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CALCULATING THE MUON COOLING WITHIN A MICE SOLID AND LIQUID ABSORBER

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Abstract

The key elements of the Muon Ionization Cooling Experiment (MICE) [1] cooling channel are the absorbers that are a part of the MICE absorber focus coil modules (AFC modules). The boundaries of room temperature solid absorbers are well defined. The density of most solid absorber materials is also well understood. The properties of solid absorber are most certainly understood to 0.3 percent. The MICE liquid absorbers are different in that their dimensions are a function of the absorber temperature and the fluid pressure within the absorber. The second element in the liquid absorber is the variability of the liquid density with temperature and pressure. While one can determine the absorber boundary within 0.3 percent, the determination of the liquid density within 0.3 percent is more difficult (particularly with liquid helium in the absorber). This report presents a method of calculating absorber boundary and the cooling performance of the MICE absorbers as a function of fluid temperature and pressure.

INTRODUCTION

The key to cooling muons (reducing their emittance) within their lifetime (2.1 μs at rest) is to use ionization cooling [2]. When a muon enters a material, energy is lost along the track. This means that both longitudinal and transverse momentum is lost as the muon passes through the cooling material. If the muon is re-accelerated in the longitudinal direction using RF cavities, the loss of transverse momentum is retained and beam cooling has been achieved.

Coulomb scattering of the muon beam in the material counters the effect of cooling. If the emittance lost due to ionization along the track is greater than emittance gained due to scattering, net ionization cooling results. The key to ionization cooling is maximizing cooling while reducing scattering.

For rapid ionization cooling one needs strong focusing within the absorber volume, in order to achieve a low value of transverse beam beta. One also wants to have a high value of the radiation length, which implies that one wants to use a low Z material for doing the cooling. In general, cooling is proportional to the number of electrons in the atom. Coulomb scattering is proportional to the number of charged nucleons in the atom squared. Thus, it is clear that hydrogen (either in liquid form or as a dense gas) is the best material to use for ionization cooling. Table 1 compares the properties of a number of liquid and solid absorbers.

Table 1. A Comparison of Various Absorber Materials

Absorber Material	**dE/dx** (MeV g^{-1} cm^2)	**Cooling Factor**
LH_2 (20.3 K)	4.12	1.000
LHe (4.22 K)	1.94	0.524
LiH	1.89	~0.35
Li	1.65	0.268
Be	1.61	0.172
Polystyrene $(CH)^K$	2.09	~0.15
C (graphite)	1.78	~0.13
6061-Al	1.62	~0.05

The last column in Table 1 compares the relative emittance reduction to the equilibrium value (the value where coulomb scatting exactly matches the cooling term). From Table 1, one can see that hydrogen should be twice as good as any other cooling material. This is not completely true because liquid hydrogen must be in a leak tight container. Helium must also be contained. The container windows will reduce the relative performance of the two liquids.

How well one can predict the performance of an absorber depends on a number of factors [3]. These include: 1) the purity of the absorber material, 2) how well one knows the density of the material throughout its volume, and 3) how one knows the position of the absorber boundary with respect to the center of the focusing magnet. In general, to meet the experimental goals of MICE, one must know each of the factors to better than ±0.3 percent.

THE PERFORMANCE PREDICTION FOR MICE SOLID ABSORBERS

All of the solid absorber materials can be purchased with purities of better than 0.997 except possibly LiH. The density of solid absorber materials is uniform to better than ±0.3 percent except for LiH and possibly graphite (depending on how the graphite is made). One can determine the absorber boundaries of all of the absorber materials to better than ±0.3 percent. Lithium hydride and lithium must be in a can (probably made of aluminum). One knows the material in the can and the thickness of the can so one can predict the absorber performance with the can. Since the solid absorbers are at room temperature with small variations, their boundaries change less than ±0.3 percent.

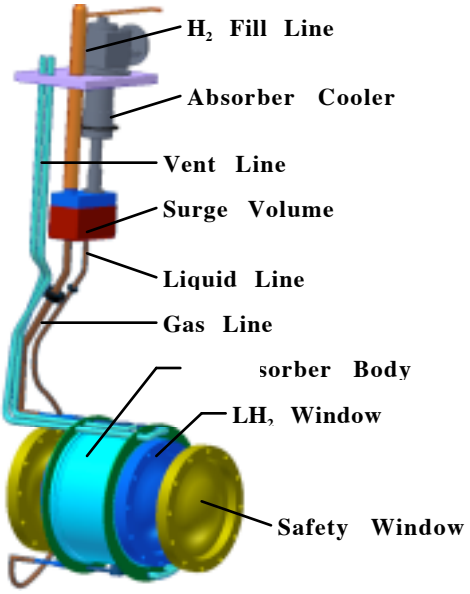

Figure 1. 3-dimensional view of the liquid absorber, its cooling system, and hydrogen (helium) supply system.

LIQUID ABSORBERS: THE PREDICTION OF THE ABSORBER BOUNDARIES

The liquid absorber [4], its thin windows [5] (including the safety windows), the piping, the surge volume and 1.5 W cooler are shown in Fig. 1. The hydrogen window separation is 350 mm, and the body diameter is 300 mm.

The prediction of the liquid absorber boundaries requires that one know the temperature of the container and the pressure within the container. The absorber container shrinks 0.425 percent when it is cooled from 293 K to 20 K [6]. Cooling from 20 K to 4 K will cause the container to shrink a further 0.001 percent. Since the body of the absorber is made from 6061-aluminum, the shrinkage is uniform in all directions. The thin windows on the absorber shrink with temperature in the same way as the absorber body.

Pressurization of the absorber body will cause it to grow in both the radial and longitudinal direction, because the outside of the absorber is in vacuum. In the radial direction, the absorber body will grow about 0.0048 mm (~0.003 percent) at a pressure of 0.12 MPa. In the length direction the absorber body will grow about 0.094 mm (~0.043 percent for a body length of 220 mm) at a pressure of 0.12 MPa.

The primary length change of the fluid in the absorber is the length change due to the deflection of the absorber windows. The window deflection in the longitudinal direction is a function of the pressure behind the window and the radial position along the window. The window deflection at the edge of the window (r = 150 mm) is essentially zero with respect to the absorber body. Fig. 2 shows the window deflection as a function of radius and pressure for the proposed MICE absorber windows. The safety windows do not deflect because the pressure differential across them is zero.

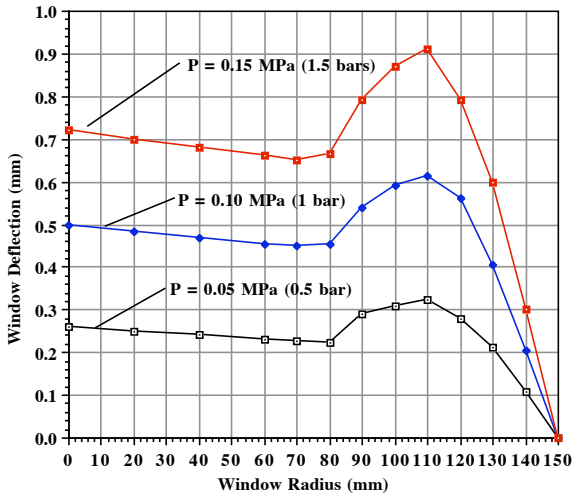

Figure 2. Absorber window deflection as a function of radius and pressure

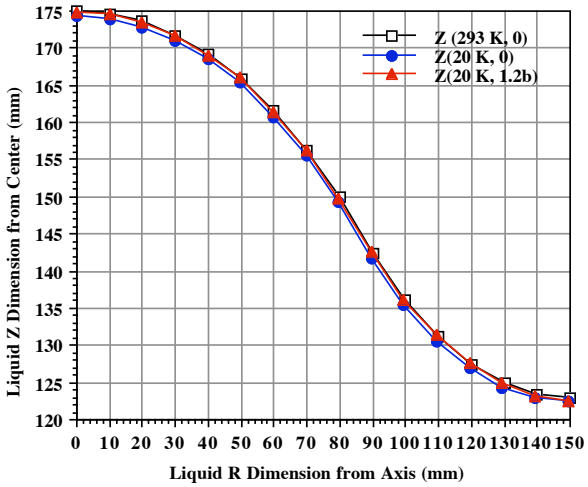

Figure 3. The absorber liquid boundary in the z direction as a function of radius and internal pressure.

The deflection of the absorber thin windows is nearly linear with pressure up to 0.15 MPa. The deflection was calculated using FEA. The FEA calculation of window deflections on the MUCOOL test 210 mm diameter windows agreed with measured deflection to within a few percent [7]. Fig 3 shows the inner position of the hydrogen windows at room temperature, at 20 K without added pressure, and at 20 K at a pressure of 0.12 MPa.

LIQUID ABSORBERS: THE PREDICTION OF THE FLUID DENSITY

The second part of the liquid absorber characterization problem is knowing the density of the hydrogen or helium in the liquid absorber. Fig. 4 shows density of liquid hydrogen at its saturated liquid pressure and at a pressure of 0.12 MPa (a pressurized absorber) as a function of the liquid temperature [8]. Fig. 5 shows density of liquid helium at its saturation pressure as a function of the liquid temperature [9].

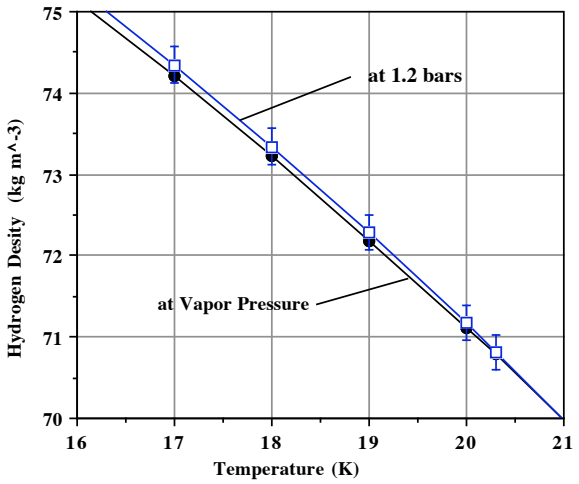

Figure 4. The density of liquid hydrogen as a function of temperature at its saturation pressure and at 0.12 MPa.

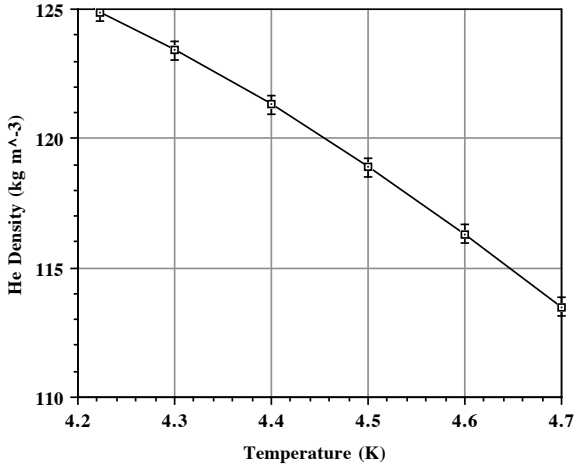

Figure 5. The density of liquid hydrogen as a function of temperature at its saturation pressure.

From Fig. 4, one knows the density of liquid hydrogen to 0.3 percent provided one knows the temperature to about ±300 mK. The density of liquid hydrogen is not very sensitive to pressure even at 17 K. One can measure the absolute temperature 20 K to better than ±100 mK with available sensors. It appears that a liquid hydrogen absorber can be characterized to ± 0.3 percent. Variations in density due to the pressure gradient across the absorber (~240 Pa) appear to be small. Variations in density due to the 0.7 W heat load through the insulation also appear to be small. Because the heat-load of 0.7 W is on the surface of the absorber, the formation of hydrogen bubbles is not expected to be a large factor.

From Fig. 5, one knows the density of liquid helium to ±0.3 percent provided one knows its temperature to ±20 mK. Absolute temperature measurements of ±20 mK are difficult to achieve at 4 K. Characterization of a liquid helium absorber to ±0.3 percent is much more difficult to achieve. The variations due to the pressure gradient across the absorber (~400 Pa) appear to be small. The heat flow into the absorber case is probably not a problem, but bubble formation may be a problem because more bubbles will be formed.

The liquid absorber characterization is complicated by the presence of a second set of safety windows located about 100 mm from the absorber windows. The second set of windows is identical to the first. In addition, there are four layers of multi-layer insulation (MLI) between the absorber windows and the safety windows. The second set of windows and the MLI are completely predictable.

CONCLUDING COMMENTS

Solid absorbers for MICE can be characterized to better than ±0.3 percent, with the possible exception of a lithium hydride absorber. Solid absorbers fabricated from beryllium, polystyrene, magnesium and aluminum can be accurately machined so that they can be characterized to better than ±0.1 percent.

Liquid hydrogen absorbers can be characterized to better than ±0.3 percent. Hydrogen absorbers can be fully characterized over a temperature range from 15 to 21 K and a pressure range from 0.01 to 0.14 MPa. Helium absorbers are difficult to characterize to ±0.3 percent. Helium absorbers are more affected by bubble formation than are liquid hydrogen absorbers.

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