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An integrated tool for helium recovery and evaporative cooling

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Abstract. We present the design of an automated tool that can be used to extract left-over cryogen, either helium or nitrogen, in an MRI magnet and push helium into a recovery bag. The main design goals are to minimize the process time and overall footprint of the tool, and not to contaminate helium with hydrocarbons during the process. Also discussed in the paper is another potential application where the same tool is used as an expansion engine for evaporative cooling of an MRI magnet in a warehouse or hospital in much less time compared to a cryocooler based cooldown tool and consume less liquid helium compared to not using the tool.

1. Introduction

Helium bath cooled superconducting MRI magnets are pre-cooled from room temperature down to a low enough temperature before liquid helium is transferred into magnet to minimize liquid helium usage. Mega-Joule level energy is extracted during this process.

A couple of methods have been in use by major MRI magnet manufacturers in the factories: in a more traditional method, magnets are first cooled down using liquid nitrogen in a heat exchanger as the heat sink, then liquid helium is transferred into magnet. The other method involves using a helium refrigerator to cool the magnet from ambient to ~30 K before liquid helium is transferred into magnet, see for instance [1].

Occasionally, a traditional bath cooled MRI magnet may require cooling down from ambient temperature in a hospital or warehouse. In such a situation, using a refrigerator is not an option at all. Recently, some cryocooler based (single or double stages) mechanical coolers / cold helium circulation systems have become available [2][3]. However, if timing is critical, direct cryogen cooling (liquid nitrogen followed by liquid helium) is the method of choice. In this case, the leftover nitrogen has to be purged before helium can be transferred into the magnet. The tool described in this paper can be used in such cases to reduce the amount of liquid helium necessary to cool the magnet down. In such a scenario, some amount of liquid nitrogen is left in the magnet and the tool is used to pump on the space to evaporate liquid nitrogen during the purge process. Lowering the vapor pressure of liquid nitrogen provides additional cooling to the magnet prior to transferring liquid helium.

The main application for the tool is considered to be purge / pump down of a sealed, low cryogen or pure conduction cooled magnet where the superconducting coils are contained within a closed volume resembling the helium vessel in a bath cooled magnet [4]. This volume may be used to cool magnet down in the same fashion as a bath cooled magnet using any of the methods mentioned above. Following the initial cooling, the tool is connected to this volume, and left over

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cryogen is evacuated. This action both creates vacuum around the sealed magnet and further cools the magnet down as the leftover fluid is evacuated. If the leftover gas happens to be helium, the tool pushes the evacuated gas into a helium recovery bag in a factory setting.

2. Description of the tool

The schematic of the tool with helium recovery option is given in Fig. 1. The vacuum pump draws the cold gas out of the magnet, which flows through a heat exchanger and warms up to a temperature that is suitable for the pump. An inline throttle valve is used to regulate the gas flow rate. A blower in the downstream of the vacuum pump pushes the gas into the recovery bag as well as creating a lower pressure for the vacuum pump discharge.

The gas will be heated directly by electric heaters wrapped around the tubing containing the gas. The tubing is wrapped with insulation and coiled inside a vacuum vessel to eliminate moisture accumulation on the vessel. The heater power is adjusted in conjunction with the flow rate through the tool and the temperature sensor (T) placed at the outlet of heat exchanger. The flow rate through the system is controlled by the throttle valve, which receives input from a pressure transducer (P) at the inlet of vacuum pump. A dedicated controller monitors P and T, and adjust the throttle valve and / or heater power to the desired cooldown / pump down rate.

The vacuum pump in the system is of dry-running type as no oil vapor is desired in the gas stream. The ultimate pressure of pump is determined in conjunction with Paschen curve for a design such as the one described above [5]. Another parameter for the choice of pump is the desired pumping speed which is closely linked to the magnet design and material. A roots pump or a screw vacuum pump are ideal for the application.

The blower in the system is used to push the gas into a recovery bag as well as providing a lower backing pressure to the vacuum pump thereby increasing the pumping speed. It also should not contaminate the helium gas; therefore, a regenerative blower with sealed bearings best suits the application.

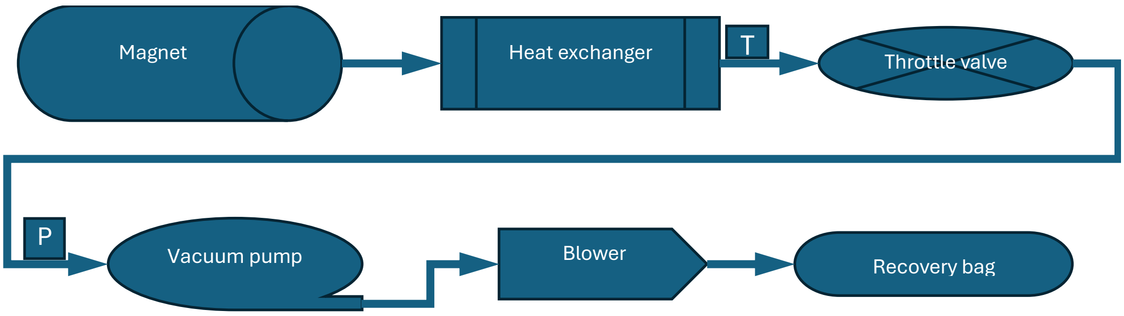

Figure 1. Block diagram of the tool (without the control circuit).

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3. Cooling potential of evacuating helium or nitrogen out of magnet

Depending on application, either nitrogen or helium is assumed inside a magnet whose properties are given in Table 1. Uniform temperature across magnet and cryogen is assumed with gas temperature 1 K lower than magnet. Gas pressure is assumed to be ambient (0.1 MPa) in the beginning of process. The target levels to be achieved by using the tool are: ≤3333 Pa for pressure, and ≤65 K and ≤5 K for temperature across solids depending on the cryogen used.

Table 1. Properties of hypothetical magnet used in design.

Item	Value
Main coils former diameter	1.0 m
Shield coils former diameter	1.5 m
Former thickness	15 mm
Magnet length	1.6 m
Helium space	2.0 m^3
Magnet lumped heat capacity (E in [J]), as a function of temperature (T in [K])	E= $5.7*10^5*T - 2.8*10^7$, 60 K ≤ T ≤ 100 K E= $44.94*T^{2.94}$, 4 K ≤ T ≤ 35 K
Composite former material (FRP) conductivity	0.11 W/m-K, 5 K ≤ T ≤ 25 K 0.32 W/m-K, 60 K ≤ T ≤ 80 K

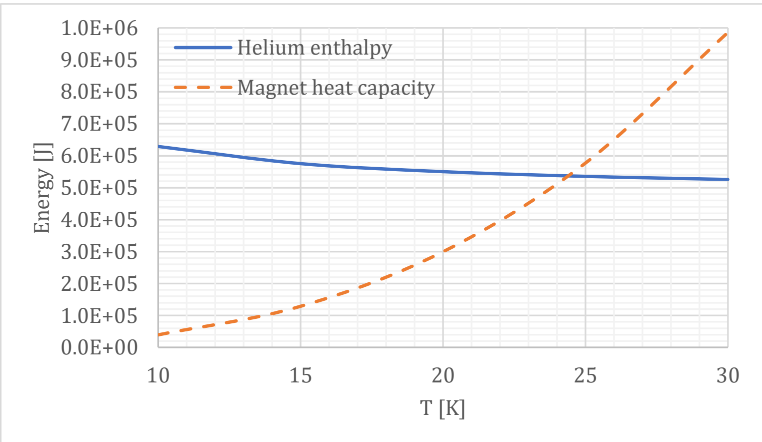

Figure 2. Helium enthalpy change during evacuation compared with heat capacity of magnet.

In Table 1, magnet lumped heat capacity, the same as internal energy, (E), is calculated from the integral $E = \int_{Tref}^{T} mCdT$ where m is mass, $Tref$ is reference temperature (4 K) and C is material heat capacity which depends on temperature. Since magnet material mass and temperature effect on heat capacity are included in this equation, total heat capacity of magnet (in Joule) at any

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temperature can be plotted against temperature to find the correlation given in Table 1. Consequently, one can calculate the change in internal energy of magnet between any two temperatures by taking the difference in E at those temperatures. Note that, similar approach is applied to helium enthalpy and nitrogen latent heat: fluid mass is calculated using magnet volume together with density obtained from starting fluid temperature and pressure information and is included in the total enthalpy of gas or latent heat of evaporation of liquid.

Evacuating cold helium gas out of magnet proves to be very useful as the change in the enthalpy of helium can provide enough cooling to bring magnet to 5 K from 25 K, assuming perfect heat exchange, Fig. 2. This can be very advantageous for a low cryogen magnet design that is precooled using a refrigerator or direct liquid helium cooling in a factory [4] as well as when combined with a single stage cryocooler whose performance vanishes below ~30 K when cooled outside factory.

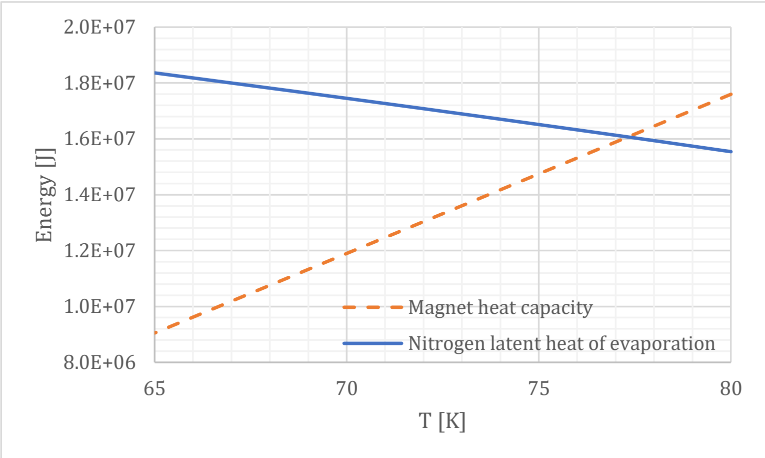

Figure 3. Nitrogen latent heat of evaporation extracted through pumping compared with heat capacity of magnet.

Nitrogen gas does not offer a similar benefit. However, evaporating liquid nitrogen out of magnet provides high cooling benefits. This case can be seen in Fig. 3 where 100 liters of liquid nitrogen at about 77 K is left inside magnet prior to evacuating all cryogen to reach target conditions. Evacuation will cool the magnet down to below 65K due to the extraction of large heat of evaporation of nitrogen which cools the magnet during this process.

4. Design of the integrated tool

4.1 Evacuation process

Lumped capacitance method is used to estimate the evacuation rate of helium gas out of magnet. The case of nitrogen is to be handled by adjusting the heat input to the gas and its flow rate, refer to the description of the tool.

The application of lumped capacitance method for evacuation of gas is justified by the fact that a slower pump down process is inherently more efficient as it allows more time for the gas-solid interaction as well as allowing more time to the solids to conduct heat internally leading to higher cooldown efficiency. Furthermore, magnets contain large quantities of copper-stabilized superconducting wire, which conducts heat internally very fast. In magnets where formers housing the coils are made of glass fibre – epoxy composites; solid conduction may be an issue. However, formers are relatively thin and are directly exposed to helium gas on one side, while in direct contact with superconducting wire on the other, which essentially makes the former being exposed to gas / vapor flow on both sides.

The Churchill and Bernstein correlation for Nusselt number for a round cylinder in cross flow is given by Eq. 1, [6], application of which to main and shield coil structures separately and forcing the maximum Biot number to stay at ≤0.1 to satisfy the lumped capacitance method yields the helium pressure – magnet temperature evolution curves given in Fig. 4. Perfect heat exchange between gas and solid is assumed with gas being 1.0 K lower than the solid during the cooldown process.

$$Nu = 0.3 + \frac{0.62Re^{1/2}Pr^{1/3}}{\left[1+(0.4/Pr)^{2/3}\right]^{1/4}}\left[1+\left(\frac{Re}{282000}\right)^{5/8}\right]^{4/5} \quad (1)$$

The cooldown time, which is the same as pump down time, is calculated using the time equation for lumped capacitance method, Eq. 2, where *T:* the final solid temperature, T_i: initial solid temperature, T_∞: gas temperature, *A:* surface area, *h:* heat transfer coefficient, and *ρVc:* change in enthalpy of solid, [7].

$$t = \frac{\rho V c}{hA} ln\left(\frac{T_i - T_\infty}{T - T_\infty}\right) \quad (2)$$

The evacuation time for a pump down starting at 22 K may be considered too long for a factory setting. Therefore, two more scenarios are studied: 1) evacuation starting at 15 K and perfect heat exchange, and 2) evacuation starting at 15 K with faster pump down. Note that adjusting the pump down speed is achieved with the exhaust valve included in the design. The resulting temperature – pressure evolution curves for these two cases as a function of pump down times are given in Fig. 5 and 6.

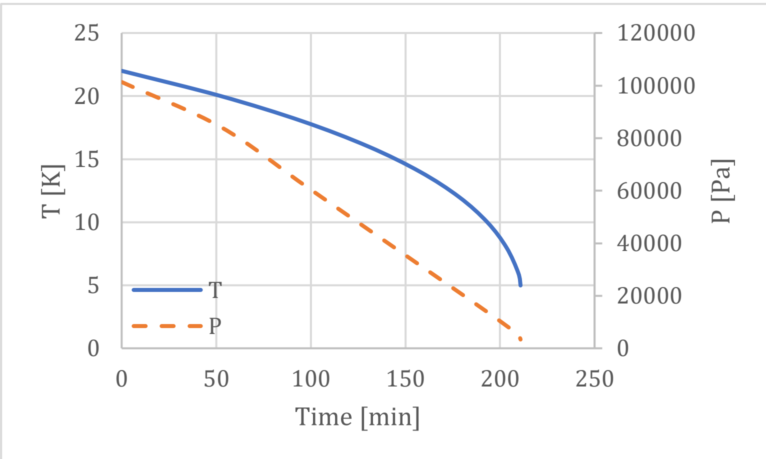

Figure 4. Evolution of pressure and temperature inside magnet for evacuation starting at 22 K.

There is still excess gas left inside magnet (as indicated by P) in the case given in Fig. 5 as perfect heat exchange is enforced for a pump down starting at lower temperature. A much faster pump down to reach the pressure – temperature targets may be more suitable for a factory where helium gas can be recovered, which is given in Fig. 6. In this case, the heat exchange efficiency between the gas and magnet is ~26%. Note that "efficiency" here is very loosely defined as the ratio of vapor mass evacuated during ideal evacuation (scenario #1, assumed to be 100% efficient) to the one that is evacuated during fast cool down (scenario #2) to reach the target pressure, i.e. impact on heat exchange is ignored, and total pump down time is kept the same as the ideal case. Consequently, compared to scenario #1, temperature profile remains the same while the pressure inside magnet reaches the target value.

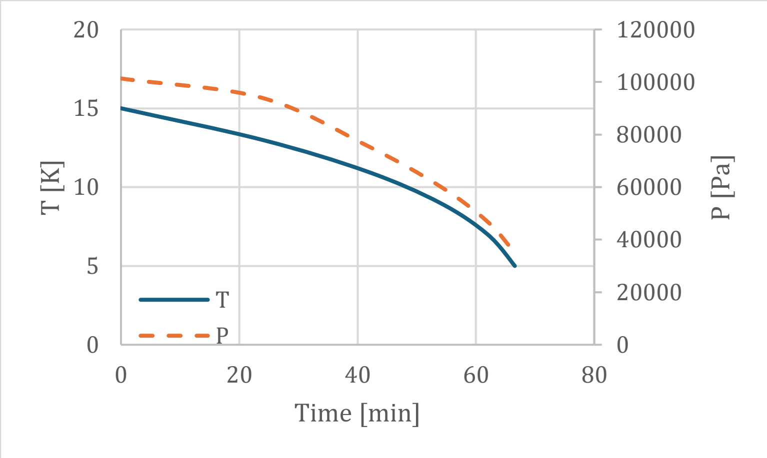

Figure 5. Evolution of pressure and temperature inside magnet for evacuation starting at 15 K, perfect case (scenario #1).

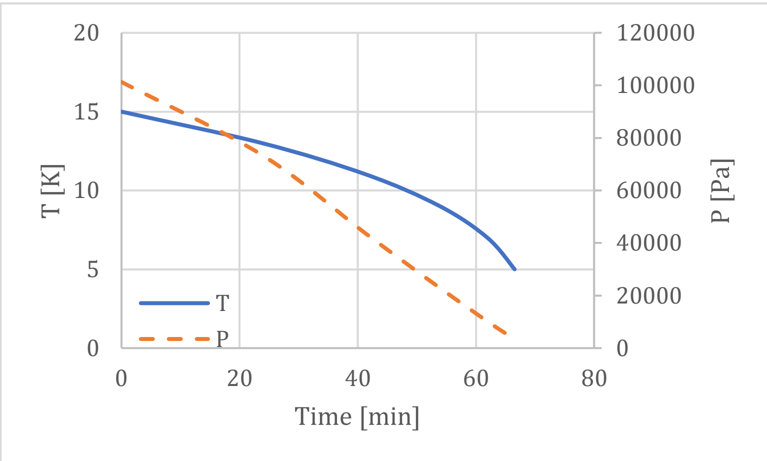

Figure 6. Evolution of pressure and temperature inside magnet for evacuation starting at 15 K, faster pump down (scenario #2).

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4.2 Mass flow rates

The mass flow rates through the tool for the three cases above are given in Fig. 7. The vapor / gas mass to cool magnet in between discreate temperature point pairs starting from initial condition in the ideal cases (100% efficient) is calculated using Eq. 1. Then, Eq. 2 is used to estimate the time that is necessary to cool magnet from one temperature to the next. Finally, the mass flow rate between the two discrete temperature points is calculated from these mass and time information. In the faster pump down case, the total time obtained in the ideal case is reinforced to increase the mass flow to satisfy the final pressure requirement.

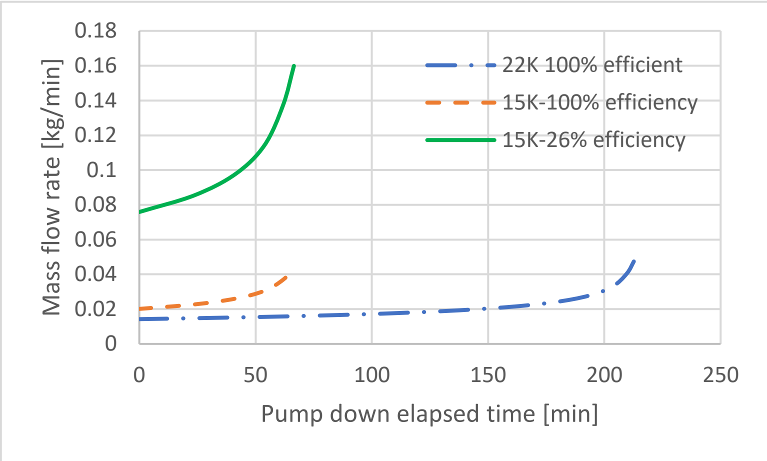

Figure 7. Mass flow rate through the tool depending on pump-down scenario

4.3 Heat exchanger

The heat exchanger is designed for the case of low efficiency (i.e. faster) evacuation where the pumping speed is much higher than ideal case. The requirement is that gas is warmed up to ≥280 K at the heat exchanger outlet.

The design has electric heaters to warm up the gas for maximum flexibility in controlling outlet temperature together with the exhaust valve flow controller, as well as minimizing the footprint. The flow conduit between magnet and vacuum tool and all internal piping on board the vacuum tool is assumed to be made of 25 mm diameter copper tubing. Connection between magnet and the tool is assumed to be vacuum jacketed and short enough to be ignored in calculations.

The heat exchanger consists of 5 m long, 25 mm diameter smooth copper pipe. The heat transfer inside the heat exchange pipe is calculated through the Gnielinski correlation for Nusselt number, Eq. 3, [8]. The friction coefficient is calculated using Petukhov correlation, Eq. 4, [9] Calculated minimum total heater power of 475 W is assumed to be distributed uniformly along the length.

$$Nu = \frac{(f/8)(Re-1000)Pr}{1+12.7(f/8)^{1/2}\left(Pr^{2/3}-1\right)} \tag{3}$$

$$f = (0.790 lnRe - 1.64)^{-2} \tag{4}$$

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4.4 Pumping speed

Pumping speed determines the minimum heater power in the heat exchanger. The state of helium gas between the magnet and the vacuum pump is in the continuum regime throughout the process as indicated by Knudsen number being much less than 1%, in the [$7*10^{-8}$-$2*10^{-4}$] range for all cases.

The throughput at the heat exchanger outlet varies in [735-1350] Pa-m^3/s range; while conductance (C_0) of the lines varies in [5-355] m^3/s range during the evacuation process. Using the faster pump down to reach to pressure target starting from 15K temperature, the system pumping speed (S_S) is calculated to be 108.5 m^3/hour, using Eq. 5 and Eq. 6. The corresponding minimum pump speed is calculated to be 112 m^3/hour, [10].

$$S_S = \left(\frac{V}{t_p}\right) ln\left(\frac{p_1}{p_2}\right) \tag{5}$$

$$\frac{1}{S_p} = \frac{1}{S_S} - \frac{1}{C_0} \tag{6}$$

where p_1 and p_2 initial and final pressures, respectively; V is the volume of gas to be pumped down at 280K heat exchanger outlet temperature and t_p is the target pump down time. In the analysis, constant pumping speed is assumed; however, in the real application, it may need to vary to satisfy the 280K heat exchanger outlet temperature.

Evacuating liquid nitrogen from ~77 K to 65 K with the system sized for helium is not detailed. However, an approximation yields that the minimum pump down time would be >2.3 hours, if the heater power in the heat exchanger is increased to ~3.5 kW.

5. Conclusions

A pump down station with integrated heat exchanger, flow control valve and control circuit is developed to evacuate superconducting MRI magnets during cooldown operations. The tool can be used for both cryogenic helium and nitrogen, and can be used in a factory, warehouse or hospital setting.

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