OPERATING AT 1.8 K:
THE TECHNOLOGY OF SUPERFLUID HELIUM

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Abstract
The technical properties of helium II ("superfluid" helium) presented from the user point of view. Its applications to superconducting devices, particularly in accelerators and to the point that it is now implemented in systems, routinely operated with high reliability. Two classes of superfluid helium as a coolant in superconducting devices, namely the operation, and the enhanced heat transfer properties at the solid-liquid bulk.

1. INTRODUCTION

Once a curiosity of nature and still today an arduous research topic in physics, superfluid helium has recently become a technical component of superconducting devices, to the point that it is now implemented in systems, routinely operated with high reliability. Two classes of superfluid helium as a coolant in superconducting devices, namely the operation, and the enhanced heat transfer properties at the solid-liquid.

The lower temperature of operation is exploited for the monotonously decreasing shape of the superconduct: in the current density-versus-magnetic field plane, shown in Fig. materials of technical interest. In this fashion, the current-carrying Nb-Ti superconducting alloys can be boosted at fields in excess of 8 T for their use in high-field magnet systems for condensed-matter physics and confinement fusion [6, 7] and circular particle accelerators and colliders. High-frequency superconducting devices, such as acceleration cavities in superfluid helium cooling is the exponential dependence of the BCS operating-to-critical temperature. Accelerators based on this technology, high-intensity machines [11, 12] and future high-energy lepton colliders operate in the temperature range which minimizes capital costs.

*) Strictly speaking, we are referring to the second liquid phase of helium, called He II bulk properties associated with superfluidity and is therefore also called "superfluid". the entropy-less component of the phenomenological two-fluid model accounting for the behavior some authors prefer to keep the qualificative "superfluid" for.
The technical heat transfer characteristics of superfluid helium peculiar transport properties, such as high heat capacity, low viscosity, and thermal conductivity [15, 16]. In order to be fully exploited, however, and transient regimes, e.g. for power heat transport over macroscopic distances, intimate stabilization of superconductors, they require elaborate cooling circuits, conductor, insulation and coil assemblies. This requires technical or economic requirements of the projects and acceptable trade-offs.
2. PRESSURIZED VERSUS SATURATED SUPERFLUID HELIUM

A look at the phase diagram of helium (Fig. 3) clearly shows the saturated helium II, reached by gradually lowering the pressure down the saturation line, and pressurized helium II, obtained by subcooling liquid saturation, and in particular at atmospheric pressure (100 kPa).

![Phase diagram of helium](image)

**Fig. 3 Phase diagram of helium**

Although requiring one more level of heat transfer and additional particular a pressurized-to-saturated helium II heat exchanger - implant helium II for cooling devices brings several important technical advantages in pressure operation in large and complex cryogenic systems clearly limited and resulting contamination of the process helium. Moreover, in the case of the low dielectric strength exhibited by low-pressure helium vapour [minimum of the Paschen curve [19], brings the additional risk of low voltage. Operating in pressurized helium II avoids this kind of problem.

However, the most interesting and specific aspect of pressurized operation of superconducting devices, stems from its capacity for a subcooled (monophase) liquid with high thermal conductivity, pressurized absorb in its bulk a deposition of heat, up to the temperature at which the superfluid helium II, which is in fact slightly subcooled due to the surface of the liquid bath, may only absorb heat deposition up to saturation line is crossed, and phase change occurs. The enthalpy working point to the transition line is usually much smaller in the case of pressurized helium II.
3. CONDUCTION COOLING

In the following we shall only consider conductive heat transport fluxes of technical interest (typically above 1 kW.m\(^{-2}\)). For most means working in the "turbulent" regime with full mutual friction between the two-fluid model [21]. In this regime, helium II exhibits a large heat conductivity, the value of which depends both on temperature and, in general, patterns of this behavior can be predicted by the Gorter-Mellink data useful for engineering design has been established in a number of different instances.

Consider conduction in one-dimension, e.g. in a tubular conduit which are maintained at temperatures \(T_c\) and \(T_w\). The steady-state heat flux is given by

\[
q' = \frac{X(T_c) - X(T_w)}{L}
\]

where the best experimental fit for \(n\) is 3.4, and \(X(T)\) is a tabulated function obtained by experiments. A plot of this function gives the apparent thermal conductivity of helium II goes through a maximum as a function of temperature.

![Fig. 4 Thermal conductivity integral of pressurized superfluid](image)

As an example, the heat flux transported by conduction between 1.2 long static column of helium II is about 1.2 W.cm\(^{-2}\), i.e. three orders of magnitude lower than what would be conducted along a bar of OFHC copper of the same geometry with respect to heat flux also results in a much weaker dependence upon length, or thermal gradient. While the heat flux conducted is

\[q' \propto L^{n-1}\]

*) C.J. Gorter and J.H. Mellink introduced in 1949 the idea of an interaction product between the components of the two-fluid model, to account for the observed transport properties.
proportional to the thermal gradient applied, doubling the conductive heat flux of helium II only reduces the heat flux by some 20%.

The variation of $X(T)$ also implies that, for each value of the critical temperature $T_c$, there exists a maximum possible heat flux at which $T_w$ reaches the critical temperature of the helium column ceases to be superfluid. Values of this limiting heat flux depend on $L$, range from a fraction to a few units of $W.cm^{-2}$, for practical applications. This clearly brings an intrinsic limitation in the applicability of isothermal cooling of long strings of superconducting devices in an isobaric, tens of watts over tens of meter distances would then require several watts of input power and a large cross-section of helium, which is both thermodynamically costly. For a more precise estimate, consider a uniform conduit of length $L$, operating between temperatures $T_c$ and $T_w$, and steady-state conduction equation to this fin-type geometry. After introducing the total heat flux flowing through the section at the heat sink. As an example, cooling a 50-m long cryomagnet string, with a uniform heat flux of 1 W.m^{-1}, by conduction between 1.9 K (temperature of the warmest bath) and 1.8 K (temperature at the heat sink), would require a helium II cross-section of about 1 cm diameter conduit. In view of such constraints, the conduction-cooling proposed for the LHC project [28] was later abandoned. It is however possible to consider cryogenic testing of single LHC magnets [29].

The high thermal conduction in helium II can however be exploited for other applications, such as cryogenic testing of superconducting magnet under test. Knowledge of temperature changes at the warmest bath then permits to assess enthalpy changes of the system, and thus total energy dissipation [31] produced by ramping losses or resistive dissipation of superconducting magnets.

4. FORCED CONVECTION OF PRESSURIZED SUPERFLUID HELIUM

To overcome the limited conduction of helium II in long strings of superconducting magnets, one must consider the convective heat transfer. One can then benefit of an additional convective heat transfer. One can then benefit of an additional coolant flow provided at the bulk fluid. In the following we shall only consider channel diameters of technical interest, i.e. typically greater than 5 mm. The pressure gradient across an hydraulic impedance is then essential to the convective heat transfer. Assuming that internal convection between two-fluid model is independent of the net velocity, reduces the problem to the case of a monophase liquid with high, non-linear thermal conductivity. The transport $Q'$ between two points 1 and 2 of the cooling loop is then

$$q'_{\text{total}} = (n+1) [X(T_c) - X(T_w)]$$

where $q'_{\text{total}}$ is the total heat flux flowing through the section at the heat sink. As an example, cooling a 50-m long cryomagnet string, with a uniform heat flux of 1 W.m^{-1}, by conduction between 1.9 K (temperature of the warmest bath) and 1.8 K (temperature at the heat sink), would require a helium II cross-section of about 1 cm diameter conduit. In view of such constraints, the conduction-cooling proposed for the LHC project [28] was later abandoned. It is however possible to consider cryogenic testing of single LHC magnets [29].
An estimate of the potential advantage of forced convection over natural convection can be made, using the same geometry and temperature boundary conditions as described in paragraph 3 above. Consider helium II pressurized at 100 kPa, flowing through a 1 m long pipe with a cross-sectional area of 1 cm², and assume its temperature increases from an inlet of 1.8 K to an outlet of 1.9 K. It is easy to show that for flow velocities over 1 m/s, convective heat transport greatly exceeds conduction.

The above calculation however neglects pressure drop along the length of the pipe. The pressure-enthalpy diagram of helium (Fig. 5) reveals a positive Joule-Thomson effect: the enthalpy of the fluid increases both with increasing temperature and decreasing pressure. For example, flowing across a pressure gradient of 50 kPa will warm up from 1.8 K to 1.9 K even with no applied heat load. The magnitude of this effect requires precise thermodynamic analysis, in order to validate its implementation in physical systems such as cryogenic loops [33].

![Fig. 5 Pressure-enthalpy diagram of superfluid helium](image)

Following early exploratory work [34, 35], several experiments have investigated heated flow of pressurized helium II in pipes and pipelines, culminating with the 230-m long test loop in Grenoble [38, 39] which tested Reynolds numbers and extended geometries characteristic of accelerated flow. In parallel to that work, mathematical models were developed for conductive and convective heat transport processes in complex circuitry and on experimental results. Pressure drop and heat transfer, both steaming as a function of the flow rate, can now be safely predicted for engineering applications with well-established laws and formulae.

The implementation of forced-flow cooling requires cryogenic pumping of pressurized helium II. Although most of the experimental work has focused on natural convection, the potential advantage of forced convection over natural convection for this application is significant.
positive displacement, i.e. bellows- or piston-pumps originally deve
The thermomechanical effect, specific of the superfluid, may also be
loops by means of fountain-effect pumps [43-46]. In spite of thei
efficiency [47], a drawback of limited relevance for using them as c
produce low pumping work, fountain-effect pumps are light, self-primi
parts, assets of long-term reliability e.g. for embarked applicia
heat loads, they have been considered [49] and tested [50] for f
superconducting magnets: the overall efficiency of the process may
configuring the cooling loop so as to make use of the heat load of t
the thermomechanical effect in the pump [51].

5. TWO-PHASE FLOW OF SATURATED SUPERFLUID HELIUM

The conductive and convective cooling systems described above,
deposited or generated in the load, over some distance through press
lumped pressurized-to-saturated helium II heat exchanger acting as qu
This is achieved at the cost of a non-negligible - and thermodynamic
difference, thus requiring to operate the heat sink several hundred
of the load.

A more efficient alternative is to distribute the quasi-isother-
length of the accelerator string. In this fashion the conduction
temperature drop - in pressurized helium II is kept to a minimum, '
dimension of the device cryostat. This leads to the cooling scheme p
CERN, and schematized in Fig. 6: the superconducting magnets operat
pressurized helium II at around atmospheric pressure, in which the h
conduction to the quasi-isothermal linear heat sink constituted by exchanger tube, threading its way along the magnet string, and in w
saturated helium II gradually absorbs the heat as it vapourizes [9].

![Fig. 6 Principle of the LHC superfluid helium cooling schem](image)

Although potentially attractive in view of its efficiency in ma:
magnets at quasi-uniform temperature, this cooling scheme departs fr
wisdom of avoiding long-distance flow of two-phase fluids at satu:
horizontal or slightly inclined channels. Moreover, no experimental
flowing saturated helium II, and very little for other cryogenic fl
Following first exploratory tests [52] which demonstrated the validation of the reduced geometry, a full-scale thermohydraulic loop [53] permitted testing of horizontal and downward-sloping helium II flows, to observe the wetting of the inner surface of the heat exchanger tube by the liquid stratification, and to address process control issues and develop uniformity of temperature at strongly varying applied heat loads, in the context of the liquid phase. As long as complete dryout does not occur, conductance of about 100 W.m\(^{-1}\).K\(^{-1}\) can be reproducibly observed across the exchanger tube, made of industrial-grade deoxidized phosphorus copper.

Once the wetting of the inner surface of the tube is guaranteed, pressurized to the saturated helium II is controlled by three thermal conduction across the tube wall, and Kapitza resistance at the contact between tube wall and liquid. While the former can be adjusted, within the bounds of tube material and wall thickness, the latter, which finds its origin in phonons at the liquid-solid interfaces and is thus strongly temperature-dependent below 2 K [54]. The use of high-purity, cryogenic-grade copper was found not required, and pressurized-to-saturated helium II heat exchanger tube - "plumber's" copper.

The final validation of the two-phase helium II flow cooling scheme was performed successfully on a 50-m long test string, equipped with cryomagnets, operated and powered in nominal conditions [55]. At heat loads exceeding 1 W.m\(^{-1}\), all magnets in the string were maintained at a narrow temperature of mK above the saturation temperature of the flowing helium II provided by the pressurized helium II baths contributed to limit the cost of introducing strong non-linearities and time delays in the system. This was coped with by elaborate, robust process control [56]. In complement to this, more fundamental experimental studies are presently conducted on a 90-m long test loop at CEN-Grenoble, comprehensively equipped with transparent sections for visual observation and interpretation of the results.

6. REFRIGERATION CYCLES AND EQUIPMENT

The properties of helium at saturation (Fig. 3) impose to maintain the temperature of the heat sink of a 1.8 K cryogenic system below 1.6 kPa on atmospheric pressure thus requires compression with a pressure rate that is several times that of refrigeration cycles for "normal" helium at 4.2 K. For example, in small laboratory cryostats, this is achieved by means of standard vacuum pumps, handling the very-low pressure gaseous helium escaping has been warmed up to ambient temperature. This technology may be supplemented using liquid-ring pumps, adapted for processing helium by impregnating the casing and operating them with the same oil as that of the main cycle [57], or oil-lubricated screw compressors operating at low suction pressure at ambient temperature is hampered by the low density of helium, which results in large volume flow-rates and thus requires large and costly, inefficient heat exchangers for recovering enthalpy of the value.
The alternative process is to perform compression of the vapour at its highest density. The pumps and recovery heat exchangers get expensive, but the work of compression is then injected in the cycle that the inevitable irreversibilities have a higher thermodynamic pumping machinery which handles cold helium must be non-lubricated and which seriously limits the choice of technology. Hydrodynamic centrifugal or axial-centrifugal type, have been used in large-capacity limited pressure ratio however imposes to arrange them in multistage thus narrowing the operational range of the system, in particular modes, unless they are used in combination with more compliant volume scheme which permits independent adjustment of flow-rate or wheel inl

The practical ranges of application of these different pumping techniques Fig. 7, setting a de facto limit for warm compression above 20'000 m³ at 1.8 K.

![Fig. 7 Range of application of low-pressure helium compressors](image_url)

The efficiency of the Joule-Thomson expansion of liquid helium atmospheric pressure and 4.2 K, down to 1.6 kPa and 1.8 K, can be now previously subcooled by the exiting very-low pressure vapour in a subcooled subcooling heat exchangers with small pressure drop on the vapour.

7. SUPERFLUID HELIUM CRYOSTATS

The high thermodynamic cost of low-temperature refrigeration may be acceptable provided the heat loads at the 1.8 K level are tightly...
Setting aside the dynamic heat loads, produced by powering of the ma
cavities, or interactions with the circulating particle beams, the
system of a large accelerator is the cryostat heat inleak, falling on
of kilometers) of cold mass. It is therefore very important, in l
construct and assemble reproducibly device cryostats with low residua

Fig. 8 Transverse cross-sections of superfluid helium cryostats fo:
(a) LHC, (b) TESLA

The structure of accelerator cryostats for devices operating in s
(Fig. 8) reflects these preoccupations. The device cold mass is s
positioned from the ambient-temperature vacuum vessel by post-type
non-metallic composites, with several levels of heat interception at
[68]. In this fashion the residual heat inleak to the 1.8 K level
orders of magnitude smaller than the heat drawn by conduction alo
ambient-temperature environment. The thermal performance achieved ir
critically depends on the quality of the heat intercepts, i.e. on the
to-solid thermal contacts under vacuum.