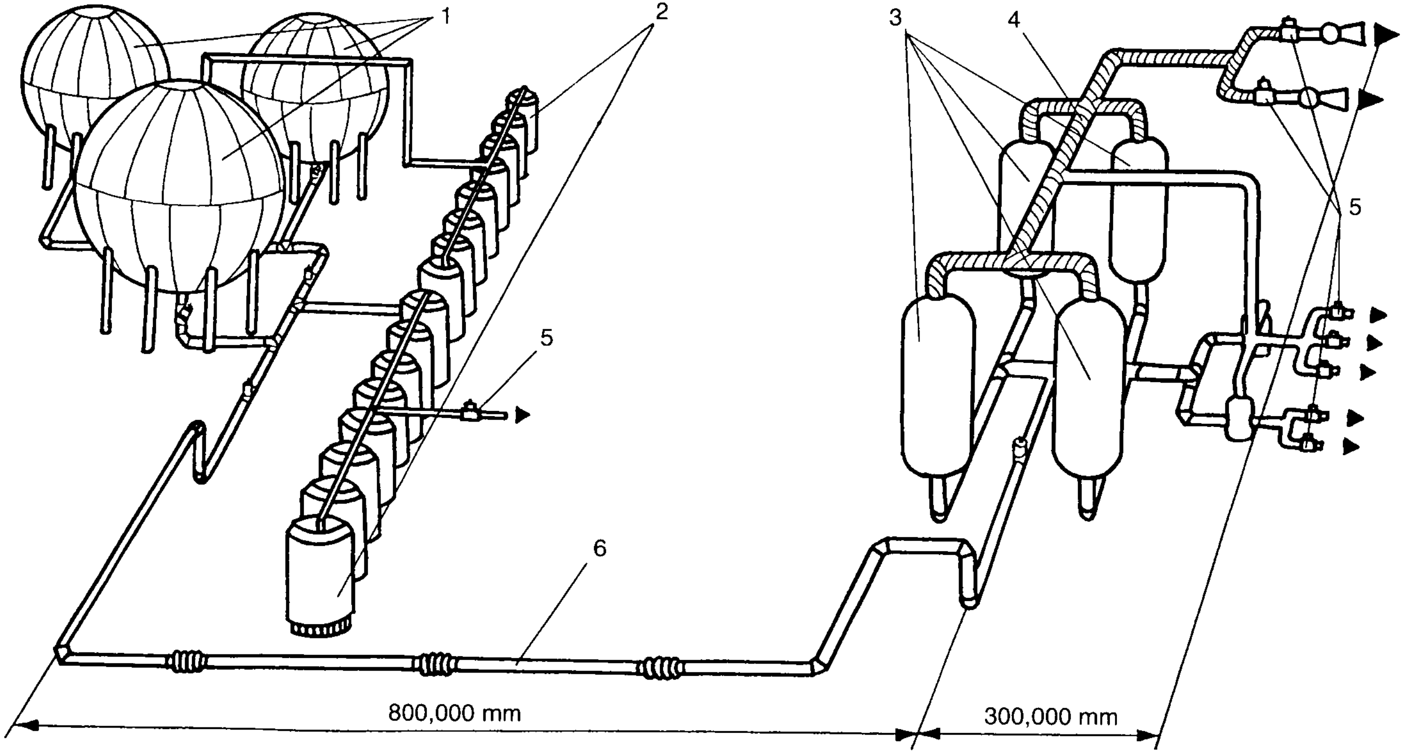

Figure 1.1. Example of a commercial gasification system: (1) liquid storage tanks, (2, 3) gasifiers, (4) gas mains, (5) outlet valves, (6) vacuum insulated liquid main (Dyachuk 1991).

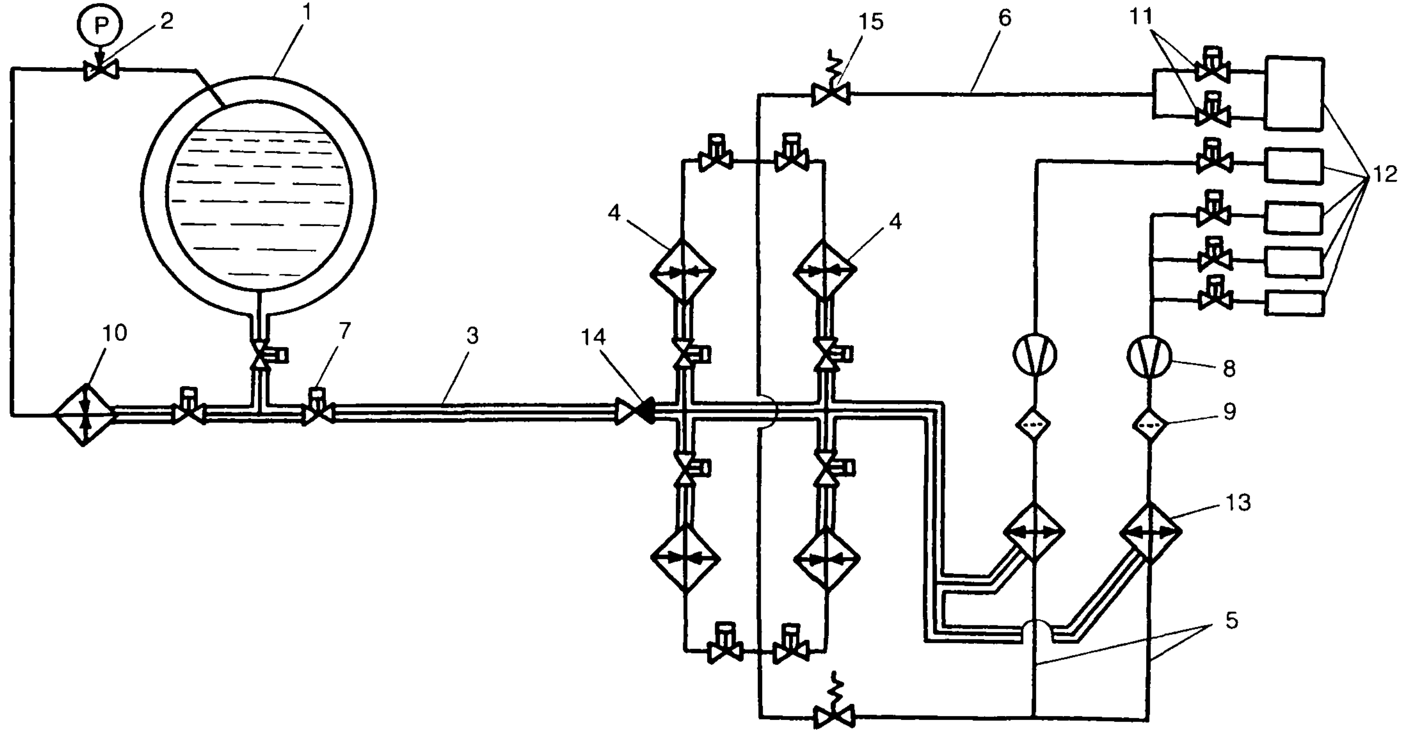

Figure 1.2. Schematic of gasification system: (1) liquid storage tank, (2) tank pressurization regulator, (3) liquid main, (4) gasifiers, (5, 6) gas main, (7) pneumatic valve, (8) flow meter, (9) filter, (10) tank pressurization evaporator, (11) outlet valve, (12) product consumer, (13) cooler, (14) check valve, (15) relief valve.

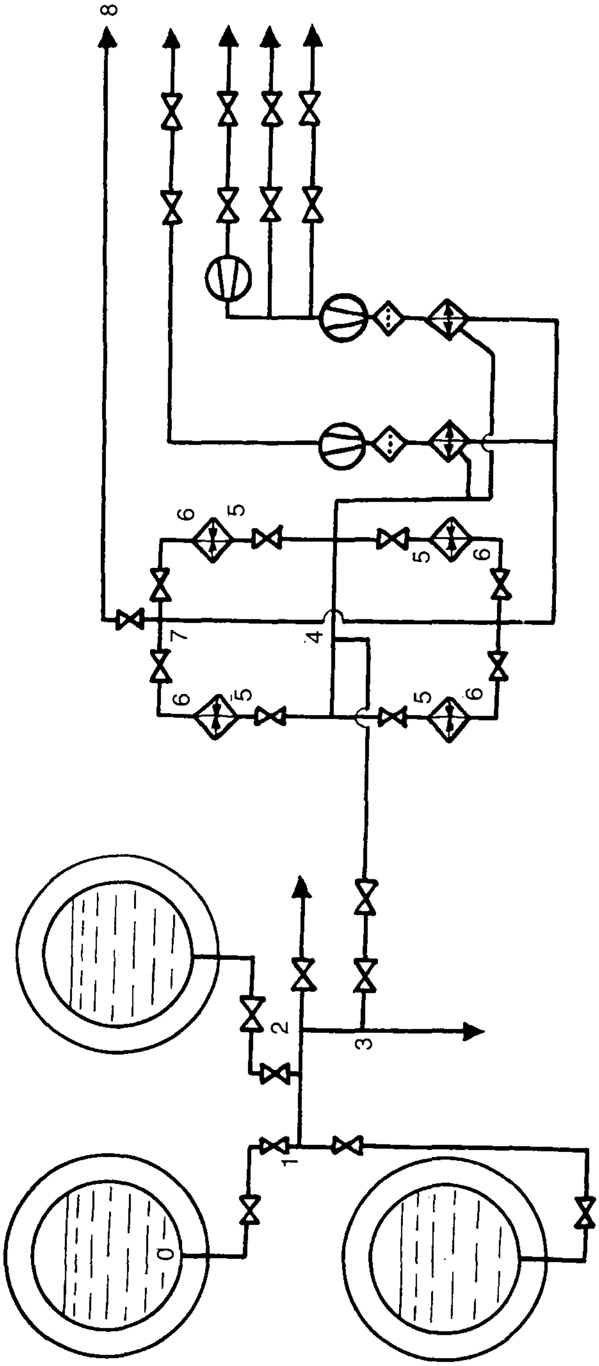

Figure 1.3. Gasification system schematic showing various hydraulic resistance elements. (See Table 1.1).

Table 1.1 *Description of elements in Russian IG-type gasifiers*

Description	Quantity	Hydraulic resistance coefficient (ξ)
Section 0–1, (liquid) dia. = 0.3 m		
Straight section dia. = 0.3 m	48 m	2.6
Turn 90 deg., dia. = 0.3 m	4	2.2
Hinged compensator	6	4.8
Valve	2	10.0
Tube inlet dia. = 0.3 m		1.0
		$\Sigma\xi(0–1) = 20.6$
Section 1–2 (liquid) dia. = 0.2 m		
Merging of flow	1	1.0
Straight section	1.5 m	0.1
Bellows dia. = 0.2 m	1	0.2
		$\Sigma\xi(1–2) = 1.3$
Section 2–3 (liquid) dia. = 0.2 m		
Flow separation dia. = 0.2 m	1	1.25
Straight section dia. = 0.2 m	3.5 m	0.3
Bellows dia. = 0.2 m		0.2
		$\Sigma\xi(2–3) = 1.75$
Section 3–4, (liquid) dia. = 0.2 m		
Straight section dia. = 0.2 m	785 m	58.9
Flow separation	1	1.25
Hinged compensator	3	2.4
Valve	2	10.0
Bellows	19	38
Turn, 90 deg.	8	4.3
Turn 135 deg.	1	0.4
		$\Sigma\xi(3–4) = 115.3$
Section 4–5 (liquid) dia. = 0.1 m		
Flow separation	1	1.25
Straight section	5.0 m	0.8
Bellows dia. = 0.1 m	1	0.6
Valve	1	5.0
Turn, 90 deg.	1	0.52
		$\Sigma\xi(4–5) = 8.2$
Section 6–7 (gas) dia. = 0.3 m		
Straight section dia. = 0.3 m	8 m	0.4
Turn, 90 deg.	3	1.6
Valve	1	5
		$\Sigma\xi(6–7) = 7$
Section 7–8, (gas) dia. = 0.3 m		
Straight section dia. = 0.3 m	300 m	15
Flow separation	1	1.25
Transition piece 0.4–0.3 m dia.	1	0.1
Valve	1	5
Turn, 90 deg.	10	5.4
		$\Sigma\xi(7–8) = 28$

As can be seen in the table, commercial gasification systems are complex, consisting of many different components including tanks, vaporizers, bellows, and valves. Transient oscillations in such systems cannot be described solely by analytical means (Filin & Bulanov 1985). Empirical results using standard measuring instruments (with an accuracy of 5 percent) are used to help understand the transient processes and to develop physical and mathematical models.

1.1.1 Cryogenic liquid gasifiers (vaporizers)

In gasification systems the phase transition is carried out in specialized apparatus known as vaporizers or gasifiers. In large-capacity vaporizers the gasification is caused by heat transfer from hot water or a superheated vapor to the cryogenic fluid. The performance of these devices can be improved by the augmentation of heat transfer between the two streams (Delhaye, Giot, & Riethumuller 1981; Stirikovich, Polonsky, & Tsiklauri 1982). In particular, use is made of different vortex generators (artificial roughness, spirals) to intensify the evaporation. The use of corrugated perforated packings with fins arranged in a staggered order (see Figure 1.4) has been shown to be one of the most efficient methods of heat-transfer augmentation.

Another type of vaporizer, known as a cold gasifier, uses heat exchange with the ambient environment to vaporize the cryogenic fluid. These gasifiers are characterized by a simple and reliable design and do not require additional power sources. Structurally, they consist of a set of parallel heat-exchange channels with developed surfaces. The free convection heat-transfer process on these surfaces is complicated by moisture condensation, desublimation of water and carbon dioxide, and in some cases by air condensation.

A proper understanding of two-phase cryogenic flow in vaporizers is necessary not only to optimize the heat transfer but also to predict the optimum flow pattern. The performance of vaporizers (gasifiers) of cryogenic fluids can be improved by controlling the hydrodynamics and heat transfer of the two-phase (vapor–liquid) flow. An example of this is seen in the operation of the IG type of vaporizers (see Figure 1.5) in the gasification system described in Table 1.1. During transient conditions in this system these gasifiers serve as generators of low-frequency oscillations (Nigmatulin, Filina, Kroshilin, & Dyachuk 1990). Analysis has suggested a number of modifications that include the creation of buffer volumes to reduce the pulsations (Dyachuk 1991). Figure 1.6 shows the cross sections of two different types of gasifier tubes.

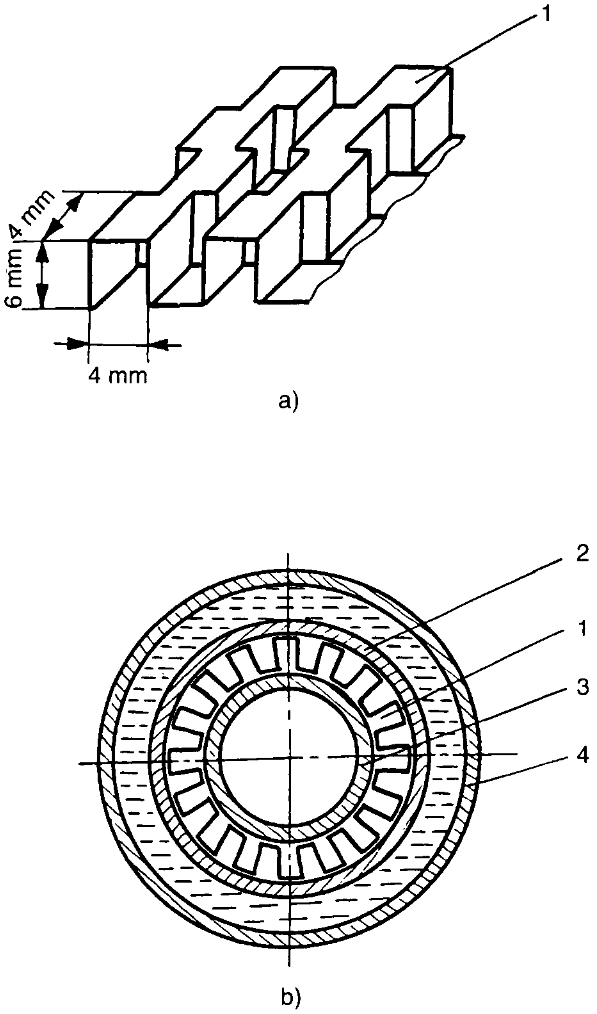

Figure 1.4. Elements of a gasifier channel: (a) corrugated fin insert. (b) Cross section of gasifier channel: (1) corrugated fin insert, (2) inner wall of heated pipeline, (3) hollow core, (4) outer wall of heated pipeline.

1.1.2 Liquefied natural gas (LNG) systems

A final example of the importance of gasification systems to the world economy is found in LNG systems. In Russia, large complexes have been built for the liquefaction, storage, and transport of LNG for commercial purposes. Natural gas is being used to provide alternative vehicle fuels and to provide energy for rural settlements. LNG gasification systems can be both fixed and

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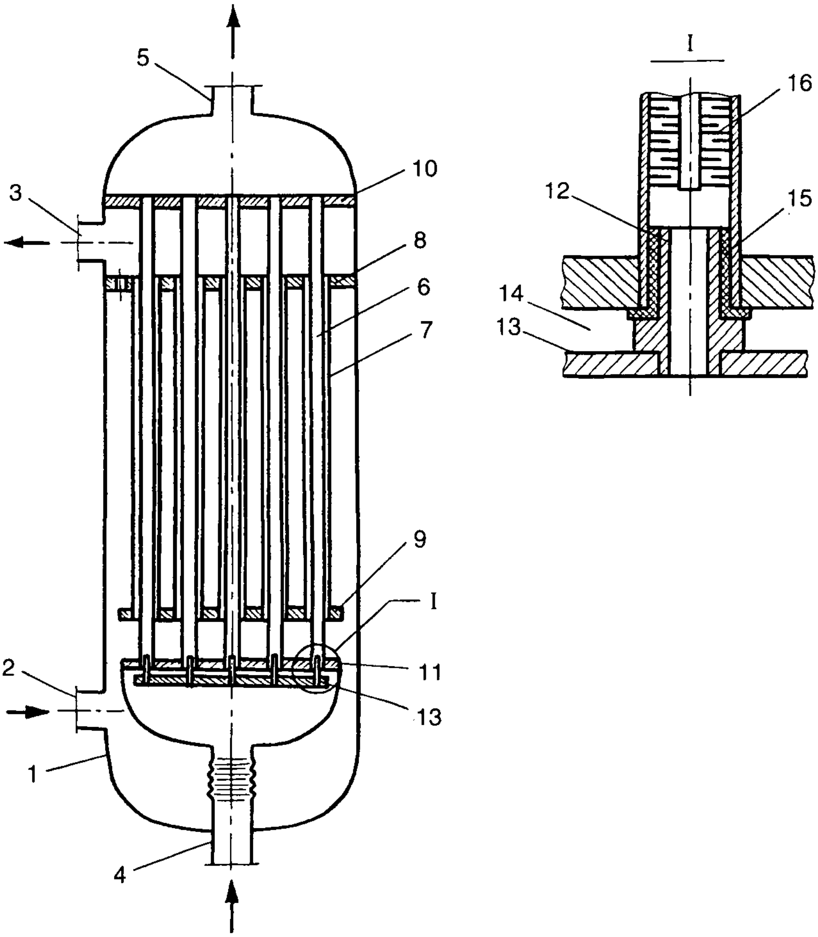

Figure 1.5. Type IG–30 gasifier: (1) casing, (2) inlet of heated fluid, (3) outlet of heated fluid, (4) inlet of cryogenic liquid, (5) outlet of produced gas, (6) inner tubes, (7) outer tubes, (8, 9) upper and lower tube sheets for outer tubes, (10, 11) upper and lower tube sheets for inner tubes, (12) branch pipe, (13) additional tube sheet, (14) clearance, (15) insulation, (16) corrugated fin insert (Dyachuk 1991).

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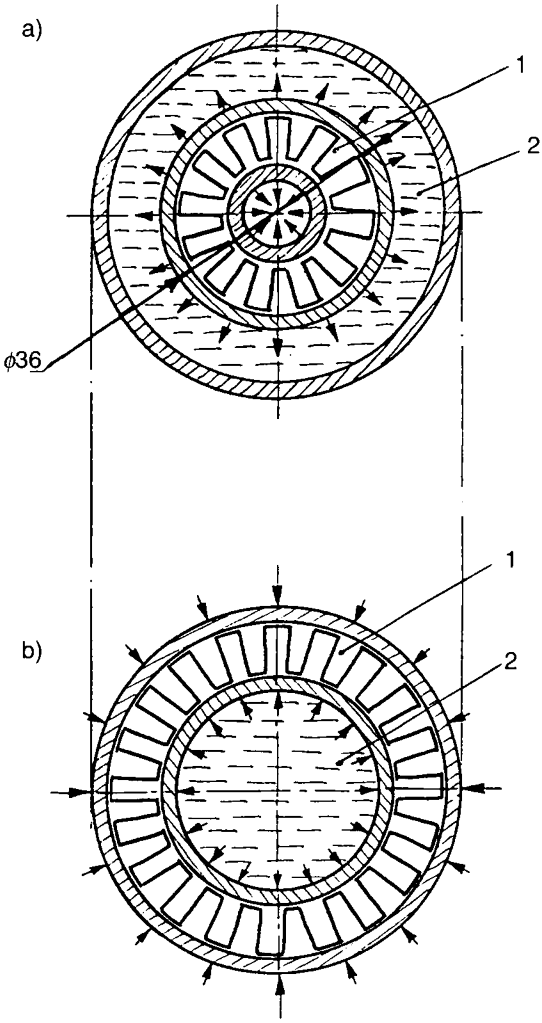

Figure 1.6. Cross sections of two different types of gasifier tubes: (1) cryogenic product space, (2) heated fluid. Arrows indicate temperature stresses.

mobile. The latter are found aboard various modes of transport – for example, ships, tractor trailer trucks, quarry dump trucks, and aircraft – that may be fueled by LNG. The problems associated with LNG gasification systems are the same as those found in other cryogenic gasification systems.

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1.2 Cryostabilization systems

Cryostabilization is another application in which a good understanding of two-phase cryogenic flows is required. Cryostabilization systems are designed to maintain the temperature of cryogenic components within desired operating parameters. Two examples of these systems are large space-simulation chambers and superconducting magnets.

1.2.1 Space-simulation chambers

These chambers are designed to provide a realistic thermal test environment for spacecraft and other flight hardware. Since full-size equipment is frequently tested the size of the chambers can be quite large. In space-simulation chambers the cold of space is simulated by heat-absorbing shields cooled to cryogenic temperatures constructed from finned channels (Filin & Bulanov 1985; Gorbachev 1987). The heat load to these shields is determined by the test requirements and may vary in magnitude and duration. Stringent requirements are specified for maintaining the temperature of the shields within a wide range of heat loads as increases in the shield temperature result in degraded test chamber performance.

A common method for cooling the shields is to use two-phase LN_2. As shown in Figure 1.7, the cooling may be done either by using natural convection loops with boiling taking place in the channels or in a separate bath, or else by making the channels a stagnant boiling bath that is periodically refilled. Efficiency in these devices is related to providing a stable flow of the LN_2 with a lack of pulsations. This requires calculating the two-phase flow in the vertical channels, allowing for the changing hydrostatic pressure.

1.2.2 Superconducting magnet systems

In order to function properly, superconducting magnets must be maintained at a temperature low enough to avoid reverting to a normal electrically resistive state. Large experimental facilities developed for the study of plasma physics and high-energy physics have made extensive use of the high magnetic fields developed by superconducting magnets. In many cases the magnets are completely or partially cooled by two-phase flows.

The Russian plasma physics experiment Tokamak 7 uses superconducting coils to form part of its plasma containment system. Forty-eight copper stabilized niobium–titanium coils are contained in a toroidal cryostat with an