Superfluid helium-3 in cylindrical restricted geometries : a study with low-frequency NMR

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Chapter 5

Cold valve

5.1 A high performance normally-closed solenoid-actuated cold valve

An electromagnetically driven normally-closed valve for liquid helium is presented, which is meant to regulate the input flow to a 1 K pot. An earlier design is modified to be normally-closed (not actuated) and tuned for durability and reliability. Here a new feature is presented which prevents seat deformation at room temperature and provides comfort and durability for intensive use.

5.2 Description of the design

Recently Bueno *et al.* [133] presented a low temperature valve for liquid helium that uses a magnetic field gradient and a permanent magnet to operate. The valve uses a ruby ball on a torlon seat to close. The ease of use and the reliability of the rather small valve has turned out to be quite convenient, and the valve is ideally suited to regulate the flow of helium to the 1 K pot of a dilution refrigerator. An essential feature of the valve is that it needs an actuating current to be closed, so in case of a power failure the valve opens automatically. In certain applications [134] it is important that the valve is closed when there is a power failure, so the possibility was investigated to design, construct and test a normally-closed valve, which would be opened by an electric current. This was less straightforward than expected, and several novel ideas are incorporated in the valve described below.

The new design is based on the earlier presented valve, which was normally-open [133]. All essential aspects can be seen in figure 5.1. A coil spring [135] is placed underneath the permanent magnet [136], which provides the closing force when not actuated. The superconducting coils [137] are counter-wound to create a linear-gradient magnetic field. The 2 times 1300 windings are made carefully to minimize the risk of quenching due to magnetic forces upon individual wires. In- and outlet are both

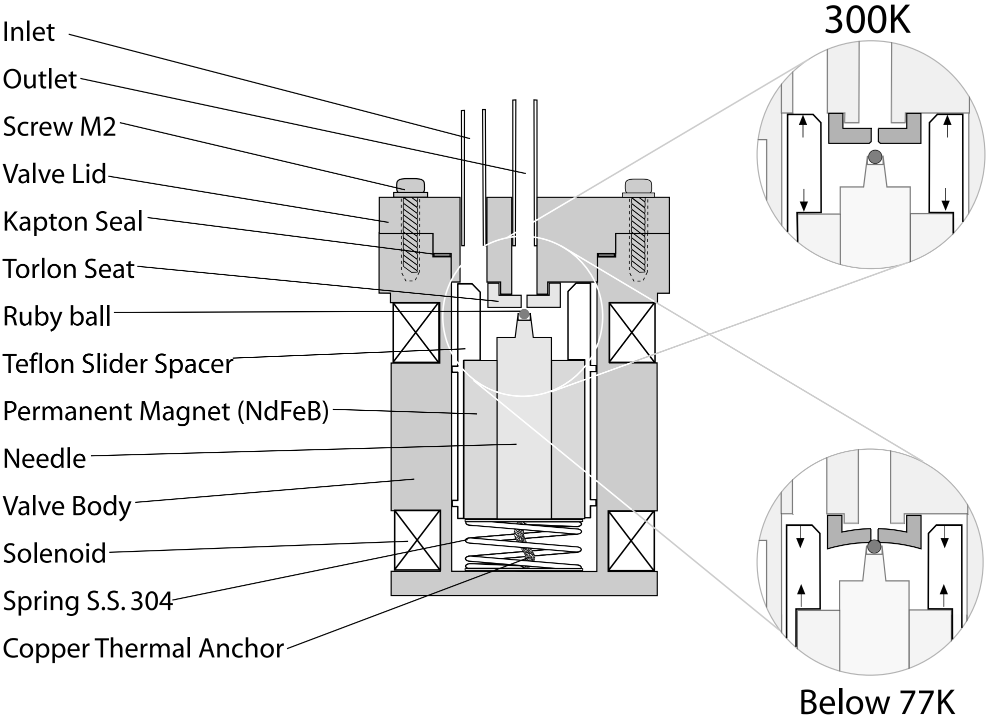

Figure 5.1: Schematic view of the valve, showing the components and nomenclature. The upper detail shows the situation at 300K: the valve is slightly open due to an expanded teflon spacer. The lower detail shows the situation at cryogenic temperatures: the teflon spacer is contracted and allows the ruby tip to press onto the seat. The seat's contact edge is elastically deformed, but the seat itself deflects as a membrane, which is shown in exaggerated form.

positioned in the valve lid, which is sealed by a greaseless kapton ring [138]. The brass needle inside the permanent magnet houses a 1 mm diameter ruby, which is the valve tip. The ruby presses on a torlon [139] seat, which has a 0.5 mm diameter hole and is glued to the lid. The permanent magnet is surrounded by a teflon slider, which guides its movement inside the valve body. Only two thin radial strips are in contact with the valve wall, to minimize friction. The top part of the teflon slider acts as spacer and functions on the basis of thermal contraction, which will be clarified below. Thermal anchoring, consisting of two copper disks interconnected by silver epoxy and soft copper braid, ensures proper thermal contact between the valve body and the permanent magnet, needle and teflon slider. The valve is 38 mm in height and 26 mm in diameter.

T (K)	$K_{calculated}$ (N mm^{-1})	$K_{experimental}$ (N mm^{-1})
300	2.71	2.70
77	2.95	3.02
4	2.90	–

Table 5.1: Calculated spring constants of an ideal compression spring [141] from literature values of the spring material properties, and experimentally determined values at different temperatures. The spring constant at 4 K is not measured.

5.3 Operating principles

5.3.1 Actuation

The closing force is delivered by the stainless steel spring which is compressed inside the valve boring. Proper seating and radially homogeneously distributed forces are achieved by end treatments of the spring, such as reducing pitch of the spring ends and grinding them flat [140]. From table 5.1 can be seen that this did not influence the spring behavior.

The actuation force comes from a force in opposite direction on the permanent magnet as a result of the linear gradient magnetic field from the two solenoids. The gradient is constant in axial direction, but not in the direction perpendicular to the axis. The magnet has the shape of a cylinder, where the brass needle resides in a hole through the center. Taking this into account the force per unit of current is calculated, by

$$F_z = \int_V \mu \frac{\partial B}{\partial z} dV, \tag{5.1}$$

with the gradient $\frac{\partial B}{\partial z}$ in Tesla per meter and μ the magnetic moment of the stack of permanent magnets, given by

$$\mu = \int_V \frac{B_{rem}}{\mu_0} dV = \int_V M dV, \tag{5.2}$$

with B_{rem} the remanent magnetic field, M the remanent magnetization, and μ_0 the permeability of free space. The volume of the stack of permanent magnets is the actual volume to integrate over, and taking into account the axial and radial symmetry Equation (5.1) becomes

$$F_z = 2\pi M h \int_{r_i}^{r_o} \frac{\partial B(z,r)}{\partial z} dr, \tag{5.3}$$

where h is the height of the permanent magnets and r_i, r_o the inner and outer radius of the magnets, respectively. The calculated and the measured values are displayed in table 5.2. Measuring the actuation force is done by lifting the permanent magnet at room temperature by moderate currents. From the weight of the magnet and

	calculated	measured
actuation force (N)	11.5	10.3
opening current (A)	1.0	1.05[1]

Table 5.2: Calculated and measured actuation force and valve opening point at LHe temperatures.

the measured current the actuation force per A is obtained. Using the calculated spring constant at 4 K from table 5.2 the opening point is calculated and measured by experiment. The values coincide well, showing no peculiarities.

5.3.2 Closure: Seat and Ruby

Valve closure is always based on the interaction between seat and tip material. In this case the tip is a 1.0 mm smooth ruby ball and the seat is a high quality plastic (polyamide-imide: PAI) known as torlon [139]. Torlon is strong and remains flexile even at LHe temperature, where other plastics become brittle. The ruby presses the seat at a contact edge to close the 0.5 mm orifice. It is the elastic deformation of this contact edge which ensures (superfluid) helium leak-tightness. The larger the elastic deformation the better the closure, however a material can only deform *elastically* up to the yield point from where its starts to deform *plastically*. By comparing controlled seat contact edge (de)formation and finite element analysis, a model is constructed. The model shows that an elastic deformation in the contact edge of $70 - 100\%$ of the yield point is where the valve closure is superfluid leak-tight and consistent. When the valve is closed rapidly and the permanent magnet and needle accelerate too fast towards the seat, the ruby strikes the seat and the forces involved could still cause plastic deformation. This is minimized by the fact that the seat as a whole can deflect as a membrane (see figure 5.1 and Ref. [138]). It is experimentally confirmed that the impact is much better absorbed this way and the contact edge deforms much less compared to the case were the seat cannot deflect like a membrane. The durability is improved, and the elastic deformation in the contact edge is only 5 to 8% less than in the non-membrane-like construction.

5.3.3 Teflon spacer

In the previous section it is argued and shown that closure depends on elastic deformation of the seat's contact edge: the higher the elastic deformation, the better the closure. However maximum elastic deformation is determined by the yield strength of the material, which for torlon is only 152 MPa at room temperature but already 216 MPa at 77K. To obtain a sufficiently large elastic deformation at LHe temperature due to the normally-closing spring force, this force would cause *plastic* deformation on the seat at room temperature, due to the lower yield strength of the torlon. To

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[1] Current increased with 0.05 A per step.

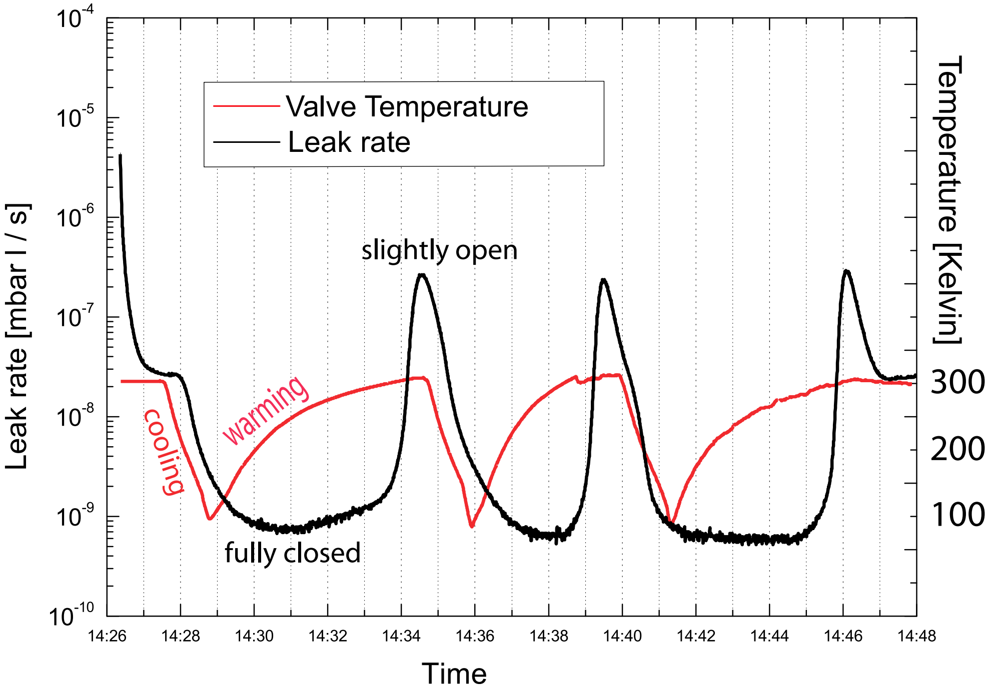

Figure 5.2: Graph showing the functioning of the teflon spacer. When cooling the spacer contracts, and the leak rate, due to a few mbar of helium pressure difference, drops to 10^{-9} mbar l s^{-1} (back ground pressure): the valve is closed. When warming to room temperature the spacer expands and lifts the tip from the seat, which is confirmed by the increasing leak rate. This cycle is repeated three times to show consistency.

avoid this behavior the teflon spacer is introduced. At room temperature the length of the spacer is such that it takes all the force of the spring and thus prevents the ruby to exert force on the seat. When the valve is cooled down to LHe temperature, the teflon spacer will start to contract, and also the yield strength of the torlon seat starts to increase. At the moment that the spacer is contracted so much that the ruby can press fully on the seat, the yield strength is large enough to ensure only elastic deformation. When warming again to room temperature the reverse happens: The seat's yield strength drops, but the spacer expands and starts taking a part of the force of the spring and thus prevents plastic deformation of the seat. The spacer only allows the full spring force on the seat at sufficiently low temperature and thus guarantees maximum elastic deformation and therefore optimal closure. Apart from the protective function the spacer has more advantages: It allows convenient and quick assembly of the valve. The risk of damaging the seat's contact edge, when mounting the valve lid, is eliminated, simply because the ruby cannot touch the contact edge. It prevents occasional dust particles (the main reason for valve failure) on the contact edge to get pressed into the material when warming to room temperature. The seat can in most cases be cleaned easily, to be leak-tight again when reused.

The spacer has been used for closing spring forces of up to 40 N and worked fine, showing no signs of wear or malfunctioning after many cooling cycles.

5.3.4 Thermal contact

The functioning of the superconducting solenoids, the seat and the teflon spacer all rely upon well controlled temperature changes. The additional copper thermal anchoring establishes proper thermal contact between the permanent magnet and the teflon slider/spacer. It ensures that all parts cool and warm evenly, so it cannot happen for instance that the seat is already warm (and thus weak) while the ruby is still exerting force because the spacer is not expanded yet. Calculations on thermal conduction show that the maximum characteristic time to get to thermal equilibrium is about 100 seconds, which is much shorter than the minimum time required to warming or cooling the valve.

5.4 Valve performance

A valve setup which needed a 12 N closing force by a spring with a spring constant of about 3 N mm^{-1}, was tested thoroughly. An actuation current below 2.0 A was needed for full opening. A flow characteristic can be seen in figure 5.3, where the maximum flow of 7 mmole s^{-1} was a limitation of the connection lines in that experiment (the maximum flow through the valve itself is at least ten times higher). Due to the precisely machined teflon slider the hysteresis is low and no stick-slip motion of the needle is observed in the flow, as was the case for earlier sliders made out of PEI (polyetherimide) and Araldite. Valves have been thermally cycled at least 20 times and at each cool down the valve was actuated at least 25 times by current step sizes of 0.2 A maximum, showing no detectable leak. Often used seats still showed leak tightness for superfluid helium. A particular seat which was closed *rapidly* (current switched from 1.8 to 0.0 A, so the ruby really impacts the seat) for 150 times, had many normal actuations and several seat cleansings showed a leak rate of only $5{\cdot}10^{-9}$ mmole s^{-1} before it was replaced. The valves with 12 N closing force showed no detectable leak (neither the ruby/torlon seat nor the kapton seal) for pressure differences of 10 bar. Even the flow control ability showed very promising results (also for very *low* flows, as seen in the inset of figure 5.3). Due to the teflon spacer, the assembly of the valves is easy and fast, allowing convenient replacement or cleaning of the seat.

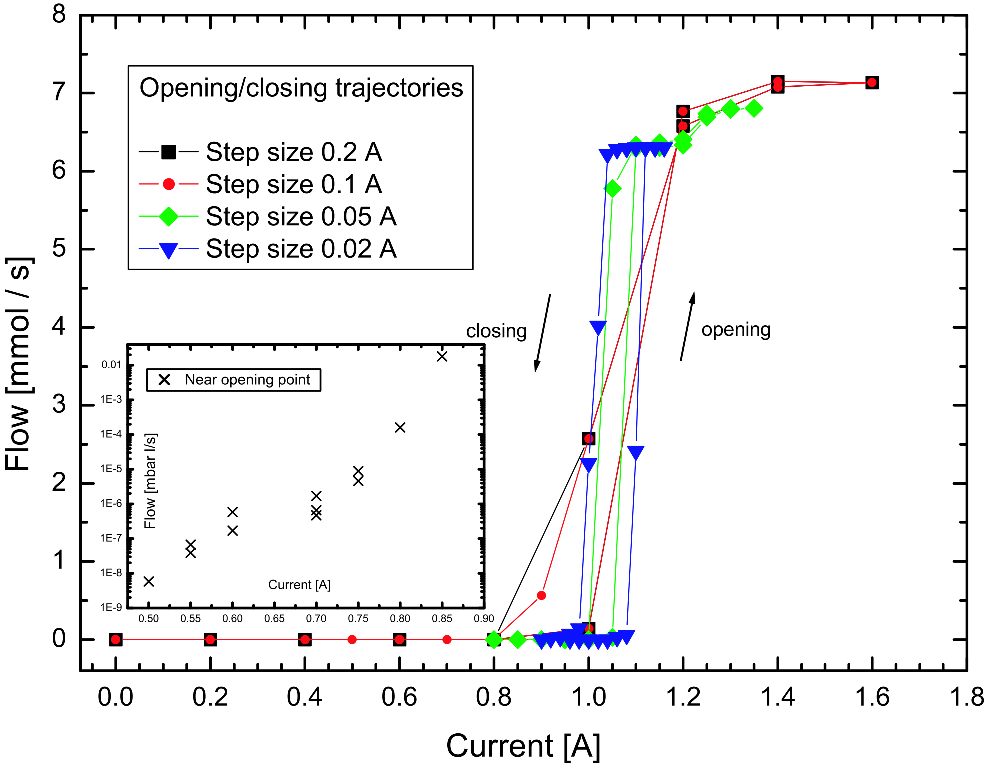

Figure 5.3: The flow through the valve versus the actuating current, that gradually opens the valve; the maximum flow is not set by the valve itself, but by the impedance of the connecting capillaries; the inset shows the flow rate near the opening point.