Convection-Type LH_2 Absorber R&D for Muon Ionization Cooling

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Abstract

A feasibility study on the liquid hydrogen (LH_2) absorbers for muon ionization cooling are reported. In muon ionization cooling, a LH_2 absorber is required to have a high cooling power greater than 100 W to cool heat deposited by muons passing through. That heat in LH_2 can be removed at either external or internal heat exchangers which are cooled by cold helium gas. As one of the internal heat exchanger types, a convection-type absorber is proposed. In the convection-type absorber, heat is taken away by convection of LH_2 in the absorber. The heat exchanger efficiency for the convection-type absorber is calculated. A possible design is presented.

Key words: muon cooling, liquid hydrogen, energy absorber, ionization loss, convection

1 Introduction

It is required to construct a high intensity muon beam for future muon and neutrino factories. A high intensity muon beam could be cooled to reduce its beam emittance before its acceleration at the later stage. To do this, muon ionization cooling which consists of alternating energy absorbing by ionization loss and RF acceleration has been proposed, and its R&D is being pursued [1,2]. As an energy absorber, LH_2 is the most efficient material owing to its sufficient ionization loss and small multiple scattering. Multiple scattering of muons, as a heating process, could disturb the cooling performance, and therefore it should be minimized. Muons deposit energy in the LH_2 absorber by ionization loss, and this energy loss becomes heating in the liquid hydrogen. A muon beam of $10^{11} \sim 10^{12}$ ppp, 15 Hz, 100 $\sim$ 300 MeV could result in heating of $\sim$100 to 300 W for absorbers 20 to 35 cm in length. Then, the major issue of the LH_2 absorber R&D is how to remove this large heat deposit.

Two methods have been considered to cool this amount of heat. One is the forced flow cooling of LH_2. This method was successfully developed at SLAC for the LH_2 target using a cryogenic pump and an external heat exchanger [3]. The other method of cooling the LH_2 absorber is convection cooling with an internal heat exchanger. This report mainly focus on the convection-type LH_2 absorber.

2 Convection Type Absorber

2.1 Cooling Power and Cooling Condition

A flow diagram of the forced flow cooling is shown in Fig. 1. The SLAC LH_2 target was operated at 2 atm hydrogen pressure. For muon cooling, operating pressure has been planned at 1.2 atm to minimize the window thickness. The forced flow type is required to operate at safely at 1.2 atm operation. The convection type has a heat exchanger built in to the absorber as shown in Fig. 2. The convection type does not require a cryogenic pump and external LH_2 loop. The total LH_2 volume for the convection type is smaller than that of the forced flow type. This is important for the safety problems associated with a flammable gas like hydrogen.

The cooling power $\dot{Q}$ of the convection type can be calculated from the temperature difference dT as follows, if the pressure drop and latent heat of helium are neglected,

$$\dot{Q} = \dot{m}_{He} dH dT \tag{1}$$

where, $\dot{m}_{He}$ is a helium volume flow rate and dH is the helium enthalpy difference. For example, if the inlet temperature $T_{in} = 5$ K, the outlet temperature $T_{out} = 15$ K, and the muon heating $\dot{Q} = 100$ W, then $\dot{m}_{He}$ becomes 53 l/hr

in liquid. This flow rate and the cooling power are achievable by a standard refrigerator.

2.2 Indirect Heat Exchanger

We have considered two types of heat exchanger for the LH_2 convection absorber. One is a direct heat exchanger pass through in LH_2 as shown in Fig. 2. This heat exchanger is made from a metal tube with fins. The triple point of hydrogen is 13.8 K. In order to avoid hydrogen solidification, the temperature of the inlet helium gas should be kept higher than 13.8 K. Absorber cooling power is proportional to a temperature difference between the helium in and out. When the inlet helium temperature is high, a high helium flow rate is required.

The absorber with an indirect type heat exchanger is shown in Fig. 3. The heat conductivity of metal is on the order of $2 \sim 3$ times larger than LH_2 at 20 K. Under these conditions, the heat flow will diffuse along and around the absorber, and it does not make a cold spot in the absorber, which should be avoided to eliminate possible solidification of hydrogen. We can introduce helium gas at lower than 13.8 K, using this type heat exchanger.

Using a simple model, the heat transfer coefficient of heat exchanger is,

$$\frac{1}{A_{LH2}h_{LH2}} + \frac{dx}{A_w k_w} + \frac{1}{A_{He}h_{He}} \tag{2}$$

where A_{LH2} is the area of the LH_2-wall, A_w is the area of the wall, A_{He} is the areas of the wall-helium. h_{LH2} and h_{He} are the heat transfer coefficients of LH_2 and of helium, respectively. k_w is the heat conductivity of the wall material, and dx is its heat transfer thickness. Using a numerical value of h_{LH2}, h_{He}, k_w and $A_{LH2} = A_w = A_{He}$ and $dx = 0.1$ cm, for a direct heat exchanger of simple metal tube, the order of the ratio of these coefficients becomes

$$1 : 10^{-3} : 10^{-1}. \tag{3}$$

If fins are used on the wall, A_{LH2} will be improved about 10 times. Then the ratio of direct heat exchanger with fins is

$$10^{-1} : 10^{-3} : 10^{-1}. \tag{4}$$

For the indirect heat exchanger with fins, when dx is 1 cm for example,

$$10^{-1} : 10^{-2} : 10^{-1}. \tag{5}$$

Under these conditions, the heat transfer coefficient of the fin-type indirect heat exchanger (Eq. 5) is almost of the same order as that of the fin-type direct heat exchanger (Eq. 4).

2.3 Convection and Boiling Heat Transfer

In order to cool high heating power in excess of 100 W, transverse flow inside the LH_2 is very important. As long as the heat input is low, natural convection can take heat away to the cool wall of the absorber. The computational simulation of natural convection with beam heating has been performed. A heater at bottom may be able to help the natural convection when the beam heating is low. When the heating power becomes higher, bubbles are formed on the beam axis. Bubbles thus formed could enhance the heat transfer efficiency. Bubbles rise to the upper wall and stir LH_2. Then, bubbles accelerate the convection speed (boiling effect). In the case of liquid nitrogen and a hot wall, the heat flux with nucleation is about 10 times larger than without nucleation as shown in Fig. 4. The maximum heat flux from hot metal to LH_2 is about 0.1 W/cm^2 at 1 atm and temperature difference between wall and liquid is 0.55 K as shown in Fig. 5. These data suggest that beam heating of 300 W could be cooled with temperature difference of 0.55 K and heat transfer area of 0.3 m^2, if we accept bubble formation. The density fluctuation of LH_2 with bubble is about $1 \sim 2\%$. The effect on the muon beam is small because the intensity fluctuation is averaged over many absorbers. It is difficult to estimate the heat transfer with bubbles formed by high beam flux. In practice, we have to measure the LH_2 temperature with high intensity beam using the prototype absorber.

2.4 Design of Convection Type Absorber

The convection-type LH_2 absorber with indirect heat exchanger was designed as shown in Fig. 6. The absorber dimensions were designed for "SFOFO2" lattice of the Feasibility Study II neutrino factory design [4]. The SFOFO2 lattice is the latter part of the proposed muon cooling channel. It has 36 LH_2 absorbers alternating with RF cavities. Heating power to each absorber is about 100 W. The absorber diameter is 22 cm and its length is 21 cm. The absorber body and its windows will be made from aluminum alloy. The heat exchanger has 24 fins of 2 mm thickness, 2 mm pitch and 12 mm depth. The total heat exchange area is 1.7 m^2. The windows are carefully designed to minimize thickness [5]. The aluminum windows could disturb the muon cooling process owing to multiple scattering. A test cryostat for convection type absorber was constructed as Fig. 7. Cold helium gas is introduced continuously, cooling the absorber and radiation shield.

In summary, we have estimated and designed the test absorber of convection type. By adopting the indirect heat exchanger and boiling effect, we obtain enough heat exchange in a convection-type absorber to cool muon beam heating up to 300 W per absorber. This absorber and the cryostat will be used for tests with beam heating at KEK and FNAL in future.

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References

[1] C. M. Ankenbrandt *et al.*, Phys. Rev. ST Accel. Beams **2**, 081001 (1999)

[2] D. M. Kaplan, Nucl. Instrum. Meth. **A453**, 37 (2000)

[3] J. W. Mark, SLAC-PUB-3169 (1984); see also E. J. Beise *et al.*, Nucl. Instrum. Meth. **A378**, 383 (1996)

[4] "Feasibility Study-II of a Muon-Based Neutrino Source," S. Ozaki *et al.*, eds., June 14, 2001.

[5] D. M. Kaplan *et al.*, to be published in *Proceedings of the 2001 Particle Accelerator Conference, Chicago, Illinois, 2001.*

Figure Captions

Fig. 1: Flow diagram of forced-flow-type absorber

Fig. 2: Convection type absorber with direct heat exchanger

Fig. 3: Convection type absorber with indirect heat exchanger

Fig. 4: Heat flux data for LN_2. In this case, the heat flux with nucleation is about 10 times larger than with natural convection only. (In the region of $dT \geq 0.1$ K, this system became unstable because of film boiling.)

Fig. 5: Heat flux in LH_2; natural convection region is below the x-axis.

Fig. 6: Prototype design of convection type LH_2 absorber with indirect heat exchanger

Fig. 7: Test cryostat for convection type absorber